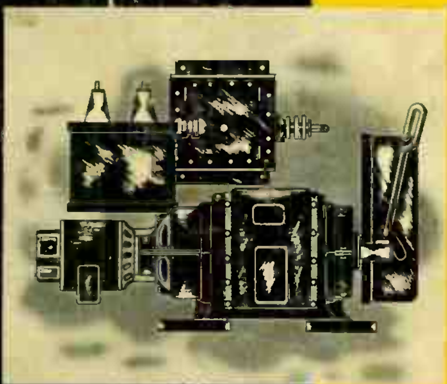
Learning

ELECTRICITY FUNDAMENTALS

by LEONARD R. CROW



The Fascinating Story of Electricity

Early Theories • Electron Theory • Static Electricity • Fundamentals • Fuses and Switches • Resistance • Ohm's Law • Magnetism • Electromagnetism • Power • Transformers • DC Generators and Motors • AC Generators and Motors • Circuits and Controls • Practical Wiring

A Howard W. Sams PHOTOFACT PUBLICATION • EFC-1

Learning
ELECTRICITY FUNDAMENTALS

by DONALD R. CROW

A *Howard W. Sams* PHOTOFACT PUBLICATION • EFC-1

Learning

ELECTRICITY FUNDAMENTALS

by

LEONARD R. CROW

Before one can hope to understand radio, television, radar, industrial electronics, or any of the other branches, he must first master the basic principles of electricity. This book strips electricity of its mysterious sounding terms, and explains its operation in simple and easily understood terms. The material covered by this book constitutes a must for anyone interested in learning the basic fundamentals of electricity, and also to those who wish to delve into the more complicated branches of electricity. It will prove equally useful for those who intend to confine their attention to such subjects as the operations and maintenance of electric motors, the maintenance and repair of ordinary household electrical appliances, and the wiring of homes and other places.

Mr. Crow, who also is the author of "Metallic Rectifiers Principles and Applications" published by Howard W. Sams & Co., Inc., has authored many books on the subject of electricity and is known extensively throughout scientific, educational, and military fields for his work in the design and development of electrical training aids. At the present time, he is Director of Research and Development of the Universal Scientific Co., Inc. He is eminently qualified, by virtue of his past experience, to present this clear and valuable text on the subject of Electricity.

Published by

HOWARD W. SAMS & CO., INC.

Indianapolis, Indiana

EFC-1
$5.95

Learning

ELECTRICITY FUNDAMENTALS

THE COMPLETE STORY OF BASIC ELECTRICITY IN SIMPLE TERMS

TABLE OF CONTENTS

Continued on back flap

CONTENTS (continued)

Published by

HOWARD W. SAMS & CO., INC.

$5.95

Learning ELECTRICITY FUNDAMENTALS

by

LEONARD R. CROW

Director of Research and Development,

Universal Scientific Co., Inc.

Author of

"Metallic Rectifiers Principles and Applications"

FIRST EDITION — FIRST PRINTING

MAY 1957

EFC-1

Printed in the United States of America

Published by

HOWARD W. SAMS & CO., INC., INDIANAPOLIS 5, INDIANA

A PHOTOFACT PUBLICATION

Library of Congress Catalog Card Number: 57-10481

PREFACE

The author of this book is convinced that the study of electricity is of more far reaching importance than any other subject in the field of science.

What would our everyday life be like without that all important invisible something we know as electricity?

Pause a moment and think of the multitude of useful appliances in our homes; the numerous and varied types of units used in transportation; the array of all the remarkable devices and means in communications, and a tremendously long list of other useful and important things, all of which would be inoperative and useless without that commonplace thing—electricity.

A study of electricity should begin with a straightforward attempt to understand the fundamental principles that underlie the construction and operation of the many electrical appliances, circuits, devices and machines that surround us on every hand. It is for this purpose that this book has been planned and developed.

The author is indebted to the General Electric Co. for their permission to quote, in two or three instances, from their excellent little booklet, "Romance of Electricity."

LEONARD R. CROW
Vincennes, Indiana

TABLE OF CONTENTS

CONTENTS—*continued*

CONTENTS—*continued*

Chapter 1

INTRODUCTION TO ELECTRICITY

THE STORY OF ELECTRICITY

Romance has to do with picturesque or adventurous scenes or incidents. Perhaps no story is more romantic than the story of electricity.

Static electricity, as such, does have importance and significance in the study of electricity and the historical development of science as we know it today.

Magnetism is very closely related to and directly associated with every electrical current regardless of how minute or how large that current may be. In fact electricity and magnetism are so closely associated that without one the other would be of comparatively little importance to man. In the study of electricity, we may well concern ourselves with a few fundamental facts about static electricity and a very complete discussion on magnetism and current electricity; therefore, our study of electricity begins as a three-part story.

One part had its origin, about 2500 years ago, on the shores of the Aegean Sea where Thales, philosopher of the golden age of Greece, absent mindedly stroked a carved and polished piece of iridescent amber. As he rubbed the fossil resin that had dripped, perhaps a million years earlier, from the trees of the vast forests along the Baltic, he made a discovery. He learned that when amber is rubbed it draws to itself light objects, such as lint, chaff, and feathers.

Another part of the story began when someone, perhaps in China, found that certain dark and heavy stones have the power of attracting, even of lifting, pieces of iron. These stones, by virtue of their strange property, were called loadstones—natural magnets.

The third part of the story of electricity is older yet, for it began when Adam and Eve watched, in fearful admiration, the sharp tongues of lightning lick across the sky.

Centuries passed—the age of Aristotle in Greece, of Pliny in Rome, of Roger Bacon, and the Middle Ages. The Renaissance swept across Europe; and science, which had all but stood still for a millennium, began to stir. Men in their newfound courage began to experiment.

Queen Elizabeth's physician, probing the mysteries of the loadstone, discovered in it the basic principles of what we today call magnetism. This same man, William Gilbert, repeating the experiments of Thales, drew on the old Greek word for amber, elektron, to coin the now familiar word electricity.

Experiments came faster now in all branches of science. Galileo working with his telescope proved the earth revolved around the sun. Harvey discovered the circulation of the blood, and Newton discovered the law of gravity.

In 1752, at Philadelphia, Benjamin Franklin flew a kite to draw down the lightning of the sky and prove it blood brother to the electricity made by rubbing amber. Thus, we have two of the three important characters in the story of electricity.

In Italy, Professor Galvani watched frogs' legs twitch and kick when two unlike metals touched them. Another Italian, Alessandro Volta, applied this discovery with a disk of copper, a disk of zinc, and a piece of paper moistened with acid between them. Thus, he constructed the Voltaic pile, the first electric battery, the first really *new* way of making electricity since old Thales rubbed amber in 600 B.C. With the development of the battery, electricity was at last freed from its static prison and, like an invisible fluid, could flow wherever wires would lead it.

In Denmark, Hans Christian Oersted was experimenting with one of Volta's new batteries. He passed electricity from it through a wire. He then brought a magnetic compass near the wire, and the restless needle, forsaking its relentless search for north, was deflected. He reversed the direction of the electric current, and again the needle was deflected, but this time in the opposite direction. With this experiment the third original actor in the story of electricity fell into line. Lightning had been proved to be electricity, and now Oersted showed that electricity in motion produces magnetism.

Such was the state of knowledge about electricity when, in 1831, two scientists—Michael Farady, at the Royal Institution in England, and Joseph Henry, at the Albany Academy in America—performed independently the experiment that showed that when a piece of conductive metal is moved in the field of influence of a magnet, an electric current is produced in the metal. This third method of making electricity opened the way for most of the marvels which are performed by this mysterious force today.

The rest is modern history. Edison, in 1879, constructed the first successful incandescent lamp. Edison, Thomson, Brush, and a score of other eager experimenters developed dynamos to generate electricity and systems to utilize it—discovering, improving, and expanding so that each year's progress far outstripped the last. Stanley and his transformer, Sprague and his motors, and Steinmetz and his mathematical wizardry broadened the applications of electricity and turned a temperamental art into an exact science.

Through the contributions of thousands of inventors, scientists, and engineers, electricity came of age. It grew and spread its network of wires across the land. It found new and bigger jobs to do—lighting homes and highways, turning the wheels of industry, hauling trains over land, and driving ships at sea. It found its voice in the telephone and the radio. It made the invisible visible. It put on the apron and cap of the housemaid and took over the tasks of washing and cleaning in millions of homes. It produced heat in electric ranges and cold in electric refrigerators. Steadily, year by year, electricity has found new fields of usefulness.

Not all the romance of electricity is in the story of its pioneers, nor in the adventures of scientists probing the invisible worlds of electrons. Some of its most romantic aspects lie in the work-a-day tasks performed by the power companies in maintaining electric service which we accept as a matter of course, but which we depend upon every hour of the night and day.

There is romance in the great turbines and generators, in the network of transmission lines, in the safeguards that surround them, in lamps, heaters and motors, even in such humble accessories as wires, fuses, and switches. There is adventure in tracing electricity from its source to our homes where it performs a multitude of services. This is the real, the vital story of electricity as it affects our lives.

Stretch out your hand to intercept a beam of sunlight. It feels warm, does it not? No wonder, for only a little more than eight minutes ago it left the blinding-hot surface of a middle-aged star, the sun. Yet in that eight minutes it has traversed 93 million miles of cold and emptiness on its way to warm your skin, to cause the flowers to bloom, and to produce the light in your living room.

Now whether your electricity comes from waterpower or from coal, it is captured sunlight just the same. The rays that warm your hand are falling, at any one time, on half the earth. They fall on lakes and rivers, on swamps and oceans. Whatever they touch, they warm. At the magic touch of this sunlight invisible vapors or ghostly mists arise—the waters that are tomorrow's clouds and next week's rains.

As Solomon wrote twenty-nine centuries ago, "All the rivers run into the sea; yet the sea is not full; unto the place whence the rivers come, thither they return again." Back to the hills goes the water, falling as rain to follow its destiny downward, ever downward. Trickles become rivulets; rivulets become brooks; and brooks become rivers. In due time, the water that sunlight pumped up from the lowlands is knocking at the floodgates of the powerhouse, ready to turn its sun-born energy into light in your favorite reading lamp or into the brown crispness of your breakfast toast.

"But," you say, "what if the electricity I use comes from steam power produced by burning coal?" True enough, nearly three-quarters of all America's electrical power is produced that way. Still you are, or should be, a sun worshiper. For that coal, too, is packaged sunlight that fell on this earth millions of years ago.

We do not know exactly how long ago coal began to form or exactly what were the processes that made it. We are sure that far back in the geologic period scientists call the Carboniferous Age, sunlight streamed down upon the upturned green foliage of vast tropical forests performing the same magic that it does today—transforming air and water and carbon dioxide gas into starch and cellulose, chemical compounds that contain carbon.

Ages passed. Untold generations of trees sprouted, grew, and died in the steaming jungles. Underfoot there accumulated a vast treasure of this carbon that had been trapped by the sun.

What happened then we do not know for certain. Climates changed, continents sank beneath the sea, and strange monsters appeared, walked the earth for a space and then vanished. Mountain ranges were heaved upward and were, in their turn, worn down to valleys. Deep in the earth mysterious chemical changes occurred, which combined with immense pressures to transform the one-time trunks and branches of the rank jungle forests into the coal we mine today. It heats our homes, runs our railroads, and provides the bulk of our electric power. Every so often someone finds in a piece of this coal the print of its origin—the shape of a leaf that, millions of years ago, reached upward toward the sky for its share of the life-giving, energy producing sunlight.

Tonight, when your hand goes out to the electric switch, you are in touch with something cosmic. It is more than a mere mechanical gadget that makes and breaks a circuit. It is a gate through which transmuted sunlight, the bounty from nature's eternal powerhouse, enters your home.

Mysterious stuff—electricity! Invisible, yet it can give us light with all the colors of the rainbow. Weightless, yet the invisible magic of its magnetic field can lift and haul loads weighing thousands of tons. It occupies no space, yet it permeates all space and all things. What is it?

The answer is, "Even after more than 2,500 years, we do not know exactly what electricity is." We know only some of the things it does, and some of the ways to produce it. These we have known for only a relatively short time. About 120 years ago an ex-bookbinder's apprentice in London and a schoolmaster in Albany Academy were worrying about the same problem. Neither knew what the other was doing—in fact Michael Faraday in England had probably never heard of Joseph Henry in America; but each of them, at about the same time, performed similar experiments. You can see the result of their experiments in any electric power station, and you can experience it any time you turn on an electric switch. These two men discovered the principle of the electric dynamo.

You can perform that pioneer experiment yourself. All you need is a length of copper wire and a toy magnet. First, wind the wire into a cylindrical coil and fasten the ends together. Then push the magnet into the coil. As you do it, a pulse of electricity will be generated. Pull the magnet out. At that instant another pulse of electricity will be generated, this one flowing in the opposite direction. Imagine yourself repeating this process at the fantastic speed of sixty times a second. Then you'll be generating sixty-cycle current—the same kind that comes over our power lines.

How much current would you be producing? Ah, there is the rub! No matter how diligently you worked your home-made generator, you couldn't generate enough electricity to cause the filament of the tiniest flashlight bulb to glow a dull red. Electricity is power, and its takes power to make power. You can't get something for nothing; the world isn't built that way.

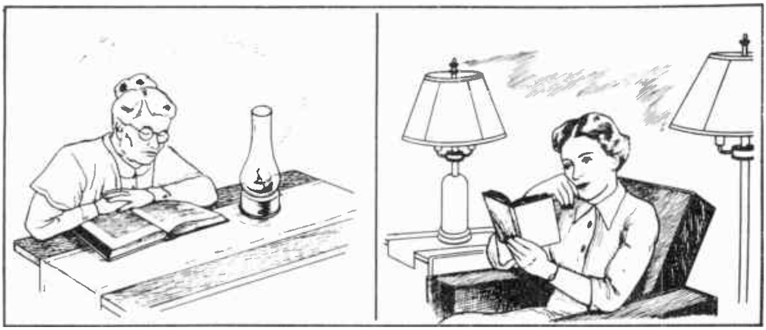
It is a far cry from Faraday's and Henry's coils and magnets to the great generators that produce today's electrical power. Just to collect the materials from them is an adventure in itself. Copper, iron, cotton, aluminum, mica, gums, and asphalt, to name a few, are used in the construction of such generators. Copper has to be drawn into wire and formed into coils. Iron has to be alloyed with a dozen other elements, cast into molds, machined into shape, forged into shafts, rolled into sheets, and punched in intricate patterns. When the parts are made and dozens of skilled hands with an accuracy that rivals a watchmaker's art, have fitted them together with a compactness that shames a jigsaw puzzle, the adventure has just begun.

Then the real miracle occurs. Power is supplied by a waterwheel or steam turbine. The giant rotor, weighing many tons, begins to turn slowly at first, then faster. A sound becomes audible—at first only a faint hum, and then slowly rising to a high-pitched whine. There is no smoke, no confusion, no spectacular shower of sparks; but something that did not exist before is being produced. There, in the spinning rotor and the heavy coils of the stator, electricity is being generated. Electricity that, an instant later, is turning a lathe in a nearby factory, cooking dinner in a house on the other side of town, pumping water, and running a milking machine on a farm far off across the hills.

About seventy years have passed since the first crude electric generators began to sing their song of power. There were only a few at first, only enough to provide the power for one or two arc lamps here and a few of Edison's little incandescent lamps there. How their music has grown. Today, in more than twenty-seven million homes and countless factories and offices, wires are attuned to their singing, wires that draw from the electric generators of the nation, power equal to the plunging strength of seventy million horses. You reach out your hand and touch a switch; the power is there. It is there waiting, because back in the powerhouse coils of wire are working magic with magnets.

When grandpa was a boy there was much more drudgery and toil in his life than we know today. He had very few of the conveniences we have these days.

If he wished to read a newspaper or a book in the evening after his day's work was done, he did so by the quavering, fitfull light of a drippy tallow candle. Or, if his family was one of those fortunate few, he touched a lighted match to the wick of one of the new-fangled kerosene lamps. At that time there were very



Electricity provides us with light today, but grandma used whatever was available.

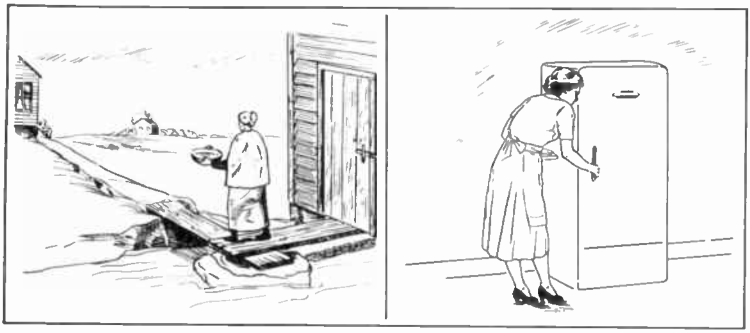
few places in the world which boasted a supply of electric power sufficient to operate the really new incandescent electric lamps.

When grandma prepared to do the weekly family wash, the chances are she took it down to the bank of the nearest creek. There she built a fire under the big, fat, black-bottomed iron kettle to boil the clothes and get out the dirt. She had no gleaming electric washing machine, such as nearly every home possesses these days.

Ironing and pressing those clothes was another big day's work. To do that job, grandma had to build a big fire in the range and then put her array of pressing irons on the stove to heat. In the hot days of summer, ironing clothes was real drudgery, because grandma did not have an electric pressing iron or mangle as her modern granddaughter has.

Grandma resorted to a variety of methods to keep her food cool between meals and to keep her butter from turning to oil. One

Grandma had no labor-saving automatic washing machine as her granddaughter has.



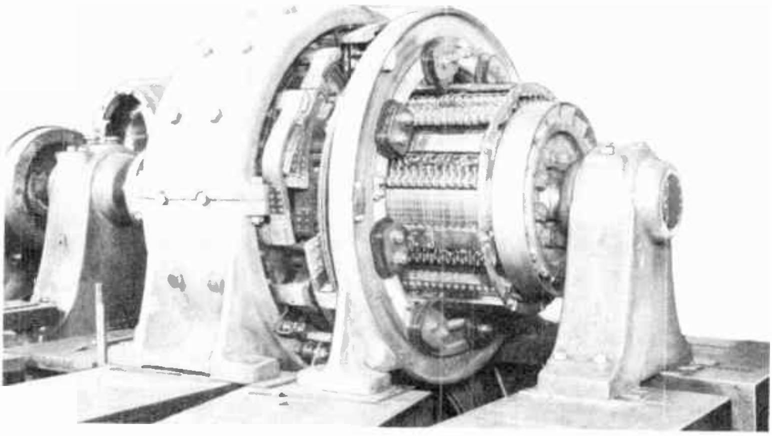
Modern electric refrigerators are a far cry from grandma's cooling system.

of the favorite methods, especially in the rural areas, was to build a little "milk-house" or "spring house" across a small running brook or over the outlet of a flowing spring. That was her system of refrigeration. She had no electric refrigerator, and such a thing as a deep freeze wasn't even dreamed of.

Electricity and its ability to serve mankind have become so great a part of our modern way of life that it is often difficult for us to realize just how recently this modern genie has been harnessed to serve us. While it is true that scientists and researchers were experimenting with electricity as far back as the days of Benjamin Franklin, it is also true that it was not until the invention of the telegraph by Samuel F. B. Morse that man actually succeeded in putting electricity to doing some kind of practical work. Even now only a little more than 100 years have passed since the telegraph was invented. The first message was sent over a telegraph wire just about fifteen years before the American Civil War broke out.

Almost thirty years passed after that before any other really practical use was found for electricity. Then Alexander Graham Bell was successful in electrically transmitting the spoken voices over a wire. This was a number of years before Thomas Edison succeeded in making a reasonable satisfactory incandescent electric lamp.

It is a somewhat general practice today to trace the birth of the Electrical Age back to Edison's invention of the incandescent lamp. There is good reason for so doing. It was his invention of the lamp that made necessary, for the first time, some kind of electric power generating machinery capable of generating more power than could be produced by chemical batteries which were then the only source of electrical energy. After inventing the incandescent lamp, Edison found it necessary to invent a dynamo to generate the power his customers needed to operate their lamps; and with its invention the Electrical Age quickly came into existence.



A large DC generator. (Courtesy Allis-Chalmers Mfg. Co.)

THE EARLY DAYS OF PRACTICAL ELECTRICITY

In his youth Edison was a telegraph operator. It was while learning telegraphy and the duties connected with an old-time operator's job that he really became interested in the possibilities of electricity. At that time the only reliable source of electrical energy was the crude "electric cells" used in telegraph work. They were adequate for that work, but their usefulness was definitely limited in a number of ways which will be discussed when we get a little farther along.

The chemical interaction between various metals and a liquid solution produced a kind of electric current which continually traveled in one direction. When Edison invented his dynamo to provide the large amounts of power called for by the use of his incandescent lamps, he built a machine which could generate the same kind of electricity as that produced by the chemical cells—which generate an electric current that always flows through a conducting wire in one direction.

Because this kind of current always flows in the same direction, it is referred to as *direct current*. Direct current is still used for many purposes. Some of our street cars and interurban railway systems use direct current as their source of power. Several of the large transcontinental railroads which have electrified their tracks through the mountains use direct current as their source of power.

The use of direct current plays a vital role in our daily lives. The electric systems of our automobiles all employ direct current. The reason for this is that the electric storage battery, which is often referred to as the heart of the system, is a direct current source. Practically all our flashlights are battery-powered and, as such, use direct current.

We find enormous quantities of direct current used in the refining of several kinds of metals. The refining of aluminum is an example, but only one. In a modern aluminum plant as much direct current electricity will be used each day as would meet the electrical requirements of an average small-size city.

In our modern world we often find low-priced metals with decorative outer coverings of some more expensive metal. The bright shiny trim on many of our automobiles is actually steel or brass covered with a thin coating of chromium. Our so-called "silverware" is often steel or other inexpensive metal covered with a thin plating of silver. There are many other similar examples.

The placing of a thin coating of expensive metal upon a base of less expensive metal is usually accomplished by a process known as *electroplating.* In electroplating an electric current is caused to flow through a liquid solution containing the expensive metal. The electric current causes the expensive metal to be deposited on the less expensive metal when the current enters the less expensive metal. Large quantities of direct current are needed to operate the huge electro-plating plants we have these days.

Because Edison invented a very effective type of dynamo to generate direct current and because he had a considerable investment in the usefulness of direct current electricity, he was always a very strong advocate of direct current power systems. In fact, in the early years of the Electrical Age, the only kind of electricity in existence was direct current.

As the need grew for electric power and it became necessary to transmit it over increasingly greater distances, certain limitations in the use of direct current electric power became evident. With these things in mind, electrical experimenters began searching for some other form of electrical power which would permit its use at greater distances from the dynamo, or electrical *generator* as the machine became more widely known.

After a period of several years engineers and experimenters became convinced that another form of electrical current would probably be more useful than the existing direct current. Strangely enough, the new kind of electrical current with which they were experimenting did not flow continuously in the same direction as did the familiar direct current. Instead, it flowed back and forth through the wires, first in one direction and then in the other.

Edison violently opposed any deviation from his established system of direct current distribution, but the other groups of electrical men were insistent that their kind of electrical power was more useful than Edison's direct current.

The dispute between the two groups remained in the talking state until the proposition was advanced that some of the tremendous energy of the falling water at Niagra Falls be harnessed and converted into electrical power. Edison proposed the installation of direct current generators. The other electrical men pointed out there was only a limited use for the enormous quantities of electrical energy that could be generated, or at least there was only a limited use for the power within the short distance that Edison could transmit his direct current. One group contended they could generate their new kind of electrical power (alternating current) and transmit it economically for many miles.

It was about this time that a newcomer in the electrical field entered the controversy. This was George Westinghouse, who had already made quite a name for himself in other fields. He offered to build the new kind of power generator and demonstrate that its power was practical, and had points of superiority over direct current.

Thus the newer kind of electric current, which we know so familiarly today as *alternating current*, came into existence in the American way of life. Since that beginning, alternating current has shown so many points of superiority over direct current that about 95% of all the electric power generated and distributed in this country today is in the form of alternating current, often abbreviated AC.

From this it might be thought that direct current is passing out of the picture, and that there is no reason for studying or understanding its peculiarities and the laws governing its production and use. This is not true, and such an idea is very misleading. Despite the fact that nearly all electric power is generated and distributed in the form of AC, there are a great many special jobs which only DC can do. For this reason we often find that power is transmitted to a job or location in the form of AC and then converted into DC to do that particular job.

SOME RECENT DEVELOPMENTS IN THE WORLD OF ELECTRICITY

Electricity has advanced a long way since its humble beginning as a worker in the everyday life of our country. The crude open "wet cell" batteries that were once so closely associated with telegraph systems have virtually passed out of existence. They are today little more than museum pieces. In fact telegraphy itself, as it was known for three-quarters of a century, has almost passed out of existence, and its place has been taken by teletype, radio, and telephone.

Many other fields have sprung into being, all of which owe their existence directly to electricity. Some of these offsprings are becoming so mighty in their own right that they almost ignore their parentage. It is a little difficult to realize that they are only a part of the ever-expanding field of electricity. While each of them is only a part of the field of electricity, it must also be recognized that some of these branches have grown to such gigantic size that each is now worthy of being treated as a separate subject.

Radio and electronics have grown to such huge proportions that it is scarcely possible for any one person to keep up with all the advances and changes taking place. Radio and electronics are merely branches of the ever expanding field of electricity.

The same is true of television, so much in the public eye today. Fantastic sums of money are being spent on the various branches of television. Yet television is only a branch or small part of electronics, which in turn, is only a small part of the broad field of electricity.

The electronic control of many industrial processes about which we read so much these days is another specialized branch of the wide field of practical electricity. Some of the activities of electronic control seem to verge so close to the magical that we often forget that electronics is only one of the many branches of electricity. When we read of burglars being trapped by an invisible beam of light, of how our army snipers can observe the activities of the enemy through electronic viewers without the enemy being aware; of how our giant bombers can drop their bombs from tremendous heights and pinpoint their target without ever actually seeing it; and of our Navy sending giant flying missiles over hundreds of miles against an invisible enemy; all these things being done through the magic of electricity, we can begin to appreciate how far we have come from the crude tele-these developments represents a specialized branch of electricity, all of these things are part and parcel of practical electricity.

Radar, the all-seeing electronic eye about which such a web of mystery has been woven, is a specialized product of the electronics branch of electricity. It was born out of necessity during the war but has since grown to occupy an accepted place in the field of commercial navigation and aviation. It has become indispensable for landing aircraft during bad weather and for guiding sea-going vessels through treacherous waters.

These many branches have one thing in common: each is a branch of electricity and is bound by the natural physical laws that govern electrical phenomena, and each responds to the laws man has learned to use in harnessing electricity itself. Before one can hope to understand radio, television, radar, industrial electronics, or any of the other branches, he must first master the basic principles of electricity. The natural physical laws which govern the flow of electric current in a wire also govern the action of electricity in its other forms.

The purpose of this book is to explain these basic principles of electricity in a manner that is easily understood. We hope to strip electricity of its mysterious sounding terms and to explain its operation in simple terms.

We feel certain that the material covered by this book constitutes a must for those who wish to delve into the more complicated branches of electricity. We believe it will prove equally useful for those who intend to confine their attention to the more prosaic activities of electricity, such as those which relate to the operation and maintenance of electric motors, the maintenance and repair of ordinary household electrical appliances, and the wiring of homes and other places. It is the intention of this book to dispel the mystery which continues to cloak the action of electricity in electrical conductors and to make it easily understood.

Chapter 2

ELECTRON THEORY

EARLY THEORIES ON ELECTRICITY

In times past several theories or explanations have been offered by investigators and experimenters in electricity to explain its nature. One was the early *"two fluid" theory* which maintained that certain substances possessed two kinds of mysterious invisible fluids that could flow from one place or object to another. If the object had more of one kind of "fluid" than of the other, it was "charged" as we now say; but if it contained both kinds of fluid in equal amounts or had neither kind, it was neutral. This theory was based entirely on what was known at that time about static electricity. Current electricity was then unknown.

Later Benjamin Franklin, an early American scientist, became very interested in static electricity and gave it considerable study. As the results of his experiments, he concluded there was only one kind of electric fluid, and he proceeded to develop the "one fluid" theory. He believed that when an object contained too much of this electric fluid, it was, what he chose to call, "positive" in charge. If it had lost some or did not have enough, he called it "negative" in charge. But if it had a normal amount, it was "neutral," or not charged at all.

He also believed the fluid would "flow" from an object or place that had "too much" (positive charge) to one that had "too little" (negative charge). We still use these terms but their meaning has been changed somewhat. Franklin's one-fluid theory seemed to account for all the facts then known about the behavior of electricity and was so simple and direct that it was generally adopted by the scientists of the time. Nothing was yet explained about the cause or nature of electricity or what it was that flowed. No conclusive proof of his theory or of the older theory could be offered. However, they were workable theories, formulated from experimental observation and study, and constitute an early example of the use of the "Scientific Method."

Man's adoption of the "Scientific Method" of experiment, study, and evaluation, as opposed to the previous "Witchcraft-Metaphysical Method," marked the dawn of modern science.

ELECTRON DISCOVERED

Finally, about the end of the last century and some 150 years after Franklin's time, the electron was discovered by Sir J. J. Thomson, an English physicist. This was revolutionary, one of the greatest scientific discoveries of all time, an adventure into the unknown. Along with X-ray, radioactivity and related phenomena, discovered about the same time, it changed the whole scientific world's way of thinking. His discovery pointed the way to modern chemistry, electronics, atomic energy, and other wonderful developments of the last 50 years. Never before had science and industry advanced so rapidly or produced so much.

Franklin might possibly have discovered the electron if an invention used by Thomson had been available. This was a device invented by Heinrich Geissler and known as a "Geissler" tube. It consists of a glass tube from which the air may be pumped.

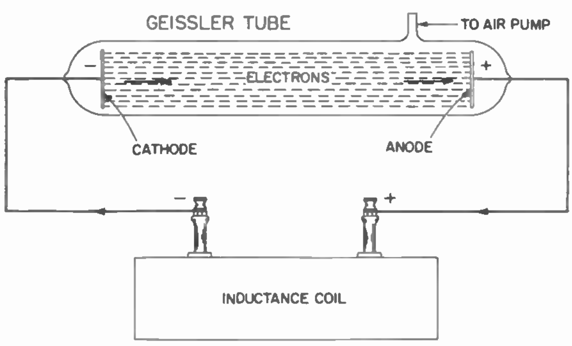


Fig. 2-1. Franklin might have discovered the electron if the Geissler tube had been known in his time.

This tube is diagrammed in Fig. 2-1. Sealed inside the tube at each end is a metal plate connected by a wire to a source of high-voltage electricity, usually an induction coil. Before the air pump is started nothing happens when the induction coil is operated because the air at atmospheric pressure offers such high resistance that no current flows between the plates. As the air is pumped out the resistance drops until it reaches a point where *current can jump the gap.* Something (although invisible) actually flows in a stream through the remaining air in the tube from the negative plate to the positive plate. Investigation by Thomson and others proved that this stream was made of tiny particles, uniform in size and *negative* in charge. He named them electrons and showed that they constituted an electric current when in motion and a static charge when standing still. You may be interested in learning more of the details about the Geissler tube and these epoch making experiments from other books.

ELECTRON THEORY

Fluid theories of electricity were soon discarded in favor of the electron theory. Stating in elementary form and omitting nuclear structure for the sake of simplicity, one may say the electron theory holds that all matter is made up of three kinds of particles within the atom. They are called *electrons, protons,* and *neutrons.* Electrons carry a negative charge and protons, a positive charge, but neutrons have no charge at all. They are neutral particles and so far as known do not enter into ordinary electrical activity such as we are considering; for that reason neutrons will be largely disregarded in this book.

Although all electrons are alike and all protons are alike, electrons and protons are not like each other. Some important facts about them are:

1. Electrons and protons (negative and positive charges) attract each other with very strong forces. But electrons repel electrons and protons repel protons. It also happens that either a positive or a negative charge will attract a neutral (uncharged) object. All this may be summed up in the statement: "Like charges repel, unlike charges attract." This is one of the fundamental laws of electricity.

2. The protons of an atom are packed closely together at its center, called the nucleus, while the electrons revolve around the nucleus in circular or elliptical paths at terrific speeds. Much as the planets of our solar system revolve in their orbits around the sun, these "electron planets" revolve about a "nucleus sun." Fig. 2-2 shows in a general way how this may occur in a 4-electron, 4-proton atom. We are indebted to Neils Bohr, famous Danish scientist, for this simple picture of the atom.

3. All electrons possess the *same negative charge,* while all protons possess an equal *positive charge.* Their charges are equal and opposite, therefore they exactly neutralize each

other, so that the normal atom is balanced in charge and neutral. This is the usual condition of atoms.

4. Protons are much smaller and heavier than electrons. Both are very tiny compared to the size of the atom, so tiny that billions of them could be assembled on the point of a pin and never be seen.

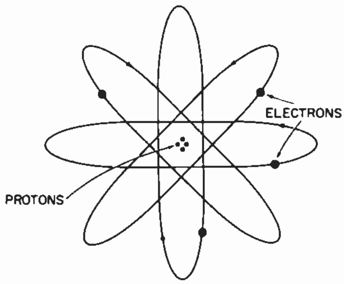


Fig. 2-2. Showing in a general way how the electrons revolve around the nucleus (protons) in a 4-electron, 4-proton atom.

There are between 90 and 100 elements (pure substances). There are also many artificial elements, man-made and not occurring in nature, that have been produced in connection with atom-bomb manufacture. Each element has a kind of atom different from that of its nearest neighbor by one electron and one proton. (The variation in neutrons is neglected here.) Beginning with a table of the elements, Hydrogen comes first, with one electron and one proton in each atom. It is the lightest known element. Next comes Helium with two electrons and two protons. The next element, Lithium has three of each; the next Beryllium, four of each and so on down the list. A Copper atom has 29 protons and 29 electrons, while Nickel, which is next above copper in the table, has 28 of each and Zinc, next below copper, has 30 of each. Thus it goes down to Uranium, the largest and heaviest natural atom, having 92 electrons and 92 protons. Uranium also has 146 neutrons which are useful in atom "splitting" but not in ordinary electrical phenomena.

The dense nucleus or central core shown in the drawings of Fig. 2-3, contains all the protons. Around the nucleus, the electrons, indicated by small circles with negative or minus signs, revolve in orbital paths. These drawings may make it appear that all electrons revolve in one plane. That is not true. There may be, and usually are, *as many orbits as there are electrons,* all revolving in different directions. See Fig. 2-2. Since this is difficult to show on flat paper, the circles are usually used. These circles show the number of electrons in each layer or "shell" of the atom.

Each shell is spaced at a fixed distance from the nucleus. The number of shells, their distance from the nucleus, and the arrangement of electrons in each shell is always the same in atoms

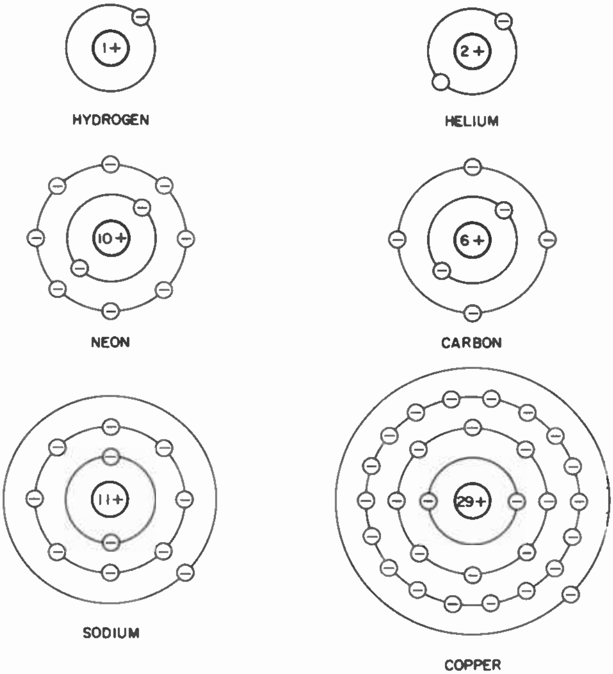


Fig. 2-3. The dense nucleus (center) of the six elements shown contains the protons around which the electrons revolve.

of the same kind. Atoms also differ in ways not mentioned here, but to name them all would take us beyond the scope of this book. You may be interested in studying the subject further in other books. The main point to remember here is that all atoms contain protons and electrons, that are positively and negatively charged.

ELECTRICAL NATURE OF MATTER

All substances are either pure elements, mixtures, or compounds. Atoms of each element group together to form molecules of that element. Compounds are the result of combination of certain amounts of two or more elements caused by the expenditure of energy in some form. There are thousands of compounds all around us. The molecules of an element are made up of only one kind of atoms. Atoms are the smallest particles into which an element can be divided and still retain its original identity. In all compounds *different kinds of atoms* (atoms of different elements), are joined together to form a molecule. The smallest particles into which a compound can be divided are molecules. If this division is carried farther, that is, if these molecules are broken up, the compound is destroyed, leaving only its various atoms. Water and common table salt are examples of compounds. In water two atoms of hydrogen (H) and one of oxygen (O) combine to form a water molecule (H_2O). In common table salt an atom of sodium (Na) and one of chlorine (Cl) combine to form a molecule of sodium chloride (NaCl). Breaking down (decomposing) water molecules results in nothing resembling water, but in two gasses, hydrogen and oxygen; breaking down salt molecules would give a solid, sodium and a gas, chlorine.

Not everything containing two or more elements is a compound. When many of the elements are mixed, they do not combine into a compound; but result in a mixture. In a mixture, the original materials do not lose their identity although the outward appearance is different. Bread is an example.

Some molecules are very complex and contain several kinds of atoms, often in large numbers. Examples of these are many drugs, chemicals, and the tissues of plants. Chemists deal largely with molecules, tearing them down and rebuilding them in different combinations to make new materials or to improve old ones. Thus many synthetic materials have come into being. Plastics and several new fabrics of nylon, spun glass, etc. are recent examples.

Since each molecule is composed of atoms and atoms in turn are made up of electrons, as previously explained, it turns out *that all matter is electrical in composition.* That is why the discovery of the electron unlocked one of nature's greatest secrets and brought us untold benefits.

STATIC CHARGES

The term "static" means standing still or at rest. A static charge, therefore, is generally at rest, standing still on the surface of an object. Tests show that static charges are never found on the interior of objects, even if hollow, but always on the outer surfaces. They move easily upon the surfaces of conductors, such as metals, and become quite evenly distributed over the flat and smooth, rounded surfaces of metal objects; but they become concentrated at points, corners, and sharp edges to such an extent that they rapidly leak off into the surrounding air. On insulators, however, static charges usually remain where they are formed until they dissipate into the air, since electrons cannot easily travel over the surface of or through insulating materials.

CREATING A STATIC CHARGE

Normally every atom has the same number of electrons in its orbits as there are protons in the nucleus, and it is electrically balanced, neither negative nor positive in charge, but neutral. If an object composed of such atoms were touched, no shock would be received, because no electrons would flow from the object into the hand, which is also normally neutral. But let every atom in an object, or many of them, gain an electron, by contact or otherwise from an outside source, and the *object will have an excess of electrons and be charged negatively.* These excess electrons will collect on the surface of the object and remain at rest there unless conducted off. This charge, standing still, is a "static" charge and a shock may now be received by a person touching the object, because the excess electrons will *flow from it to the hand.* If the number of these electrons is great enough, a perceptible shock will be felt.

A charged condition would also occur if the object were *robbed of electrons,* but it would then have a *positive charge.* Since protons are located at the centers of atoms and are so tightly bound there, they cannot escape unless the atom is split. Every atom that loses an electron or two has more protons than electrons left behind. This *excess of protons* gives every such atom and the object of which it is a part, a *positive charge.* If this object is now touched, a shock may be felt because electrons will *flow to it from the hand.*

ELECTRIC CURRENT

Although "static" electricity and "current" electricity may seem to be two different kinds they are really the same. Both consist of electric charges. *Static stands still* and does nothing. It is useless. *Current moves and does work.* It is very beneficial.

As an experiment, place on metal ball A (Fig. 2-4) a negative charge consisting of several billion electrons more than A would have normally. Then, by means of a fine wire connect A to ball B, also made of metal, which has a much smaller negative charge than A. Immediately part of the charge will flow from A along the wire to B and add to its charge. That is, the charge will divide between A and B, A losing electrons and B gaining electrons. The charge on both will still be negative, but less intense because it now covers and is distributed over a larger surface.

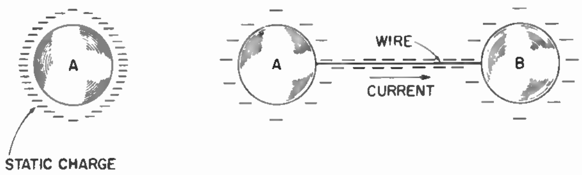


Fig. 2-4. By means of a small wire, a negative charge placed on metal ball (A) may be imparted to ball (B) to give it a charge.

On the other hand, if a positive charge is placed on A and the wire is now connected from A to B, electrons will flow the other way from negative B to positive A. In both cases a static charge causes a current of electrons to flow along the wire. While the electrons are at rest, they are static; when moving, they are current. This point should be remembered.

Chapter 3

STATIC ELECTRICITY

Electricity is generally considered as existing in two forms, static (stationary) and current (moving). In certain respects they are similar, both being due to electron activity and the forces and energies in electric fields, but they differ in behavior and usefulness. Ordinarily, static electricity is of little or no practical value, only a nuisance. It is usually very high in voltage, difficult to control, discharges in a fraction of a second, and then it is done. Current electricity may easily be controlled, may be generated at a moderate voltage, flows continually, and delivers energy that may be made to do useful work rapidly or slowly, as desired.

The statement made above regarding static electricity being of little or no value must be qualified somewhat, inasmuch as capacitors (often called condensers) are used extensively for holding or storing static charges of electricity. A few of the many applications are:

1. Capacitors used commercially for power-factor correction.
2. Capacitors used in radio transmitters and receivers.
3. Capacitors used in television.
4. Capacitors used in various commercial and industrial electronic equipments.

Here again the static electricity stored as a charge within the capacitor accomplishes no useful work. Only while moving to or from the capacitor through the circuit devices or components as current electricity does it do useful work or accomplish useful effects.

Much has been learned from experiments with static electricity. In acient times and up to about a century and a half ago it was the only kind known. Famous names are connected with its history. Among them are William Gilbert, who named it; Otto Van Guericke, who made the first machine for producing it; and our own American scientist, Benjamin Franklin, who, by flying a kite in a thunderstorm, proved that lightning was electricity. Franklin also proposed the terms *positive* and *negative,* which we still use.

In a study of static electricity, we learn something of the nature of electric charges (electrons and protons) that will help in understanding such practical devices as electron tubes, radio, television, and even electric current itself! In all our work with static electricity, an important law must be kept in mind. It is "Like charges repel each other; unlike charges attract." This is a fundamental law which helps one to explain mysteries and to understand facts.

Since there is an equal number of protons and electrons in a normal atom, the positive and negative charges are balanced and the atom as a whole is neutral. If electrons are added or removed in some fashion, the balance is upset and the atom exhibits a charge. When electrons are removed, an atom acquires a positive charge, since the protons all remain within the nucleus from which they cannot escape. When electrons are added to a normal atom, it acquires a negative charge, because its electrons then outnumber the protons. Many or all the atoms of an object may lose or acquire electrons simultaneously, thus causing the entire object to become charged so that a person gets a shock by touching it. This is due to the fact that the excess electrons in attempting to equalize the charge will suddenly flow to or from the hand in sufficient numbers to cause pain.

The law of attraction and repulsion just mentioned applies in every case of electrification and in every electric circuit. The forces of repulsion existing between free electrons and also between unneutralized protons are truly enormous compared to the size of the particles themselves. The force of attraction between protons and electrons is equally great. For example, it has been estimated that if two globules of *free electrons* the size of *small marbles could be placed one foot apart,* as shown in Fig. 3-1, they would repel each other with the tremendous force of 350 trillion tons. Also if one globule were made up of protons and the other of electrons, the attraction between them would equal this same enormous force.

Experiments with static electricity are often unsatisfactory when conducted in the warm, humid atmosphere of summer. That is because heated, moist air is a partial conductor, and electrons that make up a charge dissipate as fast as the charge is accumulated. On cool winter days, especially when the air is dry, static charges do not scatter so rapidly into space but stay longer where formed. That is why experiments with static electricity prove more successful in winter. At that time of year after a person has acquired a charge by walking across a wool rug,

Fig. 3-1. Two globules of free electrons the size of small marbles placed one foot apart would repel each other with the tremendous force of 350 trillion tons.

a surprisingly long spark may jump from his hand to a metal object such as a water faucet or a door knob. A rubber balloon, after being rubbed on a woolen sweater and placed against the ceiling or wall of a room, may cling there for hours before falling.

Fig. 3-2 is a photograph showing 7 toy rubber balloons which the experimenter rubbed briskly on his woolen coat sleeve on a cold winter day, when the air of the room was quite dry. The static electrical charge thus imparted to the balloons was sufficient to cause them to be forcefully attracted to the wall as shown. In this particular instance the balloons clung to the wall approximately 18 hours before they began falling off.

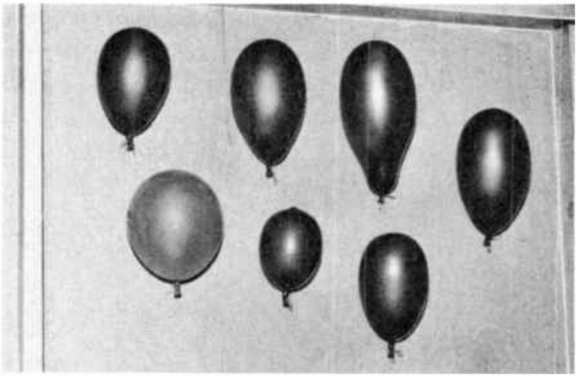


Fig. 3-2. A static charge imparted to the rubber balloons causes them to be attracted to a dry wall.

CHARGING BY FRICTION

Static charges may be produced in three ways: by *contact,* by *friction,* and by *induction* or influence. The friction method is must common, many examples occurring in everyday life. If a cat's back is stroked in dry, cold weather, small sparks of electricity will discharge with a crackling sound. If one's hair is combed when dry, it may fly about as if alive, and the rubber or plastic comb will attract bits of paper, lint, or feathers. When a toy balloon is rubbed with a woolen cloth or a cat's skin, both the fur and the balloon become charged, the fur positively and the balloon negatively, due to electrons from the fur collecting on the balloon. Likewise, if a glass rod is rubbed with silk, it will give up electrons to the silk. The charge on the glass will then be positive; that on the silk, negative. Thus static charges (electrification) may be produced by friction of unlike substances.

The materials just mentioned are among the best for the purpose, but, when conditions are right, any material, including metals, may be electrified by this method. Important conditions are a dry atmosphere, a fairly low temperature, and, in the case of conductors, complete insulation from the earth and from one's own body. Charging by contact and by induction will be explained, later.

CONDUCTORS AND INSULATORS

From the electrical viewpoint, materials may be divided into two classes, *conductors and insulators.* Most metals, some nonmetals, and a few liquids are termed conductors because of the fact that electrons pass through and over them easily. If a conducting object is charged at some certain point, the charge instantly spreads out and may even leak off to one's body or to the earth through a conducting path. Just touching such an object at any small spot with the finger will carry off the whole charge. Not knowing this, the ancients believed metals could not be electrified. They probably held them in their hands, and the charges quickly passed off through their bodies to the earth. Had they held them by means of a wood handle or other nonconductor, as in the case of the electrophorus in Fig. 3-13, electrification would have been successful.

Insulators are very poor conductors, which inhibit the free movement of electrons and confine a charge largely to the spot where it is formed. That explains why the ancients believed only certain materials, such as amber, sealing wax, fur, glass, porcelain and dry wood, were "electrified." Rubber, the plastics, most oils, and quite a few other materials may now be added to the list. If one of these insulators is charged at some certain spot, the charge remains there. It does not spread all over the object or leak off easily. About the only way it can disappear is to disperse into the air or be wiped off with the hand or a moist cloth. It should be remembered that there is no "perfect" insulator for electricity.

PITH BALL ELECTROSCOPE

Electric charges may be identified and their forces of attraction and repulsion observed by means of an electroscope. Fig. 3-3, illustrates the pith-ball type. It is made by suspending a small ball 1/4 or 1/2 inch in diameter made of elder or cornstalk pith from an insulated support by a fine silk or other insulative thread. A small cork or a table tennis ball may be substituted for the pith. Covering the ball or cork with aluminum foil or paint will improve it.

Charging is done by *contact;* that is, the charged object is *touched to the ball.* This contact gives the ball a *like charge,* the same as that on the object. Discharging is done by *contacting the ball* with the hand, an act which permits the charge to flow off to one's body and hence to the earth.

When making experiments with an electroscope one should remember several points: (1) Like charges repel each other; unlike charges attract. (2) Neutral objects are attracted by charged objects. (3) A toy balloon, a rod of hard rubber, sealing wax or other resinous material, *will become charged negatively when rubbed with fur or a woolen cloth,* while the fur or wool takes on a positive charge. (4) A *positive charge* will be placed on a *glass or porcelain rod* (vitreous material) *when it is rubbed with a silk cloth, the cloth* then acquiring a negative charge. By knowing these points, we can tell what kind of charge is being placed by contact on the electroscope. Now for some experiments.

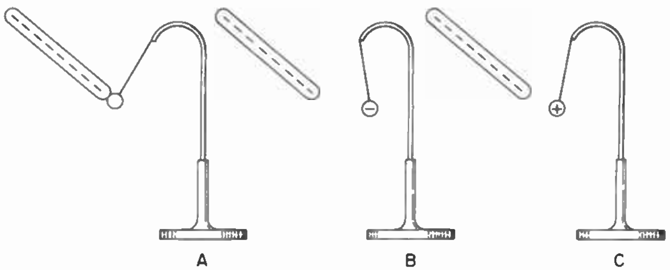


Fig. 3-3. Placing a charge on a pith ball electroscope. Electric charges may be identified and their forces of attraction and repulsion observed.

Experiment 1—Rub a rod of hard rubber or sealing wax with fur or a woolen cloth and bring it near an uncharged (neutral) pith ball, as in Fig. 3-3A. The ball is attracted and will swing over to *contact* the rod. It takes on a *like charge and is then repelled*, as in Fig. 3-3B. On the other hand, if the ball has already received a *positive charge* from a glass or porcelain rod rubbed with silk, it will be attracted by the (negative) rubber rod, as in Fig. 3-3C.

Experiment 2—If two pith balls are used, the same law applies. When the two are uncharged or neutral, they hang inert, as in Fig. 3-4A, neither one attracting or repelling the other. But if *unlike* charges are placed on them, they *attract*, as at B, and if charged *alike* as at C, they *repel*.

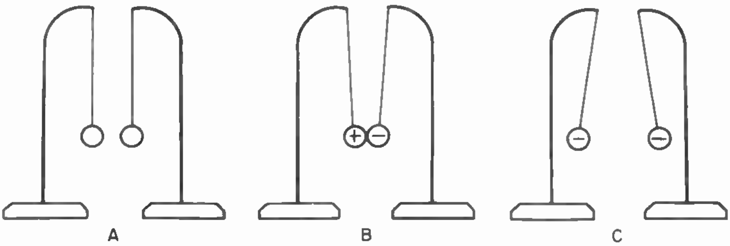


Fig. 3-4. If two pith balls are used, the same law of attraction and repulsion applies.

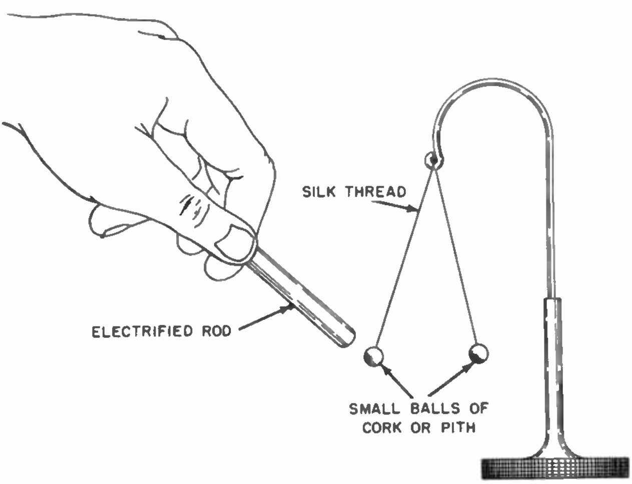


Fig. 3-5. A modified form of pith ball electroscope.

Experiment 3—A similar experiment is illustrated in Fig. 3-5. Hang the two pith balls, uncharged, from a single support and bring up the charged rod. Both balls will be attracted. Then, as they touch the rod and become charged *alike,* they repel each other and the rod as shown in the figure.

Experiment 4—Still another method of performing this experiment is to use two toy balloons instead of pith balls. Rubbing them with fur or wool gives them strong negative charges, and they will actively repel each other. If one is charged and the other is neutral, a weak attraction for each other will be observed. If each is charged separately, they will cling to a wall, a ceiling, an outstretched arm or another object.

CHARGED AND NEUTRAL OBJECTS ATTRACT

Why a charged object attracts a neutral object but does not repel it is explained by Fig. 3-6. There the object, B, a metal bar, contains just enough electrons to balance its protons, so is neutral. If it is mounted on an insulating stand or suspended by a silk thread, no electrons may leave or enter. It being a solid conductor,

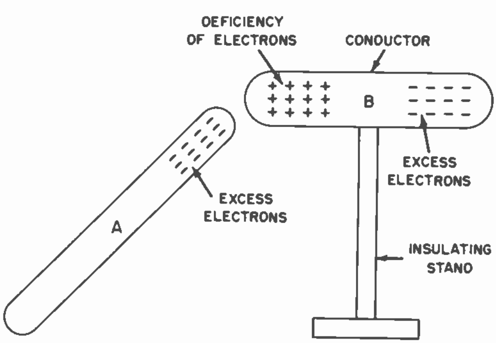


Fig. 3-6. Charged and neutral objects attract.

electrons may move about on it or through it, but protons cannot since they are tighty bound within the atoms of the material. Now bring up a charged object A, which may be a rod of hard rubber or sealing wax rubbed with wool or fur. Do not touch A and B together. Here the law of attraction and repulsion comes into action; like charges repel; unlike, attract. A, negative in charge because of excess electrons collected from the fur, repels free electrons in conductor B toward the far end, leaving the protons behind unneutralized. This has the effect of a positive charge on the near end of B, which naturally attracts the negative charge on A. If A is then removed, the displaced electrons in B return to their former places, making B neutral once more.

FOIL ELECTROSCOPE

An electroscope, shown in Fig. 3-7, consists of a strip of aluminum foil or gold leaf glued at its midpoint to a metal wire bent at a right angle. The foil forms two "leaves" about 1 inch long hanging from the rod. At the top is a metal knob or disk. The

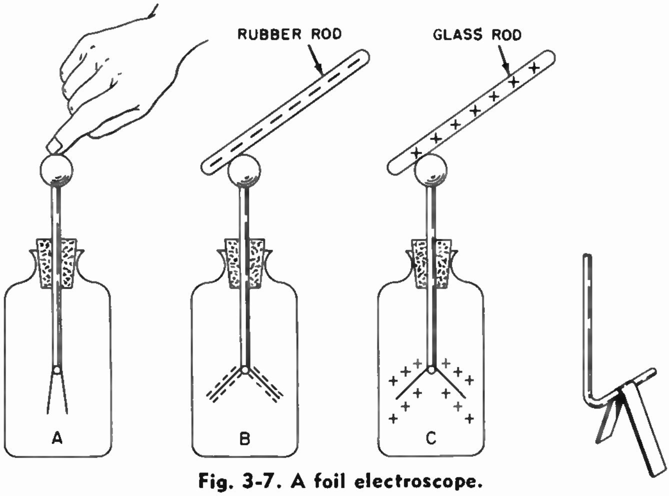


Fig. 3-7. A foil electroscope.

rod runs down through the stopper of a glass jar or flask, so the leaves inside will be protected from air currents. This electroscope is very sensitive and is generally preferred to pith balls. Charging may be done by *contact* or *induction,* as explained later. When charged, the leaves swing apart since both are charged alike and repel each other. Removing the charge by touching the knob with the hand causes the leaves to drop.

Charging by Contact—To charge by contact, first discharge the electroscope by touching with the hand, as at A, Fig. 3-7. Then touch the knob with a charged rubber rod which has been rubbed with fur or a woolen cloth. This places on the knob an *excess of electrons* (negative charge), which flows down the metal rod to the eaves, as at B, giving them a negative charge also. They repel and fly wide apart. After discharging by touching with the finger, one may give the electroscope a *positive charge* by contacting the knob with a *glass rod* which has been *rubbed with silk,* as shown at C. The leaves have now been *robbed of electrons,* but protons have been left behind. The leaves again diverge, both being charged alike. It should be noted that *charging by contact gives a charge like* that on the charging rod.

The insert in this figure is an enlarged view of the bent wire holding the metal foil.

Charging by Induction—To charge by *induction,* the charged rubber rod is *brought near* the knob of the electroscope, *but not in contact.* This is shown at A in Fig. 3-8. According to the law of repulsion, the negative charge on the rod *repels the free* electrons in the knob driving them down to the leaves of foil, and the leaves spread apart. However, if the knob is touched with the finger while the charged rod is held near, as shown at B, the free electrons are *driven off through the hand,* instead of down to the leaves, which now become neutral. Then if the finger

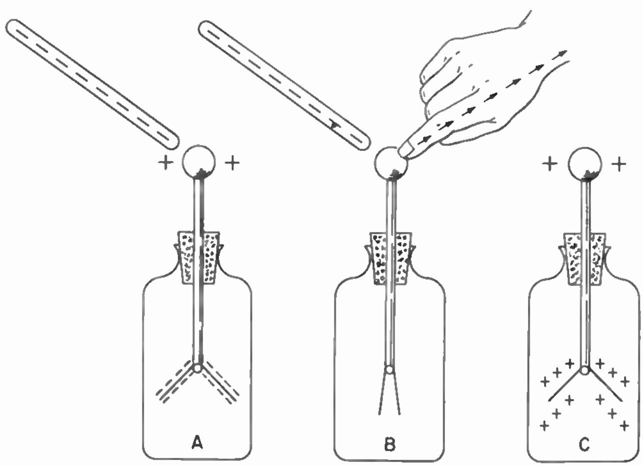


Fig. 3-8. Charging by induction.

is removed before removing the charged rod, electrons that have been driven off cannot return. So due to a difficiency of electrons, a *positive charge* is left on the electroscope. The leaves diverge and remain so until discharged.

If the same procedure is followed while using a *glass rod charged positively,* the final charge on the electroscope will be *negative.* Note that *charging by induction* gives a polarity charge *opposite* to that on the charging rod.

Proof Plane—Sometimes intense charges encountered in static electricity are so strong they tear off the leaves of an electroscope. In testing such charges, it may be best to use a *proof plane* in order to carry only a small charge to the electroscope. See Fig. 3-9. A *proof plane* is also useful in exploring parts of charged objects not accessible to the electroscope itself, such as the metal cylinder and conical bag of Fig. 3-10. The proof plane of Fig. 3-9 may be made by cementing a metal disk about the size of a copper cent to a slender glass rod or tube. It is used to pick up a *charge by contact* from a *charged surface* and to transfer it to an electroscope, either by contact or induction.

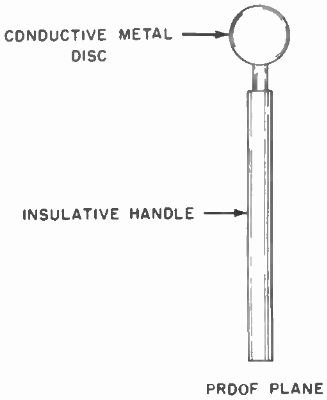


Fig. 3-9. A proof plane.

Charge on Surface—As previously mentioned, a static charge rests on the outer surface of an object, not on the inside or permeating through it. This may be verified by numerous tests and is true for both conductors and insulators. For example, if a hollow cylinder is mounted on an insulating stand, as in Fig. 3-10A and a charge is placed upon it from a static machine or other source, testing with a proof plane and electroscope will reveal that the charge is entirely on the outer surface. Also, if a charge is placed on the linen bag of Fig. 3-10B, testing will show that the charge is on the outside. Even if the bag is charged and then turned inside out by pulling on the silk thread, the charge will be found on the outside. We are assured by scientists that a person is safe from lightning if he stays inside an automobile, because the steel body acts like the hollow clyinder mentioned above. The charge acts only on the outer surface of the car and will not be felt by the occupants within.

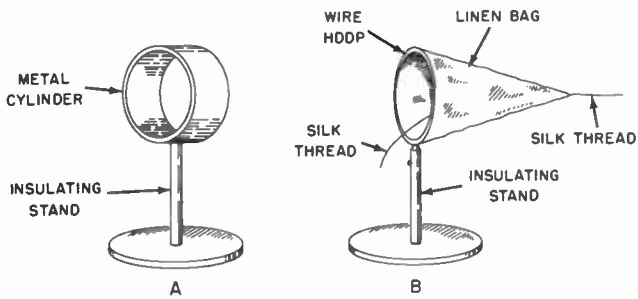


Fig. 3-10. A static charge is entirely on the outside surface of a metal cylinder or tube.

FIELD OF FORCE

The region or space surrounding and between charged bodies, in which their forces of attraction and repulsion act, is called an *electrostatic field* or simply an *electric field.* It is in some respects similar to, but not at all the same as, the magnetic field surrounding a magnet. Both can exist in and act through free space and even a vacuum. Energy may be transmitted by such fields of force through space in the form of waves, as in radio and the sun's heat and light.

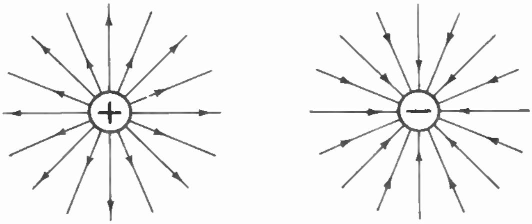
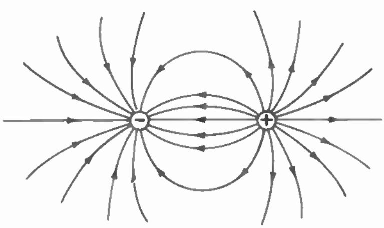
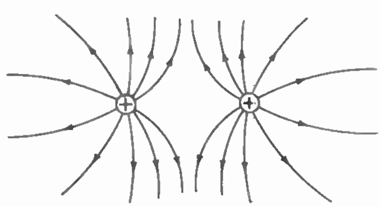


Fig. 3-11. The direction of electric fields about isolated positive and negative charges of static electricity.

In order that electric fields may be visualized, they are often represented by *lines of force,* which indicate both intensity and direction of the force and the general shape of the field. Direction is indicated by arrow heads and intensity or strength by the density of the lines or the number of lines per unit area. A method arbitrarily agreed upon by scientists uses a small positive charge to test direction. It gives the direction of the field as being away from a positive charge (source) and toward a negative charge. This is the direction a positive test charge would travel according to the law that like charges repel and unlike charges attract. Fig. 3-11 shows the direction of electric fields about isolated positive and negative charges re-



(A) Field about two unlike charges.



(B) Repulsion between like charges.

Fig. 3-12. Shape and direction of lines of force of static charges.

spectively. Note the forces radiate equally in all directions. Fig. 3-12A shows the shape and direction of a field about two unlike charges close together, attraction being indicated. Fig. 3-12B shows repulsion between like positive charges. The same drawing can also be applied to repulsion of like negative charges if the polarity markings and direction of the arrows were reversed.

It will be observed that lines of electric force spread apart, since they repel one another sidewise, but they contract lengthwise like stretched rubber bands. Since work is required to overcome the forces of attraction in separating unlike charges, *energy may be stored in an electric field.* Conversely, energy is recovered and work is done when the charges are allowed to come back together (recombine). This explains the delivery of electrical energy to a circuit by a battery or generator, since they separate negative from positive charges. It explains also the return of that energy in the form of heat, light, magnetism, etc., by the electrons as they return through the circuit and do work. One familiar example of an electric field of force is the effect of a lightning discharge on a radio set, even at a distance. The charges induced on the antenna pass into the set, causing loud disturbing noises.

THE ELECTROPHORUS

This simple type of electrostatic machine for producing static charges by induction was invented by Volta about 1777. It consists of a metal disk, A, Fig. 3-13, with an insulating handle and a plate of wax or hard rubber, as at B. One may make a wax plate by slowly melting together about 1 pound of common resin and 3 sticks of sealing wax. Pour the mixture in a shallow pie tin to cool and harden. The disk A may be of any kind of metal, but preferably brass or aluminum, about 1 inch smaller in diameter than resinous cake B. Cement a glass or wood handle to the center of the disk.

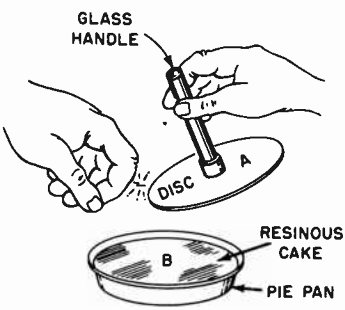


Fig. 3-13. The electrophorus.

To use an electrophorus, rub plate B briskly with fur or a woolen cloth to give it a negative charge. Then place disk A on plate B, as shown in Fig. 3-14. By repulsion this drives the free electrons in A to its upper surface. Now touch disk A momentarily with the finger to drain off the electrons, leaving A positively charged.

Next lift A with its plus charge and touch it to the knuckle of one's hand or to the knob of a Leyden jar, which acts as a "capacitor" to store the charge. A spark will jump from the knob of the jar, making it positively charged. By repeating the

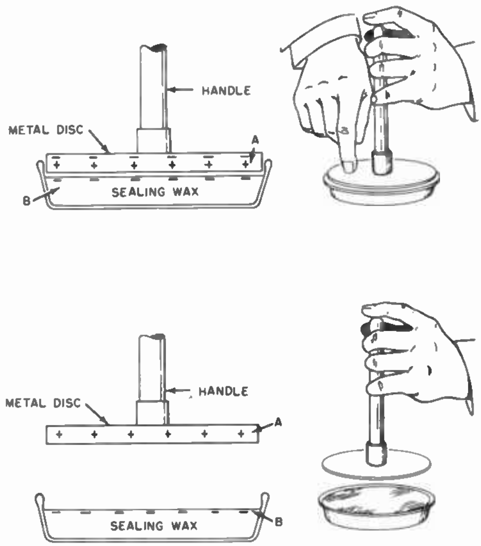


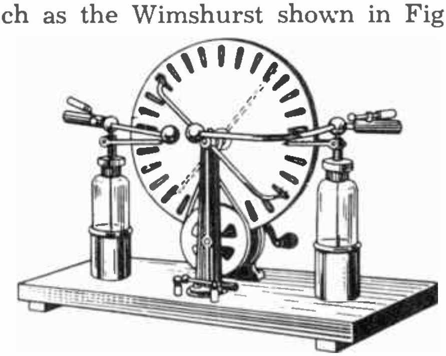
Fig. 3-14. The charges on an electrophorus.

process, which may usually be done a number of times without rubbing the disk again, a strong charge may be given a Leyden jar or a fixed capacitor. If a commercial type of capacitor is used, one terminal should be grounded.

STATIC MACHINE

Static machines produce a charge principally by induction, not friction. These machines, such as the Wimshurst shown in Fig.

Fig. 3-15. A Wimshurst induction static machine.



3-15, may be purchased from physics apparatus firms. They give a high electric potential, and a constant stream of sparks jump the air gap between terminal knobs. Such a machine is much better than the electrophorus for lecture table demonstrations and for charging Leyden jars and capacitors.

LEYDEN JAR

The oldest form of experimental demonstration capacitor, and still a somewhat common form, is the Leyden jar (Fig. 3-16) invented by Musschenbroek at the University of Leyden, Holland, about 1775. It consists of a wide mouth jar of thin glass coated inside and outside part way to the top with metal foil and closed with a lid of dry wood or other insulative material. A brass rod with a knob at the top makes contact with the inner coating by means of a dangling chain. The outer coating may be directly grounded to earth, or the jar may be held in the hand while being charged. The charge rests on the metal coatings. Two such jars are shown in Fig. 3-15 as part of the static machine.

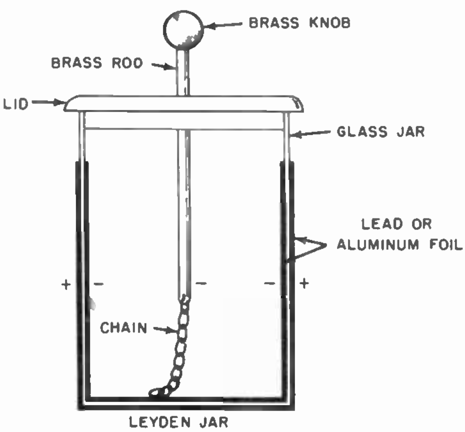
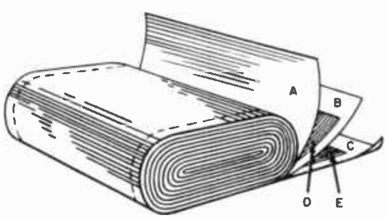


Fig. 3-16. A Leyden jar.

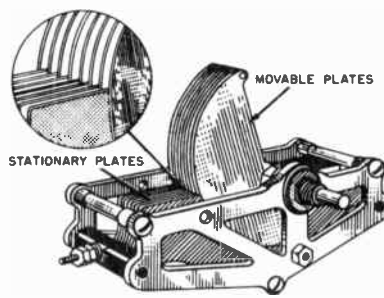
A static machine is best for charging the jar. If the knob is charged negatively, as shown in Fig. 3-16, electrons spread over the inner metal coating and repel electrons from the outer coating to the ground, leaving it positively charged. To discharge the jar, the outer coating is short-circuited to the knob with a conductor, preferably insulated when it is held in the hand. A powerful spark occurs, due to the sudden rush of electrons from the inner coating to the outer. If the jar is discharged with the bare hands, a very disagreeable shock is felt. A Leyden jar may be charged just as readily to a polarity opposite that shown in Fig. 3-16, if desired; in which case plus and minus exchange places and the direction of electron flow on discharge is reversed.

CAPACITORS

Commercial capacitors (condensers) are used to accumulate and store electric charges. They usually consist of thin metal-foil plates separated by insulation (dielectric). Since charges rest on the surfaces, the *larger the plates the greater the capacity* a condenser has for storing electrical energy. One type of capacitor is constructed of long strips of aluminum foil placed between layers of paraffined paper and then rolled tightly and sealed in a moisture proof container. This type of capacitor is usually called a *fixed* capacitor (Fig. 3-17A). Variable capacitors (Fig. 3-17B), used in tuning radios, consist of two sets of metal plates; one stationary, and the other movable with air between them as an



(A) Fixed paper capacitor.



(B) Variable plate capacitor.

Fig. 3-17. Construction of two types of capacitors.

insulator. By moving one set of plates in or out between the others, one may vary the *capacitance*. *Capacitance* is a measure of the amount of charge which a capacitor can hold.

ELECTRICAL POTENTIAL

Potential is a term used to denote *intensity of charge*. If one conductor, or one point in a circuit, has a greater intensity of charge than another, it is said to have the higher potential of the two. Electrons, like water or air, will move from a point of high potential (pressure) toward one lower in potential. Consider a circulating water system made like an electric circuit, with one pipe to carry the water from the pump to a tank some distance away and another pipe to carry it back, so that the same water is pumped over and over and none is lost. It is easy to see that the water would be at a high pressure where it leaves the pump, would lose some of that pressure along the outgoing pipe due to friction and would lose the remaining pressure along the return pipe. There may even be a partial vacuum in the return pipe near the pump. Water will flow in this system only if there is a *difference in pressure*. If the pressure should become equal at all points, even though it be high, the water would stop flowing.

The same is true of an electric circuit or of an electrified object. The intensity or degree of charge at a point or position of a circuit is called its potential and may be higher at some points than at others. If this potential were the same all over, it could be very high but no electrons would move. It is the *difference of potential* between two points, measured in *volts* that causes electron movement between them.

In electricity the terms positive (+) and negative (−) are used to refer to potential. A *zero* (reference) potential is also convenient and useful. The earth is used as zero potential reference because it is so large it can absorb or equalize any amount of charge. Working circuits are often *grounded* to the earth at certain points. The terms potential and voltage are often used interchangeably.

ATMOSPHERIC ELECTRICITY

The earth's atmosphere is charged with electricity at all times, even in clear weather. Scientists are well aware of this. Some boys became aware of it when they tried to fly a large box kite in a cool north wind. The day was sunny, not a cloud in sight. The kite flew well but was too large for the string which broke several times. To overcome this difficulty the boys substituted a fine wire for the string. This held the kite, but as it unwound from the reel the boys began to receive sharp electric shocks from the wire. These grew stronger as more wire was played out until after a time touching the wire at all became very painful. So the reel was "grounded" by holding it against a steel rod driven in the ground. The boys received no more shocks, since the rod carried the charge gathered from the atmosphere off into the earth rather than through the boy's bodies. A lightning discharge, which is really a great electric spark, is another example of atmospheric electricity. If lightning strikes a building protected by lightning rods, it is conducted harmlessly off through their grounding wires to earth, leaving the structure unharmed.

Lightning—It was about the year 1752 that Benjamin Franklin flew a kite in a storm to prove that lightning is electricity. We now know it as a roaring giant spark discharge, often miles in length, between enormous natural electric charges of opposite signs. Except for its enormity, it is the same as the tiny spark from a Leyden jar or capacitor. Investigators have learned that separation of positive and negative charges in the clouds is due in some way to upward air currents which occur in thunderstorms. The positive charges are carried to the top of a cloud while the negative charges accumulate at the bottom. It has also been found that, though during fair weather the earth's surface is negatively charged, it acquires a positive charge by induction when a negative cloud passes over. See Fig. 3-18. This "earth

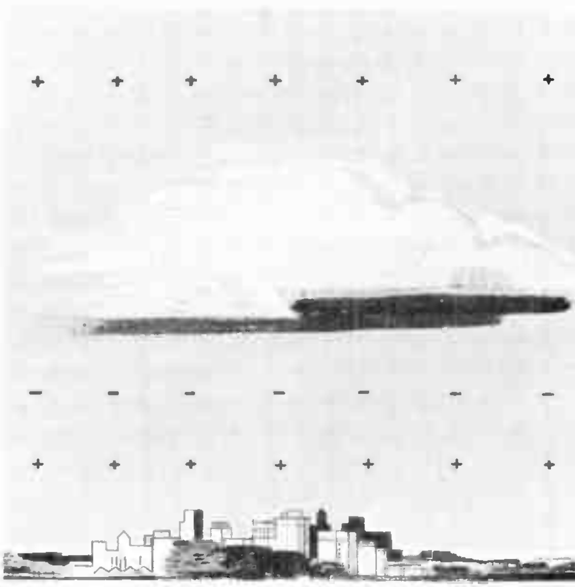


Fig. 3-18. During fair weather the earth's surface may be negatively charged, but it becomes positively charged by induction when a negative cloud passes over. (Courtesy of Westinghous Mfg. Corp.)

charge" will become most intense on tall buildings, trees, towers, and other points nearest the storm cloud, making them more likely targets to be "struck." When the electric fields of these opposite charges become strong enough between clouds or between cloud and earth, the air insulation breaks down and the lightning flash jumps from one to the other. Lightning bolts may have a potential of billions of volts and currents of hundreds of thousands of amperes, but their duration is normally only a few millionths of a second. Therefore they would be almost worthless even if they could be harnessed, but no way has ever been found to do that. The greatest known benefit derived from the lightning "flashes" of the nearly 16,000,000 thunderstorms that rage over the face of the earth every year comes from the nitrogen compounds which they produce. Nearly 100,000,000 tons result from each year's storms and are invaluable in fertilizing the soil and promoting plant growth.

Lightning in passing through the atmosphere creates a partial vacuum along its path. Thunder is the result of the sudden violent inrush of the surrounding air to fill that void. Air waves carry this disturbance to our ears far more slowly than light carries its flash to our eyes. For this reason thunder is always heard after the lightning bolt has struck. Though it may be terrifying, it does little harm; only the lightning is destructive. Every year lightning kills stock and many people, damages numerous buildings and transmission lines, and starts fires in forests and oil fields. It strikes more than once in the same place, contrary to popular belief, although once is usually enough!

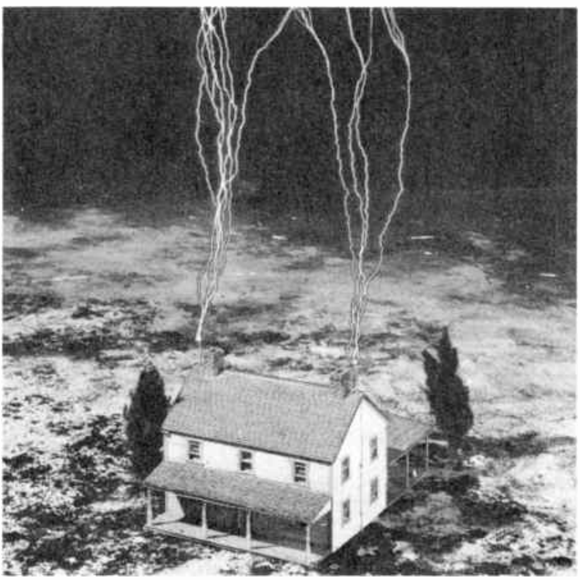


Fig. 3-19. We may protect against lightning by proper use of lightning rods.

No way has been found to prevent lightning, we try to protect against it as much as possible by the proper use of lightning rods (see Fig. 3-19) and lightning arresters. Though not perfect, these usually lead a stroke harmlessly to earth, if well designed and installed, especially when grounded by large copper cables extending deep in moist soil. A poorly grounded lightning rod is a menace, since it may make matters worse by shortening the distance for a stroke and offer only a partial path to earth to be disasterously completed through the building.

PERSONAL PROTECTION

Though lightning should be respected and feared, one should act calmly in a thunderstorm and follow a few simple rules for his own protection.

1. The most important thing to do is to get into a house, barn, or other building, the bigger the better. Roofs and walls of buildings usually make a better path than the human body for lightning to reach the ground.
2. When a storm threatens, keep off golf courses, beaches, or other open spaces. Stop outdoor games. Don't ride a bicycle or a horse, and don't operate an exposed machine, such as a tractor. You are safe, though, in a closed automobile with a steel body.
3. *Do not seek shelter under trees!* Stay away from poles and masts. Avoid exposed hilltops; a valley is safer.
4. Keep away from wire fences and all kinds of wires and metal objects. Don't venture too close to stoves and pipes in kitchens or basements, and stay away from the chimney or fireplace.
5. Stay out of the attic. Since lightning usually follows the walls of a building, it is safer to choose a place near the center of the room.

In large buildings and modern homes, you stand little chance of being hurt or killed by lightning. Hundreds of such buildings are struck every year, usually without harm to the occupants. It is wise to be careful. You may not have a chance to be sorry.

Chapter 4

ELECTRICAL FUNDAMENTALS

FAMILIAR ELECTRICAL ACTIONS

Few things in our lives are more familiar than the incandescent electric lamp. We find them lighting our homes, offices, stores, factories, and even our city streets. Of course, we have other kinds of electric lights too. . . . fluorescent lamps, luminal lamps, and the newer mercury vapor and sodium vapor lamps; . . . but none are quite so familiar nor used in so many different ways as the incandescent lamp. (See figure 4-1.)

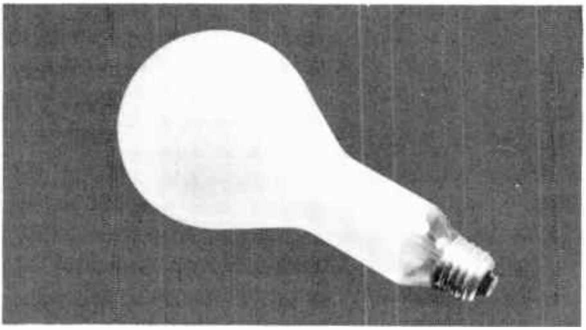


Fig. 4-1. An incandescent lamp.

Yet, despite the fact that the incandescent lamp is familiar to us, there are many things about it which are not fully understood by many people. Most of us know, for example, that we must plug the lamp cord into an electrical outlet before we can get the floor lamp to light, but just what happens beyond that point is not generally understood by the layman.

In this connection, let us turn our attention first to the cord which seems to be such a vital part of the lamp and so necessary to its proper operation. If we examine the lamp cord carefully before plugging in the lamps; and then examine it again afterward, we would find that no change had occurred in its appearance.

This examination can be carried a little further (see Fig. 4-2) by examining the cord carefully before the lamp is switched on and again afterward with the lamp turned on. Our most careful scrutiny would detect no difference in the appearance of the cord.

We might carry on this examination to every greater lengths by listening to the lamp cord while it is carrying electric power sufficient to light the lamp to its full brilliance. No matter how carefully we listened, we would be unable to hear anything moving within the cord. Even if we weighed the cord before the lamp was turned on and again while the lamp was lighted, we would detect no change in its weight.

Fig. 4-2. It is impossible to see or hear electricity traveling through a wire, nor can the passing current be detected by weighing it.

Why is it, then that a lamp cord, which apparently is no different one time from another, can carry the power to light a lamp without showing it in any manner. We know, of course, that the lamp cord does carry the necessary power. This fact, we can readily prove. The lamp will light when the line cord is connected to a source of electrical power, and only when the line cord is connected (Fig. 4-3). The lamp may be lit to its full brilliance; but just as soon as we disconnect the cord from the source of power, the light will go out. There can be no question that the lamp receives its electrical power through the lamp cord. However, just how and why are questions that few users of the lamps can readily answer.

Disconnecting the plug on the end of the lamp cord tells us one thing—that electrical power cannot, or will not, readily pass through the air. With this as a starting point we can begin our study to find out just what is required to provide a path for the electric current and how that current can be controlled.

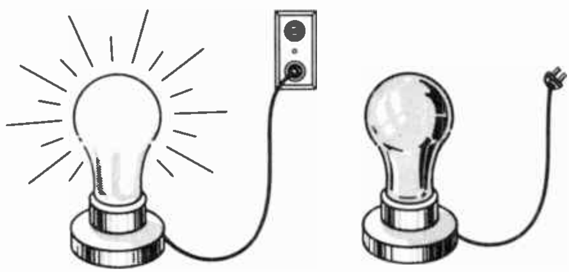


Fig. 4-3. A complete metollic path must be provided for the passage of electricity.

Copper is a work-a-day metal; not just a pampered darling locked up in chests like gold and silver. It has been a builder of civilizations. Its use dates from legendary times when man, in his search for something better than flint and stone for making knives and axes, found copper.

At that time the Stone Age ended and the Age of Bronze dawned. Bronze is an alloy produced by the addition of a little tin to melted copper. Copper lifted mankind one step higher in its long upward climb in civilization. Copper is still in the forefront as a builder of civilizations. Today its greatest service is not as swords, knives, and spears.

Copper serves us best in the wire that carries electricity. This is a passive service, requiring no spectacular qualities and no elaborate motions. Outwardly, one would never guess that electricity flowed in the modest cord that runs to our lamp or in the more robust cables whose catenary arcs swing from tower to tower across our land to form a vast network of copper through which flows the Nation's electrical power. Only silver, of all the metals, offers less resistance to the flow of electricity than does copper but silver is far more costly. That is why the arteries and veins of our far-flung electrical systems are made of gleaming, ruddy copper.

One reason electricity serves us so well is that it can be carried long distances and delivered with almost undiminished power to exactly the spot where we wish to use it. The usefulness of waterpower and of steam and gasoline engines is limited by their size, weight, and fuel supply. Electricity can be generated in a fixed convenient location and transmitted anywhere, down into mines, far across the hills and plains, under the streets of a city, in fact wherever wires can go. Without the wires to carry it, electricity would be shorn of most of its magic.

There is romance in the production of wire itself. From the mine where it had its beginning it is sent to the smelter, and on to the refinery where it is purified by the very electricity it is soon to carry. From the refinery it goes to the wire-drawing shop, where huge billets of the ductile metal are drawn out into miles of smooth, gleaming strands, each uniform in size from beginning to end. For each purpose and application there is a wire of the proper size, characteristics, and insulation. In the powerhouse and in the windings of large generators and transformers, the wires are heavy, massive, and rigid. Through them flows the current to brighten thousands of homes, to lighten the household tasks of the city, and to power a score of factories.

The wires that come down your street and enter your home are specially insulated to withstand the weather. The wire that runs to your reading lamp is of a different kind, made up of many tiny twisted strands that cause it to be flexible and withstand bending. The wire that forms the magnet coils in your electric doorbell is probably insulated with fine silk thread so that the turns can be wound tightly side by side. The wires running to the heating element of an electric range have asbestos insulation to withstand high temperatures. The wiring in your radio set is like the rainbow in its coloring, each color a clue by which to trace the circuits of tubes, capacitors, and resistors.

There are more spectacular metals than copper. Iron is stronger, tungsten is harder, gold and platinum are rarer and more precious; yet none of these can take the place of this modest reddish metal which spreads its web over all the land, supplying electrical power to more than twenty-seven million American homes.

If we were to dissect a lamp cord in our home very carefully; that is, tear it apart and really examine it, we would find a pair of copper wires inside of its insulative covering.

Then, if we were to investigate a little further, we would find that the length of copper wire in the cord constitutes only a tiny portion of the long metallic path reaching from the lamp all the way back to the source of electrical power at the central power station. We would discover that a complete round-trip path has been provided from the source of the power (the power station) to the lamp in our home, so that the electric current can travel from the source to the lamp, and from the lamp back to the source. This is a peculiar necessity which we shall explain and discuss in detail after we have mastered the fundamentals. We mention it at this time merely to acquaint you with the concept.

The fact that copper wires are used to carry electricity will not come as a great surprise to most persons. We all know that copper wires play an important part in the transmission and control of electricity. We have all seen the power wires strung along our highways in the country and along the alleys and streets in our cities. Furthermore, we all know that we cannot use our electric toasters and waffle irons unless they are plugged into a wall socket or other power outlet. We cannot use our washing machines or refrigerators unless they are similarly connected. Perhaps we do not fully understand what occurs when we make such a connection to a source of power; but we do know that such a connection is necessary if we wish to operate the appliances.

The truth is that we must provide a complete metallic pathway along which the electricity can travel. The pathway must be complete from the source of power to the place where it is to be used, and there must also be another complete metallic pathway all the way back to the source. Such a metallic pathway is generally formed of long, slender wires of copper which are so familiar to us all.

It is interesting to note that the pathway for the electric current must be complete. If there is a break in the path at any place, either in the out-going or in the return circuit, the electric current cannot move along any part of the copper wires. In addition, the out-going pathway must be insulated from the return pathway everywhere. Electricity is only able to move along pathways composed of certain kinds of materials. Those materials along which the electricity can move freely are called *conductors*.

There are many kinds of conductors. All metals are conductors. Some liquids and some gasses are conductors. Carbon is a conductor. There are a few other materials capable of conducting electricity; but, generally speaking they are not commercially important, so we shall not discuss them here at this time.

We often find that a single conductor is not adequate to carry electricity from the source to the place where it is to be used. Often many small conductors are twisted together to form one large conductor which is enclosed or encased in an insulative covering. This is done mainly to make the conductor flexible for easy handling and installation.

In order to pass electricity from one conductor to another, it is necessary only to connect the two conductors; that is, to make actual physical contact between the two pieces of metal (Fig. 4-4). This is true, of course, provided such contact completes a closed metallic pathway to the source where a current is being produced. Touching two electrical conductors together is generally referred to as making electrical contact between the two conductors.

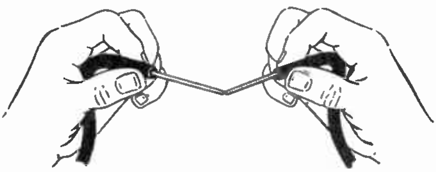


Fig. 4-4. To make an electrical connection between two conductors it is necessary only to touch the two conductors together.

Connecting two conductors has been very much simplified by the fact that electricity will pass from one electrical conductor to another if the two pieces of metal are merely touched together. In making electrical connections it is not necessary to go to all the trouble and expense required to couple two pieces of pipe or tubing together for the passage of water, gas, oil, or other similar gases or liquids. In the case of electricity, it is merely necessary for the two conductors to touch each other for the electric current to pass from one conductor to the other. However, in any instance, it is necessary to have a good mechanical connection between the connected ends even for small currents. Where large currents are to flow through electrical conductors, it becomes necessary to weld, solder, or otherwise securely bond the wires together to prevent loss due to resistance as will be explained later.

Although this manner of connecting two conductors to make an electrical connection is easy in some ways, it gives rise to a number of problems. For example: We can string out several conductors to make an extensive pathway along which an electric current can move by merely touching together the ends of the various conductors. In actual practice it is customary to wrap or twist the end of one conductor around the end of the other conductor to give a good mechanical joint and thus maintain a good electrical connection. All this is simple, but if such a bare conductor should happen to touch some other bare conductor, there would be danger of electric current going where it is not wanted. It might even cause what is known as a "short circuit," commonly called, a "short." We shall discuss short circuits in detail a little later.

Thus, it can be seen that an electrical connection made by merely touching two electrical conductors together has both advantages and disadvantages. While we can provide a pathway for an electric current by merely stringing together a number of electrical conductors, their ends mechanically joined together in physical contact with each other, we do not generally want such a crude, unsatisfactory circuit. We want the current confined to the pathway along which we desire it to flow.

Fortunately, this is not such a great problem as might appear at first glance. Just as metals and some other materials provide electricity with a good pathway along which it can flow, it is also true that there are other materials through which electricity cannot readily flow. Materials which are not capable of acting as electrical conductors are said to be *insulators*.

INSULATORS

Electricity is rebellious. Tamed and controlled it is capable of performing a thousand and one tasks with the silent obedience of Aladdin's Lamp; but unleashed and freed from all constraints, it disappears into the ground with only a flash and crackle to tell that it ever existed. To keep electricity within bounds, it is necessary to build fences, fences that we call insulators.

Some materials make good insulators; other do not. Metal like copper, iron, and aluminum are good conductors of electricity. They obviously are ruled out as fence materials (insulators) since they provide an easy path for the escape of the mischievous current. Water in its *purest* form makes a fair insulator, but let even the *slightest trace* of almost any *impurity* be dissolved in the water, and its insulating power is lost. Dry wood and cloth are moderately good for holding electricity in check. In fact, in the early days, at least one experimenter made insulated wire by wrapping copper wire with strips cut from his wife's old silk dresses.

Oil, freed of impurities, is a good insulator. In the great lead-sheathed cables that carry electric power far beneath our cities, it is oil that holds back the straining voltage and prevents it from leaping to the earth only a few tantalizing inches away.

Glass is the insulator that we see most often on the poles that carry the telephone and electric wires along our streets and roads. It is a good insulator and relatively inexpensive. The most convenient and one of the most effective insulators of all, however, is dry air.

Surround your wires with plenty of empty space and you have built a fence that no man-made voltages can jump. This is why transmission lines of bare wire are swung high above the ground. It is this air insulation that keeps their thousands of volts in place. These lines must be supported at intervals, and the supports, like the points at which electricity enters and leaves transformers and circuit breakers, require the highest fences of all. To construct these "super-fences," it is necessary to call on one of the oldest of the arts.

Even when old Omar the Tentmaker, at "Dusk of Day—watched the Potter thumping his wet clay" the art of the potter was old. Scratch the earth, in the Old World or the New, and you will turn up pieces of burned clay that once held some prehistoric man's dinner or that balanced on his wife's head as she carried water from some spring or stream. Here, preserved in enduring clay, are fingerprints that no detective can unravel, for the forgotten makers have themselves been clay these forty centuries. Scratched on the pathetic fragments are some of the earliest attempts at artistic decoration. Down through the ages, the potter has recorded the upward climb of civilization.

Today the potter still serves the vanguard of new developments. There is porcelain of fine quality upon your table, but its quality is no finer than that of the porcelain insulator that supports the wires of the transmission line. The curves of a vase may be subtle, but they are not so excitingly dynamic as the contours of the great insulating bushing of a transformer or a circuit breaker. The hand of the potter who molds and turns this mighty electrical porcelain must not shake, his eye must not waver. On the quality of his workmanship rests the responsibility for your uninterrupted electrical service.

The transmission-line insulator works without let-up. Like the traditional Dutch boy whose finger held back the water of the leaking dike, the insulator is forever holding back the rebellious forces of electricity. Across the few inches of glazed, baked clay is the incessant pressure of tens, even hundreds of thousands of unruly volts. Every second of every day, for weeks, months and years, that pressure is never relaxed.

The insulator gets no help from the weather. Sun and wind beat upon it. Swung from its lofty tower, it is chilled by the zero blasts of winter. Snow, sleet, rain, and fog coat it with treacherous films of moisture, tempting the never-sleeping electricity to escape its prison walls. Yet electricity is always ready to serve you when you want it, waiting to do your bidding at the touch of a switch, because thousands of insulators have fenced it in, tamed it, and kept it forever flowing on its way to you.

There are many materials which belong to the family of insulators. Probably the most common of these insulators are glass, rubber, mica, asbestos, dry wood, porcelain, bakelite, dry air, and paper. There are certain other materials which have specialized applications because of their superior insulating qualities. Many of these belong to the general family of plastics. Polystyrene, mycalex, and teflon number among these special insulating plastics; but there are many others. Mention will be made of some of the plastic materials which are used for insulators as we progress with our study.

One of the principal uses of insulators is to act as guides to direct the flow of electricity along the path we wish it to follow and to keep it from wandering off into places where it is not wanted. For example, the copper wire, which is so commonly used as a conductor of electricity, very often has a thin covering of rubber over the metal throughout its entire length (Fig. 4-5). When the bare wire is thus covered with protective insulation, it may touch other metal without causing a short circuit. The layer of rubber which covers the bare wire prevents it from coming into direct contact with anything and thus keeps the wire from making any unwanted electrical contact with any other conductor of electricity.

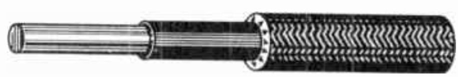


Fig. 4-5. A piece of metal wire which is covered with rubber insulation; the rubber is protected by an outer covering of fabric.

Copper wire is sometimes covered with insulation other than rubber. Within recent years the use of special types of plastic insulation has grown quite rapidly. Often a thin covering of plastic will provide better protection than a thick coating of rubber. This has made possible a great reduction in the bulk of insulated wire. Where it is necessary to pass many wires through the same passageway or to bundle them all together in a single cable as in the case of telephone wires, the smaller bulk is of great importance.

A special type of flexible, woven glass cloth has also come into widespread use within recent years as an insulating material for copper wires. In many applications it exhibits a marked superiority over rubber as an insulator. This is especially true in applications where the wire is subjected to high operating temperatures. A common example of this is found in the windings of "sealed" motors, which are used in the explosive atmosphere of coal mines, powder plants, etc. Several motor manufacturers are turning entirely to glass insulation for their motor windings. This permits motors to operate at much higher temperatures than was formerly possible and also enables more powerful motors to be constructed in smaller physical sizes than was ever before practical.

Almost all of the uses of insulation we have described thus far apply specifically to those applications requiring flexible insulation. Sometimes it is desirable to have an insulation that is non-flexible. An example of this is the switch mounting bases (Fig. 4-6), which shows three switches used to control electric currents. We shall describe the action of switches in detail later. Another application generally requiring a rigid type of insulation is the panel boards carrying the controls required for controlling motors and generators. There are several kinds of insulation which can be used in such panels. The most widely used are porcelain, ceramics, and composition insulation. All of these insulators provide good insulation against the passage of an electric current and are sufficiently rigid and strong to provide the necessary strength and rigidity to support the conducting elements in their proper positions.

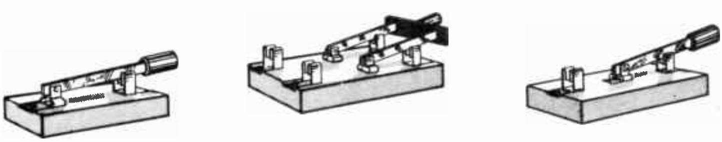


Fig. 4-6. Rigid insulation such as bakelite and porcelain is used as a base for switches.

While on the subject of insulation we should not forget to include dry air, since it is one of our most important insulators. It is fortunate that air is an insulator, for if it were not electrical engineers and designers would be faced with a major problem. Since it is, we take advantage of the fact and use its insulating properties in many ways.

HOW A CONDUCTOR CAN INFLUENCE THE FLOW OF CURRENT

While it is true that electric current can move through a piece of metal and through other kinds of electrical conductors, it is important to note that current does not flow through all conductors with equal ease. Several qualities of any conductor determine its ability to pass electric current. These qualities include its size, its length, the kind of material of which it is made, and its temperature at any given time.

Some of these influences are readily understandable and seem logical, but others are not quite so apparent.

It seems logical that a large conductor can pass electric current more readily than a smaller conductor. This closely parallels the flow of water under a constant pressure in that a large pipe or hose will pass a greater volume of water than a small hose or pipe and will pass the same quantity of water in less time than the smaller one. Fig. 4-7 demonstrates this fact more vividly than words alone!

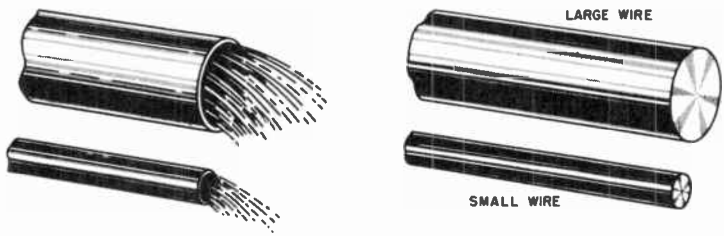


Fig. 4-7. Just as more water can flow through a large pipe with less resistance than through a small pipe, electricity meets less resistance in a large conductor than in a small one.

Again, it isn't difficult to understand that it would be harder for electric current to get through a long conductor than through a short one. Here, too, we can compare the electric current flowing through a conductor to water flowing through a pipe or hose. If the pressure is constant, less water will flow through a long pipe or hose than through a short one in the same length of time. To say this in another way; water will encounter more resistance in flowing through a long pipe or hose than it will in flowing through a short one. This, too, can be explained and understood somewhat better by the graphical portrayal in Fig. 4-8.

The two remaining factors which influence the flow of electric current through a conductor are not quite so easily understood as the factors of the length and the size of the conductor. These involve the material from which the conductor is made and the effect of temperature on the ability of a conductor to pass electric current.

We could, perhaps, continue our comparison of the flow of electricity with that of water through a pipe or a hose by stretching our imagination a little. We could compare the fact that electricity cannot flow through some substances as easily as through others with the fact that water cannot flow through all kinds of pipes with equal ease. As an example we know that water can flow through a new pipe which is smooth inside more easily than it can flow through an old one, the inner surface of which is rough and corroded.

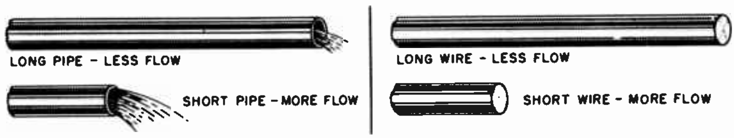


Fig. 4-8. Water meets less resistance in a short pipe than in a long one. In like manner electricity finds less resistance in a short conductor than in a long one.

So it is, to a certain degree, with the flow of electricity through conductors. It will flow through some conductors far more readily than it will flow through others. Experience and experiments have shown that electric current can move through conductors made of silver more easily than through conductors made of any other metal or of any other kind of material. It has also been proved that electric current can flow through conductors made from copper almost as easily as through those made of silver. Silver and copper are regarded as our best conductors. The current will encounter a little more opposition, or resistance, in moving through the copper conductors than through silver conductors, but not a great deal more. The fact that copper is much cheaper than silver and almost as good a conductor accounts for its being the most widely used of all metals for carrying an electric current. We have mentioned before that all metals are electrical conductors, but they certainly do not all carry electric current with equal ease. Next to copper, aluminum is the best conductor (Fig. 4-9).

There have been several instances in recent war years when the supply of copper was critically short and could not meet the needs of the electrical industry. This situation has resulted in the use of aluminum as an electrical conductor. There are places where aluminum is actually superior to copper as a conductor of electricity.

This advantage is due almost solely to the fact that aluminum is much lighter in weight than copper, and this difference in weight is sometimes an important factor. The super-voltage transmission lines which carry power from Boulder Dam to the west coast at a potential of 500,000 volts are hollow aluminum tubes made up of interlocking sections. Their light weight permits them to be strung between widely separated towers.

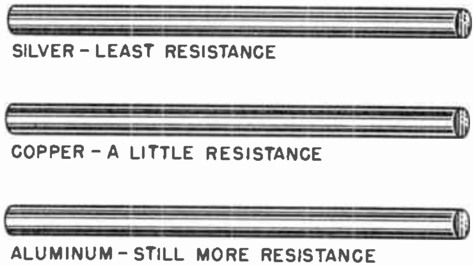


Fig. 4-9. The material from which a conductor is made affects its resistance to electrical current flow.

The effect of temperature upon the ability of a given conductor to carry electric current cannot be explained quite so easily as we have disposed of the matters of size, length, and conductor material. As a matter of fact, it is rather doubtful if anybody knows exactly how temperature acts to affect a conductor's ability to pass electric current, although there have been theories advanced for its explanation. It is well-known that as a conductor becomes warmer it is unable to carry electric current as easily as it did when it was cooler. From this we can deduce that temperature affects the ability of a conductor to carry electricity. As the temperature rises a conductor's opposition (resistance) to the passage of current increases.

All these matters will be explored in detail as we go along. In summarizing we can say that four things affect a conductor's ability to carry electricity: its size, its length, the material of which it is made, and its temperature.

HOW ELECTRIC CURRENT IS MEASURED

In a water system the amount of water that will flow through any given pipe depends upon two things: (1) the pressure built up by the pump at the central pumping station; and (2) the friction or opposition to its flow offered by the pipe. We know that if the pressure is increased more water can be forced through any given pipe. We also know, if we stop and consider for a minute, that more water would flow through the pipe if, in some fashion, we could reduce the opposition or resistance it offers even though the central pumping system is producing the same pressure.

In an electrical system we are dealing with somewhat similar effects. Electric current is caused to flow through a conductor by the application of an electric force which we usually refer to as an *electromotive force*. The current is opposed, or resisted, by certain inherent properties of the conductor itself.

Beyond this point the similarities between a hydraulic system, such as we have been discussing, and an electrical system grow less. The principal purpose of a hydraulic system is to transport water to some given location where it is used directly as such. In an electrical system a current is generated and sent some distance through a conductor, the use of the individual electrons which compose the electrical current is not our ultimate goal. We are interested in the effects which can be produced with this electric current as it flows through the conductors of our motors, lights, and appliances.

To understand this a little better we should explain that an electric current is composed of literally billions, even multiplied trillions, of these infinitely small particles of electricity called electrons. Electrons are so very minute that no one has ever seen one, even with the most powerful microscope. Yet, man has succeeded in learning many, many things about these tiny electrons and their behavior.

These electrons are in a continual state of agitation or movement. In the normal state they are moving in every direction with little or no regard for the other neighboring electrons, but under the influence of an electromotive force they can be caused to move in coordination in the same direction. When this occurs, we have an electric current, the thing which we have mentioned so many times.

In electricity and electrical work we do not generally make use of the individual electrons as such. Instead, we are interested in the effects which they cause in and around an electrical conductor when an electric current is flowing in it. Two important things happen when an electric current flows through a conductor. First, there is a tendency for the conductor to heat up (Fig. 4-10). The extent to which a conductor will heat up depends upon several factors, among which are the amount of current which flows through it and the amount of opposition (resistance) it presents to the flow of the current. Later we shall see how the resistance depends upon both length and diameter of the conductor. Often the heating effect of the current is so small that it is scarcely noticeable and can be ignored; while in other instances, the conductor may become red hot and give off great quantities of heat. The heating elements in our pressing irons and other heating apparatus, the filaments in our incandescent lamps, and the heaters in our electric stoves are all examples of how we deliberately produce heat by causing electric current to flow through specially designed heating devices.

The second thing that occurs whenever an electric current flows through a conductor is that an invisible magnetic field is set up in the immediate vicinity of the conductor. We shall not dwell upon this peculiar magnetic action at the moment, but we shall explain it a little later. It plays a very important part in man's ability to put electricity to work and to make it serve his needs.

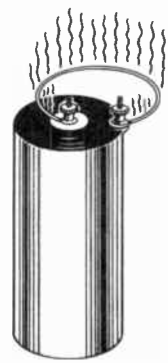


Fig. 4-10. When electric current flows through a conductor, the conductor will heat up.

We may summarize by saying that instead of using the individual electrons which comprise an electric current as we would use the individual drops of water, we make use of their effects, heat and magnetism, which evidence themselves when an electric current flows through a conductor. This means that we must find a somewhat different method of measuring electric current from that which would be used to measure a flow of water.

In the case of water it is customary to measure the quantity of water by thinking of it in the terms of so many pints, quarts, or gallons. We do have a similar unit by which we can measure the *quantity* of electricity or electrons at a given place, but this is a unit that is seldom used in practical electrical work. The electrical unit for measuring a quantity of electricity or electrons is the *coulomb.*

A *coulomb* is a quantity of electricity consisting of many electrons, just as a gallon of water consists of many drops of water. We seldom need to know just how many drops of water are in a gallon, and for the same reason we seldom need to know just how many electrons are in a coulomb. Generally speaking we are not interested in the quantity of electrons in a conductor. We are more interested in knowing the *rate* at which those electrons pass a given point in the conductor.

We encounter much the same problem in measuring the rate of flow of water in a pipe or in a stream. It is a common thing for us to refer to the *rate of flow* of water as being so many *gallons per minute*, or so many *gallons per second*. Both of these methods of measuring the rate of flow of water are used very commonly, but note that in doing so we are using two units of measurement, one representing quantity, the *gallon*, and the other representing time, the *second*. In measuring the rate of flow of electricity, electrical men have gone another step further. Instead of using a unit of quantity and also a unit of time, they have devised a single unit which includes both quantity and time.

If you think this is confusing at first, remember that this isn't the only place where such a dual-unit is found. Sea-going people have used such a unit for centuries. It is a unit for measuring speed called the *knot*. The Navy and the Merchant Marine do not measure speed as we landlubbers do, by saying a ship is moving so many *miles per hour*. Instead, they have adopted the *knot* which includes both distance and time. A seaman will say, that a ship is moving at a speed of 30 knots. We could say the ship is moving at a speed of 30 nautical miles per hour and mean the same thing, but when he says the ship is moving at a speed of 30 knots he is merely using the common sea-going term which implies both distance and time.

In measuring the rate at which electrons are moving through a conductor, an electrician could say that the electricity is flowing at the rate of one *coulomb per second*, or at the rate of five *coulombs per second*. Such a statement would be technically correct, but electrical men have a unit which measures the *rate* directly, and, therefore, do not bother to measure the quantity against the time. In this they are following the example set for them by the mariners; and instead of using the mouthfilling expression "one coulomb per second," an electrician would say the current is *one ampere*. In the same manner, instead of saying "five coulombs per second" the electrician would say the current is *five amperes*.

The *ampere* is the electrical unit which measures directly the *rate* at which electric current flows. One *ampere* is equal to one coulomb of electricity flowing past a given point in a conductor in one second.

To give the term "ampere" some meaning and bring it within the realm of our everyday experience, we can apply the term to some of the things with which we are familiar. A bread toaster, such as most of us have in our kitchen, uses electric current at a rate of approximately 5 to 7 amperes, but some of the newer heavy duty models use up to perhaps 8 or 9 amperes. One of the small traveling irons, such as many women take with them on a trip, will use about 5 amperes of current; while the heavier irons which they use in their homes, will use up to 8 or 10 amperes. An ordinary 60-watt incandescent electric lamp will "draw" about one-half ampere, while a 100-watt lamp will "draw" less than one ampere. See Fig. 4-11. The word "draw" is often used when speaking of the current drain of motors and appliances.

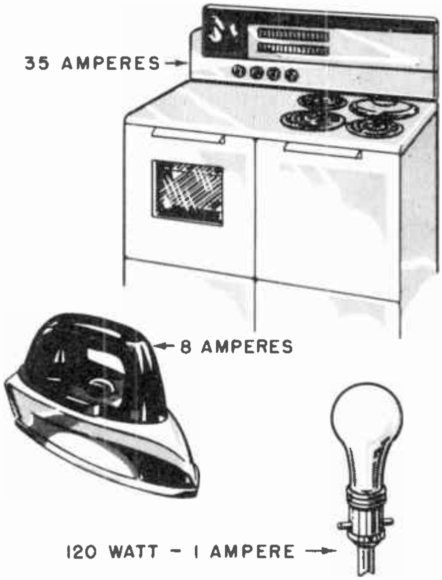


Fig. 4-11. A 120-watt lamp uses about 1 ampere of current, a pressing iron uses from about 7 amperes to about 9 amperes, and an electric range may use as much as 35 amperes.

It is very probable that you have already had some experience with this term "ampere." Most of the lighting circuits in the modern homes are protected by "15-ampere fuses" (Fig. 4-12). A fuse is deliberately made the "weak link" in the wiring circuit, so that it will "blow" and protect the wiring in the house from getting too hot and possibly setting the house on fire, should the circuit be accidentally over loaded. If you've ever had occasion to replace a fuse and no doubt you have, then you are already

Fig. 4-12. A 15 ampere plug-type fuse.

acquainted with such things as 15-ampere fuses, 20-ampere fuses, 25 and 30-ampere fuses. Each is designed to prevent more than its rated value of current from passing through it.

The ampere, then, is an electrical unit which has been invented and defined for the purpose of measuring the rate at which electrons are moving through a conductor.

It is interesting to note that the rate of flow of the current in amperes has nothing to do with the speed of the current through the conductor. This is just as true in the case of electricity as would be true in comparing the rate of flow of water through a pipe with its speed.

As is the case with water flowing through a pipe, we may have a large number of gallons per second flowing through a large pipe even with low speed or a much smaller number of gallons flowing through a small pipe at high speed, so it is with electricity flowing through a conductor. In a similar manner we might have either a large or a small flow of current through a conductor. The speed of the current through the conductor is a matter that seldom or never concerns us. We are generally interested only in the *rate* at which the current flows.

THE ELECTRIC CIRCUIT

We have pointed out that a number of similarities exist between the flow of electricity through a circuit and the flow of water through pipes. Yet, despite these similarities, electrical current flow is in no way comparable to the flow of water in many respects. One principal point of difference has been previously mentioned. We generally flow water through a hose or pipe because we want to use the water for some purpose at the end of the pipe or hose; while in the case of electricity we have no use for the individual electrons, as such, but it is the peculiar effects which are caused by the passage of the electrons through the conductor that we wish to use. To express it in simple words, it is the effects that result from the moving current that we use, not the electrons.

In a water supply system it is sufficient to have a single pipe extending from the source of the water to the place where the water is to be used. In the case of electricity, however, it is necessary to have a pathway for the current from the source to the place where it is going to be used, and it is equally necessary to have a return path from the place where the effects of the passing current are used all the way back to the source again. Thus, while a single pipe is sufficient for a water system, it is necessary to have two conductors for an electrical system, one for the current outward bound from the source and the other for its return to the source.

It is important to note that a complete round-trip path is necessary in order to secure and use the effects of the moving electrical current. If the pathway is broken at any point, the current will immediately cease to flow in the circuit. This means that it does no good to provide a pathway from the source of the current to the place where it is to be used if a return pathway is not provided for the current. There will be no current flow along the outward path unless the return path is also complete and unbroken.

We have used the term *source* several times. This is a word that is used to describe the origin of an electric current; that is, the location of the electromotive force that gives rise to the current flow. There are several possible sources of electromotive force, one of which has been mentioned. We have mentioned that certain kinds of chemical action can create an electromotive force and thus cause current to flow. Dynamos or generators and alternators are perhaps the most common sources of electromotive force. Anything that will produce an electrical pressure and thus cause current to flow, may be termed a *source*.

Any device that makes use of the effects of electrical current flow may be classed under the general descriptive term, *load*. To restate this more simply. Anything that uses electrical power is called a *load*.

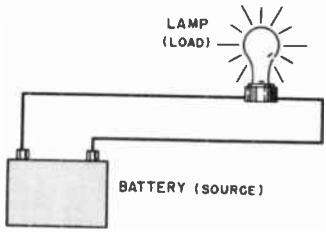


Fig. 4-13. An electric circuit showing the source and the load.

There are many kinds of loads. An incandescent lamp is a load, because it offers a considerable amount of opposition or resistance in its filament, which tends to prevent the flow of current. Electrical pressure is needed to force current through the lamps resistance; thus, electrical power is used. When the pressure is sufficient to force current through the resistance of the lamp, the action of forcing the current through the resistance gives rise to heat, sufficient heat, in fact, to cause the filament to glow brilliantly and give off light.

Lamps are only one kind of load. There are many others. Remember, anything that makes use of the effects produced by an electric current flow is called a load. A pressing iron is another example of a load.

The action of the current flowing through the resistance of the iron also produces heat. An electric motor is another example of something that uses the effect of flowing current, and it, too, is called a load; but the motor is a somewhat different kind of a load. The motor makes use of the magnetic field which is created by the flowing current. We are not ready to discuss just how a motor is able to do this, but we shall take it up in due course. In any case, the motor is just as much a load as the incandescent lamp.

To repeat—anything which makes use of the effects caused by a flowing electric current can be referred to as a *load*.

The purpose of an electrical source is to produce the necessary electromotive force needed to make current flow through a load. If current is to be forced through a load, it is absolutely essential that there be a source of some kind to provide the pressure, just as there must be a pump to provide the pressure if water is to be forced through a pipe.

On the other hand, if the source is to force an electric current through a load, there must be an electrical connection between the source and the load. To be effective there must be two complete metallic or conductive paths from the source to the load, one to carry the current to the load from the source and the other over which the current can return from the load back to the source.

This complete round-trip path constitutes an electric "circuit." Remember this important word, "circuit," for as long as one works with electricity, he will be working with circuits. In electrical and electronic equipment some of the circuits are unbelievably complex. Yet, the most complex circuits in existance can be broken down into two basic kinds of circuits, and the person understanding the basic principles of electricity will have no trouble in analyzing the most complex circuits. The two kinds of circuits are known as "series" and "parallel" circuits. We shall hear more about them later.

In discussing electrical circuits, it is well to emphasize again the importance of providing a complete round-trip path for the flow of the current. Sometimes a newcomer to the study of electricity falls into the erroneous belief that it is only necessary to provide a path for the current from the source to the load. Keep in mind the fact that a "going out" and a "returning" path must exist between the source and the load if we are to have an electrical circuit. If the round-trip path, or circuit, is broken at any point, no current will flow in any part. A moments consideration will show that the current can be interrupted in the outward portion of the circuit by making a break at any point in the return circuit.

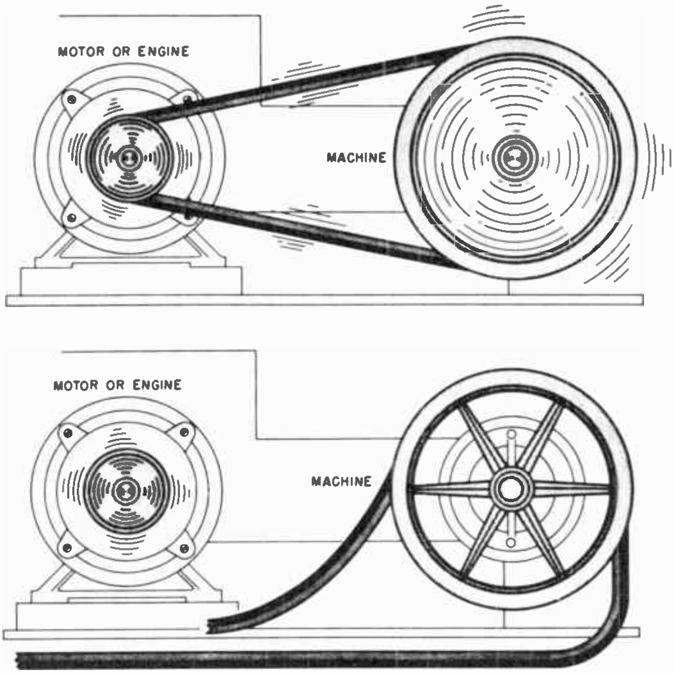


Fig. 4-14. An electric circuit must have a complete round-trip conductive path. This is just as necessary as it is to have a complete unbroken belt connecting the motor with the machine it is driving.

As a final emphasis upon the importance of having a complete circuit, let us compare the circuit to one of the belts used to transmit power from a motor or engine to the machine it is driving. Fig. 4-14 pictures this clearly. In the upper part of the illustration we see the power being delivered by the belt from the motor to the machine. Note that the belt forms a complete closed loop (circuit)! It is not enough for the belt to run from the motor to the machine; it must also run from the machine back to the motor. The lower part of the illustration makes it quite clear what happens if the belt is broken any place. Should that happen, no power can be delivered from the motor to the machine. It makes no difference at what point the belt is broken, whether on the return or on the outward-bound trip. If it breaks, no power can be transmitted.

The same holds true for an electrical circuit. The circuit must be complete, a closed circuit, or no current can flow in any part of it, and no electrical power can be delivered to the load from the source.

CIRCUIT DIAGRAMS

In working with electricity, electrical appliances, and equipment; it would be possible to show how all the various component parts fitted together by drawing pictures of them, but that would be both awkward and inconvenient. In some instances it would be extremely difficult, if not impossible, to convey the exact idea by the use of such pictures.

For this reason and others, a system of symbols has been worked out to indicate the parts used in an electrical system and to show how they function. For example, it would be possible to draw a picture of an incandescent lamp every time such a lamp was indicated in a circuit; instead it is much easier to use the simple symbol shown in Fig. 4-15.

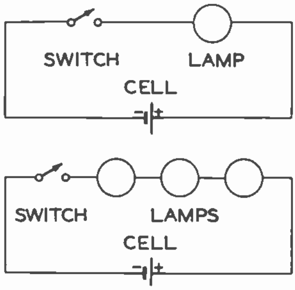


Fig. 4-15. Schematic diagrams of two series circuits.

A definite set of standard symbols has been formulated that permits an entire electrical circuit, all its parts and the manner in which it operates, to be shown by means of a drawing using symbols. These symbols are known and recognized by all electrical men. One important feature of this method of describing an electrical circuit is that the connecting conductors are indicated by drawing straight lines, or in some instances, lines which run directly from one part of the drawing to another. The insulation which covers the wires is generally omitted, except when it has some outstanding feature that warrants special consideration.

Such drawings are usually referred to as *diagrams*. Sometimes they are called *schematic diagrams*, because they indicate the scheme of operations as well as the kind and type of parts. In any case, they are drawn in a manner that is readily understood by all electrical men skilled in the art.

Fig. 4-15 shows how two simple electric circuits would look if they were drawn on a sheet of paper as schematic diagrams.

The diagram on the left shows a simple electrical circuit comprising a source of electrical pressure, a load in the form of a single incandescent lamp, and the connecting wires. The switch in this circuit is shown in the open position. The circuit is not complete unless the switch is closed. When the switch is closed, the cell will force an electric current through the connecting wires of the circuit, through the lamp, and back to the source. In this particular diagram the source of pressure is a dry cell. This is not the symbol that is regularly used to indicate a battery, which consists of several cells connected in series. The symbol used for a battery will be shown later.

In the diagram on the right of the illustration we have a second circuit. It has been made by adding two additional lamps to the first circuit. They are connected so that the current which flows through any one of the lamps must also flow through the other two lamps. This type of circuit is known as a *series* circuit. One of the distinguishing features of a series circuit is the fact that all of the current which flows in any part of the circuit also flows in all other parts of the circuit. It is interesting to note that a break in the circuit at any point will prevent the current from flowing in the entire circuit. The old-fashioned Christmas tree lamp circuits had all the lamps connected in series. If one lamp burned out, all the lamps would immediately cease burning. Almost everyone has experienced this situation and had to unscrew the bulbs, one at a time, replacing each in turn until the burned out bulb was finally located.

ELECTRICAL PRESSURE

We have mentioned several times the necessity of having an electrical pressure to force the current through the circuit. Electrical pressure, like most other kinds of pressures, is a force. It is the force that creates action in an electrical circuit, the motive power that keeps current moving in a circuit. It is quite customary to speak of electrical pressure as being *electromotive force.* In fact, we have used that expression several times, for it is apt and descriptive. Electromotive force is commonly abbreviated by its initials, *emf.*

We have described how the flow of current through a conductor is measured in terms of a special unit called the ampere. In the case of electrical pressure, it is also necessary to have some method by which its magnitude can be measured and thus compared to some kind of standard.

Pressures, such as the internal pressure of a tank of compressed air or the pressure behind a water system, are measured by the number of pounds of pressure that is exerted upon a square inch of surface. Thus it is commonly said that the water pressure in a main is 35 *pounds per square inch,* or 40 *pounds per square inch,* or some other value. Here we use units of both weight and area. Electrical pressure, however, is measured by means of a single unit called the *volt,* which was named in honor of an early Italian experimenter, Volta. He is remembered for having built the first electrical cell.

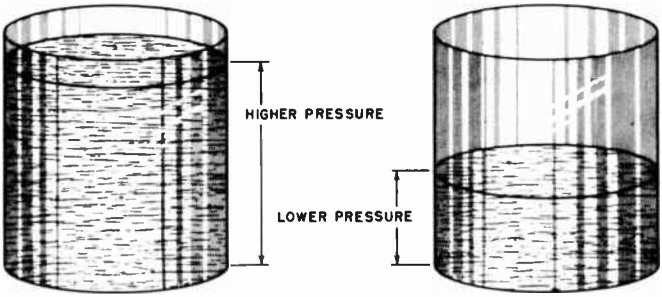


Fig. 4-16. There will be different amounts of pressure at the bottom of the two tanks because the level of water is higher in one than in the other.

Keep in mind exactly what a volt is because the term is constantly used in all branches of electrical work. It is the unit by which the magnitude of electrical pressure is measured. It is the unit used to measure the pressure that causes electric current to flow through the circuit.

Electrical pressure is always a *difference of potential* between two points of an electrical circuit. It is not at all uncommon for several electrical pressures to be present in the same circuit. This is quite similar to a condition which can be shown experimentally by using water pressures again. Let us refer to the two separate tanks or containers, partially filled with water, that are shown in Fig. 4-16. If one tank or container has a higher water level than the other, it will have a greater pressure exerted by the water near its bottom.

Then, if the two tanks are connected by means of a small pipe as shown in Fig. 4-17, water will flow from one tank to the other through the pipe because of the difference of pressure that exists between them or, to use an electrical term, because of the difference of potential.

So it is with electricity. Whenever a difference in electrical potential or a difference in electrical pressure exists between two points of an electrical circuit, current will flow from the point that is at the highest potential to the point that is at a lower potential provided there is a complete electrical path or circuit. Giving the potential of a point as so many volts always implies that the difference in potential between this point and some other reference point is so many volts. Stated simply, voltage is the potential difference measured between two points in a circuit.

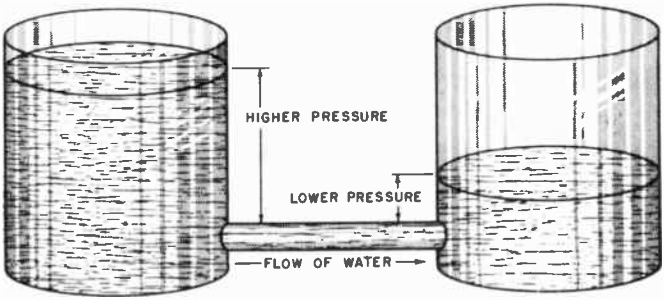


Fig. 4-17. Water will flow through the connecting pipe because of the difference in pressure at the bottom of the two tanks. This is similar to the difference of potential which often exists in electrical circuits.

The term volt is familiar to most people today; few people have not heard the term or used it. Many people employ the term incorrectly because they do not fully understand its meaning.

It is generally known that electrical power is supplied to our homes at a pressure of 110 to 120 volts. These terms are used in our daily lives. Many people also know that some of the newer homes are supplied with two voltages; either 120 volts or 240 volts. They also know that the 240 volts are considered "hotter," that is, more dangerous, and requires more respect than the lower voltage of 120 volts; but probably they do not know just why this is true.

It is also common knowledge that the power transmission lines mounted atop steel towers carry electricity at very high voltages. These lines are often referred to as "high-lines." Actually the term "high-lines" has a dual meaning, referring in its strict sense to the high electrical pressures (potentials) existing between the "high" pressure or "high" lines and the earth. Because of the high pressures involved, such lines are generally "high" above the earth and are often referred to in this sense. The conductors of such lines are kept at considerable distances from each other to prevent the high voltages breaking down the insulation of the air or the other insulators and arching across. The greater the distance between the lines, the greater will be the voltage required to break down the insulating qualities of the air.

Potential, then, is a measure of electrical pressure, and its unit is the volt. It is used for measuring the magnitude of that pressure and is always measured between two points, one of which is often a common or zero point, chosen for convenience as a reference. The greater the voltage, the greater is the electrical pressure causing the current to flow through the conductors.

SOURCE OF POTENTIAL

In the previous section we talked a great deal about electrical pressure or voltage and mentioned a few of its sources, but we said nothing about how that pressure is produced. Voltage, like any other pressure, must be produced in some manner. The high pressure behind the water which causes it to flow through the pipes into our homes is not an accident. It does not just happen! It is planned and brought about deliberately. To create this pressure, pumps are installed in the pumping station at the central pumping plant.

So it is with electricity. The electrical pressure which causes current to flow through an electrical circuit must be produced. In some cases it is produced by nature. Examples of this are the familiar lightning discharges, and the somewhat less familiar static charges of electricity. The only useable electrical pressures are those which are deliberately produced by man.

As has been mentioned before, electrical pressure can be produced by chemical means. As far back as 1786, a scientist by the name of Galvani discovered he could produce an electrical pressure by bringing together two dissimilar metals; but his source of electrical pressure had no practical value. About twenty years after Galvani's experiments, the Italian scientist, Volta, developed a source of electrical pressure which he called the voltaic pile. It consisted of alternate layers of copper and sinc placed in a pile with moist pieces of cloth between the layers. From this pile he was able to obtain a small but continuous flow of electrical current.

It was then but a step from Volta's pile to the first battery. The battery consisted of pieces of copper and zinc immersed in a dilute solution of sulphuric acid. When pieces of wire were connected to the copper and zinc plates he discovered that a continuous current would flow through the wires when they were touched together to make a complete circuit.

It was the chemical action which occurred within the battery that gave rise to a voltage (pressure). The dilute solution, which later became known as the "electrolyte," acted upon the zinc and copper plates, raising the electrical potential of one and lowering that of the other. Thus, a sizeable electrical potential difference was developed between the two metal plates by the action of the electrolyte. The difference of potential or voltage thus created would cause a current to flow through any circuit which was connected between the two plates. In this manner the chemical action within the electric cell became a source of electrical power.

This chemical source of electrical pressure made it possible, for the first time, to put electricity to useful work. The cell just described was the forerunner of the "crow's foot" wet cell, which for many years supplied power to operate America's vast telegraph network. See Fig. 4-18.

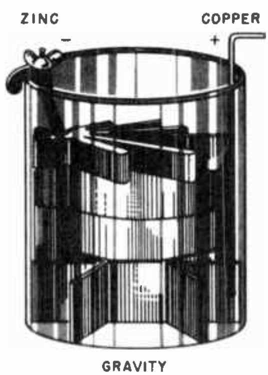


Fig. 4-18. A "crow's foot" electric cell such as was once widely used in telegraph work.

There are many other sources which can provide a difference of potential in an electrical circuit. Modifications in the original electric cell, have resulted in cells that are usable for applications totally unsuited to those of the original cell.

One of the things that limited the usefulness of the original cell was its liquid electrolyte. This liquid electrolyte made the original cell essentially a stationary device. Practically any movement caused the liquid electrolyte to spill out of the container and onto any nearby object. Since the electrolyte was a solution containing sulphuric acid, it damaged or destroyed nearly everything it touched. In radio's infancy, many a fine living room rug had at least one hole eaten through it by acid spilled from the wet battery used.

Fig. 4-19. A cut-away view of a dry cell. This is a primary electric cell. (Courtesy of National Carbon Co.)

Eventually an electric cell was designed which had the electrolyte heremetically sealed within a container. This new type of cell became known as the *dry cell.* It has been widely used as a source of power for flashlights, for the ignition systems in certain types of gasoline engines, for rural telephone systems, for most portable radio receivers, and for small portable transmitters.

During World War II, because of the vast quantity of battery powered radio, telephone, telegraph, and electronic equipment used, the weight of replacement batteries exceeded that of food required by Signal Companies.

Strictly speaking, the dry cell doesn't actually have a dry electrolyte. Its electrolyte is in the form of a moist paste mixture sealed within. A cut-away view of a dry cell is shown in Fig. 4-19. Any type of electric cell which uses up a portion of the metals comprising it and which cannot be recharged without replacing the used up metal, is called a *primary cell.* The dry cells we have just mentioned, the original crow's-feet wet cell, and many others are all primary cells.

There is another type of electric cell. This is a type which can be recharged by merely forcing current through the cell backwards; that is, in the direction opposite to its discharge. This type is called a *secondary cell* and in one of its forms is popularly known as a storage battery (Fig. 4-20). At this point it is interesting to note that the term "battery" is employed to describe the use of two or more electric cells in union with each other. One cell alone, whether a primary cell or a secondary cell, is never referred to, correctly, as a "battery." There must be at least two cells connected together before we can have a battery.

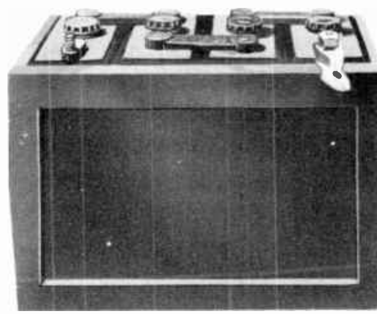


Fig. 4-20. A storage battery. This is a secondary cell. It can be recharged merely by forcing current through it in a direction opposite to its discharge.

Secondary cells in the form of storage batteries have found wide usage in our modern life. Probably their most common and familiar use is to furnish the electrical power necessary in the operation of our automobiles. The storage battery forms the central heart of a modern automobile's electrical system. The battery is charged by the car's generator while the automobile is running and stores up electrical energy in the form of a chemical change within the structure of the individual cells of the battery. Then, when the driver desires to start the automobile again, the storage battery serves as a source of electrical energy to drive the electric starting motor of the automobile, which, in turn, drives (turns over) the gasoline engine until it starts (fires).

There are many other uses for electric storage batteries. They are used in aircraft, in some underground mining locomotives, in submarines, to maintain a constant voltage on the lines of central telephone systems, and for innumerable other purposes. Some heavy duty welding machines employ a bank of such batteries to supply the heavy, intermittent peak currents required in certain spot-welding operations.

In addition to "chemical reactions," there are several other methods of producing an electrical pressure. The most important grouping of these, from a commercial use viewpoint, is "mechanical generators," into which falls the original type of generator invented by Edison and improved upon by himself and others.

This group also includes generators, alternators, converters, and inverters; in fact, it includes anything capable of producing an electrical voltage by mechanical means. See Fig. 4-21.

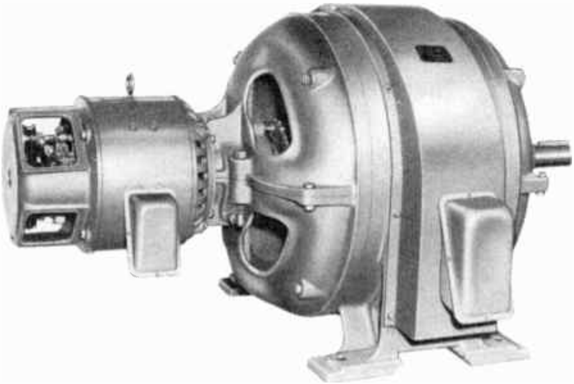


Fig. 4-21. Two generators mounted on the same shaft. The small generator supplies the exciting current for the fields of the larger generator. (Courtesy of Allis-Chalmers Mfg. Co.)

VOLTAGE DISTRIBUTION IN A CIRCUIT

It is well known that the pressure of the water in our municipal water systems is not the same at every point within the system. The pressure at any given point will depend upon the total pressure developed by the pumps at the central pumping station, and upon the losses occuring between there and the point in question. It is natural to expect that the pressure is greatest right at the pumps. Thus, if a pipe were tapped near the pumping station and the pressure measured at that point with a pressure gauge, we would find the pressure at its maximum value and nearly equal to that found at the pumping station.

On the other hand, if the pressure were measured at a point some distance from the pumping station we would find it somewhat lower. The cause would be that some of the pressure had been dissipated in various losses between the central pumping station and the point where the second measurement was made. In order to maintain a working pressure, unless a stand pipe or water tower is part of the system, one must operate the pumps at the central pumping station continuously to offset the effects of water being used and other losses.

Likewise, were we to measure the water pressure on the ground floor of an apartment building and then measure it again on the third or fourth floor, we would find the pressure reading lower on the upper floor than on the lower one. This is because the pumps are working against gravity in pumping the water to the higher level.

Much the same line of reasoning may be applied to the electrical pressure within an electrical system. Although the two systems are not identical, the general manner of reasoning is surprisingly similar.

If the pressure in an electrical system in which current is flowing, were measured near the source, the pressure or voltage would be at its maximum at that point. If the voltage forces the current through one or more successive resistances, it will be found that there is a drop in the voltage just as there was previously a drop in the pressure of the running water after the water had been forced through a long pipe. It is a technically accurate statement that whenever we force an electrical current through a resistance of any kind, we automatically reduce the pressure on the current after it has passed through the resistance. This means we have a pressure drop across the resistance. Just how much the pressure will be reduced is a matter we shall take up in more detail in a later chapter.

The important fact is simply this: we use up some of the voltage in forcing an electrical current through a resistance in the same manner that we use up some of the pressure behind the water in a pipe when we force the water through the resistance of the friction inside the pipe.

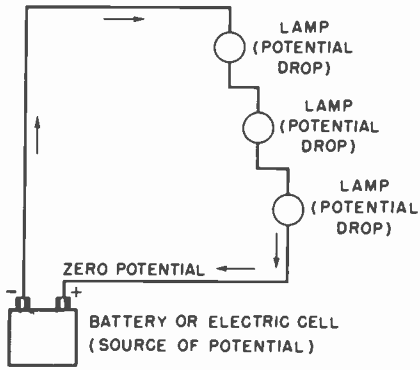


Fig. 4-22. As the current flows through the lamps under pressure of the voltage, there is a voltage drop across each of the lamps.

Whenever we use up some of the voltage in a circuit by causing it to force current through a resistance, we call that loss of voltage a "voltage drop." Men in electrical professions refer to "voltage drop" many times in their everyday work. It is important to know that the total voltage drop around a circuit always equals exactly the total voltage generated at the source. We merely mention the fact at this time. We shall discuss it in detail further on in the book.

Fig. 4-22 illustrates the action of a voltage and a current in a circuit. The action of the battery produces a difference of potential between the terminals of the battery. The battery is connected to the three lamps in such a manner as to make the voltage much higher at the upper side of the upper lamp than it is at the lower side of the lower lamp.

The electrical action, then, is such that the battery produces a difference of potential between its terminals, causing current to flow through the lamps. As the voltage forces the current through the lamps against their resistance, part of the voltage is dropped or lost in each one. By the time the voltage has succeeded in forcing the current through all the lamps, all of the voltage will have been used up; or, as we say, expended in the voltage drops. We shall explain later just how this balance between the original voltage and the voltage drops is maintained so that the two are always exactly equal.

Chapter 5

FUSES AND SWITCHES

In the previous chapter we made mention of the electric fuse and electric switch. Fuses and switches are so important in the application and control of electricity that they deserve much consideration. Therefore, this chapter will be devoted to the study of fuses and switches.

THE ELECTRIC FUSE

A firecracker, an artillery shell, or a bomb is of no use until it is exploded. In one respect the little fuse in your home electric circuit is like this; its destiny is self-destruction. However, its final errand, unlike that of a bomb, is one of mercy, in fact, one of heroism. Upon the reliability of its self-destruction depends the safety and protection from possible injury of the electric circuit in your home.

Somehow, one does not expect very much of a fuse. It's small, inexpensive and simple-looking. You would not regard it as a measuring instrument of precision. Yet, that's exactly what it is. The fiber tube or glass plug is merely the protective box that encloses an accurate device for measuring electric current. Although the measuring device that does this exacting job is only a short length of shiny wire or metal strip, it possesses some highly unusual properties.

Most metal articles are built to be strong, but this particular piece of metal is designed to be weak. As though, in proof of the old adage "A chain is only as strong as its weakest link," this piece of fuse metal is accurately designed to be the weakest part in an electric circuit.

Such a safeguard is absolutely necessary. For no matter how careful you are, there's always the chance of an accidental short-circuit or an overload on some appliance. This means that an abnormally large electric current will flow, a current that might cause trouble. However, it does not cause trouble because right then our weakest link snaps, or, as we say, the fuse blows and shuts off the electricity.

What actually happens is simple. When there is an electric current in a wire, the wire is heated. The larger the current, the hotter the wire gets. We make use of this heat in our electric lamps, toasters, and ranges. But in the fuse, when the current exceeds a pre-determined value, the fuse wire actually melts; breaking the circuit and warning you to locate the trouble and correct it.

Making this weakest link isn't so easy as it sounds, for the fuse has to develop its weakness at exactly the right time. If it is a 15-ampere fuse, it must not blow when carrying its rated current of 15 amperes. It must not even be weakened, for presumably that current is perfectly safe and proper. Yet, let the current increase above the rating, and out pops the fuse. Years of research have gone into the development of that little strip of metal inside a fuse. The choice and composition of the metal is a major triumph in the science of metallurgy. The design is more carefully made than that of many articles that cost twenty times as much.

Not all the romance of electricity is found in the big machinery. Far from it! There's plenty in the little devices that serve behind the scenes in our homes; convenience outlets, connection boxes, switches, connectors, and fuses. The chief hero of all is the fuse, which makes up the suicide squad that exists for the sole purpose of sacrificing themselves to safeguard our uses of electricity.

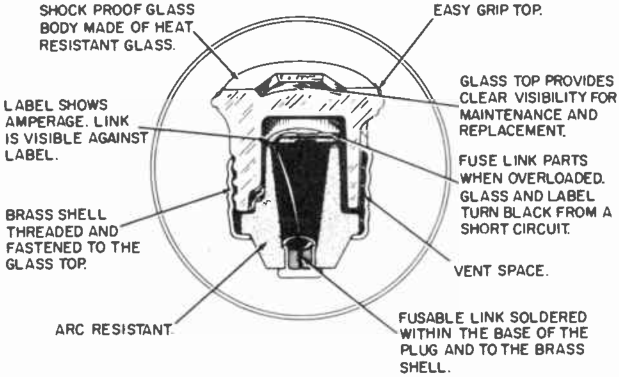


Fig. 5-1. Cross-sectional view of a fuse plug showing its various parts.

Fig. 5-1 shows a cross sectional view of an ordinary screw type fuse, the type with which everyone is familiar. The fuse protects against fire, injury, and costly repair bills. Its various parts are clearly shown and labeled in the figure. Perhaps you have never actually realized how many small precision parts are incorporated in an ordinary fuse plug.

Fig. 5-2 shows the outside appearance of the important little plug fuse. When a short circuit occurs, the intense heat instantly turns the fuse strip (fusable link) into a white hot molten mass. In fact the fuse strip explodes and is converted into a white hot gas under tremendous pressure, therefore, the fuse is provided with a vent space (shown in Fig. 5-1) to permit the safe escape of these gases.

Fig. 5-2. The external appearance of an ordinary fuse plug. (Courtesy of Bussmann Mfg. Company.)

In fusing electrical circuits always be sure to use a fuse of correct size. The right size will protect, yet will permit all the current to flow that the wiring can safely handle.

Never use fuses of too large size, as they may permit cords or wiring to burn out instead of the fuse.

When a fuse blows, do not put in a new one until the trouble that caused the fuse to blow has been found and corrected. Do not blow fuses needlessly.

Short circuits in cords caused by worn or broken insulation will blow fuses. Do not continue to use a badly worn cord. It should be repaired or replaced with a new one.

Sockets, attachment plugs, receptacles, or the connections to them sometimes get loose and cause short circuits that will blow fuses. Correct the trouble before replacing the blown fuse.

Fuses will also blow if too many lamps or appliances are connected to the circuit. In such an instance disconnect some of them before replacing a blown fuse. These things are not dangerous if fuses of the proper size are used.

When replacing fuses, always screw them in tightly so that they will make good contact in the fuse holder; otherwise heating may result and cause the fuse to blow needlessly.

FUSETRON FUSES

Sometimes fuses blow needlessly when motors on washing machines, oil burners, refrigerators, and other household appliances are started. Such motors use a moderate current while running normally, but from the instant a motor is first started until it has accelerated to about normal operating speed, it draws a current far in excess of its normal operating current. During this short period of time in starting, it often blows a fuse. This is especially true, unless the fuse is of a much higher rating than necessary for protection of the motor under normal running conditions.

Fig. 5-3. The external appearance of a Fusetron fuse. (Courtesy of Bussmann Mfg. Company.)

Recently a fuse was invented which is not blown by momentary overloads, such as those imposed by starting motors. This fuse is known by the trade name of Fusetron.

A "Fusetron" fuse is shown in Fig. 5-3. It is a combined fuse element and thermal cut-out. It protects, as does an ordinary fuse, against short circuits and overloads, but it will not blow on intermittent excess currents, such as momentary overloads produced by motors. It blows only when the overload persists.

Fusetrons may be used as replacements for ordinary fuses to eliminate needless fuse blowing. They help keep lights burning and appliances operating and often save the expense and trouble of calling a service man.

Fig. 5-4 shows a detailed cross section of a "Fusetron." From the outside, this protective device looks like an ordinary fuse, but the inside is different. It has not only a fuse link element but also a thermal cutout element.

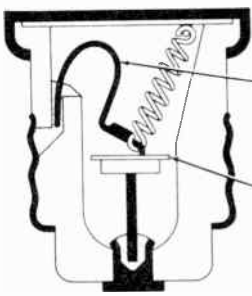


Fig. 5-4. Interior cross-section view of a Fusetron fuse. (Courtesy of Bussmann Mfg. Company.)

Excessive current resulting from any overload causes the thermal cutout to heat, and if the overload persists, the solder of the thermal cutout softens until it permits the spring to pull out the end of the fuse link, thus opening the circuit.

Because it takes some time to melt solder, even with a heavy current, the thermal cutout is not fast acting, while the fuse link is made sufficiently heavy so it will not open on a motor's starting current; therefore, the Fusetron fuse will not open on heavy motor-starting currents of short duration. When a short-circuit or an overload as high as 500% occurs, the fuse link opens in exactly the same manner as in an ordinary fuse.

TABLE 5-1. OPENING TIME OF FUSES (IN SECONDS)

CURRENT PASSING THROUGH FUSE (AMPS)	FUSETRONS				ORDINARY FUSES	
	FUSE RATINGS (AMPS)				FUSE RATINGS(AMPS)	
	15A.	20A.	25A.	30A.	15A.	30A.
30A.	38.0 Sec.	120 Sec.	— Sec.	— Sec.	3 Sec.	— Sec.
45A.	11.0	23.0	42.0	80.0	0.7	12.0
60A.	4.7	10.3	15.2	22.0	0.2	3.8
75A.	1.3	5.1	8.2	12.0	0.1	2.2
90A.	0.8	2.1	5.3	6.0	—	1.3

Referring to Table 5-1 it can be seen how the Fusetron fuse hangs on. It gives motors plenty of time to start, but observe how quickly an ordinary fuse opens on ordinary motor-starting currents. Actually, the 15 ampere Fusetron fuse carries starting current like that of a 30 ampere ordinary fuse, and blows as does a 15 ampere ordinary fuse on a prolonged overload.

The small screw type fuse plug is inadequate for handling the heavy currents encountered in the generation and distribution of electricity. This is also true in thousands of industrial and commercial applications of electricity. For this reason, fuses are designed and manufactured in an almost endless number of

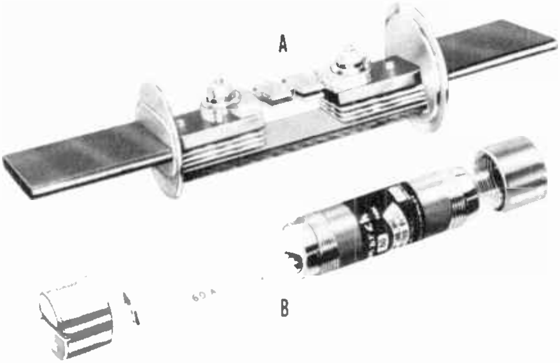


Fig. 5-5. Renewable link fuses. (Courtesy of Monarch Fuse Co. Ltd.)

styles, types, and sizes to meet all the exacting requirements for fuse protection.

Among the many types of heavy duty fuses, one that is found quite adequate for general protection and utility is the renewable link-type fuse, one style of which is shown in Fig. 5-5A. The insulative protective case has been removed in order to show the interior structure and arrangement of the fuse parts. Another style of renewable link fuse is shown in Fig. 5-5B. Renewable link fuses are designed for easy replacement of blown links. There are literally hundreds of styles, types, and sizes of fuses in addition to these described.

THE ELECTRIC SWITCH

The electric switch, in addition to the various other parts and components, constitutes an essential part of any practical electrical circuit. (See Fig. 5-6.)

An electric switch is like a lift bridge on a heavily traveled highway. When the lift is open, all the traffic is stalled. But just

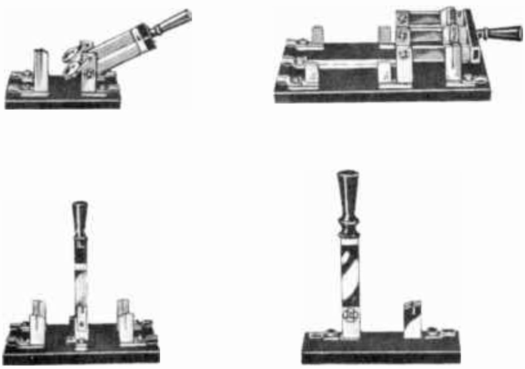


Fig. 5-6. Knife switches. (Courtesy of Metropoliton Electric Co.)

the instant the lift is closed, the instant the blades of the switch come into contact, then the traffic surges forward.

And what traffic it is! There's nothing else on earth like it. Electrons pushing and jostling their way along the copper highway of the wire—millions, billions, trillions of them, all invisible, all alike. Each one carries its own load of electric charge, its tiny contribution to the total that we call an electric current. An electric current is, in essence, a procession of continuously moving invisible electrons.

The number of electrons required to do even the simplest job staggers the imagination. To keep a 100-watt lamp burning requires a flow of six-billion-billion electrons—not per day, hour, or minute; but every second! Six-billion-billion—six with eighteen zeros after it! Yet, the individual electrons are so small that all this vast horde weighs next to nothing at all.

Now this insignificant weight of the electron is the secret of one of electricity's greatest advantages, its speed. When you throw an electric switch, something happens right now! You must spin the starter to start your automobile; you have to wait for steam to build up to start a steam engine; but electric power is always right there, poised on its toes, ready to go. It is instantaneous because the electrons have practically no cumbersome weight to get moving, no inertia to overcome. They begin to flow the instant a path is made for them, as soon as you throw the switch.

The exceedingly common and little-thought-of electric switch is after all the master, directing and controlling the countless millions of horsepower of surging electrical energy in industry, transportation, even the turning on and off of our lights or radio.

In spite of the wonders it performs, there's something friendly about a switch. It's associated with so many of our common, homely actions; things like coming home from a journey, switching on the living room light and seeing all the familiar things in

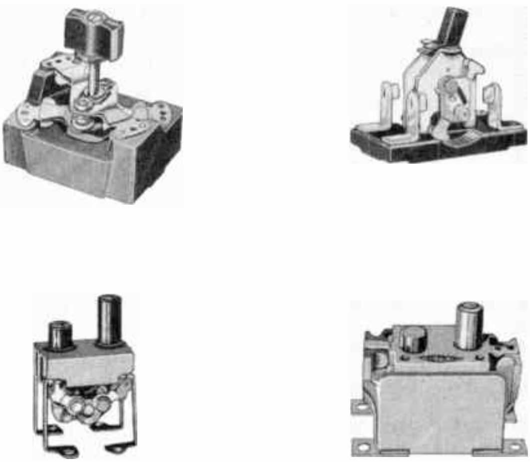


Fig. 5-7. Panel board switches. (Courtesy of Metropolitan Electric Co.)

their familiar places, or tiptoeing in and turning on the light to see that baby hasn't kicked the covers off.

Light switches are guideposts in a house. You may grope for them in a strange room, but at home your hand goes unerringly to them in the dark. You know the electricity will be there, waiting, whether it has been ten minutes or ten weeks since last you called on its service. It doesn't fail you.

Fig. 5-7 shows several types of panel board switches. Each switch in the figure is labeled.

Fig 5-8 shows an enclosed three-pole single-throw switch

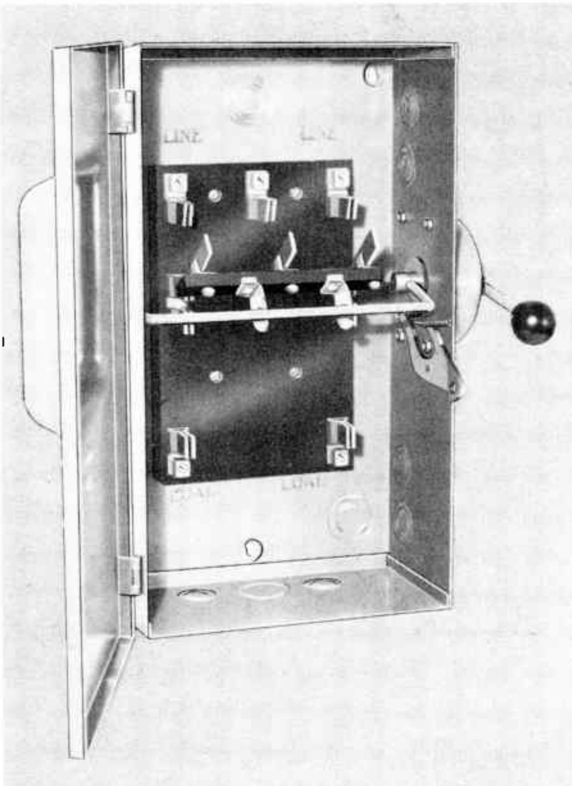


Fig. 5-8. Three-pole, single-throw switch mounted in a steel switch box. (Courtesy of American Electric Switch Corp.)

mounted in a steel switch box. This type switch has many commercial applications and in standard equipment is generally supplied in two and three pole, single-throw styles.

Fig. 5-9 shows two knife switches differing only in their mounting. The one in Fig. 5-9A is designed so that electrical connections can be made to the terminals by nuts on the front side. The switch in Fig. 5-9B is back-connected. This switch is mounted on a base or panel with the stud bolts protruding through. The electrical connections are made to the switch studs behind the panel.

Fig. 5-9. Knife switches. (Courtesy of Metropolitan Electric Co.)

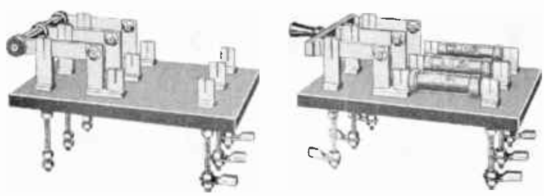


Fig. 5-10. Back-connected knife switches. (Courtesy of Metropolitan Electric Co.)

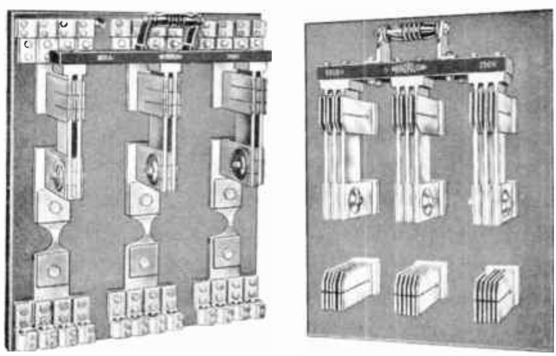


Fig. 5-11. Heavy duty switches capable of carrying large electric currents. (Courtesy of Metropolitan Electric Co.)

Fig. 5-10 shows the two types of knife switches. Both are back-connected. The one on the right side in the figure is fused.

Fig. 5-11 shows two heavy duty switches designed to carry large electrical currents. The one on the left side in the figure is a three-pole, single-throw switch. The one on the right is a three-pole, double-throw type and is capable of carrying 3000 amperes of current.

The applications for electrical switches have become so numerous that it would require hundreds of pages of illustrative and descriptive matter to cover them all. An attempt has been made, however, to describe and illustrate a few of them in this book.

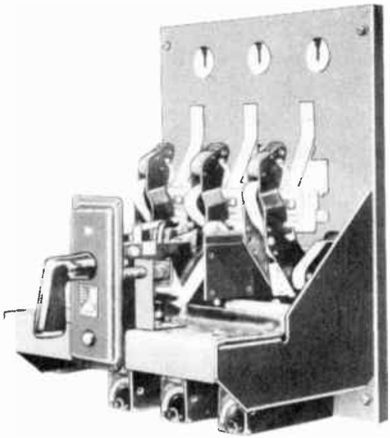


Fig. 5-12. A special type of switch known as a circuit breaker. (Courtesy of Roller Smith Corp.)

You are doubtlessly familiar with the various types of switches shown in Fig. 5-6. Knife switches vary in style, size, shape, and design, according to their uses. Fig. 5-12 shows another type of switch known as a "circuit breaker" and used frequently in industry.

Ordinarily, a circuit breaker is an electromagnetic device that automatically opens an electrical circuit when the current is in excess of a definite or predetermined value. Some circuit breakers can be reset manually, while others are reset automatically. The purpose of a circuit breaker is to protect electrical equipment from damage by opening the circuit when the current rises above some predetermined level.

There are various means of automatically opening an overloaded circuit. The circuit breakers shown in Figs. 5-13, 5-14, and 5-15 operate on the magnetic principle. With the magnetic principle, the opening of the circuit can be made as soon as the current exceeds the predetermined level.

Should the current rise be very rapid, as in a short circuit, the circuit breaker equipment should be of a type that will open the circuit as quickly as possible; yet it should be capable of allowing overloads necessary to start small motors, light incandescent gas-filled lamps, and other equipment that might be put on the line.

The combination of these two principles, high-speed operation on short circuit and delayed operation on harmless overloads,

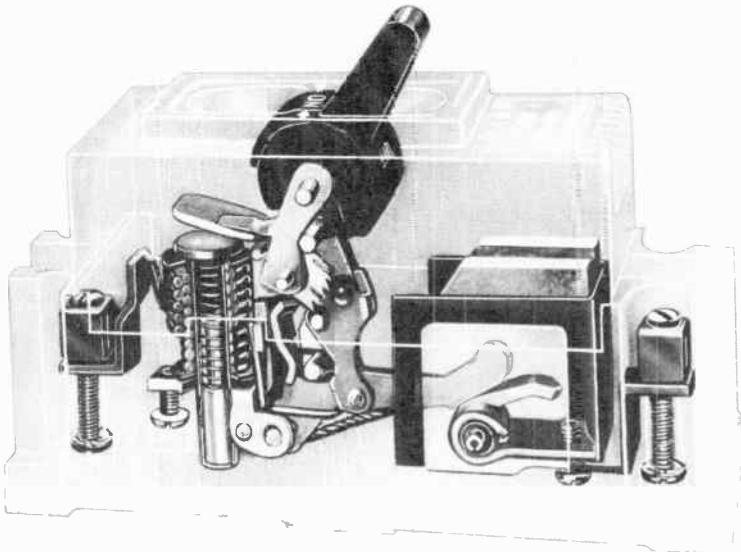


Fig. 5-13. A single-pole circuit breaker. (Courtesy of Heineman Electric Co.)

is fully met on small power applications by the magnetic type breaker. (See Figs. 5-13, 5-14, and 5-15.) It uses a hermetically

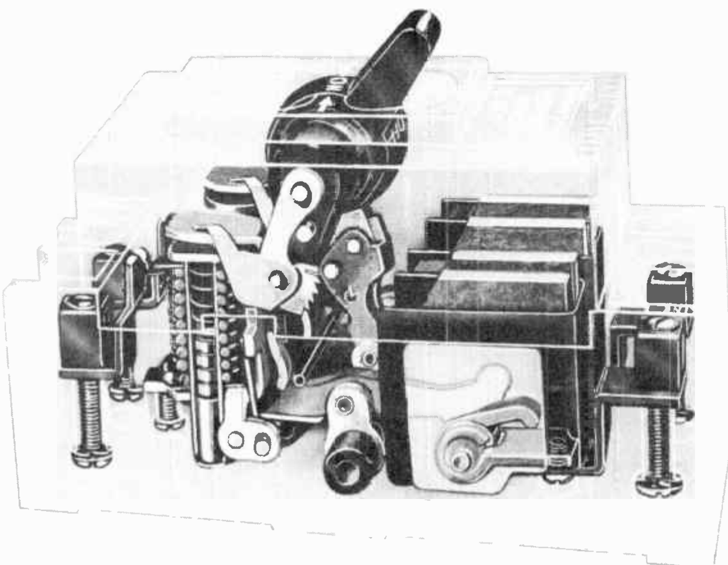


Fig. 5-14. A double-pole circuit breaker. (Courtesy of Heineman Electric Co.)

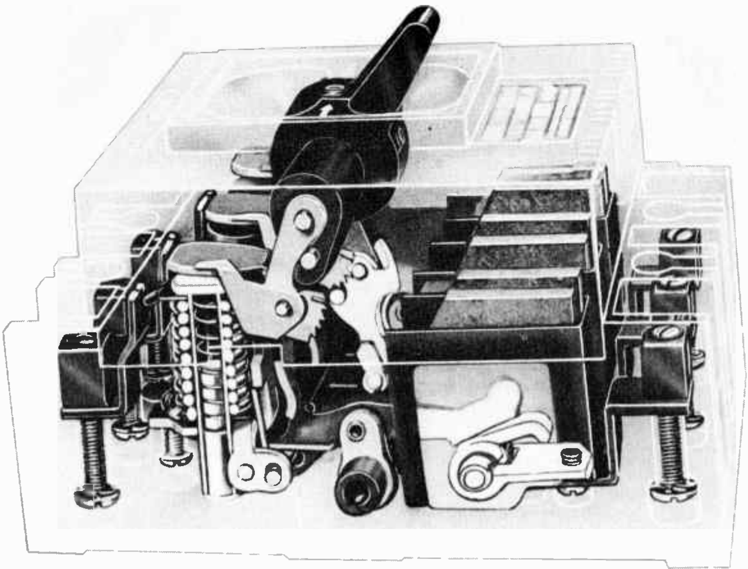


Fig. 5-15. A three-pole circuit breaker. (Courtesy of Heineman Electric Co.)

sealed tripping unit that is operated by changes of the magnetic flux; it relies on the current alone; and it is not adversely affected by changes in the temperature of the surrounding air.

A thermally operated device, after opening on a severe overload or short circuit, requires that a period of time elapse to allow thermal parts to cool off before it can be relatched and the circuit closed. However, there is no unnecessary waiting period before a magnetic type breaker can be relatched. After it has opened on overload or "short," it can be reclosed immediately, provided the overload or "short" no longer exists.

Electrically, it is of no consequence whether the breaker has tripped automatically or whether it has been turned "off" by hand. A simple way of indicating whether the breaker is opened or closed is to show only two handle positions, "on" and "off," as on any wall switch. This feature is incorporated in the three circuit breakers shown in the phantom views of Fig. 5-13, 5-14, and 5-15. The circuit breaker shown in Fig. 5-13 is a single-pole breaker; in Fig. 5-14 it is a two-pole breaker, and in Fig. 5-15 it is a three-pole breaker.

Another kind of electrical circuit breaker, frequently used in small power applications, is a mechanical breaker of the thermally operated type.

A very unique, inexpensive, and quite dependable type of automatic circuit breaker of the thermally operated type was recently developed and is known as the Mini-Breaker. It is a plug type breaker; in fact, it might more properly be called a "circuit protector" because it provides positive, permanent protection against overloads and short circuits in electrical appliances and the wiring in residential and commercial buildings. Fig. 5-16 shows this breaker, which looks very much like an ordinary fuse plug with a push button extending through the top.

Fig. 5-16. A thermally operated circuit breaker. (Courtesy of Mechanical Products Inc.)

These breakers are built in 15, 20, and 30 ampere ratings. Fig. 5-17 shows a cross-sectional view of the Mini-Breaker. The actuating element is a strip of thermostatic bimetal. Under normal

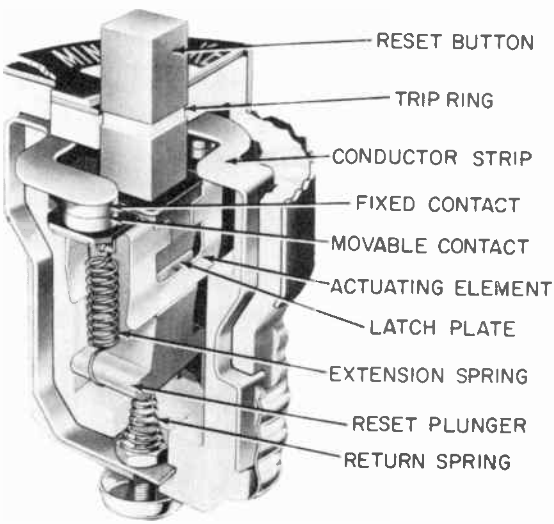


Fig. 5-17. A cross-sectional view of a mini-breaker showing its internal construction. (Courtesy of Mechanical Products Inc.)

line conditions, the electric current passes through a conductor strip and through the thermostatic bimetal actuating element which carries a pair of movable contacts. On a direct short circuit or a sustained overload, the heat resulting from the abnormal current causes the bimetal element to bend away from the latch plates on both sides of the center reset plunger, releasing it and allowing the pre-loaded return spring to force the plunger outward. This permits the twin extension springs to pull the element and the movable contacts back, away from the fixed contacts, thus breaking the circuit.

As soon as the overload or short circuit is safely adjusted or removed, one may again restore the circuit by pressing the reset button.

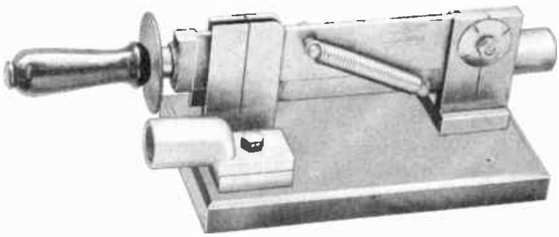


Fig. 5-18. Large electric switch having quick-break features. (Courtesy of Albert & J. M. Anderson Mfg. Co.)

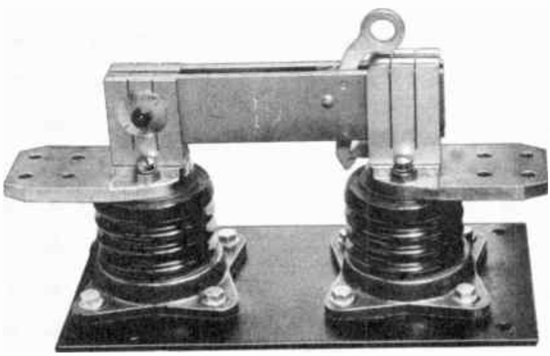


Fig. 5-19. Large electric switch arranged with latch and eye for hook-stick operation. (Courtesy of Albert & J. M. Anderson Mfg. Co.)

Fig. 5-18 to 5-27 inclusive are shown here in order to give you a better idea of the appearance and applications of some of the larger electric switches.

Fig. 5-18 shows a 600 ampere circuit-interrupting switch having quick break feature and commonly used in electric railway applications to isolate sections of trolley feeder at 750 volts DC.

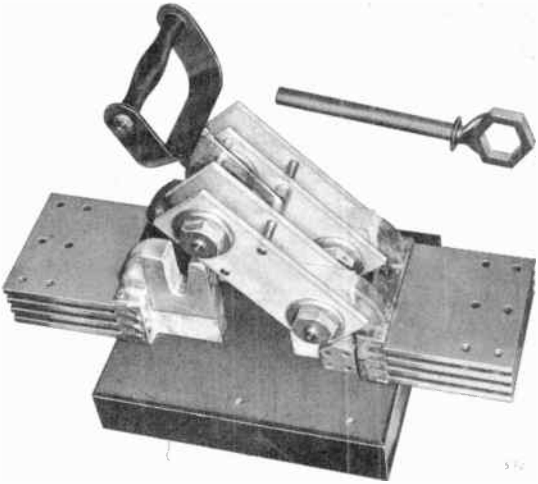


Fig. 5-20. A single-pole disconnect switch used in electro-chemical processes. (Courtesy of Albert & J. M. Anderson Mfg. Co.)

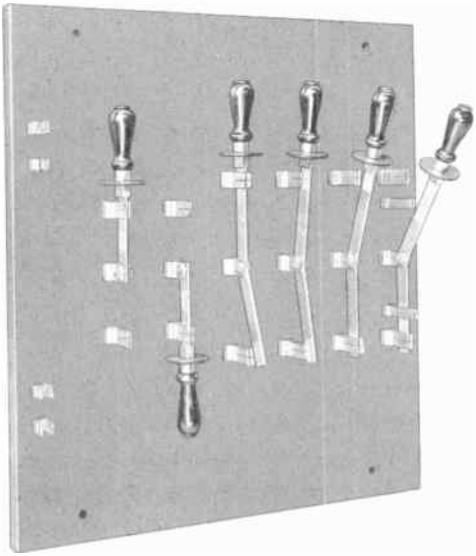


Fig. 5-21. Battery charging panel using knife switches. (Courtesy of Albert & J. M. Anderson Mfg. Co.)

Fig. 5-19 shows a typical network sectionalizing switch, indoor type, rated at 7500 volts, 2000 amperes arranged with a latch and eye for hook-stick operation. This switch is commonly used for sectionalizing secondary networks of utility systems.

Fig. 5-20 indicates a typical clamp type, single pole disconnect switch commonly used in electro-chemical processes for carrying large direct currents in corrosive atmospheres. The switch illustrated has a continuous rating of 16,000 amperes at 750 volts DC, and is mounted on a slate base approximately 24″ long, 18″ wide and 4″ thick. Clamp-

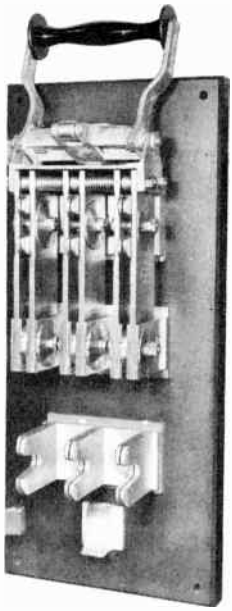


Fig. 5-22. A single-pole, double-throw switch rated at 4000 amperes, 600 volts. (Courtesy of Albert & J. M. Anderson Mfg. Co.)

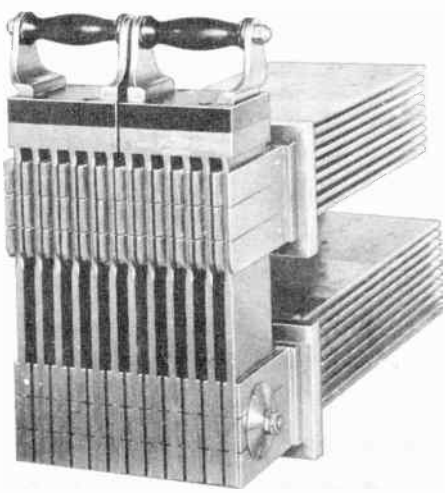


Fig. 5-23. Switchboard type of disconnect switch rated at 20,000 amperes. (Courtesy of Albert & J. M. Anderson Mfg. Co.)

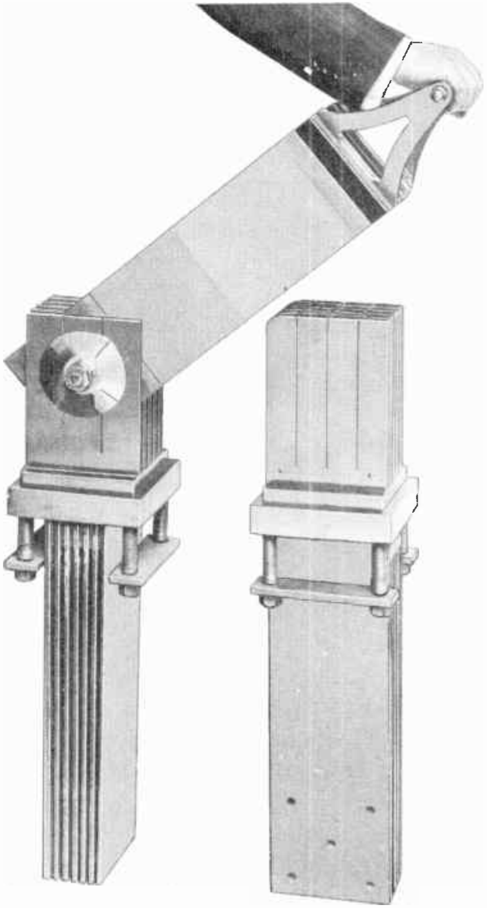


Fig. 5-24. Switch with large contact areas to permit ease of engagement with corresponding parts. (Courtesy of Albert & J. M. Anderson Mfg. Co.)

type contacts are heavily plated to assure good electrical contact and resistance to corrosion.

Fig. 5-21 shows a 60 ampere battery charging panel using two single-pole, double-throw knife switches; three single-pole, double-throw knife switches, "circuit maintaining" through the main clips; and one single-pole double-throw knife switch, "circuit maintaining" through auxiliary clips. Arrangements are used to control the charging rates of various combinations of wet cells.

Fig. 5-22 shows a single-pole, double-throw switch of the pressure contact type, rated at 4000 amperes, 600 volts. A release mechanism incorporated in the operating handle greatly reduces engaging and disengaging forces. Panel dimensions are approximately 30" by 12".

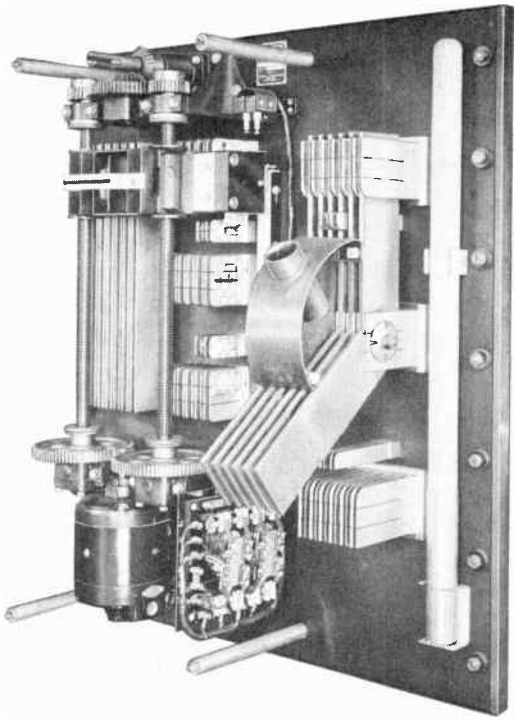


Fig. 5-25. Three-position, motor-operated switch and single-pole, double-throw manually operated switch. (Courtesy of Albert & J. M. Anderson Mfg. Co.)

Fig. 5-23 is a switchboard type of disconnect switch rated at 20,000 amperes, normally used for sectionalizing bus work in power plants at 600 volts or less. This switch is designed with large, low-pressure, multi-contact areas to permit ease of engagement with correspondingly low heating of current carrying parts.

Fig. 5-24 is a switchboard type of disconnect switch rated at 10,000 amperes, normally used for sectionalizing bus work in power plants at 600 volts or less. Such switches are designed with large multi-blade contact areas to permit ease of engagement with correspondingly low heating of current carrying parts. A single blade switch having the same ratings would require such a high contact pressure, because of its small contact area, that it probably could not be operated manually.

Fig. 5-25 shows a panel consisting of one single-pole, three-position motor operated switch and one single-pole, double-throw, manually operated switch. Each is rated at 6000 ampere, 250 volts DC and "circuit maintaining" through auxiliary clips with arc suppression means employed on motor operated section. These switches are commonly used in the equipment that automatically

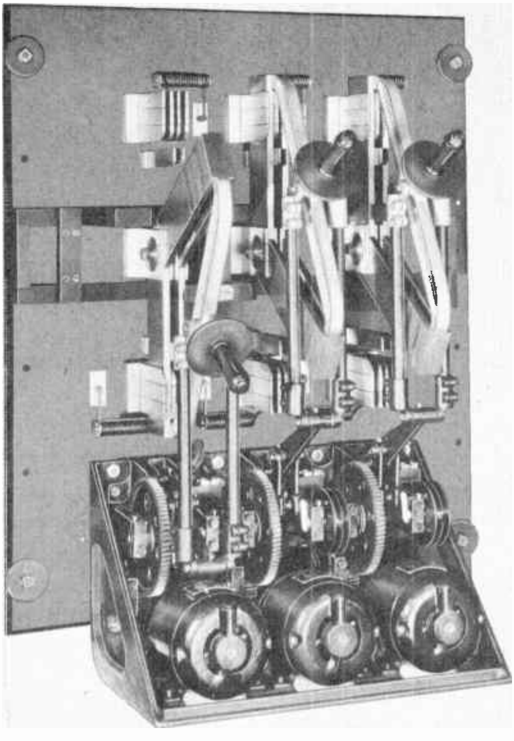


Fig. 5-26. Three single-pole, double-throw motor operoted switches. (Courtesy of Albert & J. M. Anderson Mfg. Co.)

regulates and maintains the DC voltages in utility power plants. The panel dimensions are 36 inches wide by 42 inches high.

Fig. 5-26 shows a panel containing three motor operated single-pole double-throw switches, that are "circuit maintaining" through auxiliary clips. Each switch is rated at 2000 amperes, 250 volts DC. Motor controls are interlocked for sequence operation. These switches are commonly used to automatically regulate and

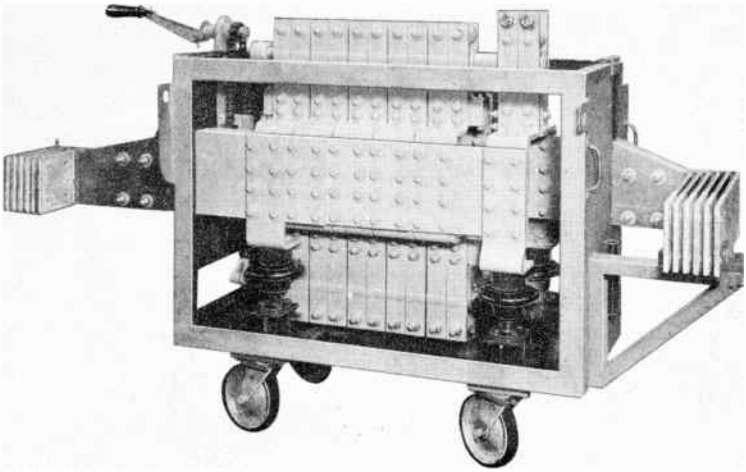


Fig. 5-27. A manually operated portable electro-chemical cell jumper switch rated at 30,000 amperes DC. (Courtesy of Albert & J. M. Anderson Mfg. Co.)

maintain DC voltages in power plants. Panel dimensions are 30 inches wide by 36 inches high.

Fig. 5-27 shows a manually operated portable electro-chemical cell-jumper switch rated at 30,000 amperes DC continuous current. The circuit-breaking section at the right end of the switch has renewable contacts designed to interrupt the total current. This switch is insulated for 750 volts above ground and 10 volts across contacts. The enclosure is corrosion-resistant and splash-proof, and the current carrying parts are cooled by forced ventilation. The assembled unit weighs 2200 pounds.

Chapter 6

ELECTRICAL RESISTANCE

THE DANCE OF HEAT

Producing heat is one of the familiar services that electricity performs in every electric iron, range, toaster, roaster, heating pad, incandescent lamp, and electric soldering iron. They all operate on the principle that when an electric current passes through a conductor the temperature of the conductor is raised. A heating element is simply a conductor or wire that is, in a sense, too small and too poor a conductor to carry the current easily. The degree of inadequacy of the wire to carry current determines the degree of heat or temperature that is produced.

Heat, for all its familiarity, is a tantalizing quantity. It can reach us through actual contact with a hot body. It can reach us by convection borne on the currents of uneasy air or it can come as radiation hurtling with the speed of light across the cold and empty abyss of space to fall as the warm, light caress of a sunbeam.

It can be created quickly by the release of chemical energy in the bright inferno of a fire or slowly in the gradual oxidation of a rusting nail, or, more mysteriously still, within every living body where food and oxygen unite to produce the heat that is the essential of life. It can be created within the invisible atomic structure of a wire by the pushing urgency of the billions of tiny electrons that we call an electric current.

If our eyes could but look within that wire, we would see a world in miniature, a world in which motion is supreme and in which every atom is spinning, vibrating, and whirling in a dizzy dance. The heat energy contained in any body is the entire sum of the energy of motion of all its myriad atoms. Rob that body of its heat and the atomic motion slows. More and more sluggish becomes the atomic movement and at last, at the absolute zero of temperature, all motion ceases; the atoms stand still in their places like soldiers at attention.

Is it any wonder then that the electric heating element shares in the romance that envelops everything that is touched by the magic force of electricity? Here electric energy poured in from the powerhouse calls the tempo of the invisible dance. You press the switch that controls, let us say, an electric toaster. An instant before, within the cool wires, the atoms were moving with slight agitation. With the flick of the switch they are incited to quickly mounting activity. At the exact tempo that the electric input calls for, the wires are glowing a cheerful cherry red at the exact temperature to make your breakfast toast.

HOW CONDUCTORS RETARD CURRENT FLOW

In the preceding chapter we touched rather briefly on the manner in which electric current flows through a conductor. Now we want to talk about some of the things that hinder the free passage of electric current through conductors.

It is well to remember that there is no such thing as a perfect conductor. Every conductor of electricity, no matter how good it may be, interposes some degree of opposition to the flow of current through it. It is this opposition or resistance that we want to understand thoroughly.

We should also emphasize again that while all metals are conductors of electricity, not all metals are equally good conductors. Some, in fact, are relatively poor, so poor they are used for that purpose only under very special circumstances. Silver is the best conductor, but even silver is not completely free of resistance. Copper is an excellent conductor, and because it is much less expensive than silver, it is far more widely used in electrical work.

Now, since every conductor offers some degree of opposition or resistance to the flow of electric current, the longer a conductor is the more resistance the current will encounter.

In fact, this generalization can be reduced to specific terms. If a conductor of a given size and kind of metal has a certain amount of resistance for some specified length, it will have just exactly twice that amount of resistance if the length of the conductor is doubled. As a practical example, if a conductor of a certain metal has so many units of resistance per 1000 feet, it will have exactly twice that amount if it is 2000 feet long. On the other hand, 500 feet of it would have only half that amount of resistance. This fact is pointed out graphically in Fig. 6-1. The first length has a certain resistance. The second length, which is twice as long, has twice as much resistance. The third length, which is half as long, has only one-half the resistance.

All of this provides us with a useful rule in working with electrical conductors of any kind: Electrical resistance is *directly proportional* to the length of the conductor, provided, of course, the conductor is the same diameter and is made of the same material throughout.

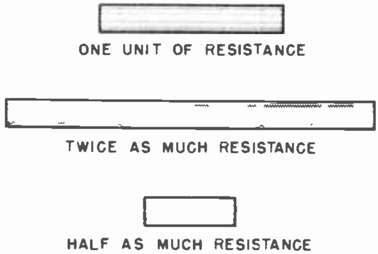


Fig. 6-1. The resistance is directly proportional to the Length of the conductor.

Thus, the length of wire has a considerable influence upon its ability to conduct electricity. The longer the wire, the more difficult it is for the current to get through it. In other words, the longer the wire, the greater its resistance.

There is another equally important factor in determining resistance, and this is the size of the wire. The larger the wire, the easier it is for current to get through it—the less resistance in the wire. On the other hand, the smaller the wire the greater will be the resistance.

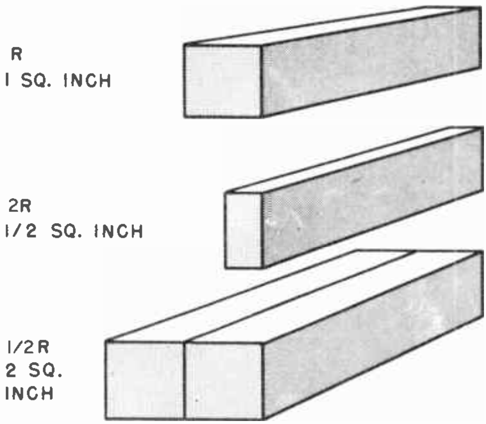


Fig. 6-2. The resistance is inversely proportional to the cross-section area of the conductor.

We can compute the effect that the size of the wire has on the resistance. If a conductor of a given size length, and cross sectional area has a certain resistance, a second wire having the same length but with twice the cross sectional area would have only one-half the resistance. If a wire of a certain cross sectional area and length has a given resistance, a second wire half that cross sectional area but the same length would have twice as much resistance.

Fig. 6-2 shows this graphically better than words alone can do. At the top of the figure we see a conductor which is exactly one inch square. Any given length of a wire this size would have a certain resistance. In the middle there is a second conductor only one-half the cross sectional area as the one above it. It is one inch high but only one-half inch thick. Thus since it is only one-half as large in cross-section, it would have twice as much resistance as the conductor at the top.

At the bottom of the figure, however, we have a third conductor which has twice the cross sectional area as the top one. It is the same height, one inch; but it is twice as wide, two inches. This conductor would have only one-half as much resistance as the top conductor in the illustration.

We can reduce all this into a simple statement: the larger the wire, the lower its resistance; the smaller the wire, the higher its resistance.

We can summerize with the universal rule: The electrical resistance of any metallic conductor is *inversely proportional* to its cross-sectional area.

CROSS-SECTIONAL AREA AND HOW IT IS MEASURED

In the preceding section we directed our attention to electrical conductors in which the size of the conductors was measured in inches. If all conductors were this size or larger, it would be an easy matter to use the inch as the basic unit of measurement. Unfortunately, they are not! By far the greater number of wires used in electrical work are much less than an inch in diameter. For this reason we must make any necessary calculations in solving a problem by using fractional parts of an inch, or we must create some new unit by which the wires can be measured. Anyone who has worked with fractional units knows that the difficulties surrounding such calculations are magnified out of all proportions.

To eliminate the necessity of having to work with very small fractional parts of an inch, electrical men have selected another unit for measuring them. They have adopted a unit which is only one-thousandth part of an inch, the *mil*. Its decimal equivalent is .001 inch.

Fig. 6-3 shows the cross-sectional area of a piece of wire that is exactly one inch in diameter. The diameter of the wire is shown in both inches and mils. Its diameter in inches is, of course, one inch. Its diameter in mils is 1000 mils. (The word "Mil" is pronounced as though it were spelled m-i-l-l.)

Fig. 6-3 shows how the diameter of a piece of wire is indicated. There is something else that is even more important in considering the usefulness of a wire for conducting electricity. That is its cross-sectional area. The total cross-sectional area of a piece of wire is another important factor in determining its ability to conduct electricity.

Since most wires used for conducting electricity are round, the cross-sectional area of wire is measured in *circular mils,* the total number of *circular mils* being a determining factor in its ability to conduct current.

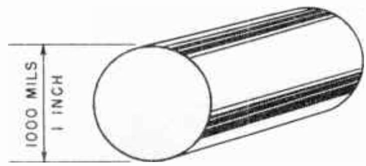


Fig. 6-3. The diameter of a conductor is measured in mils. One inch equals 1000 mils.

The total number of circular mils in the cross-sectional area of a wire is determined by multiplying the diameter in mils by itself. If, for example, we consider the piece of wire shown in Fig. 6-3, the cross-sectional area is determined by multiplying the 1000 mils by 1000 mils. This gives a total of 1,000,000 circular mils, the cross-sectional area of the wire. This is shown graphically in Fig. 6-4. Mathematically we would simply say: The cross-sectional area of any conductor in circular mils is equal to the square of its diameter in mils.

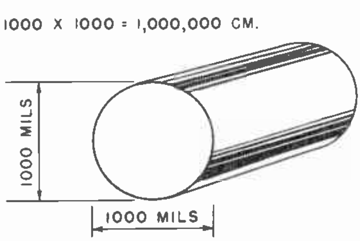


Fig. 6-4. The cross-sectional area of a conductor is one of the factors that determines the amount of current it will carry. The cross-sectional area is measured in circular mils.

One circular mil is the area of a circle which is exactly one mil in diameter. A wire, then, that is one inch in diameter or 1000 mils in diameter would have the same cross-sectional area as one million wires, each of which was one mil in diameter and had a cross-sectional area of one circular mil.

The manufacturers of wire used in electrical work have standardized their wires according to a series of sizes which are arranged in a "Standard Wire Table." These sizes run from size 1, which is quite large, to size 40, which is quite small. Each size is standardized as being so many mils in diameter and so many circular mils in cross-sectional area.

In addition to the numbered wire sizes, the manufacturers also make wires which are larger than size 1. These are numbered size 0, size 00, size 000, and size 0000. Quadruple zero, as it is commonly called, is the largest standard size wire manufactured.

However, there has been an increasing demand for wire manufacturers to make larger wires than those described in the wire tables. Much larger wires are now being made, but they are not described by numbers; instead they are described by their cross-sectional area. Wires having a cross-sectional area of 250,000cm (circular mils) 350,000cm, 500,000cm, and 750,000cm are now quite common.

Because it is so important to understand what electrical men are talking about when they mention "mils" and "circular mils," it is necessary for those who want to learn the fundamentals of electricity to master these terms. The term *mils* is the measure of wire diameter; *circular mils* is a measure of the cross-sectional area of the wire.

HOW CONDUCTOR MATERIAL AFFECTS RESISTANCE

It has long been known that silver is the best electrical conductor yet discovered, but its use as an electrical conductor has been limited because of its cost. For that reason it has been used only where its high cost was of secondary importance to other considerations.

It is often used as contacts on relays and certain types of switches. When it is used in these places, it does not corrode or pit when the sparking occurs, as do many of the other metals. With the advent of radar, silver has been used to plate many of the conductors used at high frequencies where the current travels on the surface of the conductor instead of throughout all of the conductor.

During the construction of the giant cyclotrons that were employed in the nuclear research which produced the first atomic bomb, the magnet coils were sometimes wound with specially made silver wire. In the construction of one cyclotron, the Treasury of the United States loaned the Manhattan Project several thousand tons of silver for use in the construction of the magnet coils. Here, again, the use was a very special one where cost was not the major factor; the use of silver in this special instance is no sign that it is likely to become a commonly used metal for electrical wires.

Copper is by far the most widely used metal in making wires for use in electrical apparatus. In fact, copper is so widely used that the entire electrical industry is dependent upon the copper mining and smelting industry. Whenever the production of copper is interrupted, effect upon the electrical industry is immediate and drastic. Several times within recent years the nations entire electrical industry has been threatened by interruption of the supply of copper. Copper, today, despite its usefulness for other purposes, is probably used to a greater extent in electrical work than for all other purposes put together. By this we mean that more tons of copper go into the construction of electrical conductors each year than go into the construction of all other kinds of products.

Aluminum is also a good conductor of electricity. However, it was not widely used until after World War II. The drastic shortage of copper which developed during and after that war forced the electrical industry to turn to aluminum and use it for many purposes.

There are both advantages and disadvantages in the use of aluminum as an electrical conductor. It is not so malleable (capable of being extended or shaped) as copper and does not have the tensile strength, in other words, it is more easily broken. It cannot be soldered readily.

On the other hand, where weight is an important factor, aluminum is often deliberately used instead of copper. The construction of aircraft is one case in point. There are many places in airplane wiring and construction where aluminum wire is preferred to copper for this reason.

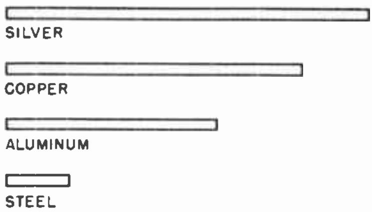


Fig. 6-5. A comparison of the resistance, but not all are the same length.

Fig. 6-5 gives some idea of the relative ability of the more important metals as conductors of electricity. All the conductors shown have the same cross sectional area and the same amount of resistance. The wire of silver is the longest, while that of copper is slightly shorter, and aluminum is shorter still. The silver wire is more than five times longer than the steel wire.

Iron wire once was widely used as a conductor of electricity. In fact, at one time it was used almost universally as a conductor in telegraph work but is seldom used today.

HOW TEMPERATURE AFFECTS RESISTANCE

We have already mentioned three things affecting the resistance which a conductor will present to the flow of electricity. These are the length of the wire, its cross sectional area, and the material of which it is made. There is still a fourth factor which has an important bearing on the resistance of the conductor. This is its temperature.

The increase in temperature of a pure metal conductor increases the resistance it offers to the passage of an electric current. In many instances this tendency is of little importance, but there are many other cases where it is highly important.

For example, the wires within the motor which carry the current making the motor rotate often carry very heavy currents. These wires often become quite hot. As the temperature increases within the motor, the resistance also increases. Often the limitations of the rating of the motor are determined directly by the increase of that temperature and its effect upon the resistance.

Lines which carry electric power between distant points are out in the weather and are also often seriously affected by the temperature. In the winter months when the temperature is near zero, the wires are able to handle up to twenty per cent more current than in the summer when the lines are heated by the sun.

This tendency of resistance to increase with a rise of temperature is peculiar to pure metals. When two or more metals are alloyed together, different effects result. It is possible to alloy certain metals so the resistance remains constant, or nearly so, over a wide range of temperature. It is even possible to compound some alloys so the resistance actually drops as the temperature rises; but these are exceptions, used only for special purposes.

Carbon and graphite are both conductors of electrical current, but their action under the influence of heat is different from that of metals. Their normal resistance to the flow of electrical current is somewhat higher than that of most of the metallic conductors, but as the temperature of the carbon and graphite is increased, their resistance to the flow of current actually decreases rather than increases. This peculiar action, called a negative temperature coefficient of resistance, is used to advantage by the designer of electrical equipment of certain kinds.

The same is true of liquid conductors. As the temperature of some liquid conductors decreases, the resistance increases. This is one of the reasons why the storage batteries used in automobiles do not perform so well in winter as in summer. On cold winter mornings the liquid electrolytic solution within the batteries is cold. This causes the internal resistance to be so high that it is difficult for enough current to pass to start the engine, especially when the battery is somewhat low on charge.

THE OHM

We have used parallel similarities of water flowing through pipes and electricity through wires to illustrate certain electrical principles. We are now fully aware that the friction encountered by the water in moving through the pipes retards the flow of water. We are fully aware of that opposition; however, we are seldom required to actually measure the magnitude, or amount, of that resistance.

In electrical circuits, however, we are interested in the magnitude of the resistance in each conductor. Resistance plays a tremendously important part in the operation of every electrical circuit, and, for that reason, it became imperative that some special unit be developed or designated which would indicate definitely how much resistance was present in any given conductor or circuit.

Perhaps this does not come as a surprise. We have shown it was necessary to adopt a special unit, the *volt,* for measuring the pressure behind an electric current. We adopted another unit, the *ampere,* to measure the rate of flow of electric current. A third unit measures the amount of resistance that is present in any given conductor. That unit is called the *ohm.* The ohm was named after an early investigator who did much experimenting with the peculiar phenomena of resistance occurring in electrical circuits. His name was George Simon Ohm. (His name is pronounced to rhyme with foam or roam.)

George Simon Ohm conducted many experiments which demonstrated beyond the possibility of doubt that there is a very close relationship between voltage, current, and resistance in any given circuit. He showed that the amount of current which flowed in a circuit depended precisely upon the amount of resistance in the circuit and the amount of voltage which caused the current to flow. This idea will be discussed at greater length in another chapter.

Basically, however, we can say that as the voltage across any given resistance is raised or lowered, the current through that resistance will rise or fall by a like amount. On the other hand, if the voltage is held constant, the amount of current that will flow through a given circuit will change as the resistance is changed.

This means that the current will rise and fall in direct proportion to any rise and fall of the voltage which causes it to flow. If the voltage is increased, the current will increase in direct proportion. If the voltage is decreased, the current will decrease in direct proportion.

On the other hand, if the voltage is held constant, the current will change if the resistance is changed. If the resistance is reduced, the current will increase. If the resistance is increased, the current will decrease.

To make this a little clearer, it should be explained that any increase in the resistance means that there is more opposition to the flow of the current. It is only natural, then, that an increase in the resistance will make it more difficult for the current to flow and less will actually flow through the circuit.

When one thing increases by some given amount and another thing decreases by the same amount, we say they change inversely with each other. If two children are playing on a teeter-totter, one end of the teeter-totter will rise as the other end goes down. We can say that as one end of the teeter-totter moves, the other end will move in the inverse direction.

Any change in the voltage which causes a current to flow or any change in the resistance through which it flows will affect the amount of current that can flow in that conductor. We can look upon the current as being the dependent element, or variable, in an electrical circuit. It is not possible to say that just so much current will flow and that all other circuit elements will adjust themselves to that of the current. On the contrary, it is the current which must adjust itself. It will adjust itself to conform to the other values of the other circuit elements.

This means that to accomplish our purpose, if we have occasion to change the value of current which is flowing in a circuit or is to flow in that circuit, we must do something to change the other elements in the circuit. If we want to increase the amount of current that flows in a circuit, we must do one of two things: we must either increase the voltage which is causing the current to flow, or we must reduce the resistance against which the current is flowing. In practical circuits we must often do a little of both.

We have mentioned that the ohm is the unit by which we measure the amount of resistance in a circuit. It is important that we also understand something about the ohm. This can be done by comparing it with a volt and an ampere.

We already know some things about the potential of a volt. We know that an ordinary dry cell will develop approximately one and one-half volts; and we also have some idea of the value of an ampere by noting how many amperes certain familiar electrical objects use. With this information as a stepping stone, we can describe an ohm in this manner: *One volt* of pressure will force *one ampere* of current through *one ohm* of resistance. This is shown graphically in the illustration at Fig. 6-6.

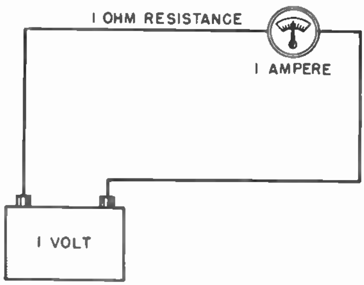


Fig. 6-6. One volt will force one ampere through one ohm of resistance.

We could draw a picture of an electric lamp, a motor, a conductor, or of many other things that are used in electrical work; but, as we have learned, it is considered a better practice to use symbols to describe many of them. There is no way of picturing resistance, but since electrical men are constantly working with resistance and must always deal with it in their calculations, it is convenient to use a symbol to indicate resistance. The symbols shown in Fig. 6-7 are used universally for that purpose. The one at the left was used for many years in the power industry to indicate resistance, while the one at the right is used by radio and electronic men. Recently, however, there has been a tendency for workers in all branches of the electrical industry to adopt the symbol at the right. The other symbol is gradually falling into disuse.

Fig. 6-7. Symbols for resistance. The one on the right is now used most widely.

RESISTANCE IN A SERIES CIRCUIT

In electrical work we often deal with series circuits. In a series circuit, current can not flow through any part of the circuit without flowing through the entire circuit. Such a circuit has all the elements connected together so that the current will flow through one after another. Fig. 6-6 is a simple series circuit. Fig. 6-8 is another. In Fig. 6-8 the current, forced through the circuit by pressure of the battery, flows through the first lamp, then through the second lamp, and finally back to the battery. The voltage of the battery must be great enough to force the current through the resistance of both lamps.

From this it is evident that when the current must be forced through two resistances in series, the total opposition or resistance will be greater than when only one lamp or one resistance is in the circuit. The total resistance or opposition in a series circuit will be the sum of all the resistances.

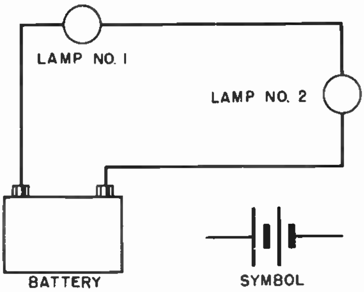


Fig. 6-8. Resistance in series.

To illustrate further, suppose we draw another circuit showing two lamps connected in series, and give their resistances in ohms. First, let us consider the matter of the battery we have been using. In electrical work it is always considered to be too much work to draw a picture of a battery every time one must be indicated. As a substitute a symbol is used. The one shown along side the battery of Fig. 6-8 is widely used. Now, when we draw a new circuit consisting of our two lamps in series with the battery, we can use the symbol instead of drawing a picture.

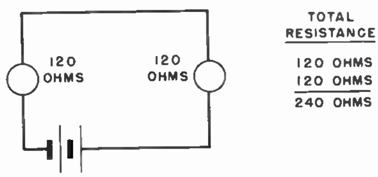


Fig. 6-9. How to determine the total resistance in a series circuit.

In Fig. 6-9 we see two lamps connected in series with a battery. Each lamp has a resistance of 120 ohms. If the total resistance in a series circuit is equal to the sum of all the resistances, it would mean, in this case, that the total resistance is the sum of 120 ohms and 120 ohms or a total of 240 ohms. This method of reasoning applies to all series circuits. It makes no difference whether there are only two loads or resistances in a circuit, or several such loads or resistances. The same rule holds true.

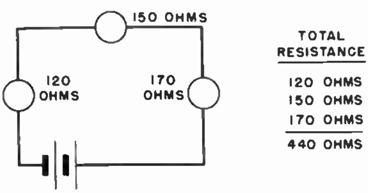


Fig. 6-10. Finding the total resistance of three resistances in series.

In Fig. 6-10 three resistances are connected in series. The value of the resistance is not the same in each instance. In the first, it is 120 ohms; in the second, it is 150 ohms; and in the third, it is 170 ohms. However, the same principle applies. To find the total resistance in the circuit, it is merely necessary to add all the separate resistances. Adding them together gives a total of 440 ohms of resistance in the circuit.

In the foregoing examples we did not take into consideration the resistance of the connecting conductor. Sometimes this must be done, although there are cases where the resistance of the connecting conductors is so insignificant that it can be disregarded.

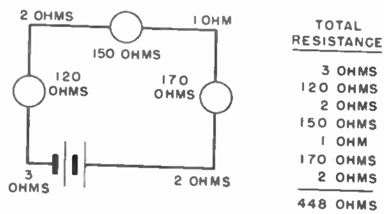


Fig. 6-11. Often it is necessary to take into consideration the resistance of the connecting conductors in determining the total resistance in a series circuit.

In Fig. 6-11 we have arbitrarily assigned values to the resistance of the connecting wires. When these are added to the other resistances, the total has risen to 448 ohms. This is not a great increase, and in this case the resistance of the connecting wires could probably be disregarded.

An important rule in connection with series electrical circuits can be summed up by saying: *The total resistance in a series circuit is equal to the sum of all the resistances in the circuit.*

Chapter 7

OHM'S LAW

VOLTAGE, CURRENT, AND RESISTANCE

Through the study of various natural physical phenomena man has discovered means of predicting certain actions when certain other conditions exist. Newton, for example, demonstrated how a natural physical law controls the action of a falling body. Benjamin Franklin demonstrated the similarity between the natural lightning in the clouds and the man-made static electricity he could produce by friction. James watt studied the action of steam in a closed kettle and from his studies evolved a knowledge of steam that lead to the invention of the steam engine.

So it has been in many other fields. Men have noticed peculiar or unusual occurances and then set about deliberately to study them until they know so much about them that they are able to predict what is likely to occur under any given set of conditions.

The field of electricity is no exception. One of the earliest students of the peculiar actions of an electric current in a circuit was George Simon Ohm, who was mentioned in a previous chapter. In Ohm's day very little was known about electricity. At that time there was no use for it. It was little more than a laboratory curiosity.

The War of 1812 between the United States and England had been ended only a few years. Europe was temporarily at peace. At that time Ohm had already been experimenting with the little known curiosity called electricity for several years.

He built some voltaic cells and made some wires through which the current could flow. During the course of his experiments, he discovered that at times more electricity would flow through the wires than at other times. This puzzled him so greatly that he decided to find out just what caused it.

After a seemingly endless series of experiments, he discovered, during the year 1826, that the more voltage from the voltaic cells he applied to the circuit the more current would flow and that the less voltage he applied the less current would flow. Then he discovered that the current was also adversely affected by the amount of resistance in the circuit.

He continued his experiments until he had proved to his own satisfaction that the current was always changed in direct proportion to any change in the voltage and always changed in inverse proportion to the amount of resistance.

He then published the results of his experiments. His proof of the relationship of voltage, current, and resistance in an electrical circuit came to be known as *Ohm's law*. It continues to be known and recognized throughout the scientific world as the fundamental rule for the determination and prediction of how the change in any of these properties affects the other electrical properties in the circuit.

Ohm presented his law in three forms:

1. The current in amperes is always equal to the potential in volts divided by the resistance in ohms.
2. The potential in volts is always equal to the current in amperes multiplied by the resistance in ohms.
3. The resistance in ohms is always equal to the potential in volts divided by the current in amperes.

It may seem a little difficult and unnecessary to remember all of this. Yet, in those few simple words is a wealth of information about electrical current and what governs its flow. If you memorize and fully understand those three statements, you will find them invaluable in your work with electricity. Every activity occuring in an electrical circuit conforms precisely with those rules.

In an effort to put some life into those rules and make them a little more realistic than words alone can do, let us see just what they mean in everyday, ordinary language. After all, it is only when things are reduced to familiar terms that they begin to have meaning for most of us.

The first form of Ohm's law states that the current in amperes is always equal to the voltage divided by the resistance. This is merely a little more exact, a more precise way of saying what we have already said several times: The current is dependent upon the voltage and will rise as the voltage rises and will fall as the voltage falls, and it is also dependent upon the resistance and will rise as the resistance becomes less and will decrease as the resistance becomes greater.

If we put the first form of Ohm's law into the form of a mathematical equation, it may look a little better and possibly appear to have a closer relationship to the things we have already been saying about it. Putting it into the form of an equation it will look like this:

$$\text{Current} = \frac{\text{Voltage}}{\text{Resistance}}.$$

If you will study that equation for a moment, you will see that it is saying exactly the same thing we have been saying: The current will increase as the voltage increases but will decrease if the resistance increases. By substituting figures for words we can show a little better just what we are trying to say.

Suppose that we have a circuit in which a potential of 10 volts is developed by a battery as shown in Fig. 7-1 and that this voltage is impressed across a lamp whose resistance is 5 ohms as shown. When such a condition prevails, a current of 2 amperes will flow in the circuit.

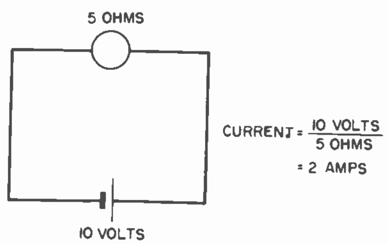


Fig. 7-1. A simple series circuit.

We could rewrite our equation to look something like this:

$$\text{Current} = \frac{10 \text{ volts}}{5 \text{ ohms}}.$$

This equation shows us at a glance that the 10 volts are to be divided by the 5 ohms, exactly the same thing the first form of Ohm's law told us a little earlier and what we had probably already deduced from our previous discussion of what went on in an electrical circuit.

By carrying out the equation and solving the problem by dividing the resistance of 5 ohms into the potential of 10 volts, we obtain the 2 amperes of current, the amount flowing in the circuit. This can be shown in this manner:

$$\text{Current (2 amperes)} = \frac{10 \text{ volts}}{5 \text{ ohms}}.$$

HOW THE SECOND FORM OF OHM'S LAW IS USED

On many occasions the amount of resistance present in a circuit and the amount of current flowing in it can be easily determined.

One might find the resistance in a circuit from the markings or nameplates on an electrical device or from having compared it with some similar resistance. The amount of current might be measured with an ammeter, a current measuring device, or learned in some other manner.

It might also be desirable or necessary to know the electrical pressure (potential) in volts causing the current to flow. If the current in amperes and the resistance in ohms are known, the voltage applied to the circuit can be easily calculated by using the second form of Ohm's law: The voltage is always equal to the current in amperes multiplied by the resistance in ohms.

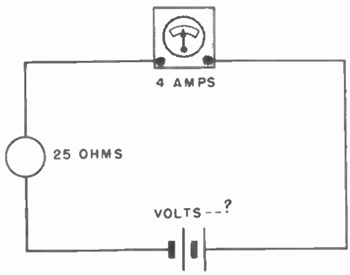


Fig. 7-2. When the current and the resistance in a series circuit are known, it is a simple matter to figure the voltage.

Suppose we have learned in some manner that 4 amperes of current are flowing in the circuit shown in Fig. 7-2. Suppose also that we know there are 25 ohms of resistance in the load. We might learn this from the label of the device or in some other manner. For the moment let us just assume that we have some reliable way of determining these things.

From these known values we can use Ohm's law in its second form to figure out the value of the unknown factor, voltage. In his law's second form, Ohm said that the voltage could always be determined by multiplying the resistance by the current. Perhaps he did not use exactly those words, but that is what he meant. In this case we can figure out the value of the voltage by multiplying the 25 ohms of resistance by the 4 amperes of current, which gives us 100 volts, the amount of the voltage.

We could set that up in the form of an equation in this manner:

$$\text{Voltage} = 25 \text{ (ohms resistance)} \times 4 \text{ (amperes current)}.$$

The answer, of course, would be the same: 25 multiplied by 4 always equals 100, no matter how we write it.

It might be interesting to see how this problem would have come out if we had known the voltage and the resistance and had wanted to find the amount of current. In that case we would have gone back to the first form of Ohm's law and set the problem up in this manner:

$$\text{Current} = \frac{100 \text{ volts}}{25 \text{ ohms}}.$$

We would have solved the problem in exactly the same manner as before. The current is equal to the voltage divided by the resistance. In this case we would have divided the 100 volts by the 25 ohms of resistance and our answer would be 4 amperes of current, just what we had before. It makes no difference which one of the factors, volts, ohms, or amperes, is unknown. By applying the correct form of Ohm's law, one can determine the unknown value.

HOW TO USE THE THIRD FORM OF OHM'S LAW

When George Simon Ohm published the results of his experiments, the third form of his rules governing the behavior of a current in an electrical circuit was stated in these words: The resistance in ohms is equal to the potential in volts divided by the current in amperes.

At first glance one might wonder just what good that rule could be to any practical electrical man. The truth is that the electrical man applies that rule almost every day of his working life.

To show how practical and useful the rule is let us return to the consideration of current flowing through an incandescent lamp. We are not concerned with a particular lamp, just any lamp. Suppose that we wished to know the resistance of the filament in such a lamp. There are several ways we could go about determining that resistance.

One way would be to apply an ohmmeter to the base connections of the lamp and read its resistance. An ohmmeter is a device which may be used to measure the resistance in a circuit. It is so designed that the resistance can be read directly on a meter scale calibrated in ohms.

Using an ohmmeter would give us a reliable reading of the resistance. The method of making such a measurement would be similar to that shown in Fig. 7-3.

Let us stop and think a moment! It is all well and good to say that we can determine the resistance of the lamp filament with the ohmmeter, but there is one little thing we forgot to mention.

The resistance we would read with the ohmmeter would be the *cold* resistance of the lamp filament. Suppose we were more interested in the *hot* resistance. After all, when a lamp is actually in use, the filament is always hot. Thus, we must measure that filament's resistance when the filament is hot, not when it is cold.

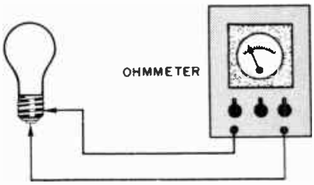


Fig. 7-3. The resistance of the filament in a lamp can be measured with an ohmmeter, but it is only the cold resistance which is measured.

Unfortunately, while the ohmmeter is reasonably accurate when applied across the cold filament, the instrument becomes useless when we try to use it on the lamp or on any other circuit when there is a voltage across it. This means that if we are going to try to measure the hot resistance of the lamp, we must do so in an indirect manner instead of proceeding to do it directly.

Fortunately, we can apply the third form of Ohm's law to a problem like this. To apply the third form of Ohm's law, we must first determine the amount of current flowing through the lamp and the voltage applied across it. We could do that by using an ammeter, a current-measuring instrument, and a voltmeter, a voltage measuring device, as indicated in Fig. 7-4.

Note carefully what we are doing in the experiment illustrated in Fig. 7-4. We are using the voltmeter to find out the pressure in volts that is applied across the lamp. To do so, we connect the voltmeter *across* the lamp. Then we connect the ammeter in *series* with the lamp so that all the current which flows through the lamp must also flow through the ammeter. In this way we can measure the current through the lamp.

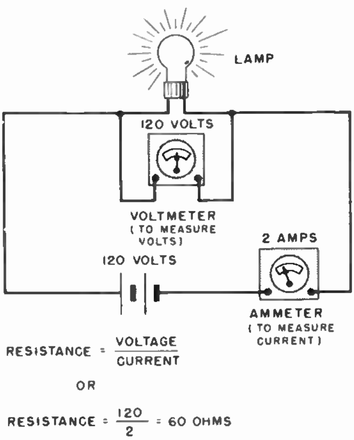


Fig. 7-4. Measuring the hot resistance of a lamp by using Ohm's law.

In the illustration the voltmeter indicates that there are 120 volts of pressure across the lamp. The ammeter indicates there are 2 amperes of current flowing through the lamp. Now we can apply the third form of Ohm's law and from it figure out the resistance of the lamp when the filament is hot. By dividing the 120 volts by the 2 amperes, according to Ohm's law, we learn that the hot resistance of the lamp is 60 ohms. This problem would be set up in this manner:

$$\text{Resistance (ohms)} = \frac{120 \text{ (volts)}}{2 \text{ (amperes)}}.$$

This is not the only place where this form of Ohm's law can be used. Motor men are sometimes faced with the problem of figuring out the resistance of the armature of a DC motor or a DC generator. It is sometimes difficult to use an ohmmeter to solve this problem because such a meter is not very accurate at the low resistance which is usually found in a DC armature. Neither is it practical to try to measure the armature resistance when the machine is running under a full voltage as we did in the case of the lamp, but there is a way.

It is possible to apply to the motor a voltage which is somewhat less than enough to make the motor operate. That voltage will cause current to flow through the armature even though the voltage is not sufficient to make the motor run.

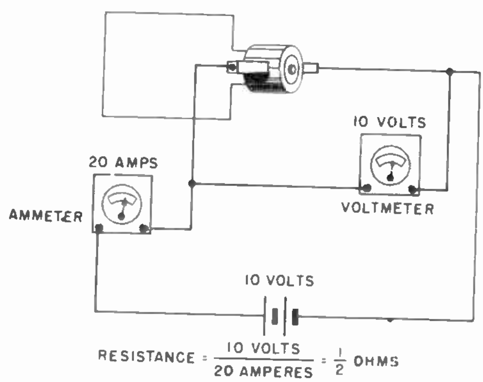


Fig. 7-5. Measuring the resistance of a motor armature by applying Ohm's law to the measured current and voltage.

Now we can measure that voltage and that current in exactly the same way we measured the voltage and current with the lamp. The two indicating meters would be connected as shown in Fig. 7-5. The voltmeter would be connected across the brushes to the armature, and the ammeter would be connected in the line to measure all the current that passes through the armature.

Here, in Fig. 7-5, the voltmeter tells us there are 10 volts across the brushes and the armature. The ammeter tells us there are 20 amperes of current flowing through the armature of the motor. Now we are ready to apply the third form of Ohm's law.

We merely divide the voltage by the current, or divide 10 by 20. The result of that division gives us the resistance of the armature in ohms. This time the resistance figures out to be one-half of one ohm. Many of the larger DC motors and generators have less than one ohm of resistance in their armatures. It is desirable to keep the resistance here as low as possible because the smaller the resistance the more efficient the motor will be and less power will be lost in converting the electrical energy from the power line into the mechanical energy which appears at the pulley of the motor.

Many other problems are solved by using the third form of Ohm's law. Radio men use Ohm's law almost as often as they use their pliers or their screw driver. Very often they have to decide how much resistance they must put in the cathode circuit of a vacuum tube. This is a very common problem since most vacuum tubes require the insertion of a resistance in the cathode circuit to make the tube operate correctly.

This is done to make the current flowing in the cathode circuit produce a voltage drop to accomplish a specific objective. Since the radioman usually knows how much voltage drop he wants and since it is easy for him to determine the amount of current that will flow in that circuit, it is a simple matter for him to select the correct value of resistance to accomplish that purpose. He does this by applying the third form of Ohm's law. He merely divides the amount of voltage drop he wants to produce by the current he knows will flow in the circuit. Then he proceeds to insert that value of resistance.

The radioman must determine how much resistance he will need before he actually assembles his tube circuits. In his case he uses Ohm's law to *predict* something, while in the other two cases we were working with electrical equipment which was already in existence.

Ohm's law is very useful to electrical men, because it is possible to use it to *predict* what will happen in an electrical circuit before it is even built or before any power is actually applied. By using the simple statements of electrical action which were worked out for us so many years ago by that patient and brilliant scientist, we are able to go about our electrical work with far more confidence. It is seldom necessary for a really good electrical man to *guess* what is going to happen in some certain circuit. By applying common sense and the rules of Ohm's law, he will *know* what is going to happen.

SHORT FORM OF OHM'S LAW

Despite the demonstrated usefulness of Ohm's law to solve electrical problems which arise in everyday work, the three forms have the disadvantage of being cumbersome to remember or to write down. Electrical men, through practical experience, have found ways to make the laws easy to remember and to use.

Since it is rather awkward to write out all the words of the laws, or rules, practical men have resorted to the use of symbols as a substitute. The second law, for example, written out in words, "The electrical pressure in volts is equal to the current in amperes multiplied by the resistance in ohms," is a correct statement but it is awkward and cumbersome.

Following their tendency to make things easier and simpler, electrical men first developed a symbol which they now substitute almost universally for the term voltage or electromotive force. They merely use the initial letter of the expression "electromotive force" to indicate voltage. This is the letter *E*. This letter is always capitalized. Wherever and whenever electrical men want to write or indicate electrical potential they now use the letter *E*.

In the second form of Ohm's law, which we mentioned a moment ago, it would be possible to take advantage of this simplification of electrical symbolization. It could be written in this manner:

$$E = \text{current} \times \text{resistance}.$$

Certainly it is much easier to write the simple letter *E* than to write out the word "electromotive force," and to the practical electrical worker the two mean exactly the same thing.

During the years, practical men have gone even further in their effort to simplify the use of Ohm's law and the use of symbols in electrical work. Take the matter of current as an example. Just as they have substituted *E* to represent voltage or electromotive force, they have selected another capital letter to rpresent the intensity of electrical current in any conductor. The first letter of the word "intensity," the letter *I*, has been selected to represent the intensity of the current. This practice was adopted many years ago and is used throughout the electrical world at this time. It has crept so completely into the everyday vocabulary of most electrical workers that many even go so far as to speak of *I* ("eye") of the circuit when they mean to speak of the current in a circuit. In nearly all written references to the current in any circuit, "I" is used as a matter of course. In fact, the letter "I" is generally used to represent electrical current, not merely when Ohm's law is being used or implied.

If *E* is used to represent voltage or electromotive force and *I* to represent electrical current, it seems that a third capital letter should be selected to represent the resistance in a conductor; and that is exactly what has occurred. In the case of resistance it seems only natural that *R* should stand for resistance.

Instead of writing the second form of Ohm's law as:

$$\text{Voltage} = \text{current} \times \text{resistance}$$

we can substitute the letters E, I, and R, which are universally used to represent these electrical properties of a circuit. With *E* used to represent the voltage, *I* the current, and *R* the resistance; it is possible to write the second form of Ohm's law in this manner:

$$E = I \times R,$$

or simply,

$$E = IR.$$

The average electrical worker thinks of the letters used as substitutes for the electrical properties in a circuit as being nothing more than a handy form of shorthand. The use of letters make it possible to solve many electrical problems through the application of the rules of algebra, if the electrical man happens to understand algebra. It should be pointed out, however, that just because letters of the alphabet are used to represent the fundamental properties of an electrical circuit, the use of algebra is not automatically implied. The truth is that the majority of practical electrical men probably do not know how to solve algebraic problems and do not pretend to do so, but they do know Ohm's law and how to apply it.

If letters can be used to represent Ohm's law when it is in the second form such as $E = IR$, one might wonder just how the first and third forms of the law would appear when letters are substituted for the words. Such substitution is very common; in fact, it is almost universal.

Let us examine the first form for a moment. It is stated as follows: "The current in amperes is equal to the potential in volts divided by the resistance in ohms." If *I* is substituted for the current, *E* for the voltage, and *R* for the resistance, the first form of Ohm's law would then look like this:

$$I = \frac{E}{R}.$$

That shorthand form tells us exactly the same as the written words: the current is equal to the volts divided by the amperes.

Now we will turn to the third form of Ohm's law. There he says: "The resistance in ohms is equal to the voltage divided by the current."

If we susbtitute letters for the electrical properties, using *R* for resistance, *E* for voltage, and *I* for current, our equation will look like this:

$$R = \frac{E}{I}.$$

Even after careful study, a person not already familiar with electrical terms is likely to forget the arrangement of these various properties in a circuit. He may not remember whether the current is to be divided into the voltage to find resistance or whether the reverse is true. To help one's memory the United States Navy devised a simple scheme during World War II. It has been used successfully by thousands of electrical men since, when it was necessary for them to remember the arrangement of the values in Ohm's law.

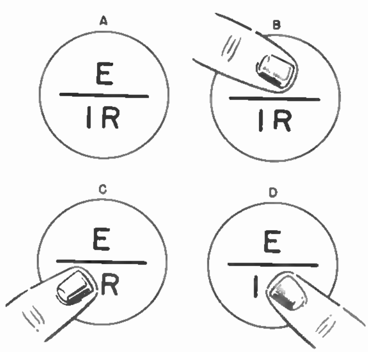


Fig. 7-6. A simple way to remember Ohm's law.

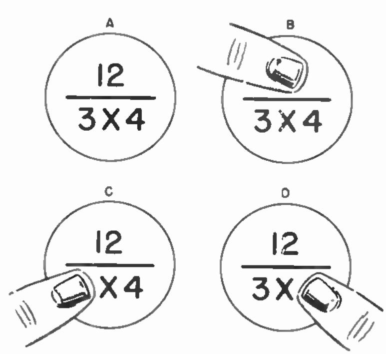


Fig. 7-7. Actual figures used instead of letters.

The symbol prepared by the Navy is shown in Fig. 7-6. There we find at A the letter *E*, above the line of the equation and *I* and *R* below the line. If one wants to determine the voltage, when the current and the resistance in a circuit are known, cover with a finger the value that is unknown. This is shown at B. Then read the parts that are left. We see that the current *I* is multiplied by the resistance *R* to give the voltage *E*.

We can carry this a step further. Suppose it is the current *I* that is unknown and the voltage *E* and resistance *R* are known.

Cover the *I* in the equation shown in A. The way this will look is shown at C. The finger covers the letter *I*, the letter *E* is above the line and the letter *R* below it. From this we know that the voltage *E* is divided by the resistance *R* to give the current *I*.

If it is the resistance that is unknown, cover the *R* in the illustration. This is shown in D where we see that the letter *E* is again above the line while the letter *I* is below; therefore, to find the resistance *R* it is necessary to divide the pressure in volts *E* by the current in amperes *I*.

Fig. 7-7 shows how actual figures can be substituted into the formulas and thus enliven what might otherwise be a monotonous series of letters. There we can see just how that little memory symbol actually works.

ELECTRICAL UNITS USED WITH OHM'S LAW

When George Simon Ohm published his famous series of laws which have remained with us in constant use for more than a century and a quarter, he was careful to point out that when the laws are used, the potential must be in volts, the current in amperes, and the resistance in ohms. All this seems natural enough. When we think of potential, we naturally think of volts; and when we think of current, it is equally natural to think of amperes.

So long as we confine our operations to ordinary electrical work, it is probable that we shall always work with the units of volts, amperes, and ohms; but there are many circuits in which the current is very low. Such circuits are often found in radio work, in industrial electronic work, in television, in radar, and even in some kinds of ordinary electrical circuits.

In radio work it is a common practice to measure the current in a fractional unit which is only a very small part of an ampere. This is the milliampere, which is equal to one-thousandth part of an ampere. The milliampere is also used in television work and other places where vacuum tubes are used.

Suppose we wanted to know what the voltage drop would be when 30 milliamperes flow through a resistance of 100 ohms. It would be very easy to jump to the wrong conclusion if we were a little careless. In fact it is a strong temptation to say the voltage would be $E = IR$, and then substitute the actual numerical values in the equation. Were we to substitute the figure 30 for the current and the figure 100 for the resistance, we would wind up with a total of 3000 volts drop across the resistor, but that would be wrong.

The current used with Ohm's law must be measured in *amperes*, not milliamperes. Thirty milliamperes is equal to .03 ampere or 30 thousandth of an ampere.

The problem would have to be worked out in this manner: Instead of substituting 30 for the current, it would be necessary to substitute the figure .03. The problem then would look like this:

$E = .03 \times 100$, or a total of 3 volts, not 3000.

The same thing is true when using sub-units of voltage or resistance.

If the voltage is measured in millivolts (thousandths of a volt) or in microvolts (millionth parts of a volt), then it is necessary to convert those sub-units into fractional parts of a normal unit. These things are mentioned here not to confuse but to act as a warning when you are working with very small values of current or voltage. Under normal conditions you will probably not encounter these very small sub-units. If you work with radio or any of the other branches of electronics, you will have to keep them in mind. Remembering them will prevent your making mistakes.

APPLYING OHM'S LAW TO ACTUAL CIRCUITS

Ohm's law can be used to work out almost any kind of problem which arises when you are working with actual electrical circuits. Let us apply it to a circuit such as that shown in the diagram in Fig. 7-8. There we see a simple series circuit consisting of two resistors in series with each other and these in series with a battery which is impressing a voltage of 60 volts across the resistors.

There are certain things about this circuit that we know, and there are other things that we do not know. These can be summed up something like this:

Knowns

1. Voltage of 60 volts.
2. Two resistors in series.
3. One resistor has 8 ohms resistance.
4. Second resistor has 12 ohms resistance.
5. Ohm's law applies to this circuit.

Unknowns

1. Current in the circuit.
2. Voltage drop across R_1
3. Voltage drop across R_2
4. Total resistance in the circuit

Before discussing the manner in which we can apply Ohm's law to uncover the information about the circuit which is unknown, we should explain how the resistors in the circuit are designated. You have probably noted that the upper one is named "R_1" and the lower one is named "R_2". Perhaps this has puzzled you a little and you have wondered just what that meant.

We have already mentioned that the letter *R* is used regularly in electrical work, and so the letter is used here, but here we have two resistors, not just one. If *R* is used to indicate the resistance of one resistor, it is only natural that the same letter should also be used in connection with the other resistor.

Often it is necessary to use some method to distinguish one resistor from the other. In many electrical circuits there will be as many as a dozen, even a hundred, resistors. For that reason, it is necessary to use some method to keep the various resistors separate and each one identified, so that when one is indicated we know it is one certain resistor and not some other one in the circuit.

There are many ways for us to solve the problem of keeping the resistors separate. We could name each one according to the purpose for which it is used. This practice is used in many kinds of electrical work. A different letter of the alphabet could be used in conjunction with *R* to designate one resistor from another; and that method, too, is sometimes followed.

The easiest method is to number each of the resistors and place that number near the letter *R*. This is the method followed here. The resistor at the top of the diagram of Fig. 7-8 is indicated as resistor No. 1, and to keep it separate from any other resistor in the circuit the figure *1* is placed near the *R*, to the right and slightly below the letter. This can be read in a number of ways. It is often read as "Resistor No. 1," "Resistor subscript 1," "R-sub-1," or, as is most frequently the practice, just simply "R-one." Calling the top resistor in this particular circuit "R-one" merely serves to give it an identity, which serves to keep it separate from any other resistor which is now in the circuit or any which is likely to be added later.

In much the same manner, the resistor at the bottom of the circuit is called "R-sub-2" or simply "R-two." This designation is to prevent that resistor from being confused with any other resistor now in the circuit or any which might later be added to it. One thing should be made clear. The presence of the figure

"2" to the right of the second resistor does not mean that resistor is multiplied by 2 or divided by 2 or that the figure 2 does anything to it except to set it apart from all others in the circuit. It is simply resistor No. 2.

Now to return to our problem of learning some of the unknown things about the circuit which is shown in Fig. 7-8. Before we can figure out how much current is flowing in the circuit or anything else about it, we must first determine the total resistance in the circuit. This is done in the manner explained in a previous chapter. To find the total resistance in a series circuit, we merely add the resistances.

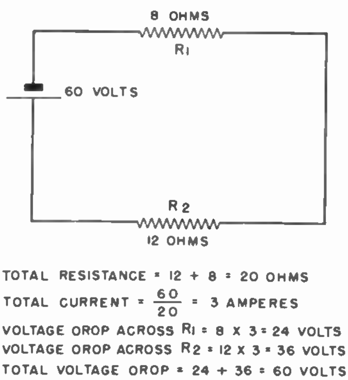


Fig. 7-8. How Ohm's law is applied to a series circuit containing two resistances.

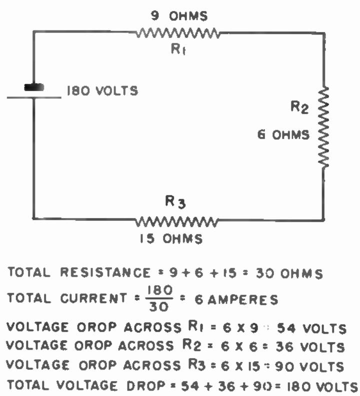


Fig. 7-9. How Ohm's law can be applied to a series circuit where there are three resistances.

In this case there are two resistances. One is a resistance of 8 ohms and the other is a resistance of 12 ohms. Adding these two gives us a total of 20 ohms of resistance for the circuit.

Now we know a little more about the circuit. We know what the total resistance of the circuit is; and with this information, we are ready to take another step to figure the total amount of current flowing in the circuit. This is done by applying the first form of Ohm's law: The current in a circuit is equal to the voltage divided by the resistance. In this case we have an applied voltage of 60 volts and a resistance of 20 ohms. Dividing the 60 volts by the 20 ohms gives 3 amperes of current.

Now we know more about the circuit. We know the voltage, the total resistance, and the current that is flowing through the circuit. There are other things we could learn about the circuit by applying the knowledge we now possess.

One thing that we might like to know is the voltage drop across resistor number 1 or, R_1. This is a simple matter if we apply our knowledge of Ohm's law: The voltage across the resistor R_1 is simply the value of the current through the resistance multiplied by the resistance in ohms of the resistor.

We know the current is 3 amperes because in a series circuit the current is the same in all parts of the circuit. From the diagram itself, we know that the resistance of that particular resistor is 8 ohms. Multiplying the 3 amperes by the 8 ohms gives us a product of 24 volts. This is the amount of volts dropped during the process of forcing the current through that resistance. If we had occasion to know the voltage drop across the other resistor, we could go about obtaining the information in exactly the same way.

The resistance of resistor R_2 is 12 ohms. The current is also 3 amperes because the current is the same in all parts of a series circuit. All that is necessary now to figure the voltage drop across the second resistor is to multiply the 12 ohms of resistance by the 3 amperes of current; that gives 36 volts.

To check our figures, we might add those two voltage drops together. Since there are no other resistances in the circuit, the sum of the two voltage drops should be equal to the originally impressed voltage at the source, or battery. An axiom of electrical work is: "The sum of the voltage drops around a series circuit should always be exactly equal to the value of the voltage originally impressed across the circuit." In this case, we can add the 24 volts which were dropped across R_1 to the 36 volts dropped across R_2. The sum of these two voltage drops is 60 volts. By looking back at the source, we see that this is exactly the voltage impressed by the source. Thus, our figures check.

While we are on the subject of Ohm's law, we might as well give another example to show how easy it is to apply these electrical principles to electrical circuits. In Fig. 7-9 we see another series circuit. This one contains three resistances in series instead of only two, but the same principles apply.

The first step in solving a problem of this kind is to find the total resistance in the circuit just as we did before.

This is done by simply adding all the resistances in the circuit. Adding 9, 6, and 15 gives us 30 ohms as the total resistance in the series circuit.

With this information we can go a step further and see how much current flows in the circuit. The current through the circuit is determined by the total resistance and the voltage applied to the circuit. Here we have a total resistance of 30 ohms and a voltage of 180 volts. The voltage is supplied by the battery as shown in the diagram. Dividing the 180 volts by the 30 ohms gives us a total of 6 amperes of current in the circuit.

This might be all the information we would need about the circuit. It is all that is needed to solve many electrical problems that arise, but it might also be necessary for some reason to know the voltage drop across resistor R_1. To learn what the voltage drop across resistor R_1 is, let us look back again at Fig. 7-8. The voltage drop across R_1 is equal to the product of the current through the resistor and the resistance in ohms. The current of 6 amperes multiplied by the resistance of 9 ohms is equal to a voltage of 54 volts. This is the voltage drop across R_1. The voltage drops across resistors R_2 and R_3 are determined in a similar manner.

The current through each of the other two resistors is the same as that through R_1. This is because, as we have mentioned so many times, the current through a series circuit is the same in all parts of the circuit.

To find the voltage drop across resistor R_2, proceed exactly as with R_1 by multiplying the resistance in ohms by the current in amperes. When we multiply the 6 ohms of resistance by the 6 amperes of current, it is found that the voltage drop is equal to 36 volts.

In the case of resistor R_3, we merely multiply the resistance of 15 ohms by the current of 6 amperes. Here we find that 6 times 15 is equal to 90 volts, the total voltage drop across resistor R_3.

We could check our figures in the same manner as we did in the previous problem. The sum of all the voltage drops around an electrical circuit is equal to the voltage impressed by the source.

We have one voltage drop of 54 volts, another of 36 volts, and a third of 90 volts. Adding them gives us a sum of 180 volts. This is the same as the original voltage impressed by the source.

Any series circuit problem can be solved in a similar manner. These are types of problems which constantly arise in electrical work. Electrical men solve them as a matter of course. Almost all electrical men (as stated before) use Ohm's law as regularly as they use their pliers or their screwdrivers. They think of it as merely being another tool to use in their profession.

Chapter 8

MAGNETISM

INTRODUCTION TO MAGNETISM IN ELECTRICAL WORK

Sometimes it seems there are so many things to learn about electricity that no one man can ever learn all of them. In a strict sense this is true. No truly intelligent man ever pretends he knows all there is to know about electricity and its allied branches of radio, electronics, and television. In fact, radio and television are only two large branches or fields of electronics; but that does not prevent many men from learning so much about electricity that they can do many things with it and earn a good living by doing those things.

It is probable that this is one of the reasons that electricity is so intensely fascinating. One never knows what new adventure lies just around the corner and what unexplored field of knowledge will suddenly open up before him and make his name stand out, like that of Edison, Westinghouse, Ohm, Faraday, Tesla, Steinmetz, and hundreds of others who have done so much to make electricity our faithful and inexpensive servant.

The truth is that when young Edison was selling candy and fruit on a passenger train, his opportunity to become a great inventor was not nearly so great as is that of a young man now entering the field of electricity. When Edison started his experiments, he did not know that there was a future in the almost unknown field of electricity.

Some of the knowledge which has helped open the doors of opportunity in the field of electricity was first acquired so many centuries ago that one wonders why so many years passed before the science achieved the perfection we know today. A classic example of unused knowledge known to the ancients for a score of centuries applies to the field of magnetism. It is hard to trace exactly just how long the peculiar phenomenon of magnetism was known to man before he put that knowledge to practical use. However, history shows that magnetism was known for nearly 1500 years before it became anything more than a useless, but interesting, scientific curiosity.

The ancient Greeks discovered the properties of magnetism more than two hundred years before the time of Christ. In a province of Greece, they found a natural ore known as magnesia which had the properties of attracting and holding small pieces of iron. That ore is now called magnetite.

Despite the Greeks' knowledge of these peculiar properties of magnetite, the ore remained simply an object of curiosity. In so far as history records, many centuries passed without anyone's discovering any practical use for it.

Fig. 8-1. Lodestones, the original natural magnets.

It remained for an experimenter in China to find, about 1100 AD, the first practical use for natural magnetite ore. He discovered that if a piece of the ore was suspended by a string, the ore would orient itself in such a manner that one part of it would always point toward the north. It made no difference which way the ore was suspended, it would always swing around so the same part pointed north.

Soon after the Chinese discovered this peculiar ability of magnetite to point to the north, the mariners who sailed their ships far beyond the sight of land, began depending upon pieces of magnetite to point out the north for them so they could sail their ships to their destinations more directly and quickly. The mariners gave the name "leading stone" to the bits of magnetite.

With the passage of time, this name was changed to "lodestone," the name the mineral is best known by today. Fig. 8-1 shows what bits of the natural magnetite or "lodestone" ore look like.

Mariners still use the same principle. Instead of lodestone, the modern mariners use a modern magnetic compass; however, still newer methods of navigation are now in use on the larger ships and planes. Nevertheless, the magnetic compass continues to occupy an important place on many of the smaller vessels. Many hunters and fishers use a magnetic compass when they venture into strange woods, or into places where roads, pathways, and other normal guideposts are few and far between.

It is a rather strange thing that both electricity and magnetism were known for many years before any connection between the two was discovered. It was only a few years before George Simon Ohm announced his discovery of the close relationship between current, voltage, and resistance that the connecting link between magnetism and electricity was discovered. That discovery, like so many others, came about as the result of an accident.

In 1820, a Danish professor named Hans Christian Oersted was lecturing to a science class in a university in Denmark. This was shortly after the close of the Napoleonic Wars. During the course of his lecture, the professor noticed that whenever a magnetic compass was brought near a wire that was carrying an electric current, the needle of the compass was deflected.

The professor was greatly intrigued by his discovery and continued his experiment. He learned that the compass needle would be deflected one way if the current was flowing in one direction, but it would be deflected in the opposite direction if the current was reversed.

Despite Professor Oersted's discoveries and experiments, it remained for another scientist to put this discovery to practical use. In 1833, thirteen years after Oersted made his discovery in the classroom, the great English scientist and experimenter, Michael Faraday, constructed a crude dynamo or electric generator by means of which he was able to change mechanical force (energy) into electrical energy.

Faraday continued his experiments with magnetism and its relationship to electricity. Many of the things we know about electricity today were originally discovered by Faraday. His name stands out among those of the great men who started the world on the pathway toward the present electrical age.

KINDS OF MAGNETS

There are few of us who are not familiar with a horseshoe magnet. We saw them during our childhood, again when they were demonstrated in the science classes in our schools, and often at other places. In general they do not differ greatly from that shown in Fig. 8-2.

A small horseshoe magnet will attract and hold bits of iron and steel which come within the reach of its magnetic attraction. Some such magnets are unbelievably powerful! It is sometimes quite difficult to remove pieces of iron which have come under their attraction.

When we say that the magnet will attract pieces of iron and steel which come within the reach of its attraction, we mean just that. One of the peculiar properties of a magnet is that it is not necessary for the magnet to actually touch a piece of iron or steel to attract it. A magnet's powers of attraction reaches out beyond the iron or steel of the magnet itself into the surrounding space.

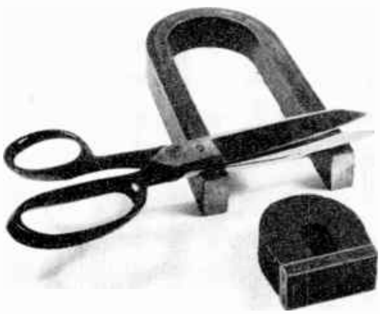


Fig. 8-2. Horseshoe magnets.

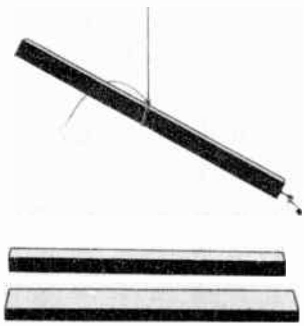


Fig. 8-3. Bar magnets.

The closer the iron or steel is brought to the ends or the *poles* of the magnet, the stronger and more powerful will be the attraction. From this peculiar behavior, it is easy to assume that some invisible force surrounds the magnet. Such force is called a *magnetic field.*

One of the interesting things about a magnet, especially a bar type of magnet such as that shown in Fig. 8-3, is that if it is suspended so it is free to rotate, it will always assume a position which is in line with the magnetic poles of the earth. This means it will line up in a north-and-south direction.

If we mark the north-seeking pole with the letter *N* to indicate the north and the other end with the letter *S* to indicate the south, we can try a simple experiment. Turn the end marked *N* until it points south. When we release the bar magnet, it will again return to its original position with the end marked *N* pointing toward the north.

This experiment, simple though it is, tells us at least one thing, that the two ends of the magnet are not alike. They may look alike, feel alike, and to all appearances seem alike, yet we know that there is something different about them just the same. This is still true despite the fact that both ends of the bar magnet will attract bits of iron and steel equally well.

Since most of the earlier magnets were made of iron or alloys of iron, it would be well for us to pause for a moment and see just what we know about iron. Iron is so plentiful and we use it in so many ways that most of us take it for granted. Iron ore can be processed for commercial use in a number of ways. Processed in one way, it is called wrought iron; processed in another, it is called cast iron; and in still a third way, it is called steel. Steel is merely iron alloyed with certain other substances. Steel can be made in a number of forms. Sometimes it is made so it will be very hard; at other times it is made soft, pliable, and easily workable. It can be manufactured in other ways to have other properties. Other kinds of alloys not containing iron have magnetic properties; but iron is the only material which is always magnetic regardless of how it is prepared. This does not mean that all kinds of iron and iron alloys have exactly the same magnetic properties. Such an assumption would be wrong. The different methods of making the alloys affect their magnetic properties in different ways; but all types of iron (ferrous) metals are capable of being magnetized to some degree.

Scientists have discovered many things about magnetism which have put it to work doing many things for us every day; however, they realize that there are still some things about it that they do not understand. Many scientists are devoting their lives to unlocking more of the mysterious secrets which yet remain unsolved. Some of these scientists hint that when they have succeeded in unlocking all of those mysterious secrets, man will have available power and forces; in quantities which can, as yet, only be guessed. Those things, however, are still in the future and not subjects for discussion here.

It is generally known that many substances are influenced to some degree by the mysterious forces of magnetism and that not all substances are equally affected. Iron and its alloys are affected most strongly. Cobalt and nickel are affected but in a lesser degree than is iron.

Iron is the only material which has any magnetic importance when the material is used by itself. Certain alloys of aluminum, nickel, and cobalt can be made into very powerful magnets when combined in the proper proportions. In fact, such alloys are rapidly assuming great importance in magnetic work. One of the alloys, known by the trade name Alnico, is made in a variety of grades and is rapidly replacing iron as a magnetic material for many purposes. The name Alnico was coined by combining the first two letters in the names of each of its constituents—aluminum, nickle, and cobalt.

MAGNETIC POLES

If we were to take two bar magnets similar to those shown in Fig. 8-4, we could use them to work out a very simple experiment. The first thing to do would be to mark the north-seeking end of each magnet with the letter *N* and the south-seeking end with the letter *S*.

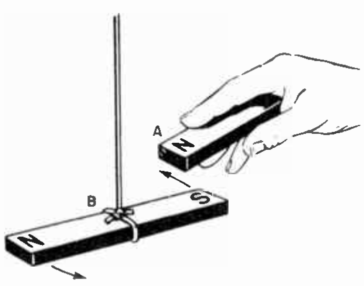


Fig. 8-4. The north pole of one magnet will attract the south pole of another magnet.

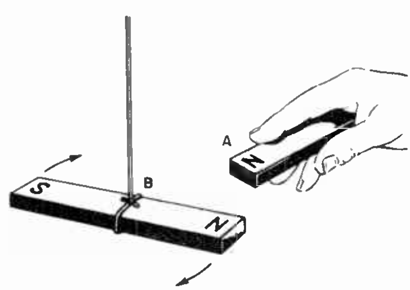


Fig. 8-5. The north pole of one magnet will repel the north pole of another magnet.

If one of the magnets is suspended from the middle with a piece of twine as shown in Fig. 8-4, the end marked with the *N* will immediately rotate so it points toward the north. This we have come to expect. Now let us see what happens when the other magnet is moved toward the suspended magnet. Just what happens will depend upon which end of the magnet held in your hand is nearest the suspended magnet.

If the end of the magnet in your hand which is marked with an *N* is moved toward the end of the suspended magnet which is marked with an *S*, the suspended magnet will be attracted toward the magnet in the hand. However, if the N end of the magnet held in the hand is moved toward the N end of the suspended magnet, the suspended magnet being repelled, will move away. See Fig. 8-5.

These two simple experiments can be repeated in a number of ways. It will be found that when the *N* end of a hand-held magnet is brought near the *S* end of a suspended magnet, they will be attracted to each other. When the *N* end of the hand-held magnet is brought near the *N* end of the suspended magnet, the two ends will repel each other. If the *S* end of the hand-held magnet is brought near the *N* end of the suspended magnet, the two will be attracted to each other; yet, if the *S* end of the hand-held magnet is brought near the *S* end of the suspended magnet, the two will be repelled again.

These observations lead to a very important fact in the laws which govern magnetic behavior. The two ends of the magnets are called *poles*. The one that points toward the north pole of the earth is called the north-seeking or simply the north pole of the magnet. The one that points toward the south pole of the earth is called the south-seeking, or south pole of the magnet. This is a fundamental law of magnetism. We state it thus: *Unlike poles attract each other, while like poles repel each other.* This basic law of magnetism holds true under all conditions regardless of how the magnetism originates. This simple rule should be memorized, because it is important in so many ways in the application of magnetism, magnetics, and electromagnetism.

MAGNETIC LINES OF FORCE

Strangely enough, the usefulness of a magnet depends upon something which we can neither see, feel, nor hear. In fact, that useful "something" is not inside the magnet at all. Instead, it occupies the space which surrounds the ends (poles) of the magnet. This mysterious and invisible force, which we put to so many uses, is called the *magnetic field*. It lies at the ends of and between the two poles of the magnet. The location of the strongest part of the field is indicated in Fig. 8-6 where clusters of iron filings are seen clinging to the poles of the magnets.

That the magnetic field actually exists in the space surrounding the magnet can be demonstrated even more clearly by placing a piece of cardboard or glass between the magnet and the iron filings as shown in Fig. 8-7. This prevents the magnet from making actual contact with the metal filings, and proves that attraction between the filings and the magnet unquestionably exists in the space surrounding the magnet because the metal of the magnet touches none of the filings yet the filings have been picked up.

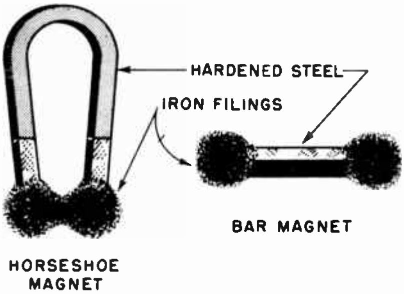


Fig. 8-6. The iron filings show where the lines of magnetic force exist.

The lines of force of the magnetic field are invisible, but it is possible to demonstrate just what kind of a pattern these lines assume around the magnet. This can be done with the same items we used in the previous illustration. The magnet is turned so the poles will be pointing upward, the cardboard is laid across the ends of the poles as shown in Fig. 8-8, and finally the iron filings are sprinkled on the cardboard. It is not essential that cardboard be used for this demonstration. A piece of glass, rubber, or bakelite would do just as well. A sheet of ordinary writing paper could also be used.

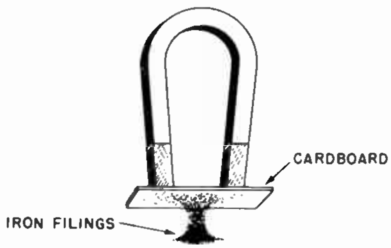


Fig. 8-7. The magnet will pick up the iron filings even though there is a piece of cardboard between.

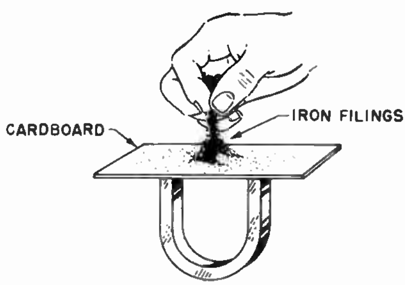


Fig. 8-8. The pattern of the lines of force can be shown by sprinkling iron filings over a cardboard placed over a magnet.

If you watch the cardboard carefully as the iron filings are sprinkled on, you will soon see them forming into a pattern on the surface of the cardboard. This is caused by the iron filings aligning themselves with the lines of force which comprise the magnetic field around the poles of the magnet.

Notice that the filings immediately above the ends of the poles stand straight up. If the filings are examined very carefully, it will be discovered that they have arranged themselves so they actually form lines extending outward from the ends of the magnet. Between the poles, the filings have arranged themselves in curved lines. Fig. 8-9 shows how the pattern of the filings would appear.

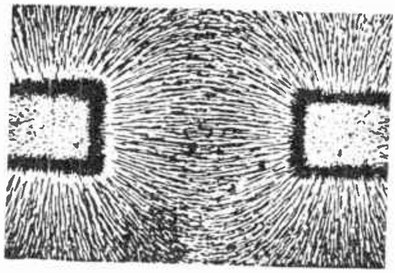


Fig. 8-9. The pattern assumed by the lines of force.

Because this peculiar force existing in the space surrounding the poles of the magnet appears to exist in definite lines, we speak of it as *lines of force*. When one works with magnets where it is necessary to indicate the lines of force of the magnetic field, it is a common practice to represent them with straight or curved dashed-lines as shown in Fig. 8-10.

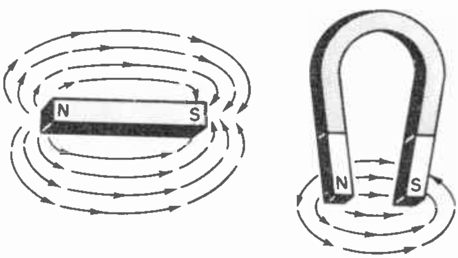


Fig. 8-10. The lines of force seem to travel in curved lines.

Scientists agree that when a magnet is formed, the lines of force emerge from the north pole of the magnet and then travel in curved lines until they re-enter the south pole of the same magnet. This assumption is not one of those things which can be definitely proved, but it is generally accepted.

Once the line of force extends itself through space to join the north and south poles of the magnet, it does not move any more until something happens to change the magnetic arrangement. It just exists there in the space surrounding the magnet. It is invisible and there is a certain air of mystery about it. In fact, there are many things we do not know about that line of force and all of the thousands of others alongside it but we do know that the magnetic force exists.

The line of force forms a circular or elliptical path from the north pole of the magnet outward through the space surrounding the metal of the magnet, re-entering the iron of the magnet at the south pole; then it passes through the metal of the magnet to link up into a continuous intangible line. We might think of the lines of force as being similar to rubber hands which are able to pass lengthwise through the metal of the magnet and then fan out in all directions at each pole of the magnet to form a

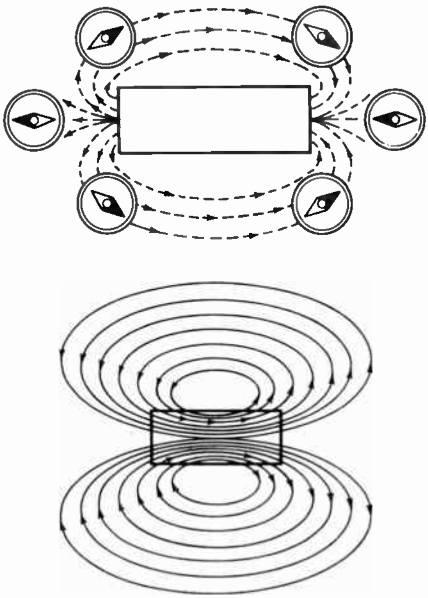


Fig. 8-11. The lines of force assume direction in the manner shown.

field in the vicinity of the magnet. This field is real, though intangible.

Since all of the lines of force which extend out through space also pass through the metal of the magnet, it is only natural that there is a much stronger concentration of magnetic lines of force within the metal than in the space surrounding it, where they spread out. Were it necessary to draw a diagram to indicate direction of the force in and surrounding a magnet, the diagram would appear something like that shown in Fig. 8-11. The illustration shows the concentration and distribution of the magnetic forces about the metal of the magnet by the use of these imaginary lines of force.

The magnetic lines of force find it much easier to pass through iron and other ferrous metals than through air. If there is a piece of iron near the magnet, the lines of force will enter the iron and pass through it. This action can be demonstrated by studying Figs. 8-12 and 8-13.

In Fig. 8-12 we see a magnet with the lines of force surrounding it in space. At some distance away is a piece of iron. It is so far away that few, if any, of the lines of force from the magnet extend to it.

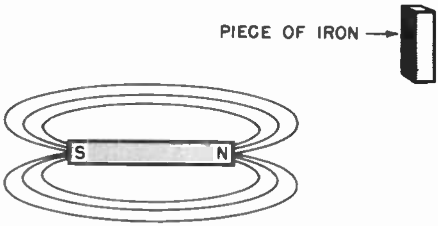


Fig. 8-12. The soft iron is not materially affected by the magnetic lines of force while at a distance.

In Fig. 8-13, however, the piece of iron has been moved closer to the magnet. It is close enough now that some of the lines of force find it easier to pass through the metal of the iron than through the air alone. This is illustrated by the diagram of Fig. 8-13.

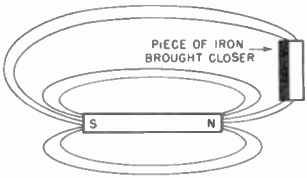


Fig. 8-13. When iron is moved closer, some of the lines of force enter it and try to draw it nearer the magnet.

Remember, we mentioned previously that the lines of force act very much like rubber bands. We might even go a step further and say that they act like stretched rubber bands.

Just as rubber bands which are stretched try to shorten their length by snapping back, the magnetic lines of force which exist in the space around a magnet, try to shorten their length. The first thing those lines of force that have found an easier path through the iron bar try to do is to shorten their length. This has the effect of drawing the iron bar closer and closer to the magnet. As the iron bar is drawn closer to the magnet, more lines of force find an easier path and pass through the iron bar, rather than through the air. As more lines of force pass through the iron bar, more will be trying to shorten their lengths and thus cause the attraction of the magnet for the iron to become greater. As the iron bar is attracted nearer to the magnet, the attraction between them becomes increasingly stronger. This continues until the iron bar actually

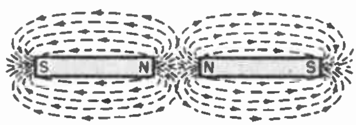


Fig. 8-14. There is no mingling of the lines of force when like poles are brought together.

touches the magnet, the touching giving the greatest attraction of all. At that time, virtually all the lines of force which emerge from the end of the magnet will pass through the iron bar, thus holding the two pieces of metal tightly together.

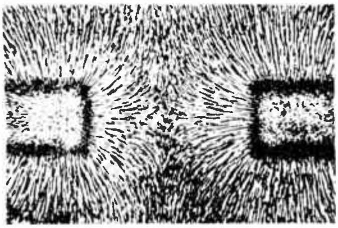


Fig. 8-15. Pattern formed by lines of force when two north poles are brought near each other.

It is important to note that magnetic lines of force will pass through iron in only one direction at a time. If we have two magnets and try to bring the two north poles together as in Fig. 8-14, the lines of force from neither magnet will enter the other. If we bring the two north poles close to each other and place them both under a piece of cardboard and then sprinkle iron filings on the cardboard, we can see plainly that the two sets of lines of force tend to repel. The pattern of the filings will look somewhat like that in Fig. 8-15.

On the other hand, if we bring the south pole of one magnet near the north pole of the other magnet, there will be a mingling of the lines of force from both magnets. The lines of force from each magnet will enter the other magnet. This is shown quite clearly in Fig. 8-16. Here we see the strong attraction of one pole of one magnet for an unlike pole of another magnet.

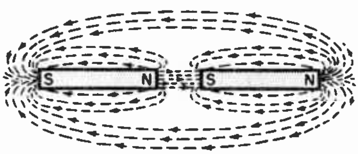


Fig. 8-16. How the lines of force act when the unlike poles of two magnets are brought near each other.

THE MAGNETIZATION OF IRON

Perhaps you have wondered what would happen to a magnet if you should break it into pieces. From our observations of magnets and the way the lines of force fill the space around them, one might think that if a magnet were broken, the magnetism would also be broken and that breaking the magnet into two pieces would leave the north pole on one piece of the original magnet and the south pole on the other piece.

Yet, strangely enough, such would not occur at all. If the bar magnet shown at A in Fig. 8-17 were to be broken into two pieces as shown at B in the same illustration, we would then actually have two magnets, each with a north and a south pole.

We could even go another step further as shown at C in the same illustration and break each half into two more pieces. We would then have four magnets, each having a north and south pole.

While this seems rather strange at first glance, it all ties in logically with the basic theory of magnetism. The generally accepted theory is that each molecule of iron is, in itself, a

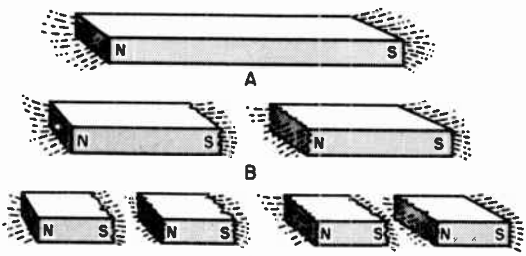


Fig. 8-17. Breaking a magnet results in the formation of new magnets which assume polarities as shown.

miniature magnet. Under normal conditions there is no systematic arrangement of the molecules, with the result that the magnetism of one molecule will be effectively cancelled by the magnetism of a neighboring molecule. Thus, normally, the iron does not possess any important degree of magnetism.

Under the magnetizing force, such as that exerted by a nearby permanent magnet, the molecules within a piece of iron will reorient themselves. They will align themselves so all their north poles point in one direction and their south poles in the opposite direction. When this occurs, the iron is said to be magnetized.

The illustration in Fig. 8-18 shows in a graphic manner just how these molecules are oriented under conditions when no magnetism is present, when the iron is partially magnetized, and when it is fully magnetized. At Fig. 8-18A the molecules can be seen to be arranged in a heterogeneous manner, some pointing in one direction and some in another. There is no tendency for the magnetism of any one molecule to be reinforced by the magnetism of another. On the contrary, the magnetism of one molecule is effectively cancelled by the magnetism of its neighbor, which might be pointing in the opposite direction.

If the bar of iron is brought close to a permanent magnet so that some of the lines of force of the permanent magnet will pass through the bar of iron, some of the molecules will begin to reorient themselves into some semblance of a pattern. We would then say the iron has become partially magnetized. If the individual molecules could be pictured, they might appear like that of Fig. 8-18B.

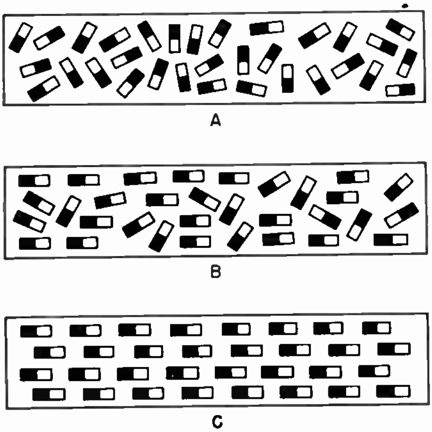


Fig. 8-18. How the molecules line up under the influence of magnetism.

Then, after the bar of iron has been brought more directly into the magnetic field of the permanent magnet and has more magnetic force applied to it, more of the molecules will line up with their north poles pointing in one direction and their south poles in the opposite direction. The polarity of the molecules and their arrangement might be pictured as shown in Fig. 8-18C.

Soft iron is easily magnetized. It becomes a magnet in its own right when placed in a magnetic field. This indicates that the molecules are easily forced into alignment by the magnetic force. Soft iron loses its magnetism just as easily as it acquires it. Just as soon as the magnetizing force is removed, the soft iron loses its magnetism.

Steel is much harder to magnetize than iron. Some steels resist very effectively any attempts to magnetize them with a weak magnet. This indicates that the molecules of some steels tenaciously resist any attempt to realign them so that all the poles of the individual molecules (magnets) point in the same direction.

Curiously enough, though, once sufficient magnetizing force is applied to a bar of hard steel to make it accept the magnetism, we find that it is just as hard to remove the magnetism as it was to make it accept it in the first place. Because of these peculiar properties of soft iron and steel, each is used for the purpose for which it is best adapted. In those places where it is desired to magnetize the metal for only a short time, it is the common practice, and the correct one, to use soft iron. On the other hand, if it is necessary that a piece of metal be magnetized so it will retain its magnetism for a long period, hard steel must be used.

Soft iron will retain very little magnetism after the magnetizing force has been removed. All magnetic materials lose their magnetic properties when sufficiently heated. For any magnetized material there is some particular temperature beyond which it cannot be heated without losing its magnetism.

A PERMANENT MAGNET WILL MAKE SOFT IRON A TEMPORARY MAGNET

It is not difficult to induce magnetism into soft iron by using a fairly strong permanent magnet. If the permanent magnet is brought close enough to the iron to attract the iron to the magnet, some magnetism will be induced in the soft iron. If the permanent magnet is brought so close to the iron that it can be touched, the magnetism in the soft iron becomes much greater.

In Fig. 8-19 we see a horseshoe magnet being used to induce magnetism in other pieces of iron. As each piece of iron is brought under the influence of the magnet, the iron then becomes a magnet in its own right. Of course, that magnetism is only temporary; but while under the influence of the permanent magnet, the iron is itself a magnet.

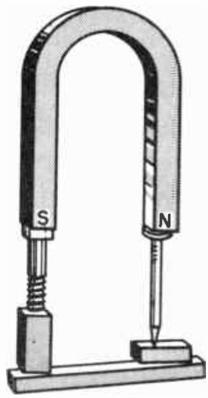


Fig. 8-19. A permanent magnet will induce magnetism in soft iron.

The reason, of course, is that lines of force from the permanent magnet pass through the pieces of iron (ferrous metals). As long as magnetic lines of force pass through a piece of soft iron, that piece of iron will be a magnet. A piece of soft iron or steel actually offers less reluctance (resistance) than air to the passage of magnetic lines of force. This makes it a good conductor for the magnetic lines of force and cause it to act like a magnet as long as some source of magnetomotive force is supplied to produce the field. This type of magnet is called a *temporary magnet*. It is a magnet only as long as some source, external to the magnet itself, produces a magnetomotive force to make it so.

This external force may be a winding surrounding the piece of steel and energized by an electric current or it may be a permanent magnet, or it may be the earth's magnetic field. At least, a temporary magnet is not a magnet in exactly the same sense as a permanent magnet is.

MAGNETISM HAS NO INSULATION

Magnetic lines of force do not pass through all kinds of material with equal ease; however, they will pass through any kind of material. They pass through air quite readily, but they pass through iron much more easily. In fact, the lines of force can pass through some kinds of iron several thousand times more easily than through air.

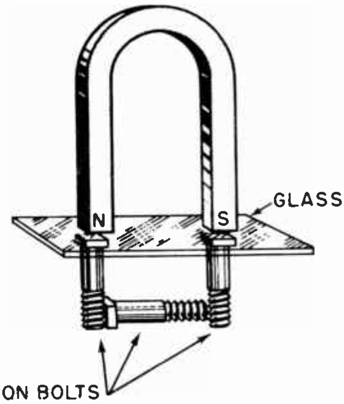


Fig. 8-20. There is no insulation for magnetism.

The lines of force can pass through glass, rubber, porcelain, wood, bakelite, brass, or anything. This fact can be easily demonstrated. We partially demonstrated it when we caused the lines of force to pass through the cardboard to make the iron filings line up. We could use a piece of heavy glass as shown in Fig. 8-20.

We can readily pick up the iron bolts by causing the lines of force to pass through the glass before entering the bolts. This shows that the lines of force can readily pass through the glass.

In fact, magnetic lines of force can pass through anything. There is no known insulation for magnetism.

There are times when it is desirable to prevent magnetic lines of force from reaching certain places. Since it is impossible to insulate against the lines of force, it might seem that we are powerless to prevent them from going where they are not wanted. This is not true! When man found it impossible to insulate against them, he simply devised means to divert them.

To keep lines of force from reaching places where they are not wanted, we take advantage of the fact that some materials permit the passage of the lines of force much better than others. We merely place a piece of good magnetic material between the magnet and the place where we do not want the lines of force to penetrate. The lines of force will follow the good magnetic material and the other object is "shielded."

Chapter 9

ELECTROMAGNETISM

MAGNETIC FIELD OF AN ELECTRIC CURRENT

In an earlier chapter we explained that we do not use the individual electrons which move through a conductor to form an electric current. On the contrary, we make use of the peculiar effects which are created when the electrons move in the form of such a current.

We have explained in considerable detail how the act of forcing the electrons to move through a conductor against the resistance which is present causes the wire to become heated. We explained that the more current forced through a wire, the hotter the wire would become and that the greater the amount of resistance, the more heat would be developed.

We went on from there to show you some of the ways in which that electrical action could be put to practical use. One of the most common and best known ways is that of heating the tiny filament in an incandescent lamp to make it glow and give off light. Another is the heating of special electrical elements in bread toasters, pressing irons, coffee percolators, and electric ranges to produce heat to accomplish a number of useful purposes.

Another peculiar action which accompanies the passage of Electrons through a conductor was also explained previously. This is the production of a magnetic field around the conductor which is carrying the electric current. It is this action which has caused electricity to become the tremendously useful servant it now is.

Whenever an electric current flows through a conductor, a magnetic field will be built up around that conductor. We could modify this statement slightly and say that whenever a *stream of electrons* move consistently in the same direction, a magnetic field will be built up around the moving electrons. This would be absolutely true.

From this, it can be deducted that the action of electrons moving consistently in the same direction is what creates the magnetic field, not merely the fact that they are moving within a conductor. This distinction might appear minor and of little importance; however, in these days of rapid developments, in the field of electricity, no new fact concerning electricity is unimportant. Even the apparently unimportant difference we just mentioned has already assumed considerable importance. In television, for example, we have the action of a moving stream of electrons which must be controlled, a moving stream of electrons which are *not* confined to the restrictions of a metal conductor. Inside the cathode-ray picture tube, we have a stream of electrons which form a beam. This beam of electrons is the pencil which draws the pictures on the face of the picture tube of the television receiver. Wherever the beam of electrons strikes the fluorescent screen of the tube, the fluorescent material will glow and give off light. These many pin-points of light and darkness make up the picture we see.

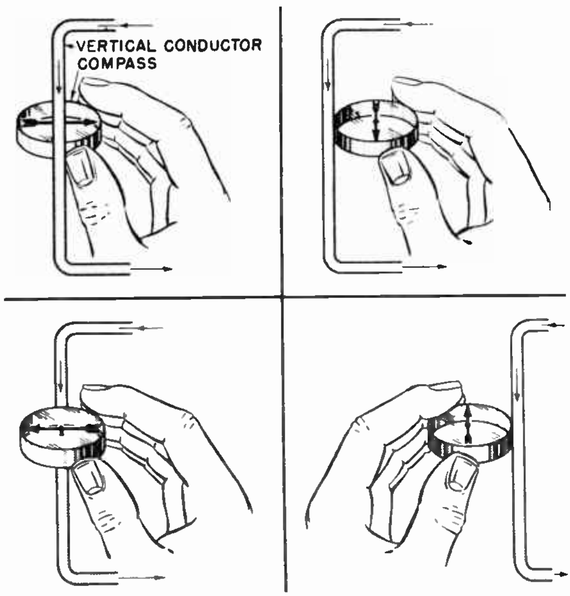


Fig. 9-1. The presence of a magnetic field around a conductor carrying an electric current can be detected by using a compass.

The stream of electrons being shot swiftly toward the fluorescent screen from the electron gun in the small neck of the tube produces an electromagnetic field around them. By causing this magnetic field to interact with other magnetic fields which are controllable, we are able to make the beam of electrons do many seemingly magical things.

It is not the purpose of this elementary book on electricity to go into an explanation of the operation of a television receiver. Nevertheless, we shall say a television receiver is an electrical device whose design incorporates the fundamental electrical and magnetic principles that will be discussed in this chapter.

Returning to our simple statement that a magnetic field will be built up around any conductor which is carrying an electric current, you might be inclined to wonder just how we know this is true and how we can prove it. Actually, it is a relatively simple matter to prove.

You have probably often seen a magnetic compass shaped like a little glass-topped pill box, with its freely swinging magnetic needle which always turns so it is pointing toward the north. We can use such a simple compass to prove that a magnetic field builds up around a conductor which is carrying an electric current.

Fig. 9-1 shows how we can use a simple compass to detect the presence of a magnetic field around a conductor which is carrying an electric current. By holding the compass on first one side of the wire and then on another, we can readily detect the presence of the magnetic field. The compass can be moved upwards or it can be moved downwards, and always the needle of the compass will reflect the presence of the magnetism.

This relationship between a current-carrying conductor and magnetism was discovered by the Danish science teacher, Professor Oersted. It is the basic principle which underlies most of the uses to which we put electricity.

LINES OF FORCE AROUND A CONDUCTOR

The magnetic lines of force are absent when there is no current passing through a conductor. Not until a current begins flowing do the lines of force appear. This fact assumes considerable importance in a study of this relationship; however, at the moment, we will pass it by, and only mention the fact that it does occur.

The lines of force which surround a conductor carrying electric current form themselves into definite patterns much like those around the poles of a permanent magnet. The first indication of the patterns formed by the lines of force can be seen when the compass is moved to various positions around the conductor. It will be observed that the needle of the compass will assume a different position for each different location of the compass.

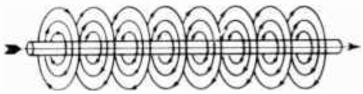


Fig. 9-2. Magnetic lines of force surround a conductor in the form of concentric circles.

If enough time is devoted to such experimentation, the pattern of the lines of force can be worked out; however, such patterns have already been worked out by many other experimenters. It has been proved that the lines of force form concentric circles around the conductor. These circles, together with arrows indicating the direction of the lines of force, are shown in Fig. 9-2. It should be clearly understood that Fig. 9-2 represents merely an artists conception of the arrangement of the lines of force around the conductor. The lines of force would be more numerous and concentrated than is indicated by the drawing, but the drawing does serve to indicate the arrangement of a few of the lines of force. Remember also that lines of force actually do not exist; they are convenient means of picturing this invisible magnetic force.

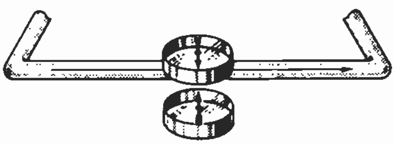


Fig. 9-3. One way to determine the direction of the lines of force.

If the compass is moved to various positions above and below the conductor, the needle will line up with the lines of force at each position. This is shown in Fig. 9-3. By taking a large number of successive observations of the needle in the manner shown in Fig. 9-3, one soon sees that the lines of force follow the pattern shown in Fig. 9-2.

To prove that the magnetic field is present only when current is flowing, additional observations should be taken with the current turned off. When there is no current flowing, the needle of the compass will line up under only the influence of the magnetic lines of force of the earth. The presence of the conductor will have no influence on the needle. This is a very clear indication that it is not the metal itself, which at times influences the needle, but something else. If we again permit current to flow through the conductor, we can again see the needle of the compass influenced by the nearness of the conductor. This proves that it is the presence of the electric current which influences the needle, not the metal of the conductor.

As additional proof that the magnetic field about a conductor takes the form of a circular path around it, you can try the experiment shown in Fig. 9-2 and Fig. 9-3 in a somewhat different manner. First place the compass above the conductor as shown in Fig. 9-3. You will note that the needle of the compass will be positioned at right angles to the wire. Next, hold the compass under the conductor instead of above it. You will see that the needle is still at right angles to the conductor; however, the needle will now be pointing in the opposite direction. This indicates that the direction of the lines of force above the conductor is opposite to that below the conductor and indicates rather clearly that the lines of force do circle the conductor.

MAGNETIC FIELD AROUND A COIL

It is reasonably easy to indicate the direction of current through a conductor when the conductor is shown lying flat in the drawing. When we try to imagine the direction of current in a wire when we are looking directly at the end of the wire, or "head-on" as we say, we are faced with a more difficult situation. Of course, current would not actually flow in a wire which was so cut, because the circuit would not be complete. However, we can imagine a complete circuit and assume that our eye can look at its cross-section when we come to the problem of studying the action of the current and the magnetic field that surrounds it.

A symbol has been adopted for indicating the direction of current through a conductor when the conductor is imaginarily viewed from the end. This symbol is shown in Fig. 9-4A. It is an arrow inside the conductor to indicate the direction of current. Note that the tip of this arrow just reaches the end of the wire where it is supposedly cut. This fact was used in selecting a symbol to indicate the direction of current in a conductor viewed directly from the end. In Fig. 9-4B, we can see the wire cross section at its end, just as though we were looking into the end. The dot in the center is the tip of the arrow which designates the direction of the current flow. Thus, whenever a dot is placed within the cross-section of a wire which we have cut in

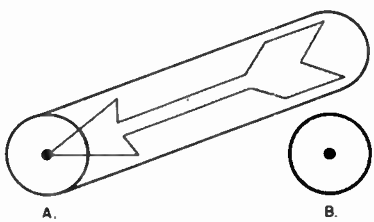


Fig. 9-4. How an arrow is used to show the direction of current flow.

our imagination, it means that the current is moving outward toward the observer at that point.

Why place so much stress on this matter? The reason is that we shall soon find it necessary to indicate the direction of the current flow in a wire which we have imagined cut for the purpose of observation. For example, we are going to wind conductors into coils and attempt to observe the action in and around those conductors when current is passing through them. To correctly interpret what happens, we must know in which direction the current is flowing. To show its direction we resort to the two symbols. We place a dot within the cross-section end-view of the wire to represent the point of an arrow moving toward us and to show the direction of the current. The second symbol, a cross, is placed in the end of the wire to represent the tail of the arrow moving away from us and to represent current flowing away from us.

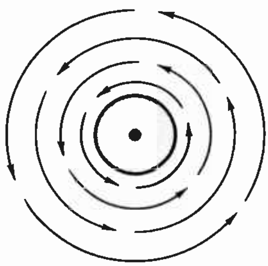


Fig. 9-5. The magnetic lines of force form in a counterclockwise direction around a conductor when the current is moving toward the observer.

Previously in this chapter we indicated that the lines of magnetic force which surround a conductor when a current is flowing through it will tend to form a circular pattern. That is, the magnetic lines of force circle the conductor and therefore, the current flow. This can be shown graphically by imagining we cut a piece of wire in which current is flowing so we can look into the end of the wire and thus observe the direction of the current and the pattern of the magnetic lines of force surrounding the conductor.

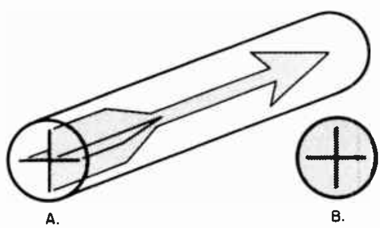


Fig. 9-6. How an arrow is used to show the movement of current away from the observer.

Fig. 9-5 indicates what we would see if our eyes were capable of looking into the end of a wire carrying a current. We would see the cross section of the conductor; the tip of the arrow showing the direction of the current flow, indicating that the current is flowing toward us; and, finally, the magnetic lines of force surrounding the conductor, with the arrowheads on the magnetic lines of force showing them counterclockwise around the conductor.

Electrical men have also developed a symbol to indicate the direction of current away from their point of vision and to indicate the pattern the lines of force around the conductor will take. In Fig. 9-6A we see the imaginary arrow inside the conductor pointing away from the observer to indicate the fact that current is moving away from the viewing point.

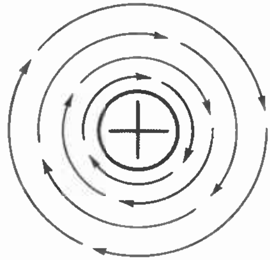


Fig. 9-7. The magnetic lines of force form in a clockwise direction when the direction of current flow is away from the observer.

Fig. 9-6B shows how the feathers in the tail of the arrow would look if we were to cut the conductor right at that point and could look into it.

Of course, it should be understood that no such arrow could be seen if it were possible to look inside such a conductor; however, there is nothing to prevent one from imagining that it does exist. In electrical work our imagination must be used often, because we deal with many things and actions which our senses cannot perceive.

In Fig. 9-7 we have gone a step further to show what we could see if we were able to look into a conductor carrying current away from us. We would see the tail-end of the current moving away from us and the magnetic lines of force which surround the conductor. But note the lines of force here are in a direction opposite to that shown in Fig. 9-5 where the current was traveling toward us. These methods of indicating the direction of current flow did not originate with us. Electrical science has employed them for many years.

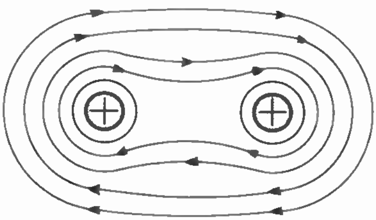


Fig. 9-8. How the lines of force link together around two parallel conductors carrying current in the same direction.

You may find this all very interesting, yet fail to see how it has any practical importance. If you will bear with us a little longer, you will begin to see how very important these things are to an understanding of the mysteries of electrical and magnetic phenomena.

We have shown the form taken by the magnetic lines of force that are produced when current is flowing through a single conductor. Now, let us see what takes place when current flows through two adjacent conductors, flowing through both in the same direction. Fig. 9-8 shows two adjacent conductors, both carrying current in the same direction. Note how the magnetic lines of force have arranged themselves about the two conductors. Instead of the lines of force forming separate patterns around each wire, they have partially combined to form a single, but larger, magnetic field.

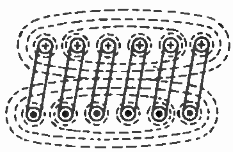


Fig. 9-9. How several parallel conductors are linked together with magnetic lines of force.

If we had three wires adjacent to each other, instead of only two, a similar pattern would result; that is, the magnetic fields of each individual conductor would combine to form a single magnetic field, larger and stronger than any of the individual fields.

In Fig. 9-9 we see five adjacent conductors, in all of which the current is flowing in the same direction. Notice the upper part of the illustration. This is quite similar to the action in Fig. 9-8, except that we have more conductors. In addition, the conductors shown in Fig. 9-9 have been formed in circles or loops cut through the center with an imaginary cutting tool of some kind so we can see inside of the conductor and observe the electrical action there.

Fig. 9-10. A length of wire wound into the form of a coil (solenoid).

In Fig. 9-10 we see the entire loop, or coil, showing that all the adjacent wires shown in Fig. 9-9 were merely separate parts of the same conductor, a conductor which has been wound into the form of a coil and sliced lengthwise. The important thing is that when a conductor is wound into the form of a coil as shown in Figs. 9-9 and 9-10, the magnetic lines of force around the individual turns tend to link together and reinforce each other. This makes it possible to concentrate the magnetism present in all the many sections of a long conductor so that all the magnetism is localized in one place instead of being distributed widely, as would be the case of a long straight conductor.

Ordinarily, the turns of a coil are wound much closer together than is shown in the previous illustrations. The usual practice is to wind them tightly together as shown in Fig. 9-11. When they are so wound, there is less opportunity for the lines of force to leak between the turns, and more lines of force are concentrated in the center and outside of the coil. One of the principal purposes in winding a conductor in the form of a coil is to concentrate as many magnetic lines of force as possible in the smallest cross-sectional area. Usually we want to concentrate them within the center of the coil.

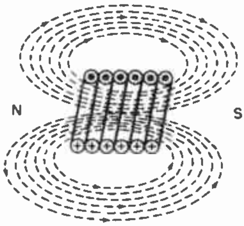


Fig. 9-11. The magnetic linkage is more complete when the turns are close together.

When the lines of force enclose the loops of the coil as shown in Fig. 9-11, a north magnetic pole will be formed where the lines of force emerge from the center, and a south magnetic pole will be formed at the opposite end of the coil. These magnetic poles are similar in all respects to the magnetic poles at the ends of a permanent magnet. The north and south poles of the magnetic field present at either end of the coil will interact with the north and south magnetic poles of a permanent magnet in exactly the same manner as another permanent magnet would. If the coils of wire were suspended in the air so they would be free to turn, they would be attracted or repelled by the poles of a permanent magnet just as another permanent magnet would be affected.

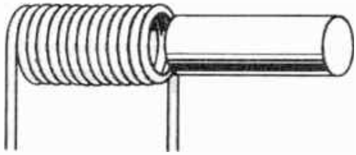


Fig. 9-12. A solenoid and a bar of iron.

A wire conductor wound into the form of a coil like that shown in Fig. 9-11 is commonly termed a *solenoid*. Whenever a conductor (wire) is formed into the shape of a coil, it can be referred to as a solenoid.

Generally speaking a solenoid is a coil which has no core. This type of coil has many practical uses, especially in radio and television work where many such coils are used. Solenoid coils are also used in countless electro-mechanical devices. If an iron bar or rod is positioned so that one end is about to enter the coil of wire as in Fig. 9-12, we can cause an interesting action to take place. The coil and the rod will be insensible to each other so long as there is no electric current flowing through the wire of the coil. The instant current begins to flow through the wire of the coil, a magnetic field will also begin building up around the coil, a field whose lines of force will assume a pattern similar to that shown in Fig. 9-11.

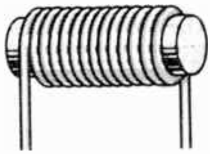


Fig. 9-13. The solenoid will draw the bar of iron within itself.

Since iron provides an excellent path for the magnetic lines of force, a number of those lines will enter the iron. Then, in accordance with the normal action of magnetic lines of force always trying to shorten themselves, the lines of force entering the iron will try to shorten their length. This acts to draw the iron rod into the coil. As more and more of the iron enters the coil, the number of lines of force entering the iron will continue to increase exerting more and more pull on the iron rod, drawing it farther into the coil. This action continues until the rod is centered within the coil somewhat in the manner shown in Fig. 9-13. Solenoid-operated valves, plungers, locking devices, and other kinds of electro-mechanical equipment operate on this principle.

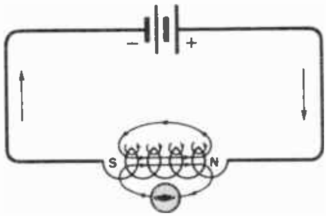
ELECTROMAGNETS

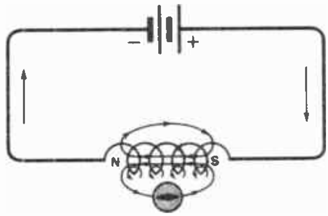
A solenoid (coil) is relatively weak, magnetically speaking, compared with the large amount of current necessary to energize it. This is due to the fact that the air space, within the coil, through which the magnetic lines of force must travel is a poor conductor of magnetism.

We can improve the magnetic properties of the coil by providing for the lines of force a path which has a lower *reluctance* than air. We term the resistance of a material to pass magnetic lines of force as the *reluctance* the material presents to the lines of force. In many ways, reluctance in a magnetic circuit is similar to resistance in an electrical circuit. If a material will pass magnetic lines of force easily, we say that material has a low reluctance. This is similar to the term applied to electrical conductors which present little opposition to the flow of current. In this case, we say the conductor has a low resistance.

Just as copper is an excellent electrical conductor, iron is an excellent magnetic conductor.

The magnetic properties of a coil can be improved by inserting within the coil a soft iron bar which has a much lower magnetic reluctance than air. The presence of the iron bar will permit many more lines of force to appear than if the coil had merely an air core; furthermore, the presence of the iron will act to concentrate the lines of force within the iron itself rather than to have them spread over a wider space or volume.





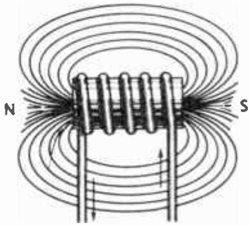


Fig. 9-14. The polarity of the electromagnet will be reversed if the winding is reversed as shown here, or if the direction of the current is reversed.

When we wind a coil of wire on a soft iron core, we have what is called an electromagnet. This is one of the most important electrical devices yet discovered. Electromagnets in their various forms are the means by which we can use electrical energy to perform mechanical work.

Fig. 9-14. shows the basic principles involved in the construction of an electromagnet. It is, basically, a simple device. It is nothing more than a coil of wire wound on an iron core, usually a soft-iron core.

Its action is equally simple. Until an electrical current is permitted to flow through the coil, the device is inert and lifeless, possessing no apparent action or activity. When electrical current flows, the device comes to life. The magnetism, which always surrounds a wire carrying an electric current, will now be concentrated in the iron core. The iron core will actually become a magnet in its own right so long as current continues to flow through the coil. The iron core will have a north pole and a south pole and will react to the laws of magnetic attraction and repulsion in exactly the same manner as a permanent magnet. It will continue to act in this manner as long as the electric current continues to flow through its winding.

One may wonder just what advantage an electromagnet possesses over an ordinary permanent magnet since both possess the properties of magnetic attraction, can attract magnetic materials, and can interact with other magnets in the same way.

The important thing is that electromagnets are controllable magnets. They become magnets when we want them to be, and they will lose their magnetic properties the instant it is desired that they do so—the instant the current is turned off.

Let us consider the properties of these two kinds of magnets for use in an application that is reasonably familiar to all of us, or, at least, can be understood by us all. Electromagnets are widely used around steel mills and around junk yards for han-

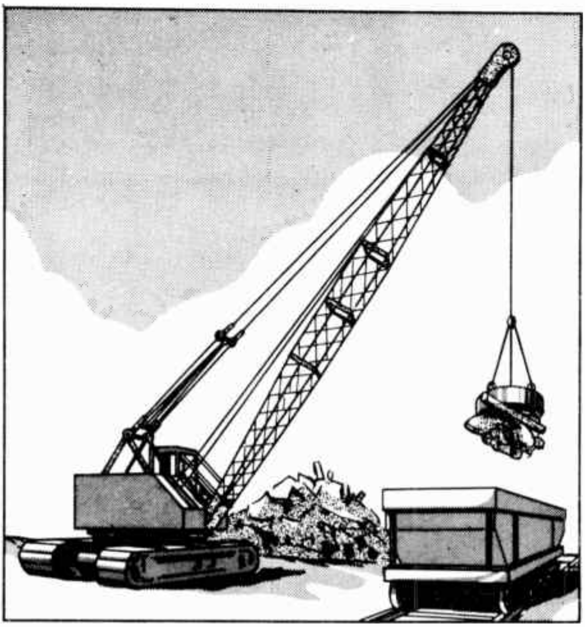


Fig. 9-15. Electromagnets are used to handle scrap iron.

dling scrap iron and steel. The magnets pick up the scrap metal from a pile, freight car, or any location.

The magnets, suspended from a giant crane, pick up and move the scrap iron to wherever it is desired. Fig. 9-15 shows a pick-up magnet carried by a crane being used to load scrap metal on a railroad car.

You might be tempted to say that is no more than a powerful permanent magnet could do. The permanent magnet could lift it, but once it had brought the scrap metal under the power of its magnetic attraction, it would continue to hang onto the scrap metal. It would not turn it loose. Comparative costs are interesting also. The cost of a permanent magnet having lifting strength equal to that of an electromagnet, would be many times greater.

When an electromagnet is used, however, we can move the metal to wherever it is desired and then cut off the electric current. Instantly the electromagnet loses its magnetism, it no longer attracts the scrap iron; and it drops the metal where it is wanted. Nothing could be handier or more simple. It is very obvious that a permanent magnet could not do this job.

It would be accurate to define or describe an electromagnet as a device in which a mechanical pull or force can be produced and regulated by control of the current in a coil of wire.

LINES OF FORCE—STATIC AND MOVING

In our description of the magnetic field around magnets, both permanent and electromagnetic, we have followed the general line of reasoning which is now accepted among the better informed electrical men. *Experiments tend to support the opinions and theories of these experienced men.* But it is only fair to explain that some electrical men are not entirely satisfied with some of these theories and are even now working strenuously to prepare better explanations.

Among the things not definitely susceptible to actual proof is the generally accepted belief that, during the formation of a magnet, the lines of force emerge from the north pole of the magnet, circle around and then re-enter the magnet at the south pole. This is believed to be true, but it cannot be definitely proved at this time.

Since this fact is generally accepted among electrical specialists and electrical workers, and since all we know about magnetism tends to support such belief, we are going to accept it here and base our explanation of certain magnetic actions on that assumption.

When we say that during the formation of a magnet, the lines of force emerge from the north pole of the magnet, and circle around to re-enter the south pole, we do not mean to imply that the lines of force are constantly and continuously in motion. Such is definitely not true; for lines of force are merely convenient symbols for showing graphically the direction and magnitude of the magnetic flux field. Let us consider for a moment, the formation of a magnet. A magnetic material becomes magnetized when that material is brought under the influence of a magnetomotive force of some kind. The magnetomotive force can be another permanent magnet, or it can be a coil of wire through which an electric current is flowing.

A piece of soft iron will become a magnet if brought close to a permanent magnet or if brought within the influence of a coil of wire through which a current is flowing. As the iron becomes magnetized, the molecules within the iron align themselves as explained in a previous chapter. The alignment of the molecules causes a concentration of magnetic force (flux) within the vicinity of the iron. This concentration is shown graphically by means of lines of force. These lines of force will emerge from the north pole of the magnet and re-enter the magnet at the south pole. As the magnetizing force applied to the iron increases even more, we shall find additional molecules aligning themselves, thus making the magnetic strength of the magnet still greater.

Note very carefully, that it is during the formation of the magnet that these hypothetical lines of force are assumed to emerge from the north pole and link themselves in a circle to re-enter the south pole. Once the iron has become fully magnetized, these lines of force become what we call static. By this we mean that they cease to move.

From this it becomes increasingly clear that the lines of force will be moving in the space surrounding the iron during that period when the magnet is being formed, but once the magnet has been formed, the lines of force cease to move and become stationary in space. They are, in effect like millions of tiny rubber bands existing invisibly in the space around the iron magnet.

We could go still another step further and say that when the magnetizing force is removed, the magnetic lines of force around the magnet will collapse and be absorbed in the magnetic material itself. Some of this action is difficult to describe or explain clearly partly because the action itself is not well understood. One thing is definitely certain and can be proved experimentally. The magnetic lines of force are directed outward from the north pole of the magnet during the formation of the magnet; they exist in space during the entire period the material is magnetized, and then collapse and are absorbed in the material, once the material ceases to be a magnet. It is these facts which are of importance to us in our study of electricity and its relationship to magnetism.

AMPERE TURNS

In an electromagnet, the strength of the magnet depends largely upon the construction of the coil and the amount of current which flows through the coil. The construction of the coil and its effect upon the strength of the magnetism follows so closely the pattern of common sense, it is not difficult for us to understand.

We have learned that the purpose of winding a conductor into the form of a coil is to concentrate the magnetism surrounding a length of wire into a smaller physical space. This makes sense! It is not difficult to understand that the more turns of the wire we put on a coil, the greater will be the amount of magnetism produced within the coil by any constant amount of electric current flowing through it.

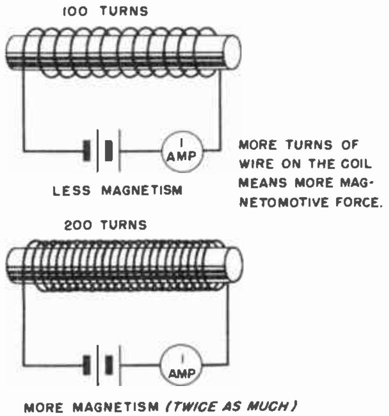


Fig. 9-16. The number of turns of wire in the coil affects the magnetic strength.

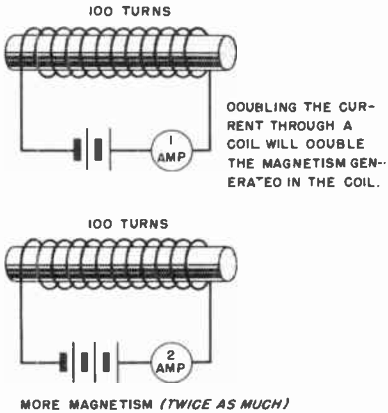


Fig. 9-17. The strength of the current through the coil affects the magnetic strength of the coil.

As an example, suppose we have a coil of wire which has 100 turns. Through that coil let us cause a current of one ampere to flow. The one ampere of current flowing through the 100 turns of wire will produce a given amount of magnetism. All this is reasonable enough. Next, instead of placing 100 turns of wire on the coil, suppose we place 200 turns on it. If we continue to cause one ampere of current to flow through the wire, it is self-evident that we shall cause additional magnetism to be developed within the coil. We should produce exactly twice as much *magnetomotive force* with 200 turns of the wire as we were able to produce with the 100 turns. See. Fig. 9-16.

On the other hand, suppose we have a coil with 100 turns of wire. By forcing one ampere of current through it, we shall have a certain amount of magnetism appear in the coil, just as we mentioned previously. Now suppose that instead of doubling the number of turns of wire on the coil, we increase the amount of current from one ampere to two amperes as shown in Fig. 9-17. We find that we have doubled the magnetomotive force generated in the coil by doubling the amount of current through the wire of the coil. This means we can double the magnetism in the electromagnet in either of two ways; (1) we can double the number of turns of the coil; or (2) we can double the current through the coil.

Electrical men discovered long ago that the number of turns on a coil and the current through it had a definite bearing on the amount of magnetism which was developed within the coil. They reduced their finding to its simplest form and formulated a standard by which they could gauge and guide their research. They determined that one turn of wire in a coil would develop a certain amount of magnetism—so many lines of force—when one ampere of current was forced through the coil of wire. With this as a standard, they proceeded to base all their measurements and calculations upon it. They agreed among themselves that a magnet with one turn of wire and one ampere of current flowing through it would be referred to as a one ampere turn magnet and that one having two turns, and one ampere of current flowing through it would be a two ampere turn magnet.

By following the same line of reasoning, they decided that a 100 turn coil having one ampere flowing through it and developing a 100 ampere turn magnet would be only a 50 ampere turn magnet if the current through the 100 turns was reduced to one-half an ampere. By the same line of reasoning, a coil with 1000 turns having only one-tenth ampere of current through it would be a 100 ampere turn magnet. What they did, of course, was merely multiply the number of turns of wire by the amount of current in amperes flowing through the wire.

It became a well-recognized fact among electrical men that the strength—magnetic strength in terms of magnetic lines of force—developed within any electromagnet was exactly proportional to the ampere turns of the magnet. They discovered, for example, that they could obtain the same magnetic strength by causing 1/1000th of an ampere to flow through 10,000 turns of wire as they could by causing one ampere to flow through 10 turns of wire or by causing one-half ampere of current to flow through 20 turns of wire, or even by causing two amperes to flow through five turns of wire. Electrical men have put this valuable bit of knowledge to use in many ways.

With a fairly high current, a relatively strong magnet can be produced by using only a few turns of heavy wire. On the other hand, if only a very small current is available, a relatively strong magnet may still be produced by causing the weak current to pass through many turns of wire.

SUMMARIZING AND SUPPLEMENTING CERTAIN FACTS ABOUT ELECTROMAGNETS

Because fundamental facts about electromagnets are so important in the study of electricity, it will be of value if we review and summarize some of the preceding material covered in this chapter. Not only are we going to review pertinent points in the next few paragraphs, but are also going to supplement certain information as we go along.

Fundamentally an electromagnet is a temporary magnet produced by electricity. Since there is always a magnetic field produced by or associated with every moving electrical charge (electrical current), regardless of how small that current may be, it follows that the simplest electromagnet is a wire through which a current of electricity is flowing. From a practical standpoint, however, a single wire through which a current is flowing does not constitute a useful electromagnet.

If we take this wire through which an electrical current is flowing and wind it into a coil (solenoid),* the strength of the magnetic field is concentrated or confined in a small space. This concentration of magnetic force about the conductor is due to the fact that the lines of force (field) around each turn of the coil reinforce all the other turns, thereby concentrating all the lines of force of the entire coil into a small space within and surrounding the coil. Winding a 100-foot length of wire into a coil does not increase the number of lines of force, or magnetic strength, produced by the flow of current through that 100-foot length of wire. There are a definite number of magnetic lines of force produced by that current flow through the 100 feet of wire the total strength of which will be constant with a flow of current which is constant. All that is accomplished by winding

* A solenoid is a coil of wire suitably wound for conducting a current of electricity and having an air core.

the 100 feet of wire into a coil is to concentrate the total magnetic field about this conductor into a small space. For example, let us take the 100 feet of wire through which a current is flowing and assume that this current is producing 1,000 magnetic lines of force about each inch of conductor. Then we multiply 100, the number of feet of wire, by 12, the number of inches in a foot. This gives us 1,200, the number of inches in the 100 feet of wire; then we multiply the 1,200 by 1,000, the number of magnetic lines of force about each inch of conductor. We find this to be 1,200,000, which is the total number of magnetic lines of force produced about the 100 feet of wire by the amount of current we have assumed is flowing through it.

Remember we have only 1,000 magnetic lines of force about any inch length of this wire; however, if we now wind the wire into a coil one inch long, we concentrate into this one-inch space not 1,000 but 1,200,000 magnetic lines of force. Winding the 100 feet of wire into a coil 1 inch long results in making our field for the one inch 1,200 times stronger. The interesting and important thing is we have not increased, in any manner what ever, the amount of electrical energy required to do this.

For most practical purposes it would not be possible to use the magnetic field of a single wire produced by passing a current of electricity through it. When the wire is wound into a coil or solenoid, the field thus produced is concentrated so that useful application may be made of it. The magnet's efficiency is greatly increased by placing a core of iron or other magnetic material within the coil. Air is a poor conductor of magentism, and substituting a core of good magnetic conductivity such as iron or steel for air greatly decreases the resistance (reluctance) of the core. For all practical purposes an electromagnet may be defined as: *A coil or winding of insulated wire wound around a core of magnetic material.* The core of electromagnets may be either securely fastened within the coil or made either removable therefrom or non-removable with limited movement within the coil.

The strength and usefulness of an electromagnet depends upon a great many factors. The strength of the electromagnetic field of a coil is determined by:

1. The number of turns of conductor (wire) in the winding.

2. The strength of the current (amperes) flowing through the coil (solenoid).

The strength of an electromagnet is determined by:

1. The number of turns of conductor (wire) in the winding or coil.
2. The strength of the current in amperes flowing through the coil (solenoid).
3. The material of which the core is made.
4. The size of the core.

The analogy shown in Fig. 9-18 is used to aid in understanding the relation that the magnetic strength of a solenoid has to the number of turns in its winding. In this figure a dry cell is used as a source of electromotive force. Let us assume that we have a simple coil (loop), consisting of a single turn, connected to a dry cell as shown at Fig. 9-18A. The current flowing through the single-turn coil will produce a magnetic field. Assume further that the magnetic field thus produced is equal in strength to the small permanent magnet, as shown in Fig. 9-18B, which has just the strength to support a piece of steel weighing one ounce. You will note that the electromagnet is provided with a soft steel core which offers much less reluctance to the flow of the coil's magnetism than does air. In this manner, we are enabled to increase greatly the effectiveness and efficiency of our electromagnet. If we increase the number of turns of wire of the coil from one to two and thus double the number of turns (Fig. 9-18C), the magnetic pull of the electromagnet is doubled. Now it will be able to support two ounces, twice the weight it previously could with only one turn. The force that it can now exert will be equivalent to that of two permanent magnets, as pictured in Fig. 9-18D. The use of 3 turns, instead of one on the electromagnet winding as shown in Fig. 9-18E, will multiply its magnetic field strength by three times. Now the electromagnet will be able to lift three times the weight, or three ounces, which would be equivalent in field strength or magnetic power to the strength of three permanent magnets (Fig. 9-18F), which can lift three ounces. Note that we haven't increased the current, but merely the number of turns, in order to produce three times the pull.

We see from the foregoing that the strength of an electromagnet with a given core and excited by a given current in amperes will produce a magnetic pull in direct proportion to the number of turns in its winding. That is, an electromagnet with 600 turns will have six times the strength (pull) that it would if wound

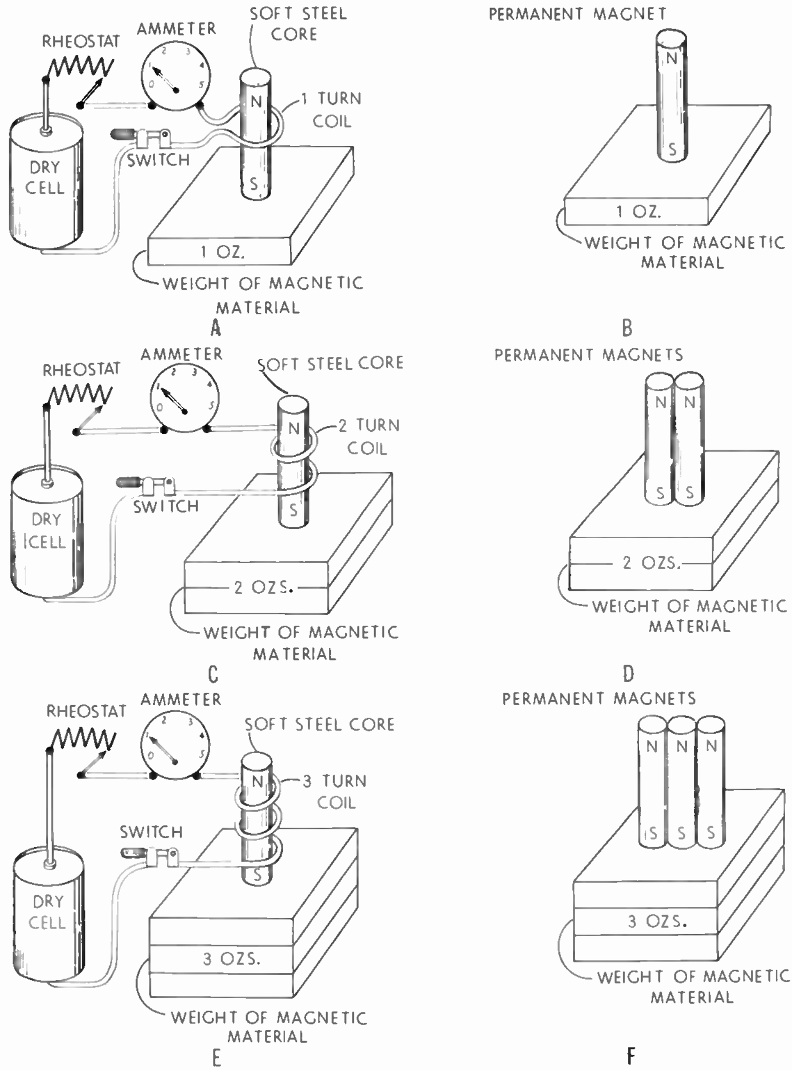


Fig. 9-18. Showing the relation of the magnetic strength of a solenoid to the number of turns in its winding.

with 100 turns, provided, of course, the same current (amperage) passes through the winding in each instance.

The relation that the magnetic strength of a coil bears to the number of turns and current is known as the *ampere-turns* rule. This rule reads as follows: *Ampere turns is the product obtained by multiplying the number of turns in a coil by the current, in amperes, flowing through the coil.* This means that a coil of 100 turns through which 10 amperes of current passes would be called a 1,000 ampere-turn coil, because 100, the number of turns, multiplied by 10, the current in amperes, gives us 1,000, the number of ampere turns in the coil. This coil would be equivalent to another coil having only 10 turns through which 100 amperes of current flows, because 10, the number of coil turns, times 100, the number of amperes flowing through the coil, gives us 1,000, the number of ampere turns.

From the foregoing facts in this chapter, it is easy to understand why it is necessary to wind a conductor (wire) into a coil if it is desired to utilize effectively the magnetic effect produced by an electrical current. A clear understanding of magnetism, magnets, electromagnets, and ampere turns is essential, for they all play a very important part in our everyday life, having much to do with the production and utilization of electricity throughout our civilized world.

To further demonstrate the fact that the strength of an electromagnet depends upon the strength of the current flowing through it, the drawing in Fig. 9-19 has been prepared. Fig. 9-19A shows an electromagnet having a core of soft steel and a winding (coil) of four turns. The current source for energizing the winding consists of one dry cell. The circuit is provided with an adjustable resistor (rheostat) for adjusting the current flow through the coil to exactly one ampere, indicated by the ammeter.* Let us assume that this electromagnet is sufficiently strong to lift just the 1 ounce soft-steel weight. The same identical electromagnet will lift a soft steel weight of two ounces (Fig. 9-19B) because the current has been doubled as shown. If 3 amperes are now allowed to flow through the electromagnet winding, a weight of 3 ounces can be lifted as shown in Fig. 9-19C, because we now have three times the number of ampere turns used in Fig. 9-19A. Thus, the strength of a given electromagnet increases in direct proportion to the increase in current passing through the winding, because the increase in current causes the effective ampere turns to increase directly in proportion.

The material of which the core of an electromagnet is made greatly affects its strength. If a winding (coil) has only air as a core, its pull (magnetic strength) will be quite small as compared to what it would be if a high grade magnetic steel were used for the core.

---

* An ammeter is a device (meter) used for measuring the amount of current in amperes.

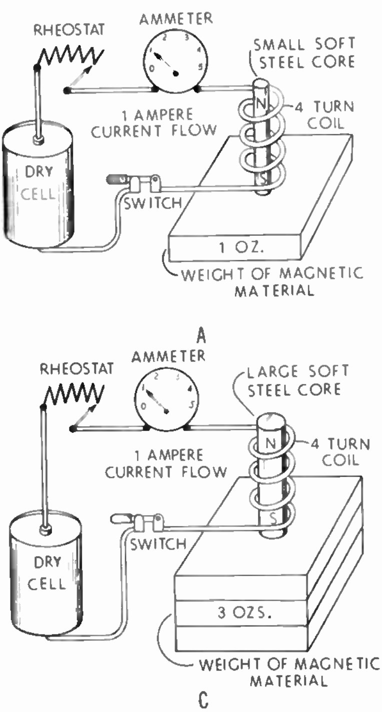


Fig. 9-19. The strength of an electromagnet depends upon the strength of the current flowing through it.

For illustration let us take an electromagnet provided with a core made of a poor grade of iron (Fig. 9-20A). Let us assume further that the magnet coil has four turns of wire for its winding with one ampere of current passing through it. Let us also assume that this electromagnet illustrated will lift a soft steel weight of just one ounce.

Suppose the same electromagnet coil, as shown in Fig. 9-20A, is energized by the same current, one ampere, but with a core made of a nickel-iron alloy. It is altogether possible to make a core of special alloy identical in size to the core in Fig. 9-20A that will lift two ounces. This is shown in Fig. 9-20B.

If a high grade special magnetic steel were used for construction of the core, an identical core could be made that would lift a soft steel weight of 3 ounces, using the same 4-turn coil and excited by the one-ampere current. We see that one of the very important things in the design and construction of electromagnets is the kind of material used in the electromagnet core.

The magnetic conductivity (permeability) of an electromagnetic core depends not only upon the material of which it is

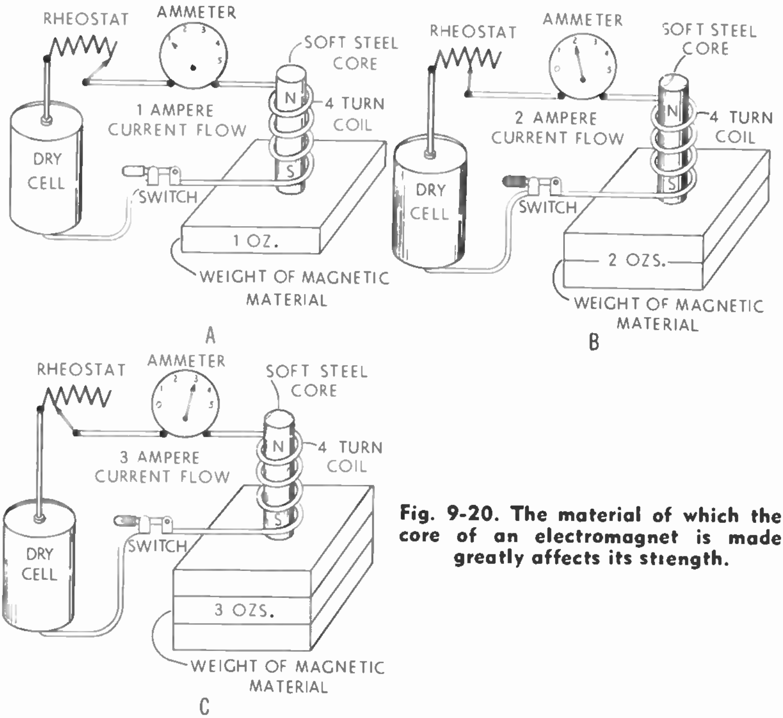


Fig. 9-20. The material of which the core of an electromagnet is made greatly affects its stength.

made but also upon its size or cross-sectional area. For illustration, take an electromagnet energized by one ampere of current and having a core of small cross-section (small diameter) and assume that this electromagnet will lift a soft steel weight of just one ounce as shown in Fig. 9-21A. If another core of the same material, but *larger in diameter*, is substituted for the small core as shown by the core marked medium size in Fig. 9-21B, the medium sized core, if it has exactly the correct diameter, will lift 2 ounces. If the core of this electromagnet, still of the same material, is further increased in diameter as shown in Fig. 9-21C, to exactly the proper size, the electromagnet can lift a soft steel weight of 3 ounces as shown.

The strength of an electromagnet will depend upon another factor—the size of the core used. The strength of the magnetic field of an electromagnet *will not* increase in direct proportion to the increase in cross-sectional area of the core. Instead, there will be a rapid increase in field strength with increased core size up to a certain point, known as the saturation point. Beyond this point, the increased cross-sectional core-area will only slightly affect the electromagnet's strength. For all practical pur-

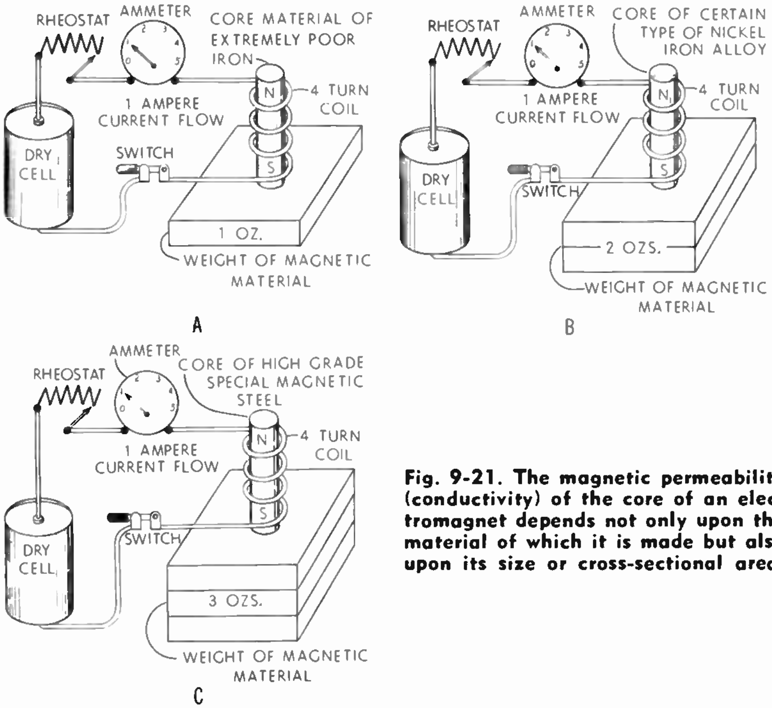


Fig. 9-21. The magnetic permeability (conductivity) of the core of an electromagnet depends not only upon the material of which it is made but also upon its size or cross-sectional area.

poses, a point will finally be reached beyond which any increase in core size will not be of any appreciable value.

TERMS APPLIED TO MAGNETIC PROPERTIES

From a strictly technical point of view we could delve deeply into magnetism and electromagnetism. The design engineer, for example, needs to know just how many magnetic lines of force a magnet having a single ampere turn will produce; how many a magnet having 1,000 ampere turns will produce; and how many ampere turns will be produced for the various other kinds and sizes of magnets. He must know that various grades of iron have varying capacities for magnetic flux. It is not enough to know approximately these values; he must have exact knowledge. For our purpose in this book such a rigorous treatment and study of magnetism is neither desirable or necessary.

The various properties of magnetism do have technical names, and it would be wise to know their meaning, since these names continue to creep into electrical men's everyday conversation and work.

The "Maxwell" is a term we would like to mention here. It is seldom used today; however, it will be found in many of the older electrical texts. The term Maxwell is applied to a magnetic line of force and was named after the personal physician of Queen Elizabeth I, of England. Doctor Maxwell was a brilliant physicist and scientist, as well as a physician, and many of his experiments were conducted in the field of magnetism. His research added to the understanding of magnetic phenomena, and the results of some of his discoveries have contributed much to our present knowledge of magnetism. This is quite remarkable since Doctor Maxwell has been dead for over four hundred years, and his experiments occurred nearly two hundred and fifty years before those of some of his better known successors.

The Maxwell is equal to one magnetic line of force. So 100,000 magnetic lines of force are equivalent to 100,000 maxwells. Generally speaking, electrical men are seldom interested in a single line of force. Even a weak magnetic field consists of hundreds, or even thousands, of lines of force. Furthermore, the term Maxwell has almost disappeared from the terminology of magnetism. It has become the increasing practice to refer directly to the magnetic field as having so many "lines of flux" rather than to its consisting of so many "Maxwells." It is becoming increasingly common to group the lines of force together and refer to them simply as the magnetic "flux," unless there is some occasion for determining, with reasonable accuracy, the number of lines of force present in a given magnetic field.

In describing the strength of a magnetic field, writers often refer to it as consisting of so many lines of force "per square inch." This method of expression is apparently very simple, yet all too often the newcomer to the study of electricity and magnetism fails to understand exactly what is meant by the term. In Fig. 9-22 we can see a drawing of an electromagnet made up of a bar of iron one inch square and long enough to be bent into the form of an exaggerated horseshoe. It has on it a coil of wire through which an electric current is passed. The electric current develops magnetism within the iron.

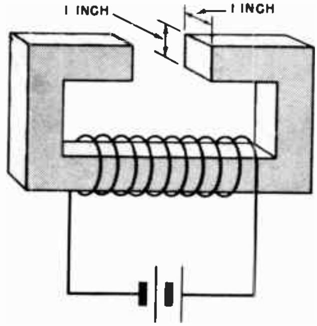


Fig. 9-22. How the cross-sectional area of magnetized iron is measured.

The cross-section of the iron core is exactly one square inch. If there are 1000 magnetic lines of force within the iron, we have a magnet which has a magnetic strength of 1000 lines of force per square inch. If there are 50,000 lines of force within the iron, we have a magnet with a strength of 50,000 lines of force per square inch. If the current is strong enough and there are enough turns of wire to create 100,000 lines of force in the iron, there is a magnetic strength of 100,000 lines of force per square inch.

If the bar of iron were smaller, we would have a different magnetic strength. Suppose the size of the iron bar was reduced so it had a cross-sectional area of only one-fourth square inch. Then if there were 10,000 lines of force in the iron, there would be a concentration of magnetic strength equal to 40,000 lines per square inch. This is due to the fact that the 10,000 lines were concentrated in one-fourth square inch. By definition, regardless of the particular cores cross-sectional area, the magnetic strength is given in terms of how many lines of force there would be in the unit of area, one square inch. This was done for convenience, just as the unit of area, the square inch, was chosen for defining water pressure as pounds per square inch.

This matter is rather involved, and one can easily become confused over the terms. The number of lines of force within the iron is dependent upon the ampere turns of the coil. The more ampere turns, the stronger the magnet and the more lines of force present. The fewer the ampere turns, the weaker the magnet and the fewer lines of force present. The size of the iron core will determine the concentration of the lines of force, the number of lines of force per square inch.

The metric system is used very extensively in electrical engineering, especially in the field of magnetics. Writers instead of referring to the concentration of magnetic lines of force as being so many per square inch, often use the term so many lines of force per *square centimeter*.

GAUSS

Because a magnetic flux of any given number of lines of force might be spread over a comparatively large cross-section of iron core or concentrated in a relatively small cross-sectional area, it is sometimes necessary to know both the number of lines of force and the area of the cross-section. This problem has been met by formulating a unit for measuring the concentration of the magnetic flux. This unit, called a *Gauss,* is a measure of the "density" of the flux concentration. It was named after an early German experimenter and mathematician, Karl F. Gauss (1777-1855).

A Gauss is defined as one magnetic line of force per square centimeter. A piece of iron having a cross-sectional area of one square centimeter would have a flux density of one Gauss if the iron had only one magentic line of force. A density of 10,000 lines per square centimeter would be a density of 10,000 Gausses; while a density of 100,000 lines per square centimeter would be 100,000 Gausses.

An advantage of using the Gauss as a unit of measurement is that it gives more information directly than do the other units of measurement. However, the beginner in the field of electricity and magnetism does not have to worry too much about these things. They are mentioned to acquaint you with the terms since they occur frequently in discussions of magnetism.

PERMEABILITY AND RELUCTANCE

Earlier in this chapter we mentioned the matter of *reluctance*. Reluctance refers to the opposition which any material presents to the passage of magnetic lines of force through it. It is thus comparable, though by no means identical, to resistance in an electrical circuit.

Often we are more concerned with the *ease* with which a substance or material will pass magnetic lines of force than with its opposition to such passage. This property is referred to as the *permeability* of the material and, in a sense, may be considered as magnetic conductivity. In other words, permeability is to magnetic lines of force what conductivity is to a flow of electricity. All materials, it should be remembered, will pass magnetic lines of force, because there is no insulator for them. However, not all materials permit the passage of the lines of force with equal ease. In fact, it is hundreds of times, even thousands of times, easier for the lines of force to pass through some materials than others. It is from 1,800 to 2,000 times easier for the lines of force to pass through some kinds of iron, for example, than through air. This can be said in a somewhat different manner: a piece of iron one inch square will permit the passage of from 1,800 to 2,000 times as many lines of force as the same space occupied only by air. Magnetic lines of force can certainly pass through the air; yet, if the air is replaced with a piece of soft iron, the lines of force can pass many times more readily through it.

This ability, of a material to permit the passage of magnetic lines of force is referred to as its permeability. Air has a permeability of 1. Other materials have permeabilities ranging from slightly less than unity to over 80,000. Iron has a permeability ranging from 1,000 or so to more than 2,000. Brass, however, has a permeability of less than 1. Each material has its own specific permeability, the exact value of which can be learned by looking it up in a table of permeability values found in handbooks of physical chemistry, etc.

WHERE ELECTROMAGNETS ARE USED

It is doubtful if any one could compile a complete list of applications in which electromagnets are used. They are used in so many devices, and so many new uses are being constantly found, that it would be impossible to name them all. For this reason we can cover only a few of their more important applications.

The use of electromagnets for the purpose of handling scrap iron and steel has been mentioned. This is a spectacular use and one with which most people are familiar.

One of the first uses of electromagnets was in telegraphy. Samuel F. B. Morse wound insulated wire onto an iron core to make his first electromagnetic telegraph instrument. Electromagnets have been used for that purpose ever since. Morse devised an electromagnet which would attract a movable iron bar, or armature, when the magnet was energized and would permit the armature to move away when, under the pull of a spring, the coil was de-energized. He energized the electromagnet by the opning and closing of a switch which is known today as a telegraph "key." This closing and opening of the switch, or key, caused electric current to flow or cease to flow through the coil of the electromagnet used to attract the movable armature. As the armature moved up and down, it would strike adjustable "stops," producing the familiar sounds of the telegraph instrument.

The telephone, which is so much a part of our everyday lives, also uses electromagnets, uses many of them in fact. An electromagnet is used to reproduce the sound in the headphone we hold to our ear. Electromagnets are used in the tens of thousands of relays found in telephone "central" offices.

The great generators in power plants, which produce our commercial electrical power, are able to generate electrical energy only because of the electromagnets that are rapidly rotating past other stationary electromagnets.

Electric motors have magnetic fields which are produced by electromagnets. Here we find that the interaction of electromagnetic fields produce torque that turns the shaft of the motor, thus converting electrical energy into mechanical power.

Our way of life would be completely changed were it not for the common electrical relay. Many people have never heard of an electrical relay; yet it is so much a part of our everyday lives, it is difficult to imagine what living would be like without it.

A relay is nothing more than an automatic electrical switch operated by one or more electromagnets. Relays are used in telephones, automobiles, automatic door openers, elevators, traffic lights, oil burners, street cars, diesel-electric locomotives, and innumberable other devices.

Telegraph systems, telephones, relays, motors, radio sets, television sets, and thousands of other devices contain electromagnets. They find use anywhere that it is desirable to convert electrical energy into mechanical motion or force.

Chapter 10

WORK, ENERGY, AND POWER

BASIC MEANING OF POWER

In previous chapters we have discussed various electrical properties such as voltage, current flow, and resistance. Voltage is the electrical pressure which exists between two points in an electrical system. We speak of electrical current as flowing when there is a consistent movement of electrons in a conductor in any given direction. Resistance refers to an electrical property within the body of a conductive material which tends to reduce or oppose the movement of the electrons through the material.

In those chapters we have shown why it is important for anyone wishing to learn something about electricity to understand these basic principles and properties. In this chapter we shall look into another very important electrical property, electrical power—which we shall study and investigate.

The term, electrical power, should not be strange to you. It is probable that you have used it many times or, at least, have seen it used many times.

The large companies which produce electrical energy to sell, are generally referred to as *power companies*. When dams are used to store up huge lakes of water for the purpose of generating electricity, they are commonly called *power* dams; and the electricity thus produced is referred to as *hydro-electric* power. The thing the electrical utilities sell to their customers is electrical *power*. Strange as it seems, we may use the term, power, many times during the course of a single day, and yet have only a vague idea of what it actually means.

There has grown up among us, as the result of common usage, a habit of confusing the terms work, energy, and power. All too often they are used interchangeably as though they are the same. This is unfortunate, because the words do not mean the same thing. Each has its own specific meaning; and it is well that we understand the meaning of each before discussing electrical power.

WORK

There are few words in the English language more common than the word *work*. Some of us would be insulted were any one to intimate that we did not know the exact meaning of the word. Yet, the truth is, many of us do not know what the word actually means.

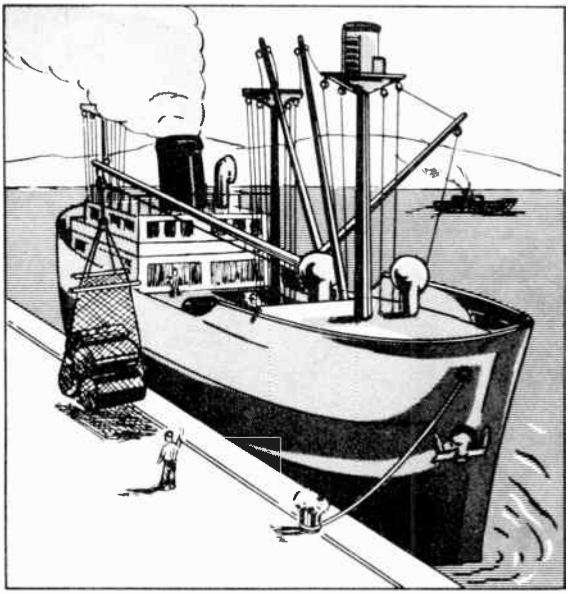


Fig. 10-1. Moving a slingful of barrels from the hold of a ship is one form of work.

Since our study of electricity will lead us, sooner or later, to the task of putting electricity to work, it is necessary that we understand what we are talking about.

In exact terms of science, work is understood to involve the application of force over a distance, such as the moving of something from one location to another. There can be many examples. It might mean the moving of a group of barrels from the hold of a ship to the deck. (See Fig. 10-1.) That would be one kind of work because it would be the moving of a weight from one location to another. It might mean the raising of a bucket of hot tar from the ground to the roof of a building. (See Fig. 10-2.) This would represent a kind of work, because it would mean the moving of the weight of the tar from the ground to another location, the roof.

There are many other examples of work. A familiar one, that illustrates the exact meaning of the term, would be that of moving a pile of coal from the street where a truck had dumped it into the basement where it is to be burned. (See Fig. 10-3.) Suppose that the coal pile is of such size that a strong man with a large scoop can shovel the coal into the basement in an hour. In shoveling the pile of coal into the basement, the man has done a definite amount of work.

A small boy with his play shovel (Fig. 10-4) might conceivably shovel that pile of coal into the basement, but certainly not within the same length of time it took the man. It might take him four or five times longer than it did the man.

Fig. 10-2. Raising a bucket of tar to the roof of a building is another form of work.

Here is the important point: Regardless of the amount of time it took each of them to do the job, both of them would perform the same amount of work. Both would move the same pile of coal the same distance to the same place. In both cases the work to be done was exactly the same; thus, both do exactly the same amount of work. Insofar as the amount of work is concerned, the element of time did not enter into the matter at all.

Many kinds of work can be reduced to the condition of moving something from one place to another. Raising a bucket of tar from the ground to the roof involves work. Raising a barrel from the hold of a ship involves work. Moving the pile of coal from the outside of the building into the coal bin involves work.

Generally speaking, work can be measured if the quantity to be moved, the height to which it is to be raised, or the distance through which it is to be moved are known. The quantity is usually computed in terms of its weight, which is due to a *force,* the force of gravity. Instead of referring to the height to which an object is to be raised, it is more correct to think of the force exerted over that distance.

Fig. 10-3. Shoveling a pile of coal into a basement involves work.

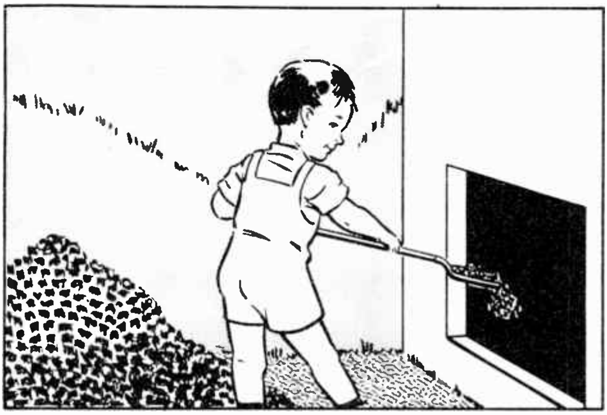


Fig. 10-4. If the boy shovels the same pile of coal as does the man, he will do the same amount of work.

In any case work will be done whenever a given weight is moved some definite distance, where again, weight may be defined as the force of gravity. It does not make any difference whether the time involved is great or small; in any case, some definite amount of work will be done in moving that given weight that definite distance.

Another example of work is that of raising a barrel of apples to the second story of a warehouse. A man could raise the barrel, but he would probably have to use a block and tackle. (See Fig. 10-5.) In raising that barrel of apples, the man would do a definite amount of work.

An electric hoist could also raise the barrel of apples, probably much faster, but would do neither more work nor less than did the man. The amount of work done in both cases would be exactly the same.

By these examples we are trying to drive home the point that work refers only to the doing of some specific task, and the element of time does not enter into the matter.

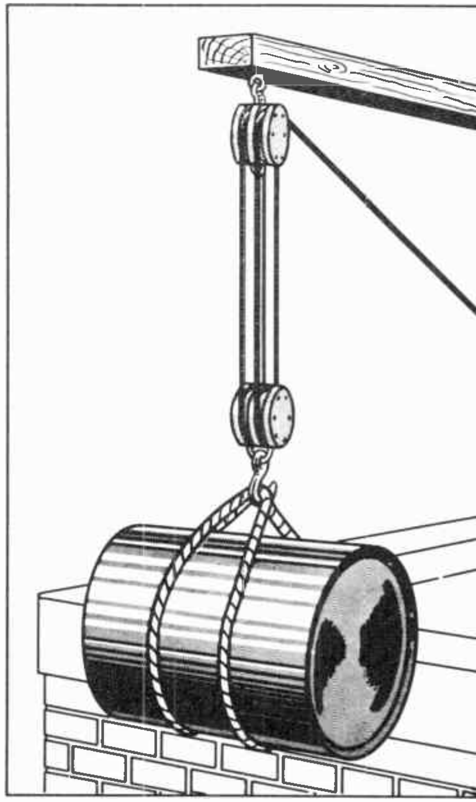


Fig. 10-5. Raising a barrel of apples into a loft involves the lifting of a specific weight a specific distance.

We can cite a very interesting example of electricity doing work. One of the jobs assigned to electricity is that of electroplating metals. Electroplating usually consists of depositing a thin layer of precious or expensive metal upon a heavy, less expensive, base metal, such as the plating of chrome metal over steel to make the bumpers and grill work on our automobiles, or the plating of silver on a base of copper or brass to make silverplated dinnerware. There are many other uses of electroplating besides these.

Suppose we have the job of depositing a half-ounce of silver on an ornamental tray. Electricity must remove the particles of silver from the electrolytic solution and deposit them on the tray. To do that job requires a certain amount of electricity to flow through the solution and through the apparatus. The plating might take only a few minutes if a considerable amount of electricity is used, or it might require several hours if only a small electric current is used. In either case, the work to be done would be the same, the depositing of a half-ounce of silver on the tray. The element of time would not enter into the consideration in any way.

WORK AND POWER

Some of the things mentioned in the previous section are worthy of additional thought. In shoveling the coal into the basement, a certain amount of work was done. The man and the boy both did the same amount of work if the quantities of coal and the distances they moved it were equal. In moving the coal, the man exerted several times as much power as the boy did. For that reason he finished the job sooner.

In the case of the plating of the tray with silver, the job could be done in a short time; or it could be done in several hours. All other things being equal, the amount of work done would be the same in either case; but if the job was done in a short time, it would require the use of more electrical power than would be needed if the job was extended over a period of several hours.

Power is a measure of the speed at which work is done. If a job is done faster, a greater amount of power must be used. This can be put into other words by saying that power is a measure of the *time-rate* at which work is done. It is not a measure of the quantity of work unless the time duration, in which the power is used, is also considered. For a better understanding of electrical power and what it means, it would be well first to consider a few other examples of mechanical power. Mechanical work usually involves the raising of something from one level to a higher one. The work done in lifting the weight can be measured by taking into consideration the number of feet the object is raised and the weight (force of gravity) of the object. These constitute the necessary information, distance and force, their product being work. Let us illustrate our meaning with something familiar. A little earlier we mentioned the problem of lifting a barrel of tar from the ground to a roof. Most of us have witnessed this, at one time or another, as we have watched men repair a roof.

If the barrel of tar weighs 350 pounds and is raised 30 feet to the roof, the work done in raising it that distance would equal the product of the weight and the distance. In this case the work would amount to 350 (the force of gravity in pounds) multiplied by 30 (the number of feet through which the weight is lifted) or a total of 10,500 foot-pounds.

If we wished to know the power required to do the 10,500 foot-pounds of work, we would have to know the time it required. Power always involves time as well as the amount of work done or to be done.

If the work is done quickly, the power must be greater than that needed if the work is spread over a longer period of time. The reverse of this can also be considered. The more slowly a job of work is done, the less power it will require.

With each passing year the public is becoming somewhat better informed regarding power. Automobile companies are constantly advertising the power of the engines in their cars. From such advertising and from our own observations, we have learned that the power of the engine has a lot to do with the performance of an automobile.

One of the things we have learned is that it doesn't require a very powerful engine just to make the automobile move, but to make it "get up and go!" a much more powerful engine is required to move the car at high speed than to move it at low speed.

How Mechanical Power Is Measured—All the advertising concerning the relative merits of various automobiles and the race between several manufacturers to build even more powerful cars makes us aware that the power of a car is measured in terms of horsepower. *Horsepower* is the unit by which mechanical power is measured.

It is of interest to learn how the term horsepower originated, since we see the term used so often. It came into existance with the invention of the steam engine.

James Watt invented the steam engine in England in 1768, a few years before the War of Independence. Strangely enough, this was the first time anybody had ever invented a practical machine capable of developing power. There were a few windmills and waterwheels in use. Other than those, no source of power existed except what man possessed in his strong right arm or what could be obtained from horses, mules, and other beasts of burden. After James Watt had invented his steam engine, he couldn't think of any use for it, and neither could anyone else for a long time. Since there never had been anything like it before, nobody knew of any use to which it could be put.

When trying to find some use for his new engine, James Watt noticed that water had to be pumped from some coal mines. Then, just as today, many of England's coal mines went deep into the ground and out under the bed of the ocean. Water seeped into the mines so rapidly that continuous pumping was necessary to prevent their being flooded. In a few of the mines, strong men worked the pumps day and night to keep the water pumped out; but in most cases horses and mules were used for that purpose.

In watching the horses plodding around and around, working the heavy water pumps, James Watt got the idea that his new steam engine could do the job just as well as the horses. He went to the owners of the mine with his idea, but they didn't think much of it. They knew how much water the horses could pump out of the mine, but neither they, nor Watt himself, truthfully knew how much water his engine could pump.

James Watt set about figuring out just how much water the horses were pumping and discovered that the average mine horse could raise 330 pounds of water to a height of 100 feet in a minute. By multiplying these two quantities together, he found that a horse was capable of pumping 33,000 foot-pounds of water per minute. From this information he went on to devise a new unit of measurement, the *horsepower,* by means of which, mechanical power could be measured. This unit, the horsepower, has remained unchanged to this day, one horsepower being equal to 33,000 foot-pounds per minute. As a matter of convenience, you will sometimes find horsepower expressed also in foot-pounds per second. Since there are 60 seconds in a minute, you would simply divide 33,000 by 60 to get foot-pounds per second. This gives one horsepower equal to 550 foot-pounds per second.

You can apply the mechanics of power to your own activities. You may never have given it any thought, but you exert power every time you take any kind of physical action. Take the simple act of climbing a flight of stairs. If you are no longer young, you are becoming increasingly aware that climbing a flight of stairs involves work and that you must exert power to climb them. Whether you are aware of it or not, climbing a flight of stairs does involve work, and the amount of that work can be put down in black and white.

If you climb a flight of stairs, 12 feet high in six seconds and you weigh 140 pounds you have done work amounting to 140 × 12, 1680 foot-pounds, in a time of 6 seconds. In doing 1680 foot-pounds of work in 6 seconds, you are expending power at the rate of 1680 × 10. or 16,800 foot-pounds per minute, since there are ten times six seconds in one minute. This is slightly more than one-half horsepower.

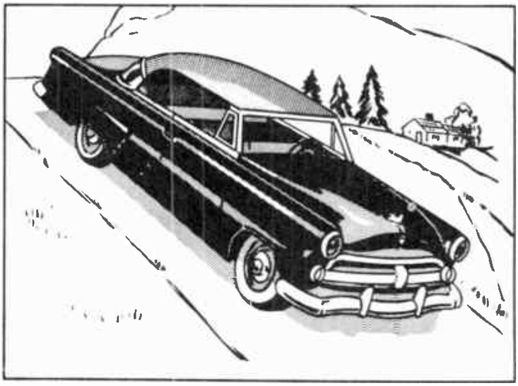


Fig. 10-6. The parked car posses potential energy due to its position on the side of a hill.

If, instead of climbing the stairs in six seconds, you went up slowly taking 30 seconds, you would do exactly the same amount of work; but you would be exerting less power.

On the other hand, if you raced up the stairs in 3 seconds, you would do the same amount of work, but you would exert twice the amount of power as when it took you 6 seconds.

ENERGY

Energy is another term we often use without being fully aware of its meaning. There are many kinds of energy. From a mechanical point of view, anything that has ability to do work has energy.

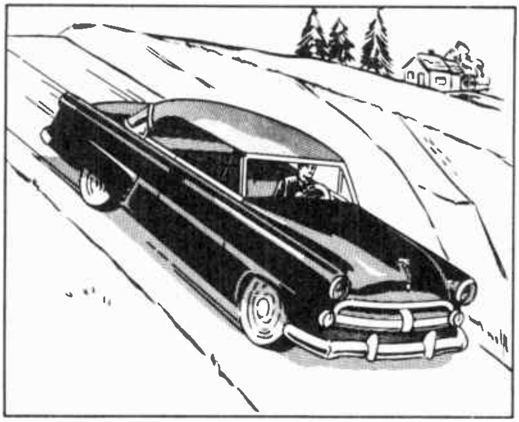


Fig. 10-7. The moving car possesses kinetic energy due to its motion.

There are two types of energy; *potential energy,* the energy something has by virtue of its position; and *kinetic energy,* the energy something possesses due to its motion.

Energy, which is potential energy at one moment may be converted into kinetic energy a moment later. An example of this would be an automobile parked on a steep hill. (See Fig. 10-6.) The car, parked in that location, possesses potential energy. It is energy due to position. If the brakes are released, the car begins to roll down the hill (Fig. 10-7) and its potential energy is immediately changed into kinetic energy because stopping the car would involve the expenditure of energy.

A brick lying on top of a wall is another good illustration of potential energy. So long as the brick remains stationary it possesses potential energy, energy due to its position. If the brick should be displaced so it falls, the falling brick acquires kinetic energy. This energy of movement will be given up when it strikes something.

Another illustration of potential and kinetic energy is in the vast body of water impounded behind a hydroelectric power dam. This immense volume of water is stationary; yet it possesses potential energy due to its position behind the dam. When released through the penstocks to turn the turbines that drive the electric generators, the fast-falling water has kinetic energy due to its motion. This kinetic energy through the operation of the generators is soon converted into electrical energy.

POWER IN AN ELECTRIC CURRENT

When electricity is moving through a conductor in the form of a current, we have a force which is capable of doing work, many different kinds of work because this current of electricity is capable of doing work at varying rates of speed, it is capable of doing work at varying powers.

When an electric current is forced through the resistance of a conductor, work is required. Voltage or pressure is used in doing the work of forcing the current through the resistance. The force of the voltage that is used is changed into heat. In doing the work, the electrical energy is changed into heat energy—the technical name for which is thermal energy.

If an electrical voltage forces current through a motor and causes the motor to run, we have caused still another kind of work to be performed by electricity. The electrical energy is changed into mechanical energy. We can say the electrical energy has been changed into the motion of the machinery.

In the case of electroplating metal, we use electricity to perform another kind of work. In electroplating, the forcing of current through a chemical solution is a form of work. In this case, the electrical energy is changed into a form of chemical energy.

An important thing to note in each of these examples is that whenever electrical energy is used, it is first changed into some other form of force or energy. So long as it remains electrical energy no work is done.

Since it is possible to perform work with electricity only when electrical energy is changed into some other form of energy, it seems entirely natural that we must introduce into the path of the electrical current something which will bring about that conversion of energy. Some device must be inserted into the path which will change the electromotive force into some other kind of force.

One method of doing this has been mentioned several times. We can use a resistance and force the current to flow through it. The presence of the resistance and the pressure behind it cause the electric current to do work. In this case, the passage of the current through the resistance produces heat.

As you already know, the magnetic fields produced by the current flow through the windings of an electric motor develop a mechanical rotation or torque in the motor which makes it capable of doing work. There are other ways in which an electric current can be made to do work; but, for the moment, we will confine our studies to these two examples.

Current, Pressure and Power—In our discussion of mechanical power, we have shown how mechanical work can be measured by multiplying the weight of an object by the distance or the height it is moved. We have shown how mechanical power may be measured by computing the mechanical work done and dividing it by the length of time in which the work is done.

This means that mechanical power, computed by multiplying the weight to be moved by the distance it is moved in a given time, is simply work per unit time.

We go about the measurement of electrical power in much the same manner. Electrical power is the amount of work a specified current will do in a unit of time, when there is a given electrical voltage behind it. The factors involved in computing electrical power closely parallel those used in measuring mechanical power.

To make the comparison complete, we must find some quantity of electricity which is equivalent to the number of feet through which a weight is lifted when mechanical power is measured. A few minutes study will convince you that it is not hard to find such a quantity.

In our previous studies we have seen the similarity between electrical force (voltage), and the weight of water which has been raised to some height (gravitational force). To put this another way; we know that when water is raised to any height it acquires potential energy, the ability to do work. This potential, in a mechanical sense, is very similar in many ways to electrical potential in the form of voltage.

Thus, we've found an electrical factor which closely parallels that of a raised object. When determining electrical power, we call this factor voltage or electrical pressure. When working with electricity, we find that potential in volts is akin to feet through which a weight can fall due to its position when determining mechanical power.

The next thing is to find an electrical factor, or quantity, equivalent to the pounds per second with which work is done in mechanics. In mechanics a pound of any kind of material is considered a definite weight of that material where weight is the force of gravity. In electricity we have a similar quantity, the *ampere*. Just what quantity in electricity an ampere is has already been explained.

MECHANICAL POWER =	DIFFERENCE IN HEIGHT X POUNDS PER SECOND.
MECHANICAL POWER =	NUMBER OF FEET OF DIFFERENCE IN HEIGHT X POUNDS PER SECOND.
ELECTRICAL POWER =	NUMBER OF VOLTS OF POTENTIAL DIFFERENCE X CURRENT PER SECOND.
ELECTRICAL POWER =	VOLTS X AMPERES

Fig. 10-8. Comparison of mechanical power and electrical power.

An ampere is a definite quantity of electricity which passes any given point per second; it is the quantity of electricity that will flow through a resistance of one ohm when a difference of potential of one volt is applied across the resistance. Thus, potential is our distance and current is our force (weight, mass) per unit time, their product giving power which is force × distance ÷ time.

Fig. 10-8 shows graphically the similarity between and a comparison of the quantities involved in determining mechanical power and those involved in figuring electrical power.

How Electrical Power Is Measured—In our everyday lives we are accustomed to using many units of measure. We use gallons, quarts, and pints for measuring liquids such as water, milk, gasoline, and oil; inches, feet, yards, and miles to measure length and distance; and other units for measuring other things.

In studying the fundamentals of electricity, we have met some new units. We have studied an electrical unit called a volt, to measure electrical pressure in an electrical circuit; the ampere, to measure the rate of current flow; and the ohm, to measure the resistance in a conductor.

We also have a unit which is used to measure the power delivered to an electrical circuit, or to measure the power used in the circuit. We should probably be surprised if there were no such unit.

The unit of electrical power is based on the amount of power needed to keep one ampere of current flowing under the pressure of one volt. This can be said in another manner: Whenever any part of an electrical circuit uses one ampere of current under the pressure of one volt, it is using electrical power at the rate of this specific unit of power.

The name of this unit of electrical power is the *watt*. It was so named in honor of James Watt, who devised the first unit for measuring power of any kind and, as previously stated, also invented the steam engine.

There are several ways of defining a watt! We can say that it is the power which must be continuously expended to keep one ampere of current flowing when there is a pressure of one volt, or we can say it is the power used when one ampere of current is forced through one ohm of resistance under the pressure of one volt. If a dry cell or other source is delivering one ampere of current at a pressure of one volt, that source is delivering one watt of power.

Probably the easiest method of defining wattage is: Wattage is the product of current and voltage, one watt being the product of one ampere multiplied by one volt.

In electrical work we have found it very convenient to use symbols to represent the various quantities we find in circuits. We have explained how E is used as a symbol for voltage, I as a symbol for current, and R as the symbol for resistance. A similar symbol is used for electrical power. The letter P is used for that purpose.

Since power in an electrical circuit is the product of the current and the voltage, we can devise an equation, or a formula, to show that relationship. Since power in any circuit always equals the product of the current and the voltage, it can be written in this manner:

Power = Voltage × Current.

Such a statement is true for any circuit. It describes very accurately the amount of power which is used in any load.

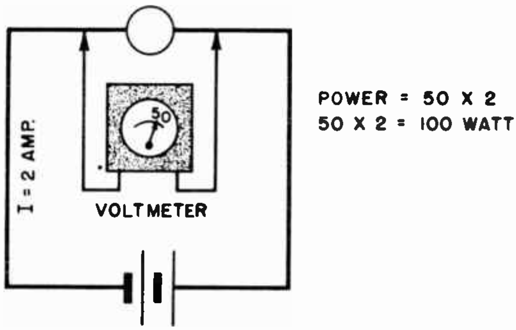


Fig. 10-9. Power is equal to the voltage multiplied by the current.

In Fig. 10-9 a battery is delivering 2 amperes to the lamp. The voltmeter shows there are 50 volts across the lamp. Since power is equal to the product of the voltage and the current, we merely multiply the volts by the amperes to determine the voltage. In this case, we multiply the 2 amperes by the 50 volts and find the lamp is using 100 watts of power.

In Fig. 10-10 we see an electric pressing iron which draws five amperes of current when plugged into a 110 volt source. If the iron takes five amperes of current from the 110-volt line, it will use electrical power at the rate of 550 watts, the product of 5, the number of amperes, and 110, the number of volts.

Since the letter *P* stands for power and the letters *E* and *I* stand for voltage and current we could rewrite the equation mentioned above in this form:

P = EI.

The letters, instead of the words of the equation, convey the same meaning and are easier to write. Electrical engineers use this and similar formulas many times during nearly every working day.

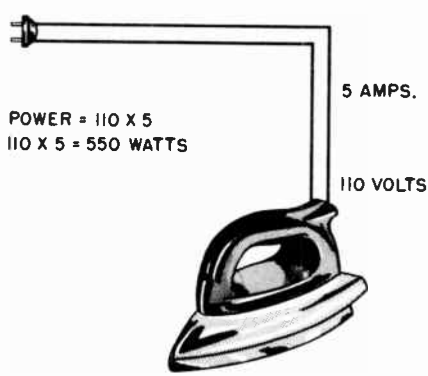


Fig. 10-10. How to figure the power used by an iron when the voltage and current are known.

This formula showing the relationship of the volts and amperes to the wattage is also known as Watt's law. You have probably noted the manner in which Watt's law supplements Ohm's law. We do not think it necessary to enlarge upon this relationship at this time other than to say that the value of voltage, current, power, or resistance in any circuit, or any part of a circuit, can be found if any two of the values are known. This fact is quite useful to the professional electrician. Thus, if you know the voltage and current, you can figure out either the resistance or the power by using either Ohm's law or Watt's law. If you know the power and current, or the voltage and power, you can easily figure out the other values.

In Figs. 10-9 and 10-10 there is a voltage drop across the loads, the lamp and the iron. Whenever there is a voltage drop across a load, we can say that power is being consumed in the load. This voltage drop is caused by the fact that the load consumes current. Whenever a voltage forces a current through a circuit, power will be consumed in that circuit. The amount of power consumed will equal the current through the circuit multiplied by the voltage across it. This rule always applies to direct current. With alternating current, however, the rule applies only when the current and voltage are in step (phase) with each other. For this reason, all of our discussion in this chapter is based on direct-current circuits.

When 120 volts forces 1 ampere of current through an incandescent lamp, that lamp will consume electrical power at the rate of 120 watts. The product of 120 volts and 1 ampere is 120 watts. If you will look at the markings on the outside of an incandescent lamp, you will find the wattage rating and the voltage.

The name plate of an electric iron generally carries the voltage and the wattage ratings. The wattage rating tells you how much power will be used by the iron when it is operated at the voltage marked. No iron, lamp, or other electrical device should be operated on a voltage higher than its rating. To do so will damage and probably ruin the device.

This fact is shown graphically in Fig. 10-11. There we see an electric iron similar to the one shown in Fig. 10-10. The iron consumes 5 amperes of current when used on 110 volts and 550 watts of power.

We can find the resistance of the iron by dividing 110, the number of volts, by 5, the number of amperes. This tells us the iron has an internal resistance of 22 ohms.

It should be remembered that this 22 ohms is the natural, the inherent, resistance of the iron. This resistance is built into the iron when it is manufactured and cannot be readily changed by the user. The resistance depends upon the kind of heating element used by the manufacturer. If the manufacturer uses a size and length of wire for the high-resistance heating element that has 22 ohms of resistance, that resistance is going to remain approximately the same during the entire life of the iron. Since the iron has been designed for use on 110 volts, it should not be used on a higher voltage.

The illustration in Fig. 10-11 shows what would happen if the iron were accidentally plugged into a 220 volt circuit instead of the 110 volt circuit for which it was designed. Remember, the resistance of the iron is not going to change just because it has been plugged into the wrong voltage. The resistance remains the

RATED AT 550 WATTS ON 110 VOLTS

CURRENT = 5 AMPERES
POWER = 110 X 5 = 550 WATTS.
RESISTANCE = 110 — 5 = 22 OHMS

ON 220 VOLTS

CURRENT = 220 ÷ 22 = 10 AMPERES
POWER = 220 X 10 = 2200 WATTS

POWER CONSUMED ON 220 VOLTS IS FOUR TIMES THE POWER USED 110 VOLTS.

Fig. 10-11. What happens when the voltage to an iron is increased.

same; but note what happens to the current. The increased voltage forces twice as much current through the resistance of the heating element. Instead of the normal 5 amperes of current, the higher voltage will force 10 amperes of current through it.

Let's look at the wattage! With 220 volts instead of 110 volts and 10 amperes of current instead of 5 amperes, the power is going to be the product of 220 and 10, not of 110 and 5. Thus, instead of the iron being heated by 550 watts of power, it will be heated by 2200 watts of power, four times as much. This will burn up the heating element of the iron in a very few minutes.

Because of its importance, one fact in particular should be noted in the discussion. Doubling the voltage applied to a resistance increases the power consumption *four times;* it doesn't merely double it.

When electric current is forced through a resistance, electrical power will be used. The electrical energy used will be the product of the power and the length of time it is used. Electrical energy will be changed into *thermal* energy, heat energy. It is scarcely necessary to go into a discussion of the action which occurs when one form of energy is changed into another form. It is enough for our purpose at this time to note that whenever *voltage is dropped* in an electrical circuit, *electrical energy* is changed into some other form of energy. In the examples described here, the electrical energy has been converted into heat energy.

RELATIONSHOP OF ELECTRICAL POWER TO MECHANICAL POWER

Since the measurement of all power goes back to James Watt's original horsepower, it is interesting to compare the watt to horsepower and see in what manner they are related. It has been determined as the result of a long series of experiments, that 746 electrical watts are equivalent to one mechanical horsepower. Let us see how this bit of information might be of use to us.

When one purchases an electric motor, it is usually with the intention of using the mechanical power the motor can deliver. If it is to power a refrigerator, the motor must be capable of delivering one-sixth to one-third horsepower. If it is to be used to rotate a circular saw, it may need to deliver as much as one horsepower. If it is to operate a drill press or other similar tool, it may have to deliver from one-quarter to one-half horsepower. There are all kinds of electric motors. Some very small ones deliver very little more than a flea-power, while the motors used in some of our factories develop hundreds and hundreds of horsepower.

The important point in the selection of a motor for a job is to know that it can deliver the amount of power necessary for the job for which it is designed. You would not use a 10-horsepower motor to drive a vacuum sweeper. The sweeper would probably operate satisfactorily with a motor delivering not more than one-twentieth horsepower. On the other hand, you certainly would not choose a washing machine motor to drive a stamping mill or some other heavy industrial machine. Such a motor couldn't even start the large machine, much less operate it under load. Thus a motor is selected on the basis of its power requirements.

In selecting a motor there is also another consideration, the amount of electrical power it will use. This is where the conversion factor comes into use. A motor or other electrical device, which uses the equivalent of one horsepower of mechanical power will use 746 watts of electrical power.

A watt of electrical power is relatively small when used to measure large amounts of electrical power. For that reason a larger unit has come into general use in electrical work, the kilowatt. The word kilowatt is made up of two words kilo and watt. Kilo means 1000; therefore, one kilovolt = 1,000 volts, one kilometer = 1,000 meters, and one kiloampere = 1,000 amperes. Kilo (1,000) is used so frequently in electrical work that you should know its meaning. As the name indicates, the kilowatt is one thousand watts.

A "rule of thumb" method of figuring horsepower and electrical power is that one horsepower is approximately three-quarters of a kilowatt. Seven-hundred-fifty watts would be exactely three-fourth of a kilowatt. This rule of thumb method of measuring is close enough for ordinary purposes.

Power companies do not sell electrical power! They sell only electrical energy! When one kilowatt of electrical power is used for a period of one hour, the quantity of electrical energy used is equivalent to one kilowatt-hour. The large public utility companies generally sell their electrical energy by the kilowatt-hour. If you examine your electric energy meter (often incorrectly called a power meter), you will see the word kilowatt-hour on the name plate. It is so designed that it measures the total quantity of power used between meter-reading periods. Its reading gives the total electrical energy used in killowatt-hours.

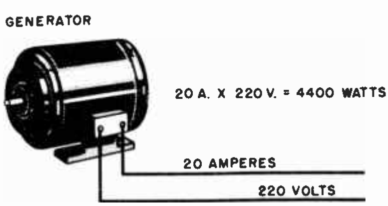


Fig. 10-12. The power delivered by an electrical source is equal to the product of the current and the voltage.

Electric energy is one of the few things that has not increased in cost as most other things have. In many cases the cost of electrical energy per kilowatt-hour is actually less today than it was twenty years ago. One can hardly think of anything else of which this is true.

The watt is used for measuring power not only when it is *used* but also when it is being generated. If a battery, generator, or other source of power delivers so much current under a pressure of so many volts, the power that is being generated is figured in just the same manner as when it is being used. The amount of current (amperes) delivered multiplied by the electrical pressure in volts gives the amount of power being generated.

If a generator is delivering 20 amperes of current at 220 volts of pressure, it is generating electrical power at the rate of 20 multiplied by 220 or 4400 watts. This is the same as saying the machine is delivering 4.4 kilowatts of power. If it delivered that amount of power continuously for one hour, it would be delivering 4.4 kilowatt-hours of electrical energy. If this energy is delivered continuously for two hours, it would amount to 8.8 kilowatt hours of electrical energy. See Fig. 10-12.

Chapter 11

TRANSFORMERS

MAKING CHANGE WITH ELECTRICITY

There's something mysterious about the way a transformer works. It has no moving parts. It makes no sound, except perhaps a faint humming. Although it contains at least two electric circuits, they never make electrical contact with each other. With its tightly wound coils of wire and closely stacked sheets of steel, the transformer turns electricity of one voltage into magnetism and then turns that magnetism back into electricity at a different voltage. Fig. 11-1 shows some of the various sizes and styles of transformers. The loss in the process is quite small.

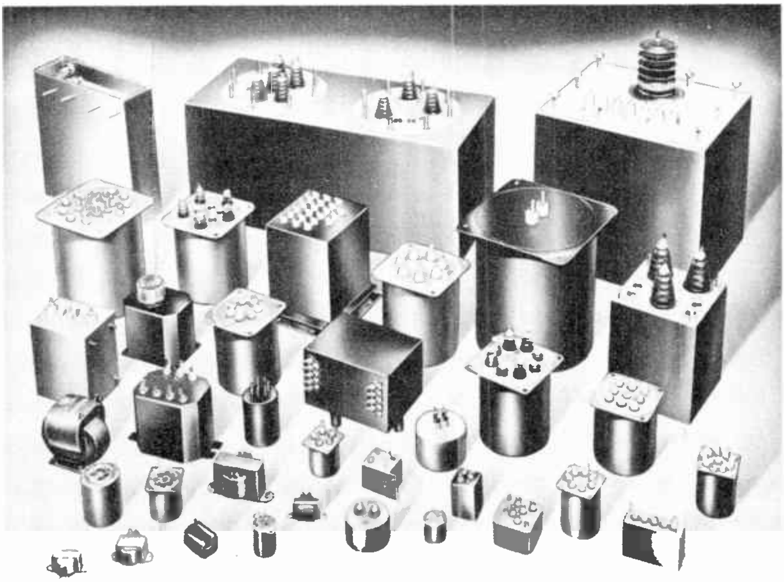


Fig. 11-1. A group of various styles and sizes of small transformers. (Courtesy of United Transformer Co.)

The transformer is a kind of change-making device. You know that a silver half-dollar is more convenient to carry around than ten nickels or fifty pennies. It weighs less in your pocket and does not jingle as you walk, yet it has exactly the same buying power. If you walk into the New York subway, you find that the turnstiles there are designed to take dimes, and dimes only; so you have to go to the change booth and get your half-dollar changed into coins of a smaller denomination.

That is almost exactly what a transformer does in the field of electricity. It changes a quantity of electric power of one denomination into the same quantity of another denomination; that is, at another voltage. Electricity at high voltage is easier to send over the wires, just as coins in large denominations are easier to carry around. The electric current, which demurely enters your home at a mere 120 volts, has probably spent part of its existence streaking over transmission lines at the awe-inspiring pressure of a hundred thousand volts or so, a voltage that would literally make your hair stand on end if you got too close to it.

This electricity has traveled many and devious paths before entering your home to dissipate its energy in your service. It has been inside many transformers; some of them may be small enough to slip into your pocket, like the ones that ring your door bell and run your radio set; others, at the substation and power station, may be almost the size of a modest house and are filled with oil for insulation and fitted out with an elaborate cooling system. The ones that serve your home, mounted on a nearby pole, are in neat tanks little larger than an ordinary milk can. No matter what their size, they all are making change in electrical units and doing it without short-changing the customer. The windings of some transformers are encased in a steel shell while in others the windings are left exposed. (See Fig. 11-2.)

One of the many amazing things about a transformer is the little toll it takes from the electric power that passes through it, twenty-four hours a day, three hundred sixty five days a year. Part of the secret of its efficiency is found in the steel that nestles in its heart, steel containing a small amount of the unusual element silicon, just the right amount, no more, no less. Into the production of this steel goes all the careful control that is exercised in forming the more spectacular alloys used in automobiles and airplanes.

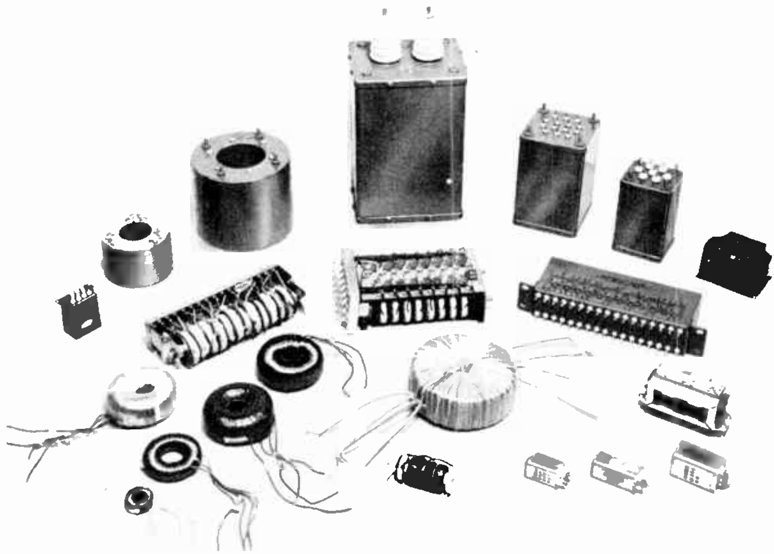


Fig. 11-2. Small transformers, some with and some without cases. (Courtesy of Raytheon Mfg. Co.)

Of the entire transformer family, the real unsung hero is the distribution transformer. There is one right in your neighborhood, although probably you have never noticed it! Its never-ending job is to step down a higher voltage to the 120 or 240 volts that you use. In a sense, it is the heart of our modern electrical systems. If it weren't for this quiet, magic-like device, performing its tireless sleight-of-hand, it wouldn't be economically possible for most of us to use electricity unless we lived practically within shouting distance of the powerhouse.

One of the most familiar transformers in our homes is the bell-ringing transformer, which steps-down the house circuit voltage to the lower voltage needed to ring our door bell. While this application is important, it represents but one of the numerous jobs the transformer can do.

Today, there are so many different kinds of transformers in use, it is difficult to select those which should be discussed and those which should be passed by without comment. Transformers enjoy such wide use that it is impossible to mention more than a few of their uses here.

In addition to the bell-ringing transformer, another familiar type, found frequently in our homes, is the electric toy-train transformer. There are few boys who have not used one of these transformers, either in their homes or in the homes of friends. The electric train transformer is in many ways quite similar to the bell-ringing transformer. It acts to step-down the voltage of the house circuit to the lower safer voltage necessary for operating the toy trains. It is usually designed to step-down the house circuit voltage to about 12 volts or to several voltages, one of which may be selected by a tap-switch on the transformer.

Transformers can do other things besides reducing the voltage from one level of pressure to a lower one. Ordinary resistors can be used to reduce voltages; however, transformers do possess two big advantages over resistors in the reduction of voltages. Transformers can reduce the voltage with much less loss of power than can resistors and a transformer's reduction doesn't depend on the current drain of the load as does a resistor's reduction.

An equally important ability of transformers is that they operate equally well to increase the voltage and to reduce it. They can do this without consuming any appreciable amount of power. Transformers are used to increase the voltage for operating neon signs. We have all seen neon signs, but few people understand how they work.

Fig. 11-3 shows how a neon sign transformer is connected. A neon sign is made of a long glass tube which is heated until flexible and then bent to spell out the words the user wants in his advertisement.

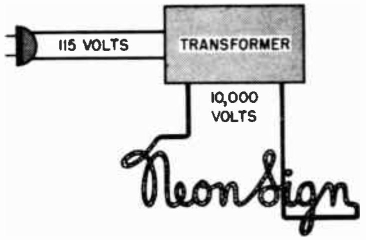


Fig. 11-3. The high voltage needed for the operation of a neon sign is provided by a transformer.

After the tubing has been formed into the correct shape with wire leads and cylindrical metal "electrodes" have been sealed into the ends, the air is exhausted with a vacuum pump; then it is filled to a certain pressure with neon, or some other rare gas. A high voltage is then applied to the external wire leads of the two electrodes. If the voltage is sufficiently high, a current will flow from one electrode through the gas to the other electrode, causing the neon gas to give off a brilliant red glow. If other gases are used in the tube instead of neon, different colors are produced.

This voltage must be quite high to force current through the gas. With small signs, the potential may be as low as 4,000 volts, but 4,000 volts is a great deal of voltage. Many of the larger signs require from 11,500 to 15,000 volts to operate properly. The voltage required to force the current through the neon gas is obtained by changing the ordinary house circuit voltage by means of a transformer into the required higher one. This action is called "stepping up" the voltage in contrast to the action of reducing the voltage. When voltage is reduced from one potential to another by means of a transformer, we refer to the action as "stepping down" the voltage.

Transformers of some type are used in all radios and television receivers. These familiar examples of electronic equipment could not work without transformers. All radios and all television receivers use two or more kinds of transformers.

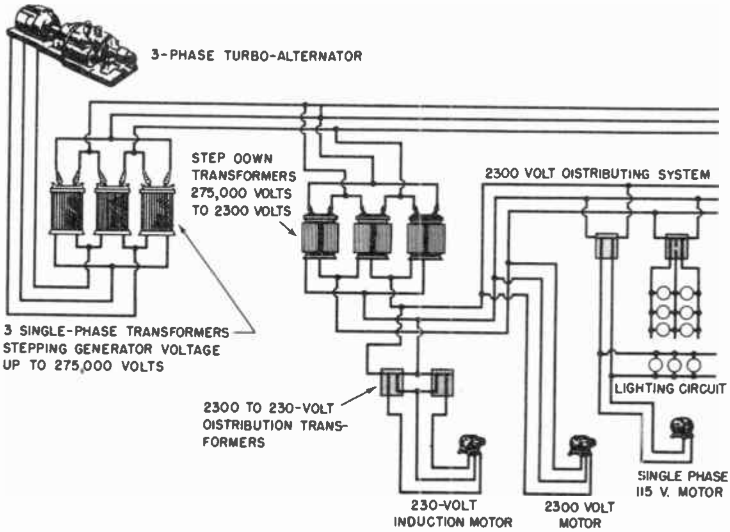


Fig. 11-4. How transformers are used for many different purposes in a transmission and a distribution system.

Transformers are used on a large scale in the distribution of electrical power by the large electrical utility companies. Fig. 11-4 gives some idea of how transformers are used in stepping up the voltages for distribution or transmission over long distances and then stepping these voltages down where they are to be used. We see in this figure three large transformers used to step up the potential to 275,000 volts for transmission over long-distance transmission lines. In some distant location a bank of three transformers is used to step-down that 275,000 volts to 2,300 volts. Additional transformers step-down the 2,300 volts to lower voltages for use with small motors and lamps. We could have shown still other transformers in the system, such as those used for ringing bells, operating toy trains, or powering radios and television receivers, which step-down the 115 volts even further.

The examples described will give you some idea of the wide use of transformers. They provide us with a flexibility in the range of available voltages that makes possible the use of electricity in so many applications.

At first thought, the act of stepping up the voltage to very high levels and then of reducing it to a lower level before using it looks rather foolish. However, there is a very good reason for doing so; it is to avoid the large losses of power which would otherwise occur in the transmission lines. If the voltage is stepped up to relatively high levels, it is possible to transmit the power over much longer distances with small loss. Power line voltages are always stepped up if the power is transmitted very far. It is dangerous, however, to attempt the use of power at such high voltages for anything except transmission. For that reason, the voltage is always stepped-down again before the power is put to use.

A transformer will not work on direct current, although transformers are very often used in direct-current circuits. Before a transformer can be used on direct current, the current must be broken up into a succession of pulses. The transformer will not work when the current is flowing smoothly in one direction. The current in the primary of a transformer must be interrupted or constantly changing in intensity. That is the reason transformers are almost always used only with alternating current. Alternating current is the kind which is continually reversing its direction of flow. It flows in one direction for an instant, building up from zero to the peak value in that direction; then it falls to zero; and an instant later it reverses and repeats the same procedure in the opposite direction. This action occurs over and over very rapidly. The value of the current in an alternating-current circuit is never the same any two successive instants of time during any one alternation. It is changing continuously and this is exactly the kind of current that a transformer requires for best operation.

ADVANTAGES OF ALTERNATING CURRENT

Substantially all of the electrical energy used for domestic and commercial purposes is generated as alternating current. In those instances where direct current is necessary, such as in electroplating, in variable-speed direct-current motors for elevators and machine tools, and in electronic circuits, the alternating current after having been transmitted over the power lines, is converted into direct current by rectifying devices.

Thus, although direct current is sometimes necessary for certain industrial purposes, the chief reasons for generating electrical energy as alternating current can be briefly given as follows:

a. Alternating current can be generated and transformed into high voltages which can be transmitted economically over great distances by high voltage transmission lines. At the application end of these transmission lines, the high voltages can be readily and efficiently reduced to any desired level by means of non-moving electrical devices called power transformers.

b. Since the alternating-current induction motor is more efficient, less expensive, and more rugged than direct-current motors it is used almost exclusively. For this reason it is necessary to have available alternating current power to operate the induction motors.

c. Alternating-current generators are simpler than direct-current generators; they may be constructed in larger sizes and are particularly well suited for economical operation by high-speed steam turbines.

d. Alternating current can be converted easily into direct current by moving or non-moving equipment to furnish electrical energy for specific applications requiring direct current.

The advantage of transmitting electrical energy at high potentials or voltages is that the higher the voltage, the greater will be the amount of electrical power that a given size conductor will carry over a given distance at a given efficiency. For illustration, a number 10 B&S gauge copper wire will carry 5 amperes at 100 volts a given distance with a given efficiency. However, this same conductor will carry 5 amperes at 1,000, 10,000, or 100,000 volts over the same conductor for the same distance just as efficiently as it will 5 amperes at 100 volts. In other words, the current or amperage is the factor which limits the amount of electrical power that a conductor will carry or transmit.

From the foregoing we can see that our number 10 wire will carry electrical power or energy over a given distance at a given efficiency as follows:

5 amperes at 100 volts = 500 watts
5 amperes at 10,000 volts = 50,000 watts
5 amperes at 100,000 volts = 500,000 watts.

Therefore, the higher the voltage (other things being equal) the greater the amount of electrical power that a given conductor will carry. Theoretically, the higher the voltage, the greater is the amount of electrical power that a given conductor will carry. Actually, this is not quite true with extremely high voltage, due to the losses caused by corona effects. Corona is a discharge of electricity appearing as a glow on the surface of a conductor carrying high potentials that exceed a certain critical value. It is due to the high voltage ionizing the surrounding air and constitutes a definite power loss.

The relative simplicity of alternating current generators and motors, the ease of conversion from one voltage level to another by motionless power transformers, the economy of generation and transmission, plus the ease of conversion from alternating current to direct current are the salient reasons for the preponderance of alternating-current generation and use.

It is largely because of the usefulness of the transformer in conjunction with the transmission of electricity that the once wide-spread use of direct-current electricity has almost disappeared. Alternating current is now transmitted nearly everywhere.

A transformer is used in automobiles to step up the direct current delivered by the generator and battery into the high voltage needed by the ignition system. This is a very special purpose, and even here the direct current must be broken up into a series of short pulses through the interrupting action of the "breaker points" in the distributor. We find this special type of transformer stepping up the battery voltage to a voltage as high as 12,000 to 25,000 volts.

PHYSICAL CONSTRUCTION OF A TRANSFORMER

From the standpoint of physical construction, few electrical devices are as simple fundamentally as an electrical transformer is.

Fundamentally, it consists of an iron core on which are wound two coils of wire. One of the coils is called the "primary" winding and the other is called the "secondary." The coupling between the windings is brought about by the magnetic flux which links them.

The primary winding of a transformer receives the electrical energy from the supply source, and transfers it to the secondary winding by induction by means of the fluctuating magnetic lines of force produced by the primary current.

The transition of electrical energy in the primary at one potential to that of a different potential in the secondary is accomplished by an energy transfer effected by the magnetic lines of force that are produced by the primary current.

This fluctuating magnetic energy produced by the primary current is efficiently conveyed through the secondary by means of a laminated steel core. The efficiency with which the magnetic energy is conveyed is primarily due to the good permeability (magnetic conductivity) of the steel core—the better the permeability of the core, the higher the efficiency of the transformer.

There are two common types of iron (steel) cores which are used in transformers, although other types and shapes are made for special purposes.

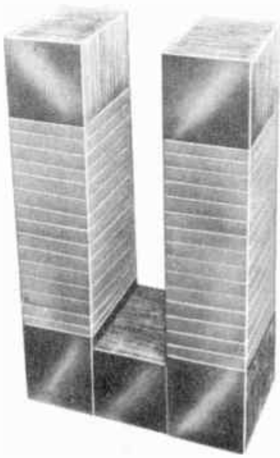


Fig. 11-5. Laminated core for a core-type transformer. (Courtesy of Eisler Engineering Company.)

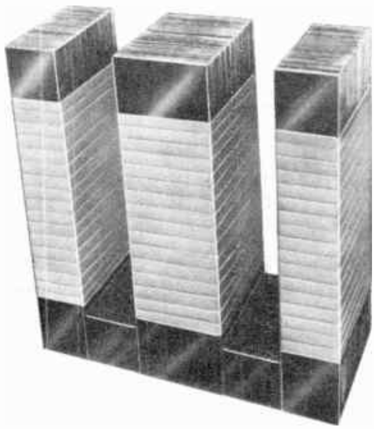


Fig. 11-6. Laminated core for a shell-type transformer. (Courtesy of Eisler Engineering Company.)

The transformer cores shown in Figs. 11-5 and 11-6 are the two most common types. Fig. 11-5 is called the "core" type, and Fig. 11-6, the "shell" type.

These transformer cores are assembled from laminated sheets of electrical steel. To reduce loss, the laminations are insulated from each other by surface oxides produced on the steel sheets during the process of their manufacture and sometimes by an application of varnish. After the transformer windings are placed on these cores, laminated steel strips are inserted into and between the protruding core ends, thus completing the laminated steel structure and providing a closed magnetic path surrounding the windings. Perhaps you are wondering why transformer cores are made of so many thin insulated sheets of steel. Presently we shall see the reason.

Transformers are designed to make losses as small as possible. One of the principal unavoidable transformer losses is the iron loss. Iron losses occur in the core and result from two factors, HYSTERESIS AND EDDY CURRENTS. Both produce heat and both represent losses which must be reduced to a minimum.

Hysteresis loss is due to the resistance the molecules (molecular magnets) of the iron structure offer to being shifted every time the alternating current reverses. The molecules of the core are forcefully shifted 120 times each second in a 60-cycle transformer. The resistance to this shifting produces friction, and the friction produces heat. Losses from hysteresis cannot be eliminated; however, they may be reduced considerably by the use of a soft steel or a special transformer steel containing silicon. The molecules of these metals shift more easily, produce less friction, and result in a minimum of iron loss due to heat.

Steel is a fairly good conductor of electricity. If transformer cores were made of solid steel, the alternating magnetic flux produced by the transformer primary winding would induce currents in the transformer core. Such currents are known as eddy currents.

They are called "eddy currents" because they eddy or circulate entirely within the iron core and are really short-circuited currents flowing within the core material. They produce heat

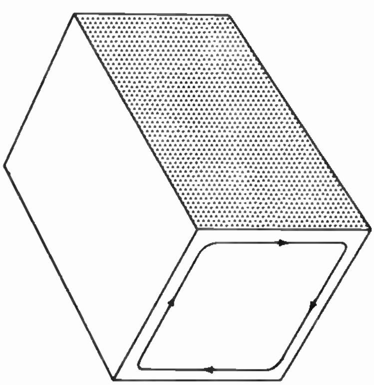


Fig. 11-7. Eddy currents are set up in a solid core through which alternating magnetic lines of force are passing.

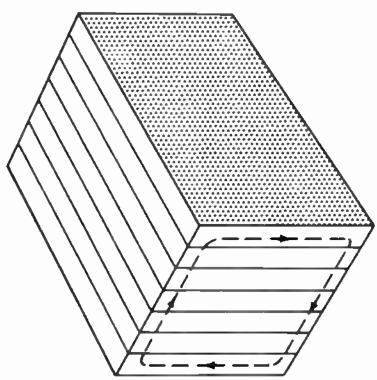


Fig. 11-8. Slicing (laminating) a steel core into thin sections (sheets) reduces the eddy currents materially.

for the same reason that any short-circuited current produces heat.

Eddy currents may be broken up by transformer cores constructed of thin steel sheets instead of solid pieces. To illustrate this, let us refer to Figs. 11-7 and 11-8. Due to induction, a current of electricity will be produced in a conductor such as a solid cross section of steel core (see Fig. 11-7) if an alternating magnetic flux is passing (cutting) through it. This, of course, would be the case if it were a part of the core structure of a transformer. One may break up this large eddy current by slicing the core into thin sections and insulating them from each other (Fig. 11-8). Small eddy currents will still flow in the sliced sections. They can be reduced in magnitude if the laminations are sliced still thinner.

While eddy currents cannot be entirely eliminated, they can be reduced to a point where the loss they cause is negligible if the slices (laminations) are made very thin.

Fig. 11-9 shows a core-type transformer with the transformer windings mounted on the two core legs and the core completely assembled. This type of core provides a complete magnetic cir-

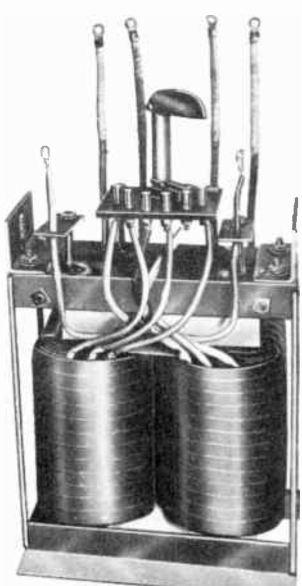


Fig. 11-9. A core-type transformer. (Courtesy of Eisler Engineering Company.)

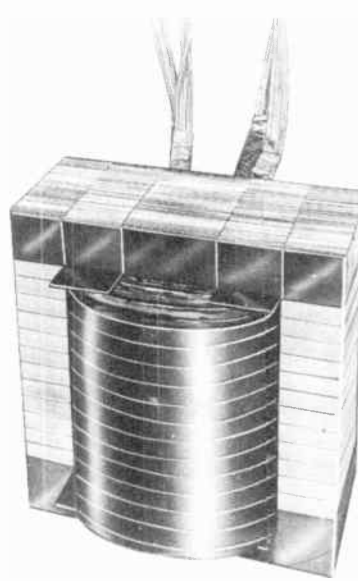


Fig. 11-10. A shell-type transformer. (Courtesy of Eisler Engineering Company.)

cuit (path) around the windings. In this transformer the primary is divided, one half of the primary winding placed on each core leg next to the core. The secondary is likewise divided, one half wound on each core leg over (on top of) the primary.

The completely assembled transformer is mounted in a frame structure for fastening into a transformer case. The core type of core shown in Fig. 11-5 is used in this transformer.

Fig. 11-10 shows a shell type transformer with both primary and secondary mounted on the center core leg and the core completely assembled. This type of core completely surrounds the windings, providing a path of low reluctance for the magnetic lines of force produced by the primary winding.

In this transformer the primary is wound next to the core, and the secondary is wound directly on top of the primary, with the necessary insulation between.

Fig. 11-11 shows a bent-iron core type transformer first manufactured in 1935. It was designed by Mr. W. F. Gakle, Vice-President of the Kuhlman Electric Company, and is the forerunner of all wound-core designs now used by transformer manufacturers.

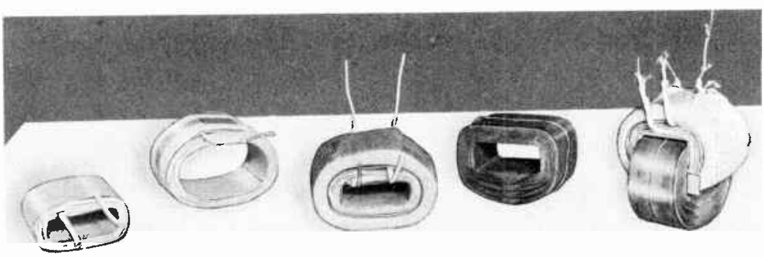


Fig. 11-11. Unassembled and assembled parts of a bent-iron core-type transformer. (Courtesy of Kuhlman Electric Company.)

The various stages of construction of the core and coil assembly of this transformer are shown in the figure. The components are: (A) primary coil, (B) secondary coil, (C) secondary and primary coils combined, (D) the bent iron core, and (E) the complete assembly.

A modification of this type transformer is shown in Fig. 11-12. It is provided with two bent cores instead of a single one.

Today there are several styles of wound cores used by transformer manufacturers.

Fig. 11-13 shows a power transformer being assembled from a precut, preformed core of laminated steel strips. This type of construction has enabled General Electric Company engineers to improve performance and reduce transformer size and weight.

This performed core, made of oriented, cold-rolled silicon steel, has given General Electric Company engineers a greater amount of flexibility in transformer designing. The losses, exciting current, noise level, weight, and size can be varied over a wider range to best suit the user's operating conditions.

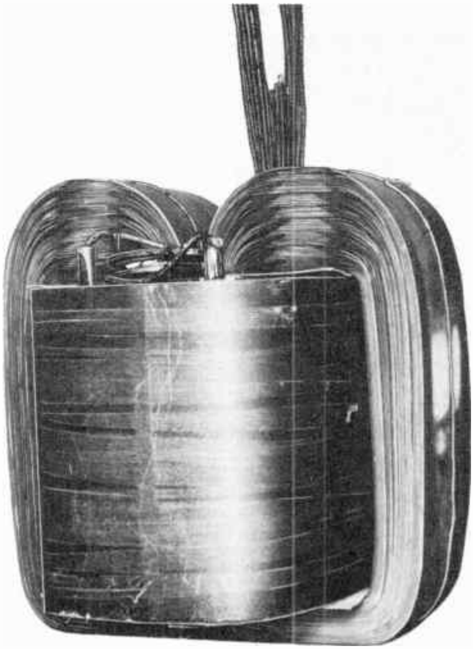


Fig. 11-12. A special type of a bent iron-core transformer. (Courtesy of Kuhlman Electric Company.)

This is done by using a minimum number of joints, an annealing process which removes mechanical strains introduced when the core is formed, and a unique clamping structure.

In the manufacture of the core, cold-rolled steel laminations are cut in progressively decreasing lengths by an automatic shear and are then stacked into a ring. A hydraulic press forms them into a rectangular shape. After they are securely banded in this shape, the core section is annealed in an electric furnace to permanently fix its shape and to remove strains. In the final assembly, two core sections are bolted together and supported in a special clamping structure designed to prevent strains on the laminations.

The steel used in the cores, called Corisil, was developed in 1937, by General Electric engineers for use in Spirakore* distribution transformers. It required the development of the low-strain, efficient magnetic circuit of the preformed core to take full advantage, in power transformers, of the highly directional (grain oriented) properties of this special steel.

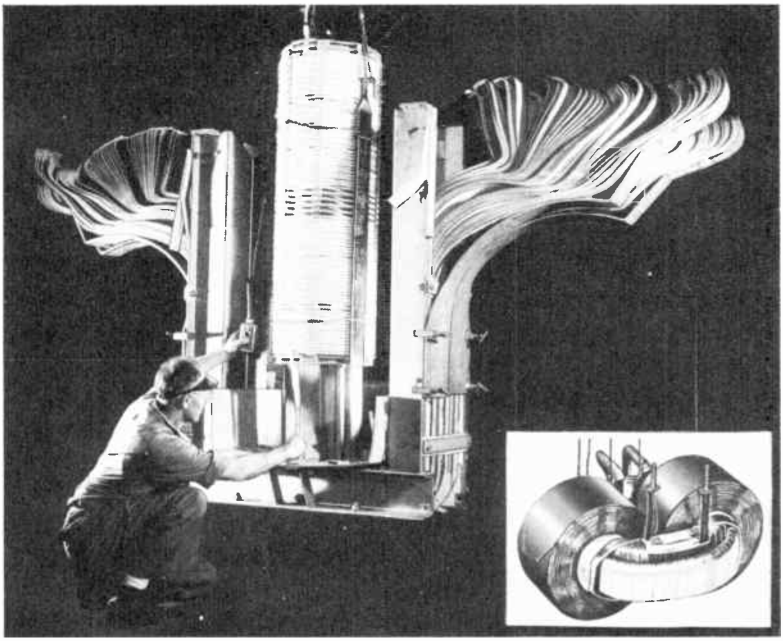


Fig. 11-13. A power transformer being assembled from a precut, preformed core of laminated steel strips. A small Spiracore transformer is shown in the insert.

General Electric Company is now building Spirakore power transformers in all single-phase ratings of 5,000 kva (5,000,000 volt amperes) and below. Many units of this design have been placed in service during the past several years.

The insert in one corner of Fig. 11-13 shows a small Spirakore transformer completely assembled. It has a two piece core which

---

* Registered Trade Mark, General Electric Company.

consists of two continuous strips of high quality electrical steel wound into compact spiral cores. The cores of this type transformer are wound around the primary and secondary windings by a special machine designed for this task.

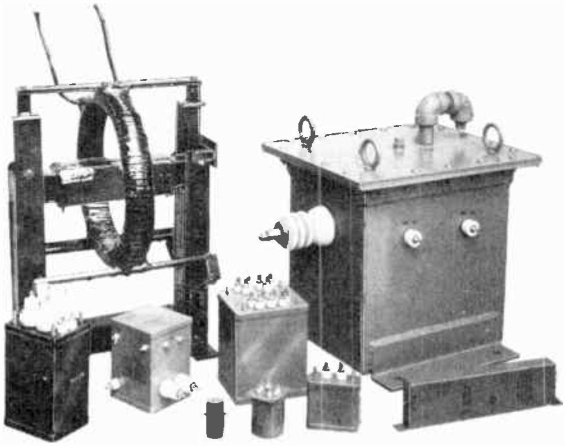


Fig. 11-14. Small high-voltage transformers. (Courtesy of Raytheon Mfg. Co.)

To illustrate and describe all types, styles, and designs of transformers manufactured would require several volumes; therefore, only a few of the general styles and designs will be shown in this book. Some special types of small high-voltage transformers are shown in Fig. 11-14.

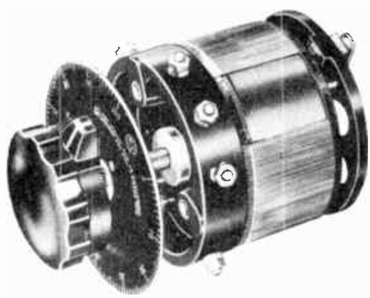


Fig. 11-15. A small variable transformer. (Courtesy of Superior Electric Company.)

There have been many styles and types of variable transformers manufactured, many of which permit voltage changes or variations by taps on the windings. One quite interesting and efficient type of variable transformer is shown in Fig. 11-15. This transformer is known as the "Powerstat" and is available in a variety of sizes and ratings.

Fig. 11-16 shows a distribution transformer mounted in its case. A section of the case has been cut away to show how the

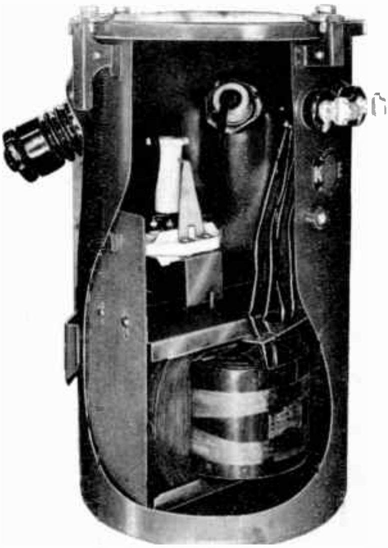


Fig. 11-16. A distribution transformer with a section of the case cut away. (Courtesy of Kuhlman Electric Company.)

transformer is assembled and mounted. Ordinarily, this type of transformer has the case partially filled with a special oil to insulate and cool the transformer. Fig. 11-17 shows the testing and tank (case) assembly room of a transformer manufacturer. Schematic drawings of both a "shell" and a "core" type transformer are shown in Fig. 11-18. The shell type is given in Fig. 11-18A and the core type is given in Fig. 11-18B.

A transformer in an electrical circuit is usually designated by the symbol shown in Fig. 11-19. The row of loops at the left represents one of the transformer windings, while the row

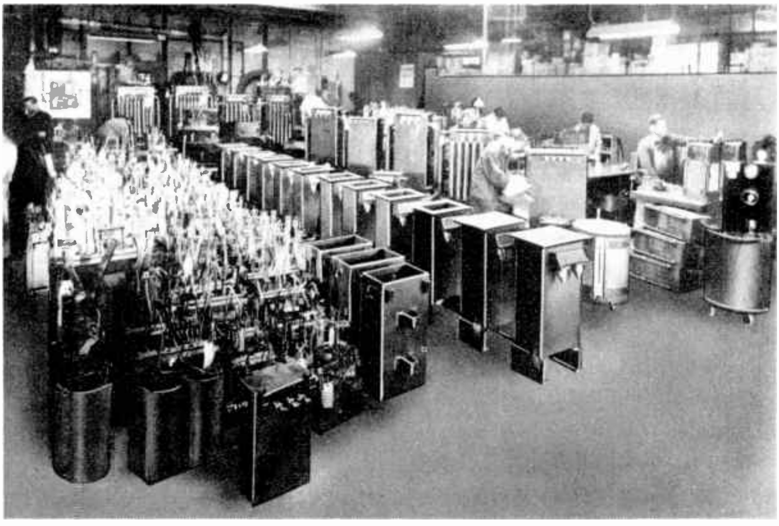


Fig. 11-17. Testing and tank (case) assembly room of a transformer manufacturer. (Courtesy of Eisler Engineering Company.)

of loops at the right represents the other winding. The parallel lines between the two windings represent the iron core.

The parallel lines used to represent the iron core requires additional explanation. Since all transformers used on commercial electrical power have steel cores, there has been a tendency for some draftsmen to omit the parallel lines on the theory that everybody knows they have to be there. This is bad practice because the parallel lines should be shown when the transformer is actually wound on an iron core.

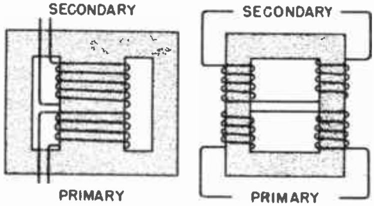


Fig. 11-18. Two common styles of transformer cores with windings.

In radio and television circuits, many air-core transformers are used. This fact emphasizes the necessity for including the parallel lines where the coils are actually wound on iron. Those special types of radio and television transformers which are not wound on iron, include "air core" transformers and those equipped with adjustable powdered-iron moulded slug cores. Each type has a different, specific symbol by which it is designated.

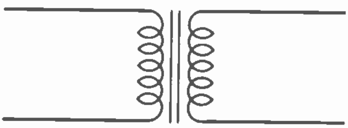


Fig. 11-19. Electrical symbol for a transformer.

In general it can be said that all transformers operating on commercial power frequencies are wound on iron (steel cores).

Fig. 11-20 shows how the windings are placed on the center leg of a shell-type transformer core. One of the coils of wire is wound on top of the other coil so they give the appearance of a single coil.

Usually the inner space inside the iron core-window, is filled more completely with the windings than is indicated in Fig. 11-20. In addition, the wire is carefully protected against "short-circuiting" to the iron core. The wire is wound onto a core form made of heavy, special insulating paper to prevent the sharp edges of the iron from cutting the insulation of the wire when the coil is assembled on the core.

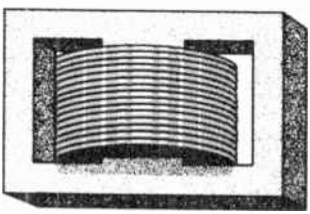


Fig. 11-20. How the coils are placed on the center leg of a shell-type transformer.

Usually, another heavy piece of insulating paper is wrapped around the outside of the coil to protect its insulation from abrasion. Still other protection is often added by enclosing the entire transformer within a metal shield to protect both the iron and the wire against damage.

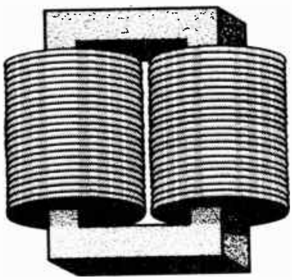


Fig. 11-21. How the coils are placed on a core-type transformer.

Transformers employing the shell-type core are usually the smaller and medium size models. These would include the bell-ringing transformers mentioned previously, the small transformers used for powering electric trains, and even the medium size transformers which "transform" the distribution voltages down to those voltages which are safe to use within our homes.

The very large high-voltage transformers used for power distribution are generally of the core-type construction. A core-type transformer with the coils in place is shown in Fig. 11-21.

The appearance of the coils in place on the iron core is frequently misleading to a person who does not know just how the coils are arranged. In studying the illustration, and even from looking at the transformer itself, a person might think that one of the coils is wound on one leg of the core while the other coil is wound on the other leg. Such a conclusion is not correct.

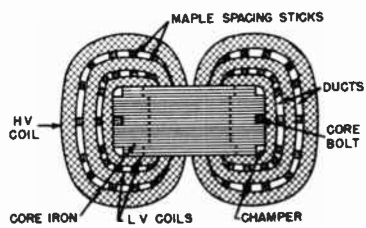


Fig. 11-22. Details of a core-type transformer winding.

Fig. 11-18B shows the manner of winding the coils on the iron core. We can see that a portion of both coils is wound on each leg of the iron core. One can understand better the manner in which the coils are actually wound for high voltage transformers by examining and studying the details of Fig. 11-22.

Two sets of coils can be seen in the drawing. One is the LV, low-voltage coil, and the other the HV, high-voltage coil. We shall explain a little later the difference between the two coils and how the change of voltage is brought about.

Fig. 11-23 is a photograph of a high voltage transformer winding.

It should be understood that this type of transformer is used only for power applications where very high voltages and large currents are handled. Since the current flowing through the wires of the coils will be large, it is understandable that the wires will tend to heat. To prevent the wires from becoming overheated, space is provided between the layers of the coils for the circulation of some cooling liquid such as insulating oil. After such transformers have been constructed, they are mounted inside a large tank, which is then filled with a special insulating oil. The oil tends to seal any break in the insulation

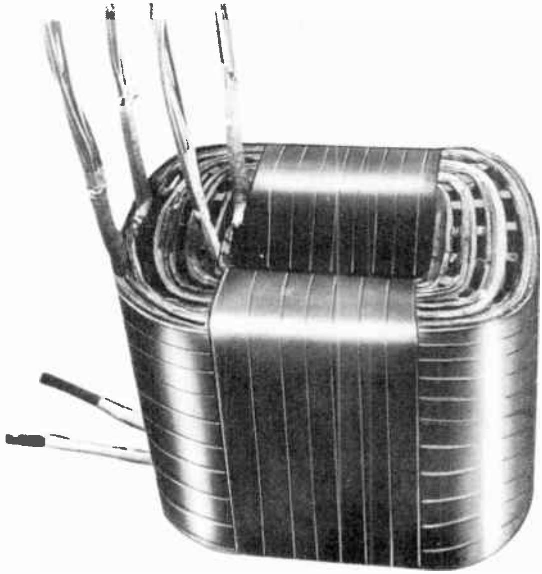


Fig. 11-23. A high-voltage transformer winding. (Courtesy of Eisler Engineering Company.)

between any of the coils and also provides cooling for them. Fig. 11-24 shows a large oil-insulated, self-cooled, outdoor-type of power transformer.

The layers of the coils are often separated with spacers of wood or plastic to provide ducts through which air can be blown or through which the cooling oil can pass. It should be kept in mind that we are still discussing the type of transformer which is used for high voltages and high power. Such methods of cooling are not necessary in small transformers. The smaller types can radiate most of the heat which is developed about as fast as it is produced.

It should be noted that the low-voltage coils are placed nearer the iron of the core and that the higher voltage coils or wind-

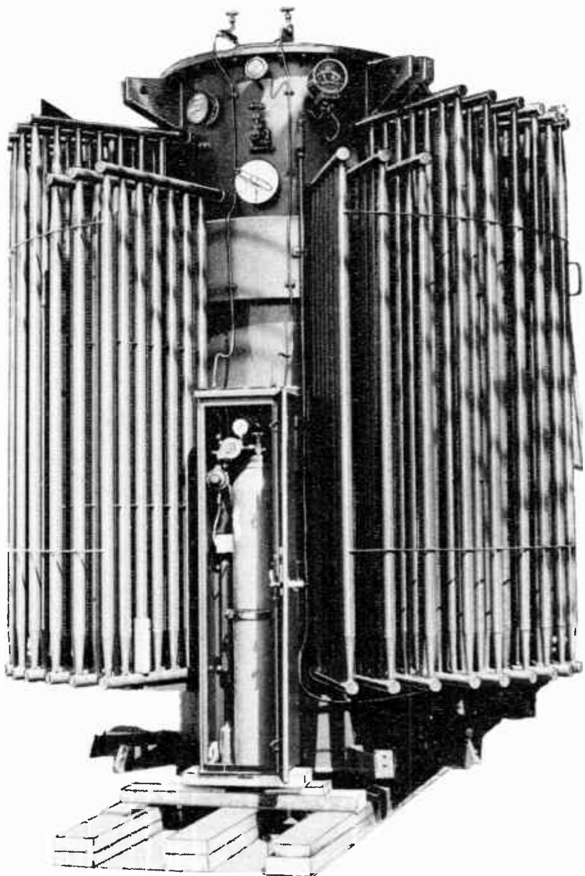


Fig. 11-24. Large oil insulated self-cooled outdoor type of power transformer. (Courtesy of Central Transformer Corp.)

ings are wound over (on top) of the low-voltage windings. This method of construction reduces the hazard of voltage breakdown of the high-voltage coils to the iron of the core.

PRINCIPLES ON WHICH A TRANSFORMER WORKS

Before going further with our discussion of how a transformer operates, one more principle of electricity should be studied, the principle of *electromagnetic induction.*

Basically, the principle of electromagnetic induction is very simple. If an electrical conductor is physically moved so it cuts across magnetic lines of force, a voltage will be generated within that conductor. More accurately stated when a conductor cuts magnetic lines of force, a voltage is *induced* within the conductor.

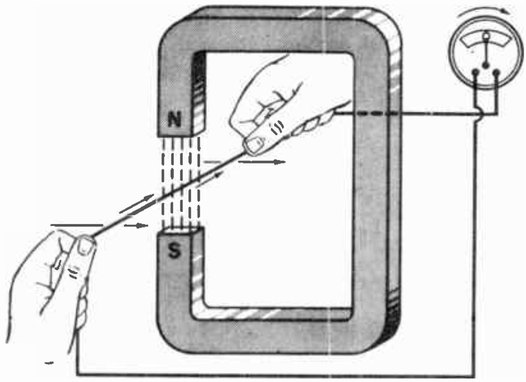


Fig. 11-25. Moving a conductor across magnetic lines of force at right angles to them induces a voltage in the conductor.

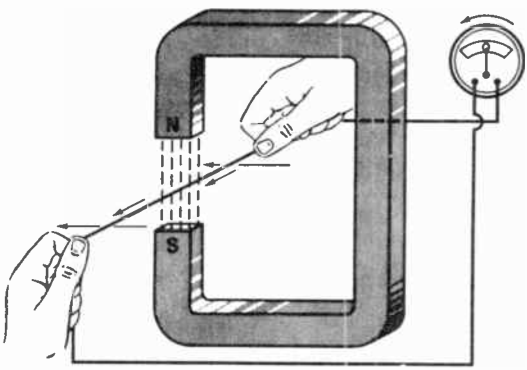


Fig. 11-26. Moving the conductor in the opposite direction induces a voltage with an opposite polarity.

Fig. 11-25 shows a demonstration of this principle. If the conductor is physically moved so it cuts across the magnetic lines of force between the two poles of the magnet, a voltage will be induced within that conductor. The presence of that voltage can be detected by connecting a meter into the circuit as shown in the illustration. If a center-scale meter is used, the principles of electromagnetic induction can be shown even more clearly.

If the conductor is moved from a position in front of the magnet toward the back so that the conductor will cut through the magnetic field, a voltage will be induced within the conductor. The conductor must cut across the lines of force to have a voltage induced within it. Movement parallel with the lines of force does not result in the conductor cutting flux lines; hence no voltage is induced in the conductor by such movement.

If the conductor is moved from the front of the magnet toward the back so that the conductor cuts the magnetic lines, a voltage will be induced, the polarity of which can be determined by observing the movement of the meter needle. If the direction of the movement of the wire is reversed, it moves from inside the magnet toward the outside and voltage will also be induced; but this voltage will be of a polarity opposite to that induced when the wire was being moved inwardly.

When the conductor moves so it cuts through the magnetic field in the direction of the arrows indicating conductor movement in Fig. 11-25, a voltage will be induced giving rise to a current flowing in the direction shown by the arrows paralleling the conductor. The meter needle will swing in the direction shown by the arrow above it.

If the conductor is moved through the magnetic field in the opposite direction, (as shown by the arrows in Fig. 11-26), the voltage induced within the conductor will be reversed. This gives rise to a current through the conductor in the direction of the arrows parallel to the conductor in Fig. 11-26. Due to the reversed polarity, the meter needle would also reverse its movement and swing to the left, as shown by the arrow above the meter in the figure.

What is it that causes this curious behavior? The truth is that probably no one knows. We have formulated some extremely plausible and equally useful theories to explain it; still nobody knows exactly why voltage is induced, any more than we know why water flows downhill. All of us know, of course, that water will flow downhill; and if we are asked why, would vaguely attempt to explain that it does so because of the pull of gravity. Since the nature of gravity is not known, no one knows exactly what causes the water to flow downhill.

We do not have to know exactly why the voltage is induced! The important thing is that we know the voltage will be induced, and we can put this knowledge to use. This fact is the secret behind all electrical generators. Conductors or groups of conductors are caused to rotate through magnetic fields. As the coils of wire cut through the magnetic fields, within their conductors a voltage is induced which is used to force current through external circuits and thus produce useful effects.

At the moment, though, we are interested in another aspect of this principle. In Figs. 11-25 and 11-26, we stressed the fact that the conductor was moved through the magnetic field. Actually, we can accomplish the same result by holding the conductor motionless and moving the magnetic field as shown in Fig. 11-27. If this is done, a voltage will be induced in the conductor as a result of the *relative* movement between the conductor and the magnetic field.

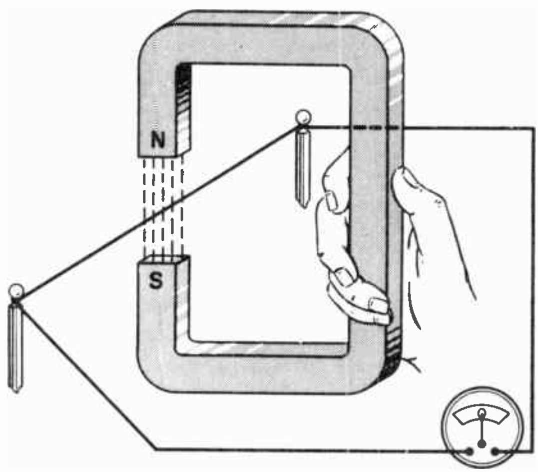


Fig. 11-27. Moving the magnet while the conductor is stationary will also induce a voltage within the conductor.

It is the *relative* movement that is important. It makes no difference which is moved, the conductor or the magnetic field, as long as one or the other is moved a voltage will be induced in the conductor.

The movement of the magnetic lines of force can be produced without resorting to physical movement of the magnet. In the preceding description, the magnetic field was produced by a permanent magnet. We have learned in previous chapters that magnetism can be produced in other ways, the best being to magnetize a piece of soft steel by passing a current of electricity through a coil of wire wound around the steel.

By the use of electromagnetism, we can cause magnetic lines of force to move through space during the interval in which the current is building up in the wire; and we shall have a second movement of the lines of force at the instant when the circuit is broken and the lines of force collapse. By making our core of *soft steel,* instead of *permanent-magnet steel,* and providing it with a winding, we obtain an electromagnet (Fig. 11-28) in which the magnetic field can be made, broken, and controlled. With such an electromagnetic arrangement, we can cause magnetic lines of force to move in first one and then the opposite direction. The lines of force move in one direction at the instant the current starts to flow and in the opposite direction at the instant the current ceases to flow.

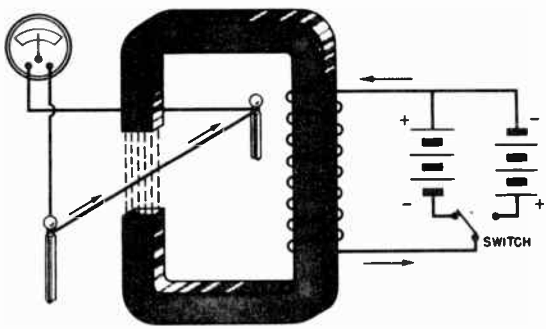


Fig. 11-28. During the instant a magnetic field is building up across the gap in the iron, the moving magnetic lines of force will induce a voltage in the conductor.

As shown in Fig. 11-28, a current will flow in the direction of the arrows through the coil wound on the soft-steel core of the magnet when the switch to the battery is closed. The important thing is that at the instant the current begins to flow it produces a magnetic field around the iron and a magnetic field will appear in the gap through which the conductor passes. As the magnetic field builds up across that gap, the lines of force in the field will cut across the conductor inducing a voltage in it.

Thus, at the instant the switch to the battery is closed, a voltage will be induced in the second conductor.

This induced voltage will exist only during that brief interval in which the magnetic field is building up. Once the magnetic field has built up to its full strength, the lines of force cease to move across the gap and no voltage will be induced in the second conductor.

It makes no difference how long the switch to the battery remains closed, nor how long the current flows through the coil, nor how long the core remains magnetized; a voltage will be induced in the second conductor *only* during the short interval in which the magnetic flux is building up. Once the total flux is established, the induced voltage in the second conductor disappears.

However, if the switch to the battery is opened, the circuit is broken and current ceases to flow through the coil. When that occurs, the magnetic field will collapse back into the core and through the coil. When the magnetic field collapses, the lines of force reverse themselves and pass back into the iron or steel core from whence they came. This collapse constitutes a second movement of the lines of magnetic force, opposite to the direction they took when building up.

This movement of the lines of force in the opposite direction again induces a voltage within the wire located in the air gap of the magnet. This new voltage is in the opposite direction to that which was induced at the instant the current originally built up.

Let us look at this matter from a little different viewpoint. We learned that a voltage would be induced within the second conductor at the instant current began flowing in the first conductor. We have also learned that a second voltage would be induced at the instant the current stopped flowing in the first conductor.

We can carry this experiment further by throwing the switch to connect the other battery. This is shown in Fig. 11-29. We see that the battery on the right will cause a current to flow in the coil on the steel core, but the current flows in the opposite direction to that from the first battery. This is not surprising since the polarities of the two batteries are reversed.

Note now that the voltage induced in the second conductor is also reversed. It becomes evident that the direction of the current in the second conductor can be controlled by controlling the direction of current in the coil.

The flow of current, as a result of the induced voltage in the second conductor, will last only during the short instant of time it takes the current to build up to full strength in the coil. After that, the voltage induced in the second conductor will die out and the current will cease to flow there. A voltage will again be induced in the second conductor at the instant the circuit is broken to the second battery.

With these simple experiments, we have gone a long way toward explaining the strange action of a transformer. When current builds up in the first conductor, the coil connected to the batteries, the magnetic field will build up in the core. As that field builds up, it will cut across the second conductor, inducing a voltage in it. When the circuit of the first conductor is broken and current ceases to flow, the core's magnetic field will collapse. With its collapsing, the field will again cut across the second conductor and induce a voltage within it, this time in the opposite direction.

Note that the voltage is induced in the second conductor *only during the interval when the current in the coil is changing.* That *changing* current is important because it is the *change* in current which causes the magnetic lines of force to move. Moving (changing) lines of force are required to induce a voltage in the second conductor.

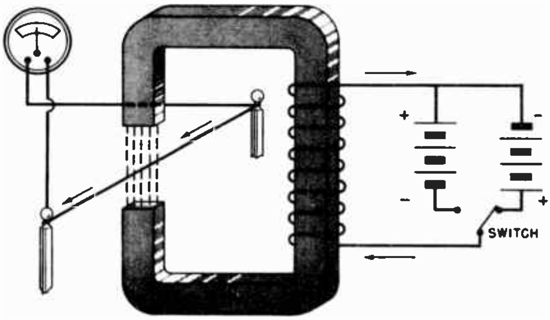


Fig. 11-29. If the current through the coil is reversed, the voltage induced in the wire in the gap will be reversed.

This statement can be generalized to say: Anything that causes the current in the first conductor (coil) to change, either to increase or decrease, will induce a voltage in the second conductor.

Now, instead of having a gap in the core as shown in Fig. 11-28 and 11-29, let us wind a second coil on the iron core as shown in Fig. 11-30. In place of having the first conductor connected first to one battery and then the other, we have it connected to a source of alternating current. Ordinary electric current which flows through the circuits of most of our homes is alternating current which reverses its direction of flow 120 times per second, thus going through a complete cycle 60 times each second. This is the well-known 60-cycle alternating current which is mentioned so often in connection with the electrical appliances we buy in the stores.

Suppose we have the circuit set up as in Fig. 11-30. Careful inspection will show that there is very little difference between it and its operation and those which have just preceded it.

The reason for having two batteries in Figs. 11-28 and 11-29 was to provide a source of voltage which could be easily reversed. Alternating current provides a source of voltage which is constantly reversing itself many times a second, far faster than could possibly be caused by a double-throw switch and batteries.

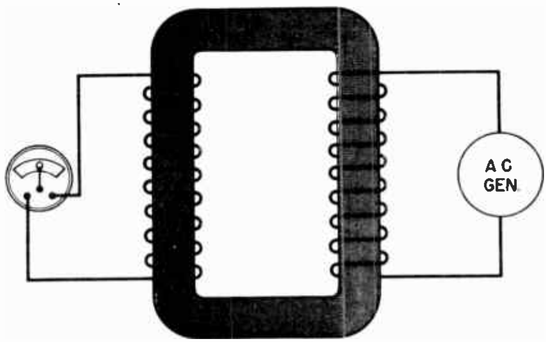


Fig. 11-30. By connecting the first coil to a source of AC voltage, we can cause the magnetic lines of force in the iron to keep continually moving, and continually inducing a voltage in the second coil.

Thus the current is constantly rising and falling in the coil connected to the AC power source. In brief, it is constantly *changing!*

Since the current in the coil is constantly changing, the magnetic field built up in the core is constantly changing and the magnetic lines of force in that field are constantly *moving.*

The second coil of wire is not actually located in an air gap as in the previous illustrations, but it is wound right onto the iron core in which the magnetic flux is constantly changing. In this position the constantly changing magnetic flux passing through (cutting through) the coil will induce within it a voltage.

Since the current in the first coil, called the "primary" coil in transformers, is constantly changing, it follows that the magnetic flux in the core is also constantly changing. This follows, because, as we have shown the magnetic flux and its polarity are dependent upon the current flowing in the primary coil. As the direction of the current in the primary coil changes, the direction of the magnetic flux also changes.

It should be remembered that the polarity of the voltage induced in the second coil, called the "secondary" in a transformer, is dependent upon the direction in which the magnetic field is moving. The magnetic field periodically builds up to a maximum, and falls off to zero, reverses and builds up to maximum in the opposite direction, and again falls to zero, after which it repeats; the voltage in the secondary coil will build up, die out, and reverse just as the voltage in the primary coil does, except in the opposite direction.

The voltage produced in the secondary coil is induced there as a direct result of the magnetism created by the current that flows in the primary coil. That is the principle on which a transformer works. There is no electrical connection between the primary and the secondary winding. The transfer of energy from the primary to the secondary is accomplished solely by a changing magnetic flux.

DIRECTION OF THE INDUCED VOLTAGE

The polarity of the voltage induced in the secondary coil of a transformer is such that it will force current to flow in the opposite direction to that of the current in the primary. This is another fundamental principle of transformer operation. This action of the current is shown in Fig. 11-31.

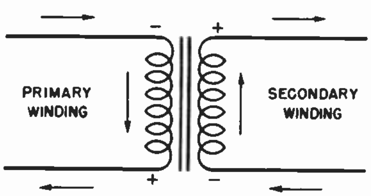


Fig. 11-31. Current in the secondary winding is always in the direction opposite that in the primary.

This action of the current flowing through the secondary winding in a direction opposite to that of the current in the primary is taken advantage of in a number of ways in electrical power work. The voltage across the secondary at any instant has a polarity that is opposite to the voltage across the primary at the same instant.

STRENGTH OF THE INDUCED VOLTAGES

We have learned from a previous chapter that the strength of the magnetism produced in any coil will be directly proportional to its ampere turns. One ampere of current will produce so many lines of force in one turn of a coil, two amperes will produce twice as many lines, three amperes will produce three times as many, etc. From this it follows that the amount of magnetism produced in any coil will be directly proportional to its ampere turns.

By reasoning along somewhat similar lines, you can see that the voltage induced in the secondary coil is going to depend upon the magnetism generated by the ampere turns of the primary coil and upon the number of turns on the secondary winding. The important factor here is the number of turns on the secondary winding.

With a given number of ampere turns on the primary winding, just so many volts will be induced in one turn of the secondary winding; twice that number in two turns; three times that number in three turns, etc. This results from the fact that all the turns of the secondary are in series with each other. We learned, when working with dry cells, that when several voltages are connected in series, the total voltage equals the sum of all the individual voltages.

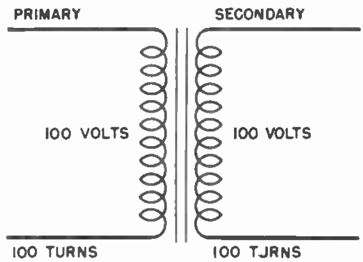


Fig. 11-32. If the secondary has the same number of turns as the primary, it will also have the same voltage.

It can be shown simply, without recourse to theoretical considerations, that a transformer having the same number of turns on the primary and secondary windings will have a voltage induced in the secondary equal to the voltage applied across the primary. This is indicated in Fig. 11-32.

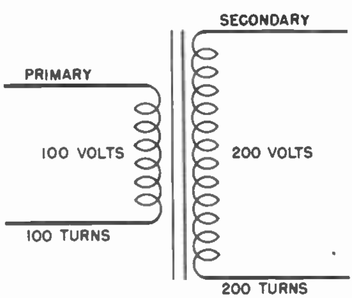


Fig. 11-33. If the secondary has twice as many turns as the primary, the secondary voltage will be twice as great as the primary voltage.

In Fig. 11-32 we have a transformer which has 100 turns on the primary and 100 turns on the secondary. When 100 volts are impressed across the primary windings of the transformer, 100 volts will appear across the terminals of the secondary.

We could carry this a step further. If only 75 volts are placed across the primary winding, only 75 volts will appear across the secondary of the transformer. It should be understood very clearly that when we speak of 75 volts and 100 volts we are speaking of 75 volts and 100 volts of alternating current.

If instead of having 100 turns on the transformer shown in Fig. 11-32 we have 200 turns as shown in Fig. 11-33, there would be an increase in the voltage across the secondary winding of the transformer. This is indicated in Fig. 11-13. We can see that by doubling the number of secondary turns, the voltage is doubled.

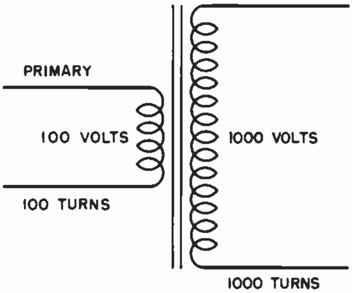


Fig. 11-34. If there are ten times as many turns on the secondary as on the primary, the voltage across the secondary will be ten times that across the primary.

We can carry this line of reasoning even further. In Fig. 11-34 we have 1000 turns on the secondary of the transformer but only 100 turns on the primary. If we apply 100 volts to the primary of this transformer, we shall obtain 1000 volts across the secondary winding.

By applying this same principle, it is possible to obtain as much as 10,000 to 15,000 volts from the ignition coil (open-core transformer) in an automobile from no more than 6 volts applied to the primary. That is accomplished by winding the secondary of the coil with thousands of turns of fine wire. The 6-volt direct current power from the storage battery of the automobile is interrupted by the pair of breaker points located in the distributor of the ignition system; and this interrupted current is passed through the ignition coil's primary winding, thereby inducing a high voltage in the secondary of the ignition coil.

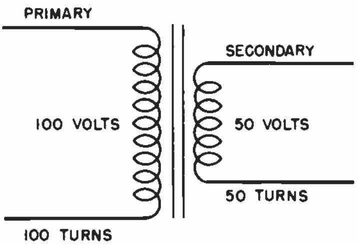


Fig. 11-35. If there are only one-half as many turns on the secondary as on the primary, there will be only one-half as much voltage.

We can obtain lower voltages than those applied to the primary of a transformer by using fewer turns on the secondary than on the primary winding. Fig. 11-35 shows how we can transform 100 volts on the primary winding to 50 volts on the secondary winding by using 50 turns on the secondary winding and 100 turns on the primary.

This stepping-down of the voltage can be carried much further, as we intimated in the discussion of bell-ringing transformers. The bell-ringing transformer steps-down the 120-volt house potential to about 6 to 14 volts for use in the bell circuits. That could be done as shown in Fig. 11-36. There we see 240 turns on the 120 volt primary winding. There are only 16 turns on the secondary winding, far less than on the primary. This results in a large reduction, giving 8 volts for the secondary. Some bell-ringing transformers have a few more secondary turns and will produce a higher secondary voltage of 10 to 14 volts.

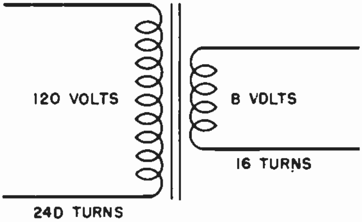


Fig. 11-36. How the 8 volts for a door bell are obtained from the 120-volt house-circuit voltage by using a transformer.

By this time, you are probably wondering how one figures the voltage for the secondary of a transformer when a given voltage is applied to the primary. The procedure is simple. There is a definite relationship between the voltages and the number of turns on the two windings. It works out that the voltage of the secondary winding will be equal to the voltage of the primary winding multiplied by the ratio of the secondary turns to the primary turns. Let us see just how this rule is applied. With 100 turns on the primary and 100 turns on the secondary, the voltages were the same on the two windings. Applying the rule that the voltage on the secondary is equal to the voltage of the primary multiplied by the ratio of secondary to primary turns, we must first determine the ratio of turns. In this case the ratio is 1:1, so we multiply the primary voltage (in this case 100 volts) by 1, and of course the result is 100 volts, which is what appeared at the secondary in Fig. 11-32.

In the case of Fig. 11-33, we had 100 turns on the primary and 200 turns on the secondary. This meant a ratio of 2:1 or twice as many turns on the secondary as the primary. The voltage on the primary was 100 volts. Multiplying the 100 volts by 2 gives the 200 volts shown in that illustration.

In Fig. 11-34 the ratio was 10:1, which means we would have to multiply the primary voltage by 10. Since the primary voltage is 100 volts and the ratio of turns is 10, we merely multiply the 100 volts by 10 and come up with the 1000 volts as shown in that illustration.

The same rule applies when the primary winding has more turns than the secondary. In Fig. 11-36 there are 240 turns on the primary and 16 turns on the secondary. This gives us a ratio of 16:240 or 1:15. Since the primary voltage is 120 volts, we proceed in exactly the same manner as before, multiplying the 120 volts by 1/15, which gives 8 volts as shown in the illustration.

There is a single basic formula covering all this. It is expressed as:

$$\frac{\text{Secondary volts}}{\text{Primary volts}} = \frac{\text{Secondary turns}}{\text{Primary turns}} \text{ or } \frac{E_s}{E_p} = \frac{T_s}{T_p}$$

If any three of the terms in this equation are known, the fourth (unknown) can easily be determined.

STRENGTH OF THE COMPARATIVE CURRENTS

Since it is so easy to increase or decrease voltage by merely altering the turns-ratio of a transformer, one might assume that power could be stepped up or down with equal ease. Such an assumption would be highly erroneous, and against all the laws of nature and physics, since it violates the law of conservation of energy.*

Merely stepping up the voltage from one level to another doesn't step up the power. To step up power, it would be necessary to maintain the current at the same level or cause it to increase in the same ratio as the voltage.

Actually, no such thing occurs! Instead, as the voltage is stepped up from one level to another, the current will decrease from one level to another. To put this in other words: As the voltage is increased by some ratio, the current is automatically reduced by the same ratio. The power transferred by the transformer is neither increased nor decreased, except for a slight decrease due to transformer losses.

Fig. 11-37 is similar to Fig. 11-33. In both circuits the transformer has a step-up ratio of 1:2, increasing the voltage from 100 volts at the primary to 200 volts at the secondary. In Fig. 11-37 the secondary is connected across a resistance load. Such

---

* Actually there is a loss in any power conversion whether it be mechanical or electrical. It is impossible to get as much power out of a transformer as is put into it, because no device can be made to operate at 100% efficiency. There is always some loss. However, if we assume a transformer to be operating at an efficiency of 100%, the amount of transformed energy from the transformer is neither increased or decreased. Only the relative ratios of the voltage and current (amperage) are changed.

a load might be one of many things. In any event, it is a device which requires a current of 5 amperes when a potential of 200 volts is impressed across it.

A load which requires 5 amperes of current at 200 volts is using power at the rate of 1000 watts. This is determined by applying Watt's law: "Power is always equal to the product of the voltage and the current."

It requires only 100 volts across the primary to produce 200 volts in the secondary. Note also, that while we have only 5 amperes of secondary current, there are 10 amperes of current in the primary circuit. To put this in other words: Although the transformer has stepped up the voltage from 100 volts on the primary to 200 volts on the secondary, it has automatically stepped down the current from 10 amperes in the primary to 5 amperes in the secondary.

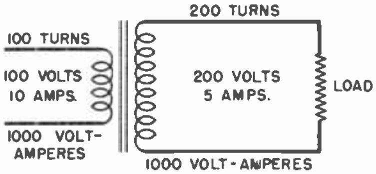


Fig. 11-37. As the transformer steps up the voltage, it automatically steps down the current.

Now, take a look at the power in the two circuits. The load is using 1000 watts of power (5 amperes at 200 volts), and the primary is delivering 1000 watts of power (10 amperes at 100 volts). The voltages and the currents have changed, but there has been no change in the amount of power. The power has been neither increased nor decreased. (This assumes a perfect, no-loss transformer.)

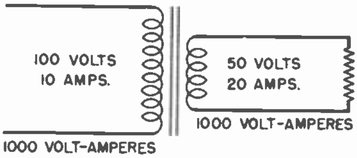


Fig. 11-38. As the transformer steps down the voltage, the current in the secondary increases.

This illustration can be carried further so we can see what occurs when the voltage is stepped down by the transformer from a higher voltage on the primary side to a lower voltage on the secondary side. This is illustrated in Fig. 11-38. One hundred volts are stepped down to 50 volts, and the secondary is feeding a resistance load. As before we have assumed an unnamed resistive load which might be any one of a number of devices.

At any rate, our load requires 20 amperes of current when 50 volts of pressure are impressed across it. This means the load is using 1000 watts of power, the product of 50 volts and 20 amperes being 1000 watts or volt-amperes as shown in the illustration. The term *volt-amperes* is often used in connection with transformer ratings instead of single term watts. There is a difference between the terms, but that is something we shall discuss later. At this moment, we can think of watts and volt-amperes as being the same thing, which they are in direct current circuits.

By studying the diagram in Fig. 11-38, we see that when the load in the secondary is taking 20 amperes, the current in the primary circuit is only 10 amperes; but the voltage in the primary is 100 volts. Thus we find the power delivered to the primary is exactly the same as the secondary is delivering to the load—1000 watts. The transformer has transformed both the current and the voltage but has not altered the power.

The current in the secondary always decreases by the same ratio that the voltage increases. If the voltage is doubled, the current is halved. If the voltage is quadrupled, the current is reduced to one-fourth. If the voltage is raised to 10 times by the transformer, the current in the secondary will be reduced to one-tenth the value of the current in the primary.

This means that if the voltage of the primary is multiplied by the secondary to primary turns ratio to find the voltage in the secondary, you do just the reverse to find the current in the secondary. To find the current in the secondary, you divide the current in the primary by the secondary to primary turns ratio.

We have already mentioned the fact that, although the windings of a transformer consist of two coils of wire, both of which are good conductors, neither makes electrical contact with the other in any way. Its method of transmitting or transferring electrical energy is indirect. It first converts the electrical energy into magnetic energy; then it reconverts it into electrical energy. Due to this double conversion process, the transformer is enabled to perform the duties which have made it invaluable in the field of electrical science.

HOW POWER IS DISTRIBUTED

Electrical power may be generated at almost any voltage desired. Public power companies generate power at various voltages, but a very common one is shown in Fig. 11-4. There we see the generator (also called an alternator when the power generated is in the form of alternating current) producing power at some given voltage. Many such alternators generate power at 2,300 volts. Other common voltages are 2,400, 4,150 and 4,160 volts.

Power at these voltages can be sent out directly over the distribution system of the power company. The distribution system consists of networks of wires strung on the power poles located along the back alleys of our cities and along the roads and highways in the rural areas. The voltage used on the distribution system is called the "distribution voltage." In the drawing that shows such a system, in Fig. 11-4, we can see the distribution system potential is 2,300 volts.

Such voltage is far too high for ordinary use except on a special high-voltage motor, such as the 2,300-volt motor shown in the lower part of the drawing.

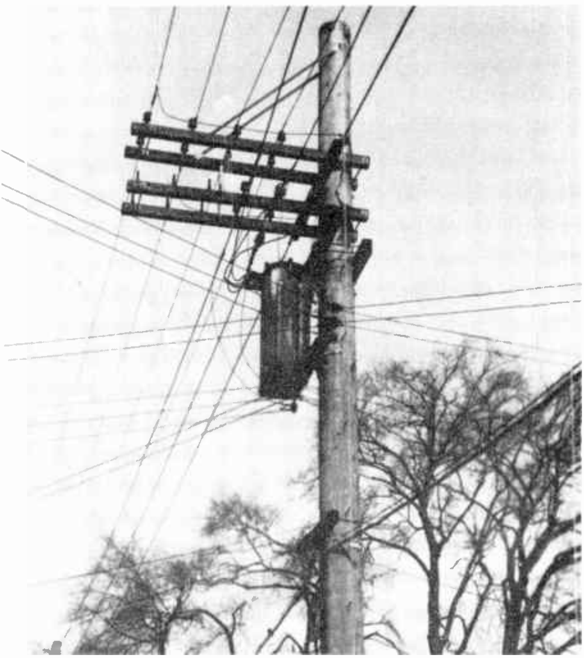


Fig. 11-39. A distribution transformer mounted on a pole.

Before the power of a high-potential distribution system can be used, it is necessary to step the voltage down to a lower one. This is done by a distribution transformer. In the drawing in Fig. 11-4, we see a distribution transformer being used to drop the 2,300 volts to 230 volts.

Distribution transformers are usually mounted on one of the power poles near the home or the business place of the customer.

Fig. 11-39 shows a distribution transformer mounted on a pole. The high-voltage distribution system would consist of the wires on the upper cross-arm of the pole. Wires would lead from that system to the primary of the transformer. Other wires would carry the low secondary voltage power from the transformer to the lines leading into the customers' homes. In the photograph you can see the wires branching out from the power pole to the customers' homes.

Sometimes the low-voltage lines will be strung from the pole carrying the transformer to other poles and hence to the nearby homes. Such wires generally are strung on the lower cross-arms of the power pole. Usually the wires carrying the low-voltage current will be smaller than those carrying the high-voltage current, but this will not always be true. The size of the wire in any given case will be controlled by the current (amperes) that the wire must carry.

Sometimes the generators are located several hundred miles from the distribution system. In that case the power generated by the alternators is stepped up to a much higher voltage. The transformers used for that purpose are very large and are usually located close to the power generating station. You have probably noticed the huge, tank-like housings near a generator station. They contain the step-up transformers that step up the voltage from the alternators to the value required for long distance transmission. Some of the transformers are almost as large as a small house.

Huge transformers are used to step up the 2,300 volts generated by alternators to much higher voltages used on the transmission system. The transmission system may operate at voltages from 11,500 volts up to about 500,000 volts. Actually, 500,000 volts are still high for nationwide use at the time of this writing, but experimental work has progressed to the point where engineers have found that even this great voltage can be transmitted over power lines. Voltages ranging up to 300,000 volts are now in common use.

It should be perfectly clear to you, that no consumer could use electrical power at the voltages used in transmission systems. Before that power can be used, the power company must again step the voltage down for use by the distribution systems. This is done at installations which are known as electrical "substations." They look like the transformer banks where the power from the alternators is stepped up to high voltages; but, their purpose is to step down the high voltages.

Transformers, switching gear, and high-voltage wiring are all located within a completely fenced-in area in much the same fashion as in the station where the voltage is stepped up. The main difference between a "sub-station" and the power-generating transformer station is that the sub-station is remote from any power-generating stations. Sometimes they are nearly as large as those used to step up the voltage. Fig. 11-40 shows a typical substation having several large transformers. A fence surrounds the entire installation and warning signs are prominently displayed to prevent children and other persons from wandering near the transformers.

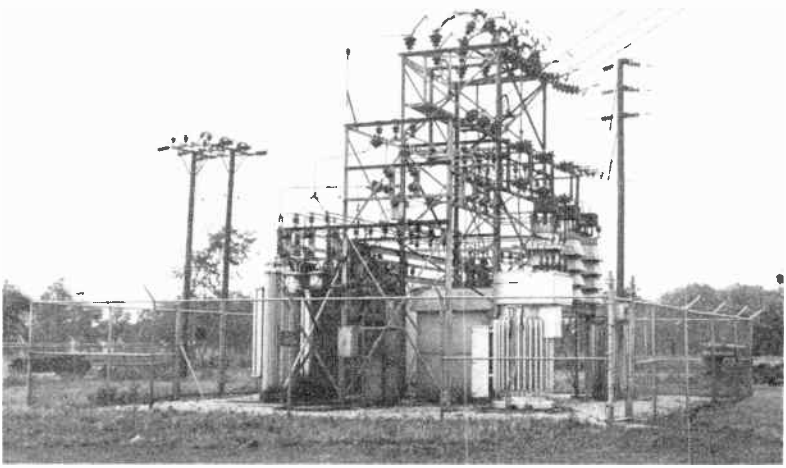


Fig. 11-40. A typical substation where several power transformers are used. (Courtesy of Kuhlman Electric Company.)

In the rural areas, on the farms and in farming communities, the Rural Electrification Administration, better known as the REA, has brought electricity to the farmers. Much of the old-time drudgery, which for centuries had been accepted as a necessary part of farm life, has now been eased by the use of electricity.

Transformers have played a tremendous part in bringing electricity to the farmers. Local REA co-operatives purchase electrical power from public utility companies or from some government generating plant. Often the generating plant is a huge hydro-electric plant hundreds of miles away.

The electrical power produced at the generating plant, is first stepped up by transformers to an extremely high voltage which may range from 65,000 to 300,000 volts and is transmitted at that voltage to the distant locality where it is needed. There it is fed into the sub-station owned by the REA co-operative company and stepped down to the voltages used on the distribution system of the co-operative. The REA co-operatives employ voltages of 2,400 and 4,160 volts on most of their distribution systems. They could use other voltages and sometimes do. Voltages of 2,400 and 4,160 are generally employed because they are "standard" voltages. Transformers and other equipment can be obtained readily for these voltages as stock manufactured items.

These lines carrying power to the rural-electric co-operatives are the familiar and well-known "high-lines" which now criss-cross so much of the farming area of our country.

When a farmer or other rural user wants electric service, he arranges for the co-operative to install a transformer on the power pole to step-down the electrical power to a voltage he can use. The transformer which is installed will probably look like the one shown in Fig. 11-39. Many companies build transformers, and for that reason they will vary somewhat in appearance. The purpose of the transformer is the same in all cases: it is to step-down the high voltage to a low voltage which can be used on the farm.

Many farms have power brought in from the pole transformer by three wires. This is the well-known "Edison three-wire" system of power distribution. This system makes two voltages available to the user. The exact voltage will vary slightly from one community to another, but it will average 120 volts for lighting and similar purposes and 240 volts for heavier motors, such as those for well pumps, and electric ranges.

HOW TRANSFORMERS ARE CONNECTED

It is possible, just as with any other sources of voltage to connect two or more transformers in series or in parallel. The farmer or other user of electricity does not care what distribution voltage the power company or the co-operative uses. Often, since the matter does not concern him, he never knows. He is interested in just one voltage, the voltage that is supplied to him at his farm, his home, or place of business. He must know what that voltage is in order to purchase electrical equipment that will operate properly on the electrical power available.

If he knows the value of the voltage at the secondary of the transformer, he can rightly regard that secondary voltage as his source of power. He does not care how the power company gets the power to the transformer, as long as it provides power at a voltage he can use.

It is fortunate that transformers can be connected in parallel because such connection gives an added flexibility that is advantageous. Take for illustration the transformer shown in Fig. 11-39. It is being used to supply power to several users, or customers. If the combined demand of those customers increased to the point where it exceeded the transformer's capacity, the power company could add another transformer in parallel with the first and then use both of them to supply the increased power requirements.

Fig. 11-41 outlines a typical arrangement which shows how six customers can obtain power from a single distribution system. Transformer X is supplying power to three customers in much

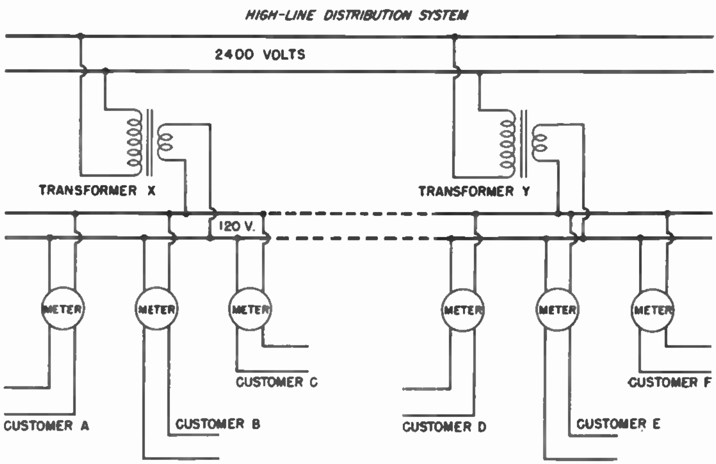


Fig. 11-41. How two transformers can be connected to supply power to a group of customers.

the same manner as the transformer shown in Fig. 11-39. The distribution voltage is 2,400 volts, and each customer is furnished power at 120 volts.

In Fig. 11-41, another transformer, designated as transformer Y, is shown supplying power to three additional customers. The first group of customers, A, B, and C, might be only a short distance down the highway from customers D, E and F; they might be even in the same block in the city.

As often happens, a transformer is installed to serve only the existing customers; then proves inadequate when other houses are built and additional customers require service. This could be the situation diagrammed in Fig. 11-41.

The figure shows the arrangement of the wires for each of the customers and the positioning of the wires for the distribution system. If the customers A, B, and C require more power than the transformer X could supply while transformer Y wasn't loaded to its rated capacity by the customers at D, E, and F, the power company could solve the problem easily by paralleling the secondaries of both transformers (as shown by the dotted

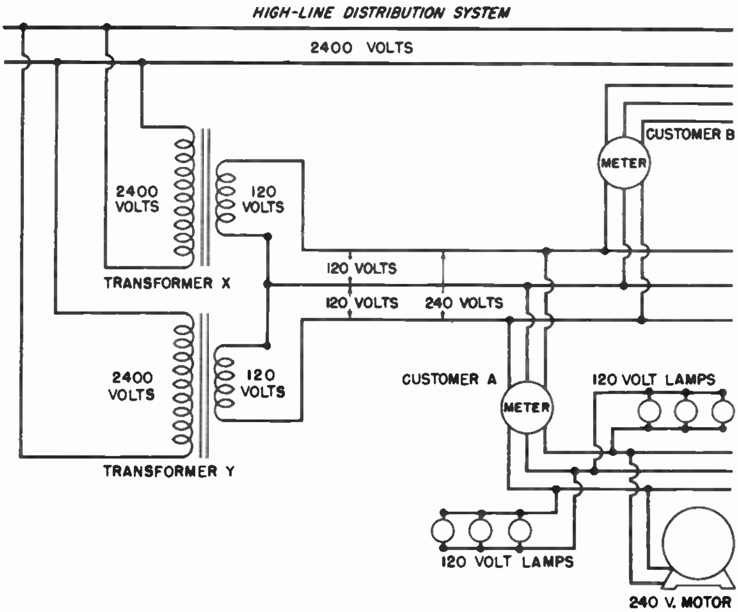


Fig. 11-42. How two transformers can be connected to a distribution system to supply power for a three-wire Edison system.

lines), thus putting all the customers on one line. The company would thus be spared the expense of removing the transformer at X and installing a larger one. There are many variations of this, and similar conditions.

Suppose that only transformer X was used to supply all customers originally. When the increasing load on it become too great, the company might decide it was impractical to remove that transformer and substitute a large one, or they might not have a larger transformer available. This latter condition has occurred many times in recent years due to the shortage of copper and steel. The company could still solve the problem by adding a second small transformer, as at Y, and use it to supplement the original one, X. The connections that would be required between the two would be the same as shown in Fig. 11-41 by the dotted lines. This connection would then become a permanent part of the system.

Instead of connecting transformers X and Y as shown in Fig. 11-41, one could connect them to deliver two different voltages to the customers. Many customers, especially on the farms and in places of business, need more than one voltage. In addition to the normal 120 volts required for incandescent lamps, refrigerators, and household appliances a higher voltage, such as 240 volts, is necessary to drive larger motors and to operate electric ranges.

One method of connecting two transformers to furnish two different voltages is shown in Fig. 11-42. Here we see the two primaries connected in parallel across the high-line voltage in the same manner as is shown in Fig. 11-41. The diagrams are not exactly alike in physical layout but electrically, the two are connected in the same manner.

Instead of the secondaries being connected in parallel as in Fig. 11-41, they are now connected in series with each other. The voltage at any instant is twice as great across the series-connected secondaries as it would be across only one. Since each secondary will have a nominal potential of approximately 120 volts across it, the two secondaries in series would have 240 volts across them.

This method of connection provides us with two voltages which are often needed. A third wire, connected to the junction of the two secondaries, is called the "common" or "neutral" wire. We can tap off between the "neutral" wire and either of the other two wires. This provides the ordinary 120 volts needed for so many electrical appliances around the home or business. Across the two outside wires, the ones connected to the opposite ends of the secondary windings, we can obtain the 240 volts necessary for the heavier types of motors and other heavy-duty equipment. Electric ranges, because of their heavy power requirements, are always connected across the 240 volts with a third wire connected to the neutral. Most ranges have convenience outlets on the top of the stove for lamps, mixers, and other appliances which are connected across only 120 volts of the power supplied to the range.

In our studies of transformers, we have treated them as though there were only one winding on the primary and one on the secondary. This is exactly how many transformers are built; however, not all transformers are built that way. As electrical engineers gained experience in the construction and use of transformers, they found that greatly improved flexibility resulted when both the primary and the secondary had two windings instead of only one.

Let us see how such divided windings can be put to good use. In Fig. 11-43 we see a transformer which has two windings on the primary, either of which can be connected directly across 1,200 volts of electrical power. The secondary winding is also divided into two parts, either of which will deliver 120 volts when either of the primary windings is connected across 1,200 volts.

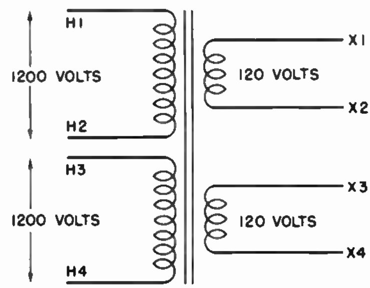


Fig. 11-43. A transformer with two high-voltage and two low-voltage windings.

This transformer can be used in many ways. It can be used with only one of the primary windings connected to a source of power, and only one of the secondary windings connected to a load. For reasons of economy it would not likely be used that way, except in an emergency. The connections for that use are shown in Fig. 11-44.

The two primary windings could be connected in parallel to the source of power, and the two secondaries could be connected in parallel to the load. Such a connection is shown in Fig. 11-45. Connecting the windings as shown in Fig. 11-45 would permit the transformer to operate on the same voltages and deliver the same voltage, as in Fig. 11-44, but with twice the load capacity. Because twice as many windings are used in Fig. 11-45, it is possible for the transformer to handle twice as much current and thus twice as much power as it can in Fig. 11-44.

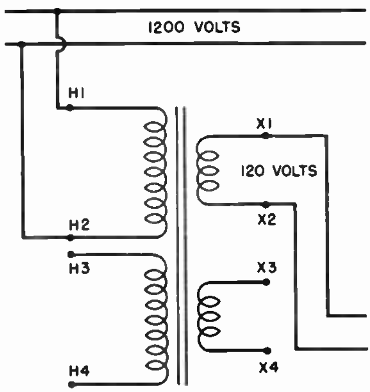


Fig. 11-44. How a transformer would be connected when only one high-voltage and one low-voltage winding is in use. This is not a normal method of using the transformer.

There are still other ways in which the transformer with two windings in both the primary and secondary can be used. Fig. 11-46 shows how the primary windings could be reconnected so the transformer could be connected to a 2,400-volt distribution line. This is the manner in which the primary windings are usually connected. When they are connected in series in this manner, the full voltage of the distribution system is divided between the two primary windings. One-half the high voltage is across one winding and the other half across the other winding. Note, however, the secondary windings are still connected as in Fig. 11-45. They are connected in parallel with each other to supply 120 volts to the load.

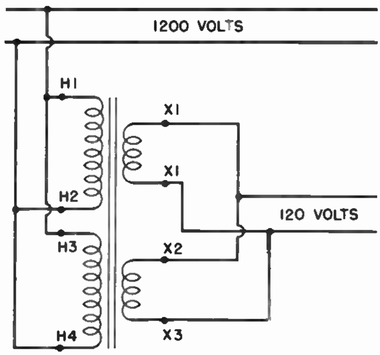


Fig. 11-45. Both primary windings and both secondary windings connected in parallel.

The secondary windings could be reconnected in such a manner that the single transformer could deliver the same two voltages that the two transformers deliver in Fig. 11-41. In fact, this is the manner in which such transformers are most frequently used.

Fig. 11-47 shows how the secondary windings would be connected in series with each other and a tap taken from their midpoint, the connection between them. The line from the junction of the secondaries would be the "neutral" wire just as in Fig. 11-42.

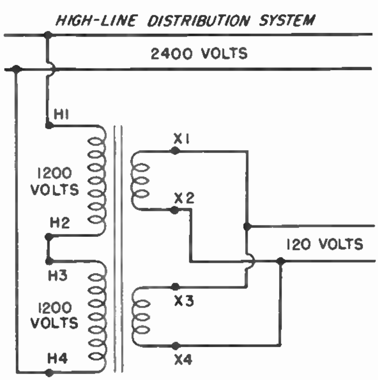


Fig. 11-46. The high-voltage windings are connected in series to serve as the primary for connection to 2400 volts. The low-voltage secondary windings are connected in parallel.

The neutral wire in such wiring systems is nearly always "grounded." This means it is actually connected, both physically and electrically, to the ground of the earth. For this reason, it is often called the "ground wire."

If the wiring is installed in accordance with the National Electrical Code, as it should be, the neutral wire will always be grounded. Unfortunately, some wiring is installed by "handymen" who probably neglect to ground the neutral wire—should they even know the need for such grounding. Some ungrounded wiring was installed years ago, before the necessity for such grounding became apparent. There are many reasons why it is necessary to ground that neutral wire. We shall point out a few instances to show the danger of not having the ground connection.

Look at the diagram of Fig. 11-46. Note that the secondary windings are wound around an iron core of a transformer, the primary of which carries a potential of 2,400 volts. This means

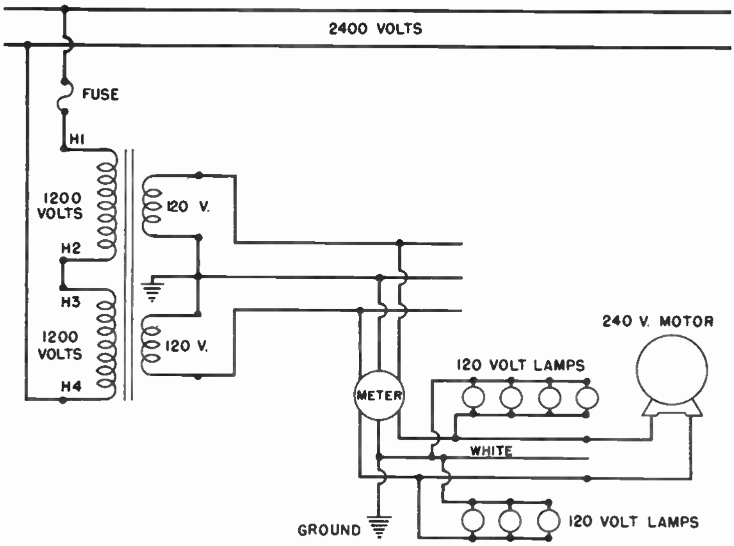


Fig. 11-47. The manner in which this type of transformer is most often used.

that if the primary and secondary should become grounded to the core or shorted together, an electrical pressure of 2,400 volts would exist between the low voltage secondary and the ground of the earth, a pressure which is several hundred volts higher than the voltage applied to the electric chair in our prisons. This means the 2,400 volts in the distribution system is far more than enough to kill a person. In fact, any person who chances to contact that 2,400 volts in such a manner that the current has a path through his body is almost certain to be killed. For that reason, we must use every precaution to safeguard against accidental contact with that high voltage.

Let's take a second look at that transformer. The only insulation between the wires in our home and that high voltage on the distribution system is the insulation between the windings. Of course, the insulation between those windings is adequate for all normal conditions. Every effort is taken to make such transformers safe. Due to lightning, accidents, storms, and other causes, a ground or short may occur between the high voltage and low voltage windings. In this instance, the 2,400 volts will be in direct contact with the customer's electric wiring. Anyone, while standing on the ground and accidently touching one of the electrical outlets, electrical fixtures, pumps, or anything else electrical, would probably be electrocuted.

The entire secondary system can be protected by grounding. Grounding the "neutral" of that system does not interfere with its normal operation. If a short circuit should develop between the primary and secondary windings of the transformer, the current will immediately find a good pathway to the ground through the grounded neutral of the secondary system. A very large current will flow, blowing the fuse or circuit breaker in the primary circuit to the transformer. Of course, blowing the fuse would shut off all the electric power and cause an inconvenience, but that would be preferable to the accidental electrocution of someone in the household.

Not all distribution transformers in the city are necessarily fused, but they are nearly always protected in some manner. In rural areas nearly all transformers are individually protected by fuses. The fuses are located near the top of the pole on which the transformer is mounted. They are high-voltage fuses, and no unauthorized person should ever tamper with them or attempt to change one. The trained lineman have special equipment so they can change the fuses without danger to themselves.

The neutral or ground wire in the secondary electrical system which supplies electrical power to the home, the farm or the place of business is, or should be, a whitish or grayish color. The National Electrical Code clearly specifies it shall be such color to distinguish it from all the other conductors in the system. When the system is grounded by connecting the neutral wire directly to ground, no part of the electrical system will ever be more than 120 volts above or below ground. This makes it possible to have 240 volts of electrical power available, yet still not have any voltage more than 120 volts from ground. This is accomplished by having one of the wires 120 volts above ground at the same instant the other "hot" wire is 120 volts below ground. While neither wire is more than 120 volts from ground, there is a 240 volts potential between them. This was shown in the series-connected, 120 volt (sources) secondary windings on the transformer with their junction wire, the "neutral," grounded. At any instant the outside wires are opposite in polarity.

The actual grounding may be done in any of several ways, so long as the grounding is adequate and secure. In some localities the local inspector will have his own ideas of exactly how the grounding should be accomplished. Where this is true, the directions of the inspector should always be followed, regardless of your opinion or the opinions of others.

In the city, a good mechanical and electrical connection between the neutral wire and the place where the cold water pipe enters the building from underground is usually considered the best kind of ground. The connection must be made between the point where the pipe enters the building and the water meter to prevent the ground from being broken by removal of the water meter.

In the rural areas a good ground can be made by connecting the neutral wires to the water pipe at the place where it goes underground or into the well. However, in some rural areas the inspector will not accept this type of ground. He will insist on having a ground-rod or pipe driven into the ground at the meter and the neutral wire connected to the rod or pipe at that location. The reason for this is that sometimes farmers and other rural residents will remove the water pipes from the ground or the well for repair, breaking the ground connection and leaving the system ungrounded.

A three-quarter inch galvanized steel pipe, nine or ten feet long, driven into the ground to its full length, will usually be accepted by the inspector as an adequate ground connection. Other inspectors, however, will insist on a one-half inch copper rod, eight feet long. The inspector usually knows the local conditions and will insist on what he thinks to be the best method for that locality. In any event, it is always wise to do what he says, for the customer will not receive electric power until the inspector has approved the installation.

ALTERNATING CURRENT SINGLE-PHASE AND THREE-PHASE POWER

The terms "single-phase transformers" and "three-phase transformers" are often heard. Likewise, the terms "single-phase power" and "three-phase power." The beginner in electricity is often puzzled as to the meaning of these expressions.

All the electrical power we have discussed up to this time has consisted solely of single-phase power. Single-phase is a type of electrical power which consists solely of one electrical current constantly flowing back and forth in a single closed circuit.

There are two other common types of electrical power, known as two-phase and three-phase. In some instances electrical power is produced and used in six, twelve, and even more phases, but these instances are few and will not be discussed here. Two-phase electrical power has fallen into disuse, so our discussion of transformers and transformation will be limited to single and three-phase power. Three-phase power consists of three different currents, all generated by the same machine. These three currents flow through three different circuits.

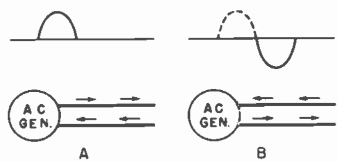


Fig. 11-48. A single-phase generator connected to a line.

Fig. 11-48 represents a single phase AC generator connected to a line. The generator generates a current which alternately flows first in one direction and then in the other.

In Fig. 11-48A we see the current in the upper line leaving the the generating machine, while in the lower line the current is returning to the machine. This is represented by the graph just above the generator and the line.

In Fig. 11-48B we see the current flowing in the direction opposite that in Fig. 11-48A. Here the current is flowing toward the generator in the upper line and away from it in the lower one. This action can also be represented by the graph just above the drawing.

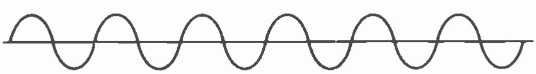


Fig. 11-49. A single-phase alternating current sine wave can be shown graphically in this manner.

The flow of electrical current back and forth in a circuit can be shown by a continuous wave as in Fig. 11-49. This is the customary method of showing, by means of a drawing, how the current flows. When the curve is above the horizontal central line, the current is assumed to be flowing in one direction. When the curve is below that line, the current is assumed to be flowing in the opposite direction.

A curve drawn in the manner shown in Fig. 11-49 would represent a single-phase alternating current, because it represents a single current flowing back and forth. The word "alternating" is usually omitted when speaking of single and three-phase currents, for "phase" implies alternating current.

This voltage is generated by a machine in which coils of wire are positioned in such a manner that they will be cut by the lines of magnetic force surrounding a moving magnet. A single-phase current is generated when there is only one group of coils so connected that current flows in all the coils with the same intensity at the same time.

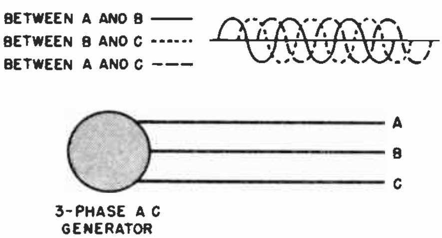


Fig. 11-50. A three-phase generator connected to three line wires. The voltage and current will rise and fall in the three line wires in time relation to each other as shown.

Instead of having only a single set of coils in the machine, in which the currents and voltages rise and fall together, it is also possible to install other sets of coils, positioned between the original coils in such a manner, that the current will rise and fall within them exactly as it does in the first set but slightly before or behind it in time. If three such sets of coils are installed in the machine, three separate currents and voltages will be generated all alike and having the same rise and fall, but each one rising and falling at a slightly different time.

Such a generator will ordinarily have three wires as shown in Fig. 11-50 instead of only two wires as in Fig. 11-48. The voltage and current will rise and fall in the wires A and B of Fig. 11-50, as shown by the solid line in the graph at the top of the drawing. This is exactly as shown in Figs. 11-48 and 11-49. If the bottom line, the one marked *C*, is removed, the current and voltage will rise and fall in the lines *A* and *B* just as it did in Fig. 11-48. If line A is removed, the current and voltage will rise and fall in lines B and C as shown by the dotted line in the graph above the drawing. The sole difference between the voltages in lines B and C and those in lines A and B is a slight displacement (difference) in time. The voltage does not begin to rise in B and C until after the voltage has reached its peak in A and B.

The same thing is true of lines A and C. If line B is removed, A and C will carry voltage in the same manner as either of the other pair of conductors. The voltage will rise and fall as shown by the dashed line in the graph at the top of the illustration.

When all three lines are used, we find the voltage rising first in one line in one direction, then in the second line, and finally in the third line. The current and voltage never rise in any of the two circuits at the same instant.

Three wires are required for both three-phase power and the power in an Edison three-wire single-phase system, such as was shown in Figs. 11-42 and 11-47. Three-phase power has three different phases, in each of which the current is rising and fall-

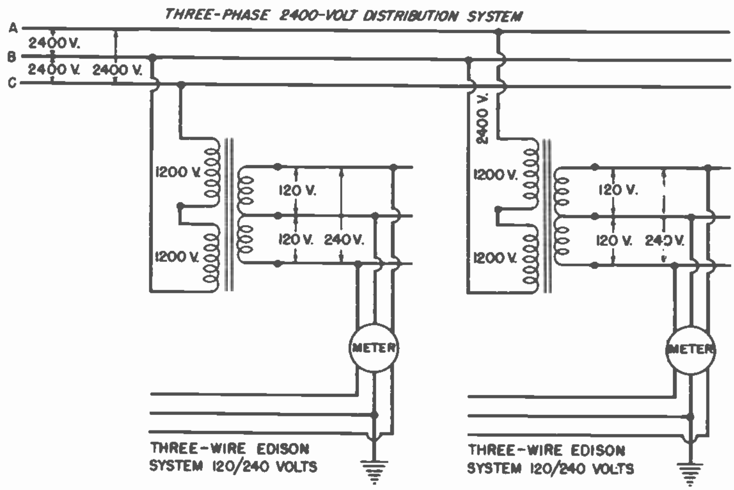


Fig. 11-51. How three-wire Edison-system power can be tapped off individual phases of the three-phase power distribution system. Power for use in the Edison system can be tapped off the distribution system between any two of the three wires.

ing at different times, while the Edison three-wire system has only single-phase power in which the current and voltage rise and fall at the same time in all parts of the system.

Three-phase power is necessary to run very large induction motors. When such motors are used, a special "three-phase" line will be brought in by the power company. It will be metered by a meter separate from the one used to measure the single-phase power.

In Fig. 11-51, we see how a single-phase Edison system can be obtained from a three-phase power distribution system. In cities and in many rural areas, the power distribution system is a three-phase system with the power for the individual customers tapped off from only one of the three phases. This is shown more clearly by Fig. 11-51 than it is in Fig. 11-4.

In Fig. 11-51 we see the primary of one distribution transformer connected across the wires B and C of the three-phase system. The connection between the primary of the transformer and the high-voltage line is the same as it should be if the source of voltage were single-phase instead of three-phase. The third wire, wire A, is merely ignored as though it were not there. The secondary of the transformer supplies a three-wire Edison system just as was shown in Fig. 11-47.

The other transformer in Fig. 11-51 has its primary connected across wires A and B of the three-phase distribution system, omitting wire C. This is also connected as though it were simply a source of single-phase voltage. So long as the secondary system of the second transformer is not connected in any way with the secondary system of the first transformer, everything is all right and there is no reason for the two to be connected in any manner. The currents and voltages in the secondary system of one transformer rise and fall at slightly different instants of time from those in the secondary system of the other transformer. This results from the fact that the primaries of the two transformers are connected to different "phases" of the three-phase distribution system.

The primary of a third transformer could be connected between wires A and C of the three-phase distribution system, and power could be fed into a secondary system in the same manner as is done with the two transformers shown in Fig. 11-51. The power from that phase would be the same except its voltage and the current would rise and fall at instants of time slightly different from those of the other two systems. You will note that the voltages between any two of the three wires in a three-phase system are always the same. This differs from the voltages in the three wires of an Edison three-wire single-phase system.

HOW THE TERMINALS OF A TRANSFORMER ARE MARKED

In several of the diagrams and illustrations in this chapter the terminals of the coil windings on transformers have been marked H-1, H-2, X-1, X-2 and so forth. Perhaps you have wondered why!

In a diagram showing the connections to a transformer, all the wires are laid out in clear geometric patterns. Electrical diagrams are valuable because they enable us to see just where each wire goes and to what it is connected. It is usually easier to understand the operation of a circuit or an electrical device by studying its diagram than it is by examining the wiring or the object itself.

Practically all transformers have several wires extending out of them. Unless these wires are marked in some manner, it is often difficult to know just how the transformer should be connected into a circuit or even what kind of a transformer it is. For this reason they are generally marked; but if the markings are to mean anything, it is necessary that all transformers be marked in the same manner.

Electrical manufacturers have agreed that all leads to the high-voltage windings shall be marked with the letter "H." To further identify the high-voltage windings, their terminals or leads are progressively marked H-1, H-2, etc. The first high-voltage winding has its terminals marked H-1 and H-2; the second, H-3 and H-4. If there are more than two high-voltage windings, additional windings are marked in the same manner, H- with progressing numbers.

All low-voltage winding terminals or leads are marked with an "X." You might wonder why the letter "L" is not used instead of an "X." The letter "L" has a number of other uses in electrical machinery, one of which is to designate the connections from a machine to the line. If the low-voltage terminals on a transformer were marked with an "L," someone might mistake them for the terminals which should be connected to the line. If such a connection were made, the transformer might be burned out as soon as it was connected on the line.

You might also wonder why transformer windings are marked for low-voltage and high-voltage instead of being marked primary and secondary. This is a fair question, but it is easily answered.

The winding into which the power is supplied from the power source is the primary winding. In most of the drawings in this chapter, the primary winding has been the high-voltage winding. When it is such, the transformer is used to step the voltage down. However, the primary winding is not always the high-voltage winding. In Fig. 11-4, three single-phase transformers are used to step the voltage up from the generated voltage to the transmission line voltage. In that case, the transformers are being used to step up the voltage, and the primary windings are the low-voltage windings, while the secondaries are the high-voltage windings.

It should be remembered that any transformer can be used to step the voltage either up or down. If the proper low voltage is applied to the low-voltage winding of a transformer, the voltage which will appear at the high-voltage winding terminals will be a high voltage. The same transformer, with a high voltage applied to its high-voltage windings, delivers a low voltage from the low-voltage winding.

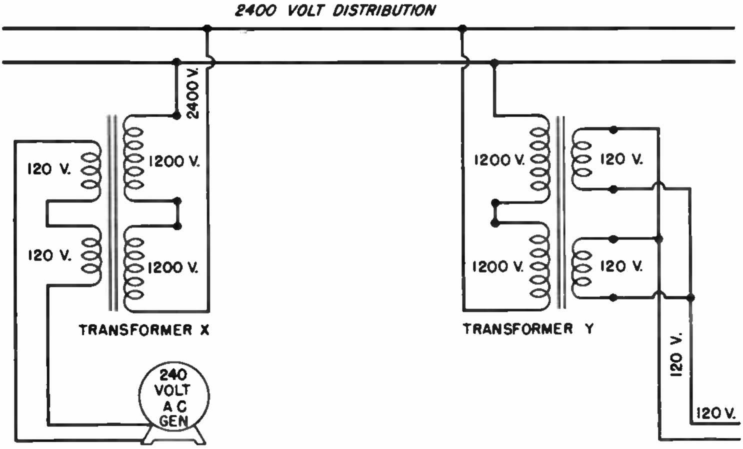


Fig. 11-52. Two transformers that are exactly alike can be used in two different and opposite manners.

In Fig. 11-52 we see how two transformers which are exactly alike can be used in two different ways. The first transformer, which we have called X is used to step up the voltage from a 240 volt alternator to 2,400 volts for a distribution line. The other transformer Y, which is identical to transformer X, is used to step-down the voltage from the 2,400 volt distribution line to 120 volts for use in a lighting circuit.

The high-voltage and low-voltage windings of both transformers are identical. In one case the high-voltage winding is used as the primary, while in the other, the low-voltage winding is used as the primary. Therefore, the terms primary and secondary, refer to the manner in which the transformer is connected between the line and the load. The terms high-voltage winding and low-voltage winding refer to the type of voltage which can be applied to those particular windings.

MULTIPLE-WINDING TRANSFORMERS

In the transformers described in the preceding sections of this chapter, the windings were similar. They were designed solely for the purpose of stepping-up a single voltage from one level to a higher one or for the purpose of stepping-down a single voltage from a higher level to a lower one. Most commercial electrical-power transformers fall under the latter category.

There are many special-type transformers, each built to do some specific job. Manufacturers of electrical equipment find it necessary, at some time or other, to build a special-type transformer to accomplish some special job or to operate a special type of machine or equipment. Many of them are designed to supply special voltages which vary greatly from the standardized voltages we have mentioned.

Probably the most frequently encountered of these special-type transformers are the so-called "power transformers" found in many radios, television sets, and other electronic devices. The schematic diagram of a typical electronic power-supply transformer is shown in Fig. 11-53. These transformers are used to transform the ordinary 120-volt supply voltage to other potentials required for the proper operation of the electronic tubes.

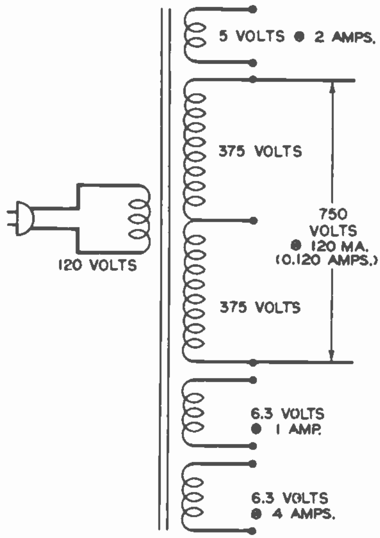


Fig. 11-53. Diagram of a typical radio power supply transformer showing primary and secondary windings.

The primary of this type of transformer is connected through a switch to a line cord and plug, which may be connected into any convenience outlet within the house, shop, place of business, or wherever the device is to be used. This winding is almost invariably wound so it can be connected directly to a 120 volt AC source of power.

Instead of a single secondary winding, or two identical windings, as we have described in previous sections, this type of transformer has several different windings, each producing a different voltage.

At the top of the diagram can be seen one secondary winding which furnishes 5 volts at a drain of 2 amperes. This winding is usually used to supply the filament heating current needed by a "rectifier" tube.

There are two 6.3-volt windings at the bottom of the diagram, rated at 1 ampere and 4 amperes respectively. Some transformers have two 6.3-volt windings as shown here, for purposes of isolation, while others have only one 6.3-volt winding. Both these windings are used to furnish cathode heating current for the electronic tubes. All of the windings we have mentioned so far have been step-down windings, functioning like the bell-ringing transformers mentioned earlier in this chapter.

There is still another winding on the transformer secondary, the center-tapped 750-volt winding. It is the winding used to step-up the voltage from 120 volts to a value that after full-wave rectification, has the proper voltage to act as the "anode supply" for the device's electronic tubes.

It is not a function of this book to discuss vacuum tubes, radios, television, or other similar electronic devices. However, this type of transformer will be encountered by many readers of this book; and since it is not exactly like any of those we have described, it seems only logical to mention it and to describe its action and functions.

In summary, a transformer is an electrical device having no moving parts and capable of converting electrical energy of one potential into that of a different potential by the process of electromagnetic induction.

Any transformer winding to which electrical power is applied, regardless of whether it is low or high voltage, is called the primary. Any winding which delivers power to a load is called the secondary.

Transformers make virtually no noise other than an occasional low-pitched hum. With ordinary care, transformers have a very long life; many of which have had very little attention, are still in use after 35 to 40 years of service. There are many cases on record of transformers having given even longer periods of service. Some of the new transformers coming into use will no doubt have even better performance records.

Chapter 12

DIRECT CURRENT GENERATORS AND MOTORS

Storage batteries and dry cells generate enough electric current to operate door bells, electric chimes, burglar alarms, annunciators, and other devices requiring only small currents for their operation. However, batteries are far too expensive for supplying light, heat, and power. Dynamo electric machines are used for this purpose. Machines designed for generation of direct current electricity are called dynamos or direct-current generators; while generators that produce alternating current are usually called alternators. Both the direct-current generator (dynamo) and the alternating-current generator (alternator) have relatively few parts. The principal parts are: (1) the frame; (2) the field magnets; (3) the armature; (4) a pair of brushes, more on certain machines; and (5) a commutator, if direct current is generated, or slip rings, if alternating current is generated. Fig. 12-1 shows an elementary generator (dynamo).

A dynamo of somewhat different design is shown in Fig. 12-2. Two views of the armature are shown in Fig. 12-2A. The base, field poles, field windings, brush holders, and brushes are shown in Fig. 12-2B. Fig. 12-2C shows the frame and brush rigging. Fig. 12-3 shows the parts of the generator assembled and ready for operation. The machine shown here is shunt connected. This is not a commercial or industrial type of generator; it is the elementary educational type, designed for use as an electrical training aid.

A modification of this generator is shown in Fig. 12-4. Here the machine has been converted to a permanent magnet generator by the substitution of permanent magnets for the field poles and coils. In this machine the field magnets are two Alnico permanent magnets, magnetically and mechanically linked together by a soft steel core. The soft-steel U-shaped core carrying the two armature coils revolves, passing over the poles of the field magnets. Voltage is generated in the rotating armature coils as they pass (cut through) the magnetic fields produced by the permanent magnets. These two coils and the U-shaped soft steel core constitute the armature of the generator. For the power generated in the armature coils of a direct-current generator to become available for useful work, it is necessary to connect the coils to a device known as a commutator.

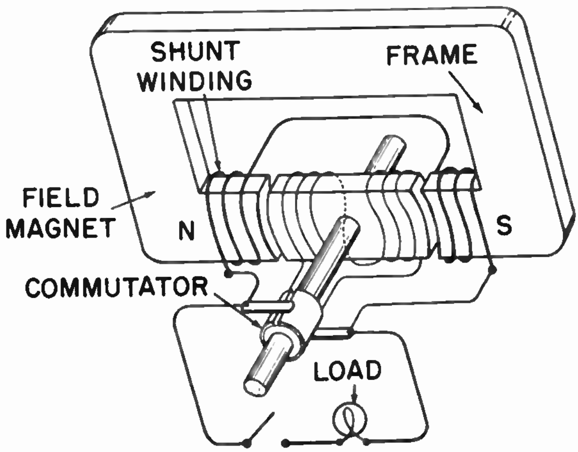


Fig. 12-1. A simple type of elementary direct-current generator (dynamo).

A commutator is a cylindrical arrangement of copper segments, mounted radially on the shaft of the armature and separated and insulated from each other and from the armature. The armature coils are connected to these copper commutator segments. All direct-current generators actually generate alternating current, because each time an armature coil cuts (passes through) the flux of one field pole, a current is produced in it in one direction, and when the same coil is rotated further until it cuts the magnetic field of the other (opposite) field pole (field pole of opposite polarity), a current is generated in it in the opposite direction. The commutator acts as a reversing switch to change the bi-directional (two-direction) current generated in the armature to a unidirectional (one direction) current for the circuit to which the generator is connected.

This unidirectional current is collected from (taken off) the commutator segments by brushes which contact (rub against) the rotating commutator segments. They are positioned to produce mechanical reversal of the alternating voltage generated in the armature coils, the reversal resulting in a unidirectional

The action described in the two preceding paragraphs is what will occur during one half-cycle, or one-half rotation of the loop. During the following half-cycle, in which side C_1 of the loop will be at the top and side C_2 will be at the bottom, the voltage and current in the loop will be reversed. The slip ring R_2 will still be connected to side C_2 of the loop; and since the voltage and current within the loop have been reversed, it naturally follows that the voltage and the current at the slip rings and brushes is reversed and current will flow through the lamps in the opposite direction.

Such a loop, then, if connected to a pair of slip rings and brushes, will cause to flow in the external circuit an alternating current which will light the lamps, if the voltage and current are large enough. All this is well and good, so far as it goes. What we wish to do at this time, however, is to generate direct current, a current which flows continuously in the same direction at all times. If we are to use the rotating loop as the source of direct current, it is necessary to make some alterations in the design of this generator, alterations that will change the alternating current within the loop into direct current before it is delivered to the external conductors.

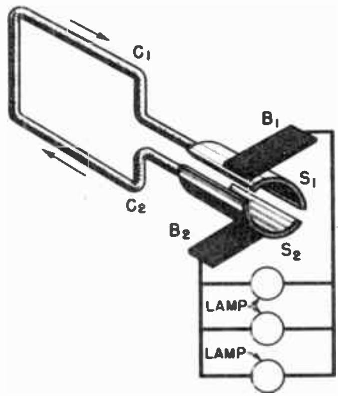


Fig. 12-15. A commutator, consisting of two or more segments, can be used to tap the current inside the rotating loop.

This alteration can be made by substituting, for the slip rings, a commutator such as that shown in Fig. 12-15.

A DIRECT CURRENT COMMUTATOR

Before we become involved with the technical aspects of the construction and electrical action of slip rings and commutators, it would be wise to study the illustrations in Figs. 12-14 and 12-15 to carefully note how they differ.

We have described how each side of the rotating loop in Fig. 12-14 is permanently connected to one of the slip rings. This means that the polarity of the two slip rings is always changed as the polarity of the voltage within the loop is changed. Since moving conductor or coil is increased (as the rate at which they cut the magnetic flux is increased).

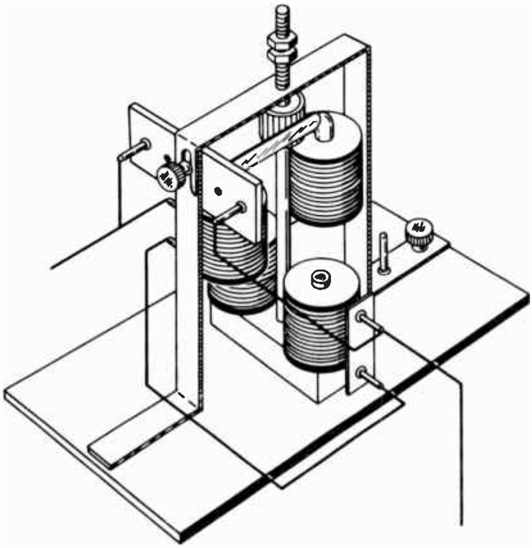


Fig. 12-3. The experimental direct-current generator assembled ready for operation.

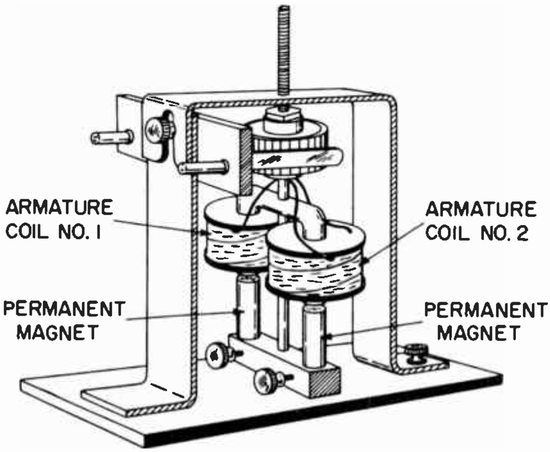


Fig. 12-4. A permanent-magnet type of experimental direct-current generator.

From the foregoing, we can easily see how a generator's armature, having *many turns* of wire revolving through a magnetic field at high speed, driven by a prime mover, will have a much greater voltage generated in it than does a coil with *few turns* moved through the same field by hand.

The steel core of the armature and that of the field, together with the steel structure of the frame of a generator, offer far less reluctance (resistance) to the flow of magnetism than does air. Thus, they provide a good magnetic circuit for the magnetism of the machine and increase its efficiency.

An armature coil passing through the influence of a field magnet's north pole will have a voltage set up (induced) in it in one direction. When this same coil passes through the magnetic field of the south pole of the machine, a voltage is induced in it in the opposite direction; therefore, all current produced by generator action (induction) is alternating.

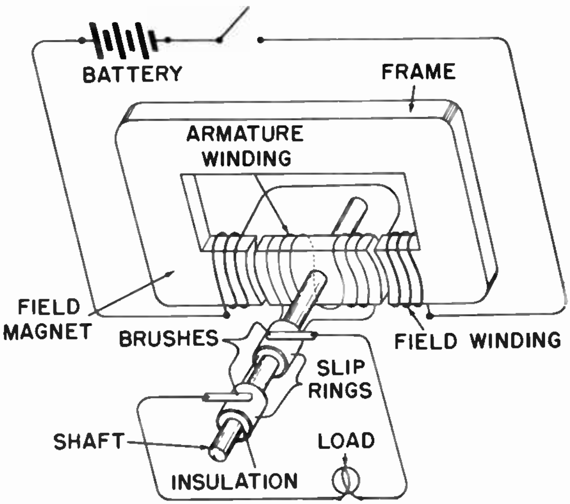


Fig. 12-5. Simple type of elementary (alternator) alternating-current generator.

For this reason, all direct-current generators (dynamos) always produce or generate alternating current. If the armature coils of such a machine are connected to a pair of *slip rings* (continuous copper bands, insulated from each other and from the armature shaft, alternating current can be taken from these slip rings by means of brushes. (See Fig. 12-5.)

In order to secure direct current from a dynamo, it is necessary to substitute a commutator for the pair of slip rings. As explained before, the commutator consists of copper segments or bars (most commutators have many segments). It has one segment for each armature coil; in other words, it has as many segments as there are coils on the armature. The armature coil ends are connected to the armature segments, so that the alternating current generated in the armature, as it rotates through the magnetic flux of the generator field, is mechanically rectified to give a unidirectional current. This direct current is often referred to as "continuous current" although the expression is not technically accurate.

The commutator for an elementary or simple generator, as shown in Fig. 12-1, consists of a single copper ring (cylinder) split in half lengthwise to form two segments insulated from each other and from the armature shaft.

In the assembly of this generator, the two armature coils may be connected either in series or in parallel, depending upon the current and voltage desired. If the two armature coils are connected in series, the resulting output voltage will be greater than if they are connected in parallel; but the current (ampere) output will be less. If they are connected in parallel, the output voltage will be less than if connected in series, but the current in amperes (or milliamperes as in the case of this small machine) will be greater. In either connection, one end of the armature winding is connected to one commutator segment and the other end to the opposite commutator segment. The two brushes touch the commutator as shown in Fig. 12-1, each commutator segment being contacted by one or the other of them. These brushes rub (ride) the commutator segments under spring tension as the armature revolves. The commutator is fixed on the armature axle and turns with the revolving armature. This rotation of the armature and commutator in unison or synchronism (together) is very important because, electrically, it connects the end of the armature coils alternately to each brush, acting as a mechanical reversing switch to transfer the current, by brush contact, each time the generated current in the armature reverses. Although the current in the armature winding alternates (reverses its direction) twice for each rotation of the armature, that current which flows through the external circuit from brush to brush flows in one direction only, due to the mechanical reversing-switch action of the commutator-brush arrangement.

From the foregoing we have learned that an electric dynamo (generator) is a machine that converts mechanical power into electrical power. For practical use and application, this mechanical drive is supplied by some machine, such as a gasoline engine, water wheel, windmill, steam engine, turbine, or electric motor.

A machine that turns (drives) the generator is called a *prime mover*. The power that is produced by this prime mover is converted (changed) into electricity by the electric generator.

THE DUTY OF A GENERATOR

An electrical generator produces an electromotive force (voltage). This voltage is developed by the process known as electromagnetic induction which, as previously explained, involves the cutting of magnetic lines of force of a magnetic field by passing (revolving) conductors in the form of coils through (across) this field; thereby, inducing (in the coils) an electron movement which gives rise to what we call a voltage or potential.

VOLTAGE IS PRODUCED BY A GENERATOR

The movement of the conductors (coils) through the magnetic field causes the electrons in the conductor to be repelled, or to move away, from the atoms in one end of the wire and to crowd toward the other end of the wire making it predominantly negative and the opposite end of the wire positive. This produces a potential difference that will cause a current to flow if the voltage is applied to an external circuit. This fundamental principle of "electric-current generation" by changing mechanical energy into electrical energy is the only method known today for economically generating electricity on a large scale.

ARMATURE COILS CUT FLUX

The armature conductors of a direct-current generator are wound in the form of coils. These coils may be mounted on the armature in various ways. Usually, they are mounted in slots provided in the iron core of the armature. In the simple generator shown in Figs. 12-1 and 12-3, the armature winding consists simply of two coils placed upon the armature core. It is essential that the coils be mounted on a core of iron, steel, or other material of good magnetic conductivity; so that the conductors, when rotated through the magnetic field, will cut as many lines of force as possible. The greater the number of magnetic lines of force cut by the coils, the greater the voltage generated in the armature winding and the greater the current flow produced. The armature coils connect to the commutator bars (segments) which conduct the generated current through the brushes to the outside circuit. The magnetism emerges from the north (N) *field pole* (See Fig. 12-1), crosses the air gap between the armature core and the field pole into the iron core of the armature, passes through the armature core and across another air gap into the south pole (S) and hence goes through the frame of the machine back to the north (N) field pole where it started. When the armature rotates, its windings cut (move) first through a north pole and then through a south pole of field flux. The armature coils, therefore, cut the flux lines, first in one direction and then in the other, causing the current generated to flow in first one direction and then in the opposite direction. A current, such as this, which flows first in one and then in the opposite direction, is called an alternating current.

SEPARATELY EXCITED GENERATORS

Permanent-magnet type generators are not used for generating commercial power, but they are finding rapidly growing use in portable electrical generating units where permanent magnets

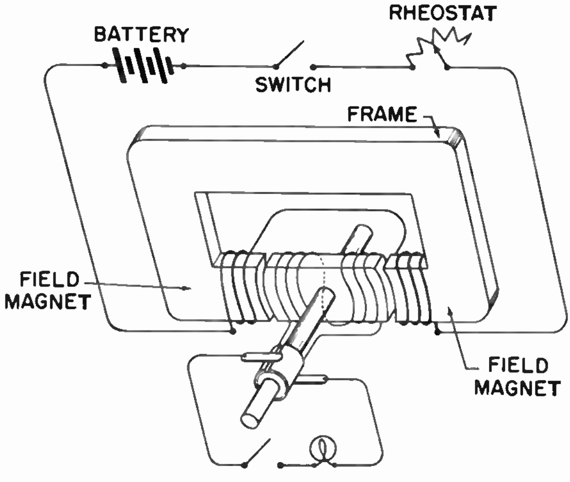


Fig. 12-6. Elementary separately-excited direct-current generator.

supply the magnetic field flux. Small light-weight 400-cycle alternators, using permanent magnet fields, are being manufactured in quantity for military use.

Commercial and industrial generators are designed and manufactured so that the strength of their field magnetism can be increased or decreased to meet various requirements. This control of the field strength could not be accomplished by the use of permanent magnets, since the strength of a permanent-magnet field is fixed. Even more important is the factor of cost. Permanent-magnet fields having the same strength of the wound-coil fields would have a cost several times greater.

In order to magnetize the fields of a generator, it is necessary to provide the field poles (cores) with a suitable winding through which a current of electricity may be made to flow.

Sometimes, generators have their field windings excited by a direct-current source, such as a storage battery or another generator. When a generator receives its field excitation (field current) from an independent source, it is known as a *separately-excited* generator.

Fig. 12-6 shows an elementary generator, separately excited by a battery. The rheostat in the field circuit can be used to regulate the current flow and, thereby, control the strength of the field magnetism. By the strength of the field magnetism being controlled, the voltage output of some generators can be varied from zero to several times the nominal value.

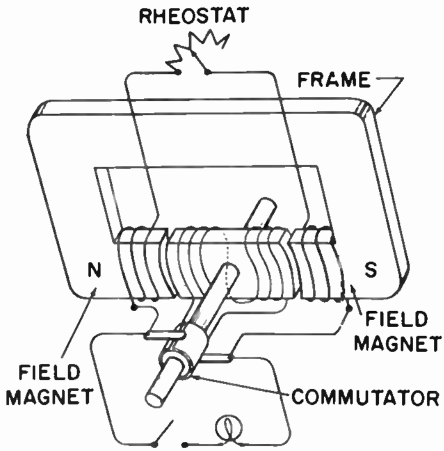


Fig. 12-7. Self-excited shunt-wound DC generator.

Separately-excited generators have certain limitations, and for most commercial and industrial applications, direct-current generators are self-excited. A self-excited generator supplies its own field excitation from a portion of the current generated by its own armature. Fig. 12-7 shows how the field windings may be connected so that a portion of the armature current can flow through to the field coils. In this fashion, the field magnetism may be produced by current generated in the armature winding.

The current necessary to magnetize the fields of a direct-current generator amounts to only a small percentage of the total current generated. Therefore, the field coils have many turns of a wire small enough to limit the current through the field winding to a fractional part of the total current of the machine. A field rheostat (Fig. 12-7) is used to vary the field excitation to compensate for load or speed conditions.

VOLTAGE BUILD UP OF A GENERATOR

Even after all the parts of a generator are manufactured and assembled into a complete operating machine, the machine will not generate even though the armature is driven at a high speed. The field poles or cores must be magnetized to produce magnetic lines of force for the armature conductors to cut. Therefore, a new generator must be externally excited before it will begin to generate a voltage. If the generator is externally excited once, its field cores will retain a very weak magnetic field after the external excitation is completely removed. This weak magnetic field that remains in the field poles of a generator after it has been magnetized is known as *residual magnetism.*

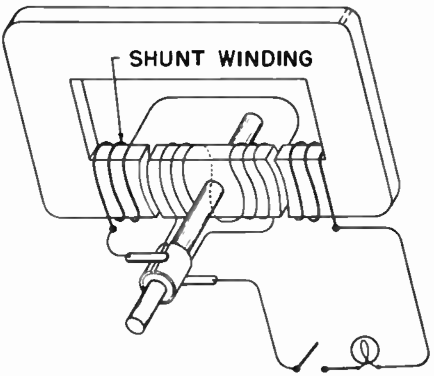


Fig. 12-8. Series-wound DC generator.

It is this residual magnetism in the field poles that makes self-excitation of a generator possible. As the armature conductors (windings) begin to revolve, they cut this weak residual magnetic field, and generate (induce) a small voltage, which sends a little current through the field winding. This field current adds its effects to the existing residual magnetism to increase the strength of the magnetism in the field poles. This, in turn, increases the voltage generated in the armature winding. This process continues, until the machine has built up to normal voltage.

Current may then be taken from the brushes of the machine up to its normal capacity. However, if a load is connected to the generator before its field is built up, the generator will not build-up. This is due to the fact that the small armature current generated by cutting the residual magnetic field flows through the low resistance of the load rather than through the high resistance of the field windings. As soon as the field of a generator has built up to its normal operating strength, a normal load may be placed on the generator.

Fig. 12-8 shows a direct-current generator (dynamo) which is self-excited, since the generated voltage of the machine causes a current to flow through the machine's field windings and, thereby, magnetizes them.

Because the only circuit through this machine is a series circuit, the machine is known as a series-wound generator. More information will be given concerning series generators later in this chapter.

A dynamo in which a portion of its generated current is shunted through the field winding is known as a shunt-wound machine. Figs. 12-1 and 12-7 show clearly how the field and armature windings of a shunt-wound generator are connected.

The voltage of a shunt-wound generator falls off as the load increases. The load resistance decreases as the load increases, thus robbing the high resistance field's current. Finally, with a large load, the load resistance may reach a point where the decreased current through the field winding (due to its high resistance) has so weakened the magnetizing field that the output voltage is extremely low, approaching zero as the load approaches a short circuit.

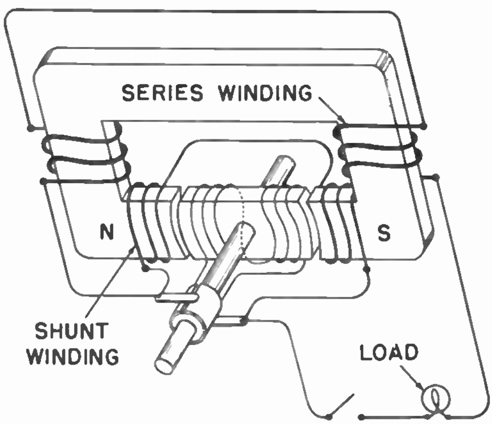


Fig. 12-9. Compound-wound DC generator.

In order to maintain a more constant strength of the generator field, as the generator load is increased, it is necessary to supplement the shunt winding in some manner. In order to do this, a series field winding can be provided in addition to the shunt winding. The fields of the generator are provided with a compound type of winding; therefore, this type of generator is called a compound-wound generator.

Fig. 12-9 shows a compound-wound generator. The fields are provided with a set of coils, having a few turns of heavy wire in series with the load. An additional set of coils is in shunt with, or across, the armature.

Commercial and industrial compound-wound generators usually have their series windings wound directly (around) on top of their shunt windings. For purposes of illustration, the series coils in Fig. 12-9 are shown wound on the field-core structure near the shunt windings. Under small load conditions, the shunt winding supplies practically all of the magnetizing current for the generator fields; but as an increasing load robs the shunt field winding of more and more of its magnetizing current, the generator voltage likewise decreases since there are fewer magnetic lines of force to be cut by the armature coils. It is this decrease in voltage that is so perfectly offset by the series winding of a compound generator. The series winding of a compound-wound generator is designed with just the right number of turns to keep the magnetizing current at a level high enough to maintain a constant output voltage over the full load range.

Because the entire load current of the generator flows through the series winding, the magnetizing effect of this winding increases as the load increases. In a properly designed compound generator this increase is in just the right proportion to offset the decrease in magnetizing current of the shunt winding, which occurs with an increasing load, and keeps the voltage output of the machine constant.

The preceding information on direct-current generators is quite elementary and requires additional supplementary explanations which follow later in this chapter. This information is not to be considered as a duplication of the information already given but as merely supplemental to it. In the early days of the electrical age, the only kind of electrical machinery used was the DC machine. The only motors were DC motors, and the only electrical generators were DC generators.

With the passing of time, this condition has undergone a radical change. Today, the major portion of all electrical power is generated in the form of alternating current. Since it is much easier to change the voltage of an alternating current than it is to change the voltage of direct current, there is a great advantage in the use of alternating current. The ease with which its voltage can be changed has resulted in the general use of alternating current. It makes possible the stepping-up of a low generated voltage to a high transmittable voltage and thus the reduction of loss of power over the distance of transmission.

The complete dominance of alternating current as the form of commercially available electric power has naturally resulted in AC motors being used almost universally. Consequently, we are more familiar with AC, than DC motors. In fact, one might even ask, why waste time in studying DC motors at all?

Unfortunately, many men who call themselves electricians do not understand the principles behind the operation of DC machines. Yet no one can honestly consider himself well informed in the basic fundamentals of electricity unless he does understand the principles involved in direct-current machines.

Despite the predominance of alternating current in the field of public and commercial power applications, there still are many jobs which only direct-current machinery can properly handle. In our Nation's steel industry we find virtually all the huge rolling mills being driven by immense DC motors, motors so large they often stand as high as a two-story house. Many of the printing presses which turn out such unbelievable quantities of printed matter every day are driven by DC motors. Nearly all trolley cars, electric trolley buses, interurban electric trains, elevated trains, most of the elevators in our modern skyscrapers, coal mine machinery, and many other machines are driven by DC motors.

Why, you may ask, is it that DC motors are used for these purposes when AC power is so much more plentiful? The answer is their flexibility! DC motors are more flexible in their operation than AC motors, and where variable speed is required for high starting-torque, DC motors are almost invariably chosen. Such motors can be driven at very high, relatively low, or any intermediate speed. Furthermore, many DC motors can be started under full load and come up to speed from a standing start, such as a street car or an interurban train, which no reasonably sized AC motor could budge. Yes, DC motors definitely still retain an important place in the electrical scheme of things.

You may have no intention of going into industrial electricity; you may not intend to work in a steel mill or in any other industry where such motors are used. Why, then, should you know anything about DC motors and generators?

Perhaps the best answer to that is to point to an automobile. If you own or drive an automobile or if you ever expect to own or drive one, you should know something about DC machinery. Today, every automobile and motor truck has at least one DC generator to generate the electrical power it uses and it has at least one DC motor for starting the gasoline engine that drives it. Many of the newer automobiles have additional DC motors located at strategic positions in and around the body to perform duties which are now becoming a part of modern motor-ing. They are used to operate windshield wipers, to raise and lower windows, to adjust the position of the drivers seat, to raise and lower the tops of convertibles, and to tune the radio. Who knows to what use motors will be put in tomorrows automobiles? Is it any wonder that a knowledge of DC motors and generators should be considered an important part of every electrician's training?

DC motors and generators have taken to the air in planes! A single aircraft, such as the B-36, contains DC motors and DC generators literally by the dozen. They move airfoils; drive gun turrets; transfer fuel between wing-tanks to maintain trim; operate bomb hoists; open bomb-bay doors; generate auxiliary DC power; send their voltages to the cockpit engine speed instrument dials; spin the radar antennas; furnish DC power for the numerous electronic devices which include: several radio receivers for different frequencies, I.F.F. (Identification Friend or Foe) transponder, Radar Tail Warning equipment, Radar "bombing through the overcast" equipment, Radio Compass receiver, Glide Path and Beacon receiving equipment for blind landing; and others too numerous to mention. With the exception of the Radar Tail Warning and Blind Landing equipments, these equipments all have, in addition to their regular DC motor generator power supply, one or more DC motors, some as high as ten.

There is still another place where a knowledge of DC motors and generators is important. That is on the farm or other isolated localities where the DC generators and battery electrical systems are still used. We grant you, there are not so many of those systems as there were before the days of the rural "high-lines;" however, there are still many thousands in daily use.

DIRECT CURRENT GENERATORS

In the study of DC machines, it is a good practice to study generators before trying to study motors. This procedure serves to make the operation of both motors and generators easier to understand.

The purpose of the DC generator is suggested by its name. It is intended to generate electrical power in the form of direct current and voltage. This means it is intended to generate a voltage which will cause current to flow continuously in one direction. This contrasts with the action of an AC alternator which generates electrical power in a form in which the current is constantly reversing its direction of flow.

We have already explained how a voltage can be induced in a conductor by causing that conductor to cut across magnetic lines of force. Fig. 12-10 repeats this illustration, preliminary to showing how this action can be utilized to generate a continuous flow of current. When the electrical conductor AB in the illustration is moved in the direction of the arrow at the bottom of the illustration so it cuts across the lines of magnetic force, a voltage will be induced in it. So long as the conductor is not part of a closed circuit, no current will actually flow within the conductor, but the voltage will be induced within it just the same.

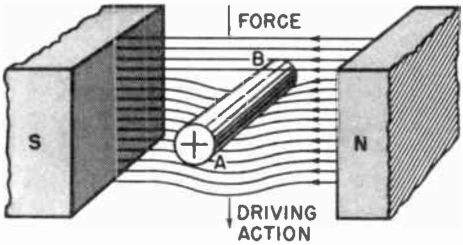


Fig. 12-10. A voltage is induced in a conductor when it is moved through a magnetic field.

If the circuit is completed as shown in Fig. 12-11, a current will flow. In this illustration, the circuit has been completed by a second wire connected from one end of the main conductor to the other end and positioned so that it is not cut by the magnetic lines of force.

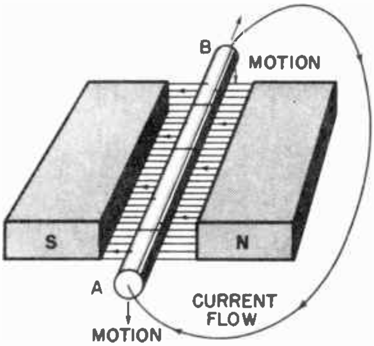


Fig. 12-11. A current will flow in the conductor when it becomes a complete circuit.

Emphasis must be placed on one point to make certain it is clearly understood. A conductor, moved so that it will cut the magnetic lines of force, will have a voltage induced within it; this voltage will be induced regardless of whether or not a current also flows. The current will flow only if there is a complete circuit. It should be clearly understood that moving the conductor through the magnetic field induces a voltage in the conductor; as a result, a current will flow if the circuit is completed.

This may seem a minor point; but many electricians and some engineers will insist that a generator generates current. It does not; it generates voltage! The current flow is a result of the induced voltage. To insist that it generates current reveals one's incomplete knowledge of the generation of electricity by electromagnetic induction.

REVOLVING LOOP IN A MAGNETIC FIELD

One way to understand what happens in a DC generator is to study what happens in a loop of wire when the loop is revolved within a magnetic field. This is shown in Fig. 12-12.

If a handle is attached to the loop so it can be rotated, we have an elementary kind of armature. At the left of the illustra-

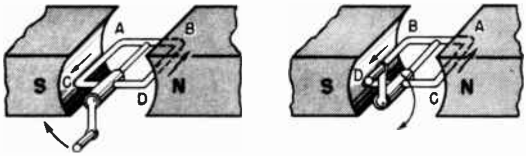


Fig. 12-12. When a closed loop is rotated within a magnetic field, an electrical current will flow within the conductors of the closed loop.

tion, the four corners of the loop are labeled A, B, C, and D. Now let's see what happens when the loop is rotated by turning the attached handle in the direction shown by the arrow. At this particular instant, the side of the loop BD will be moving downward. This part of the loop will be cutting across the magnetic field in exactly the same manner as does the conductor in the two preceding illustrations. It follows that a voltage will be induced in that portion of the loop for the same reason that it was induced in the conductor shown in the two previous illustrations.

At the instant that side BD is moving downward, the other side of the loop, AC, is moving upward. Such action will also induce a voltage in that part of the conductor. Since side AC is moving through the magnetic field in the opposite direction to that of side BD, the voltage in side AC will be in the opposite direction to that in side BD. The voltage induced in each side of the loop causes current to flow in the direction indicated by the arrows adjacent to each side.

Even though the voltage is induced in opposite directions in the two sides of the loop, the current flows in the same direction around the loop circuit, the net result being to place the two voltages in series with each other. This means the total voltage induced within the loop is just double that induced in one side.

After one-half revolution, we find the loop positioned as shown at the right in the illustration, and see another action taking place. The current previously moved through side BD in one direction, but it now moves in the opposite direction. The same thing is true for the direction of current in the other side of the loop, between A and C.

As the loop is rotated within the magnetic field the voltage induced in the loop will be first in one direction and then in the opposite direction. The current will likewise flow in first one direction and then in the other. This is what we know as alternating current. As previously stated, the voltage and current within the armature of a DC generator is always alternating before it actually leaves that part of the circuit.

It is interesting to note that, while the current will flow in one direction during one half of each revolution and in the opposite direction during the other half, there will be an instant when no current will flow in either direction. This is the instant between reversals, the instant when the loop is in the "neutral" position, as shown in Fig. 12-13. At this particular instant, the two sides of the loop are cutting no magnetic lines of force. Instead, they are momentarily moving parallel to the lines of force and not cutting any of them. Since they are cutting no lines of force, no voltage is induced in either portion of the loop.

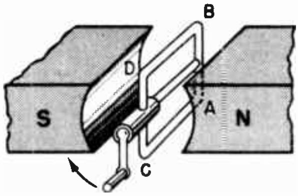


Fig. 12-13. When the conductors of a closed loop are moved so that they do not cut magnetic lines of force, no voltage will be induced within them.

TAPPING THE LOOP WITH COLLECTOR RINGS

We should realize that the current flowing within the loop of wire shown in Fig. 12-13 will serve no useful purpose so long as it is confined within that loop. Otherwise, one might consider the induced voltage and the current flowing in the closed loop with complete detachment and wonder if such an action could be used.

There is no reason, however, why that loop cannot be tapped and its current caused to flow through an external circuit. Fig. 12-14 shows one method of accomplishing this.

In Fig. 12-14, the loop has been opened up at one end and the two ends attached to two separate circular rings, R_1 and R_2.

The two rings actually form two terminals by means of which electrical contact can be maintained to the rotating loop. In the parlance of the electrical worker, these rings are called "slip rings."

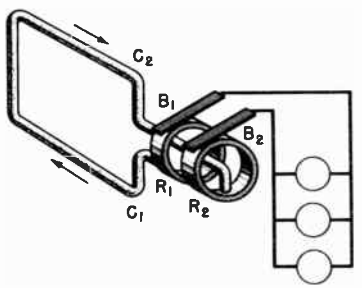


Fig. 12-14. Opening the loop and connecting the two ends of the conductor to slip rings make it possible to tap the current within the loop.

In Fig. 12-14, three incandescent lamps are supplied with electrical power by the generator. This requires a connection between the two slip rings and the conductors which carry the current to the lamps. That electrical connection is provided by two "brushes," shown as B_1 and B_2 in the illustration. The two brushes rest (ride) on the two rotating slip rings and conduct the electrical current from the rotating slip rings to the external circuit.

Thus, the combination of the two rotating slip rings which are electrically and mechanically connected to the rotating loop, and the two brushes, which rest lightly but firmly on those rotating rings, make possible a continuous electrical connection between the rotating member and stationary conductors.

Let us now observe the action which takes place when the loop, represented by C_1 and C_2, is *rotated within a magnetic field* similar to that shown in previous illustrations in this chapter. With a magnetic field of given strength, polarity, and position, the direction of the voltage induced at that instant is such that current will flow through conductor C_2 toward slip ring R_2. Since slip ring R_2 makes continuous electrical contact with brush B_2, the current will flow through brush B_2 and the connecting conductors to the connection at the left of the three lamps.

At the same instant, the voltage induced in side C_1 of the loop will be in the opposite direction. This means electrons will be attracted away from slip ring R_1 at that instant, leaving it deficient in electrons. Since brush B_1 is resting upon and making electrical contact with that slip ring, the right side of the lamps will have electrons attracted away from them. An electrical potential difference (voltage) will be produced across the three lamps, and a current will flow through them. If the voltage created by the rotating loop is great enough, the current forced through the lamps will cause them to glow.

current through the external circuit. Actually, they rectify the alternating current generated in the armature coils by mechanical rectification, producing a direct current for use in the external circuit. Thus, the brushes and commutator perform a vital function in the generation of direct current.

Early experiments demonstrating how magnetism could produce electricity consisted of moving a wire back and forth rapidly near the poles of a permanent magnet. Of course, in order to show that magnetism (magnetic lines of force) could produce

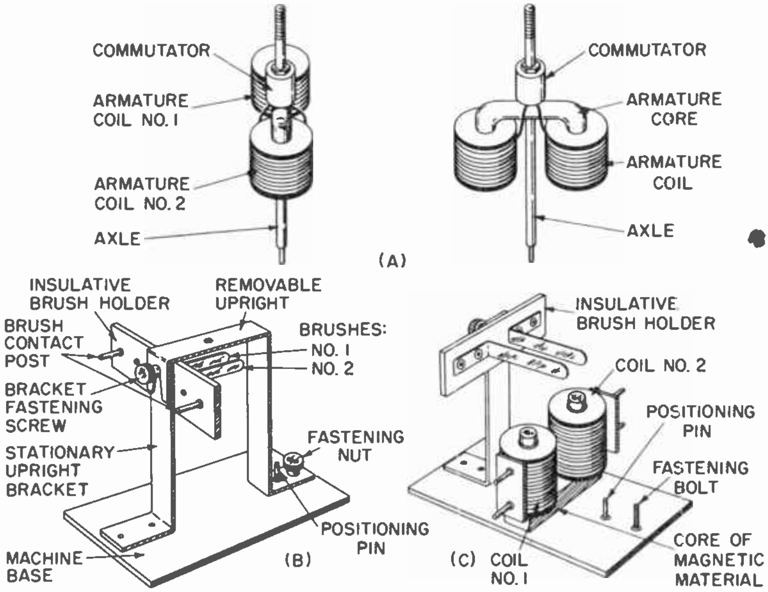


Fig. 12-2. Parts or components of an experimental direct-current generator.

electricity, it was necessary for the moving wire to be connected into a complete metallic (conductive) circuit, so the induced voltage could produce a current flow. To detect this current, it was necessary to connect some type of electrical indicating device into the circuit. Many of the early experimenters used, for their indicating device, a simple galvanometer.

A single conductor cutting through a magnetic field will generate a barely detectable voltage; however, this voltage can be multiplied by winding the single conductor into a coil, each turn adding its voltage to the next, and moving the coil through the same magnetic field. It is equally true of the coil, as of the single wire, that the voltage will increase as the speed of the

the polarity of the voltage within the loop changes twice during each complete rotation or revolution, the polarity of the slip rings will also reverse twice during each rotation.

Note that this action is not followed in the case of the commutator in Fig. 12-15. Here each side of the rotating loop is permanently connected to one segment of the commutator. The two segments of the commutator are arranged so the brushes rest upon them; but as the loop rotates within the magnetic field, the segments of the commutator also rotate.

Now, instead of each brush continuously contacting one side of the loop, we now have an entirely different situation. As the loop rotates, the commutator segments rotate with it, and the brushes alternately contact first one and then the other commutator segment.

This means that instead of the brushes being continuously connected to the same side of the rotating loop, they are now connected alternately first to one side and then to the other.

The action which takes place within the circuit can now be better appreciated. The voltage and current within the loop reverses twice during each revolution of the loop. Simultaneously the brushes are alternately connected to first one side of the loop and then to the other. If now we can make the change of the brush from one segment to the other occur at the same instant the current within the loop reverses, the problem of how to keep the current flowing in the same direction in the external wires connected to the two brushes has been solved.

Suppose, for example, that the voltage and current within the loop are such that the current will flow in side C_1 of the loop as shown by the arrow. The current will flow in the direction of the arrow to segment S_1 of the commutator, through brush B_1, and hence to the connections on the side of the bank of lamps.

During the following instant, the loop will rotate so that C_1 is at the bottom and C_2 is at the top. The voltage and current within the loop will reverse also. Instead of the current in C_1 flowing toward the commutator, it will now be flowing away from it.

However, when the loop has reached this position where the voltage and current within it have reversed, the two commutator segments moving with it have also changed position. The current in side C_2 of the loop will be flowing toward the commutator segment S_2 which is now in electrical contact with brush B_1. So we see that while the voltage and current within the loop have reversed, the voltage and current at brush B_1 is still in the same direction. The voltage and the current in the external circuit connected to the lamps is still in the same direction as during the preceding instant. They will maintain this same direction; for every time the voltage and current within the rotating loop reverse, the brushes shift contact to the other segment effecting a re-reversal that results in the external current always being in the same direction. Thus, the voltage and the current to the external circuit will not reverse as in the case where slip rings are used.

There is a serious drawback to using a single rotating loop within a magnetic field. Although the voltage and current will not reverse in the external circuit as the reversals occur within the loop, the voltage will drop to zero within the loop twice during each rotation.

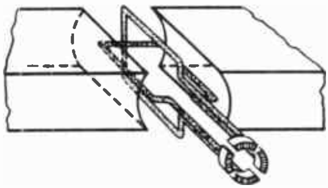


Fig. 12-16. Two loops, placed at right angles to each other and rotated at the same time make it possible to tap off a near continuous flow of current which does not drop to zero at each half-cycle.

To prevent the voltage and current dropping to zero in the external circuit each time the voltage and current drop to zero within the loop, it has become the standard practice to use more than one loop or coil on the rotating armature of a generator. Fig. 12-16 shows two such loops rotating within a magnetic field. Each end of the two loops is connected to a separate segment of the commutator, four such segments being required for the two loops.

Even two loops are not enough to maintain the even, smooth voltage that is produced by a chemical battery. Although the voltage cannot drop to zero when two coils are used, there is, nevertheless, a very pronounced dip. A large number of coils are necessary to maintain the voltage and current at a more constant level.

A rotating cylindrical core, which is made of magnetic material, called the armature, is provided with slots into which the coils are placed. The armature core slots are designed to encompass the coil sides. If many separate coils are used following each other closely in cutting the magnetic field, the output voltage will be practically constant at approximately the maximum value induced in each coil. Just as one coil passes out of the position where its induced voltage reaches a maximum value, another coil begins to approach a position where maximum voltage is induced in it.

Figs. 12-17 and 12-18 show graphically how the voltage output of a direct-current generator becomes more constant as the number of armature coils is increased. Fig. 12-17 shows an elementary two-coil armature. Below the armature is a graph showing the fluctuating voltage waveform produced by one revolution of the armature.

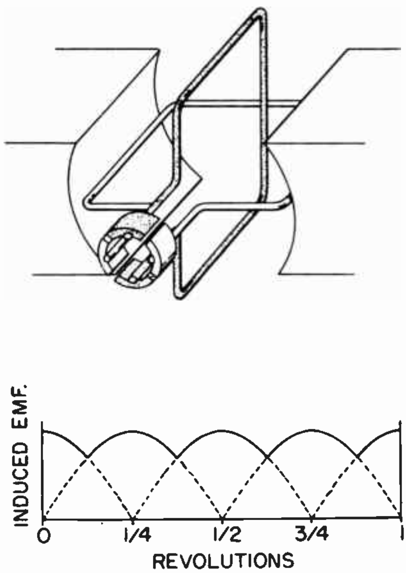


Fig. 12-17. An elementary two-coil armature and the fluctuating voltage waveform produced by it.

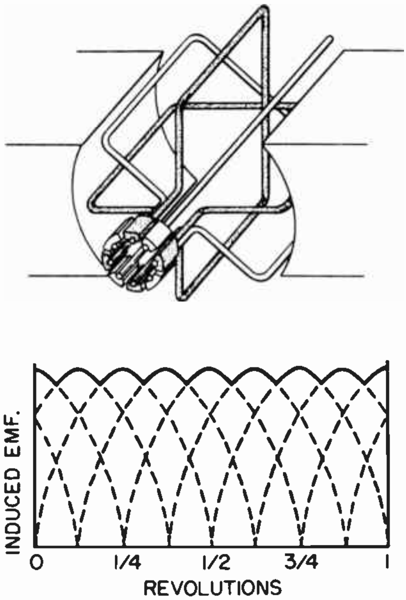


Fig. 12-18. An elementary four-coil armature and the fluctuating voltage waveform produced by it.

Fig. 12-18 shows an elementary four coil armature. In the lower half of the figure, a graph shows the fluctuating voltage waveform produced by one revolution of this armature. The same speed of rotation was used to produce the graphs shown in Figs. 12-17 and 12-18.

A comparison of the two graphs demonstrates clearly that increasing the number of armature coils of a generator produces a more constant voltage. The resultant waveform of each of these generators is shown by the solid black part of the graph.

From this observation, it is understandable why commercial direct-current generators have armature windings consisting of many coils.

THE MAGNETIC CIRCUIT

It should be understood that so far as we have progressed, our description of the operation of a DC generator has necessarily been sketchy. A great many mechanical details have been omitted in the interests of simplicity, so we could devote our entire attention to the electrical action.

One of the things barely touched upon in the introductory sections of this chapter was the path structure of the magnetic circuit. We merely indicated that a source of magnetism is necessary to generate electricity and let it go at that. In order to obtain any usable power from a generator, it is necessary to provide a magnetic path having the lowest possible reluctance. Since iron and other ferrous materials provide the best possible magnetic path, it is necessary to construct the field-frame and armature of steel to provide the low reluctance path needed.

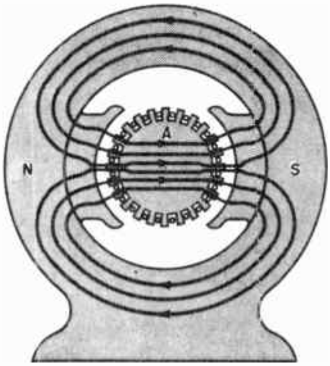


Fig. 12-19. The magnetic circuit of a generator or motor. The armature, the field cores, and the frame are all made of iron. The iron provides a low reluctance path for the magnetism.

Fig. 12-19 pictures the basic essentials of the magnetic path needed for a direct-current generator or motor. The magnetic path consists of the outer frame, the field cores, and the inner rotating armature. The armature is marked with an "*A*" in Fig. 12-19.

The magnetic field is produced between the north and south poles. Those poles may be energized in any of several ways. The lines of force emerge from the north pole, pass through the iron of the armature and back into the south pole. Within the frame, the lines of force move away from the south pole through the iron of the frame to the north pole.

The armature is free to rotate within the magnetic field and constitutes a very important part of the magnetic circuit. The entire magnetic circuit is of iron except for the very small air gaps between the surface of the armature and the faces of the poles. All, or nearly all, of the magnetic lines of force pass through the iron of the armature.

It is the general practice to cut slots lengthwise in the face of the armature in which to imbed the conductors of the armature coils. The slots in the face of the armature can be seen in Fig. 12-19. The little circles in the slots represent the conductors of the coils.

Since the iron of the core is a fairly good electrical conductor and is rotating in the magnetic field, one may wonder why a voltage is not induced in the iron as well as in the insulated conductors. A voltage will be induced in the iron! Electrical currents will flow in that iron and something must be done to minimize them. Such unwanted currents, called "eddy currents," will cause the iron of the core to become quite hot unless they are kept under control. See Figs. 11-7 and 11-8 of Chapter 11.

To prevent the eddy* currents from building up to a proportion where they cause unnecessary and dangerous heating of the armature iron and large electrical losses, the armature is built up of many thin slices (sheets) instead of a single piece. These thin sheets of iron that make up an armature core are called "laminations," and a core of this type is known as a "laminated core."

These laminations are insulated from each other in the armature core, sometimes by the coating of oxides formed on the surface of the steel sheets in their process of manufacture. Sometimes the laminations are dipped in varnish or other insulative coating before assembly.

If you ever work with DC armatures, you will see the laminations, and perhaps wonder why they are built up of these thin sections. The laminations reduce the *eddy currents* which would otherwise build up and cause overheating and electrical power losses. This laminated structure results in making the motors and generators run cooler. The laminations, therefore, help to increase efficiency by reducing the electrical losses in the motor or generator.

THE FRAME

The rotating armature in a generator or a motor revolves on a steel shaft to which it is fastened. The steel shaft passes through the center of the armature. The shaft hole is shown in Fig. 12-20. The shaft is supported by bearings, one at each end of the generator or motor in which it rotates. In the earlier

---

* An explanation of eddy currents is given in Chapter 11.

machines the bearings were usually made of bronze or babbit, but many of the newer machines employ ball bearings to reduce friction.

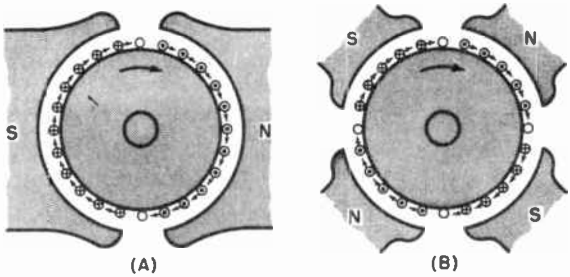


Fig. 12-20. Armatures used with a two-pole magnetic field and a four-pole magnetic field. The north and south poles of the magnets alternate around the armature.

The bearings are set into the "end bells." The end bells fit into each side of the frame and form the two ends of the motor or generator. Fig. 12-21 shows the position of one bearing with respect to the machine frame in partially assembled machine.

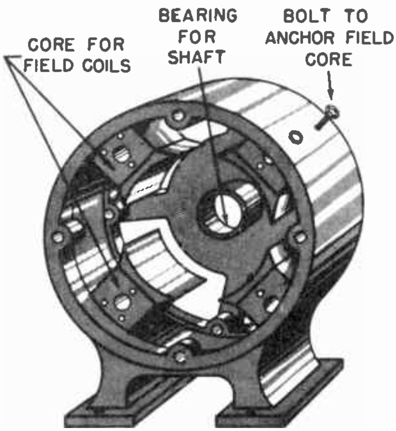


Fig. 12-21. The end bells and field cores are mounted on the frame. The bearings in the end bells receive the shaft on which the armature rotates.

From this, it can be seen that the frame acts as the skeleton upon which all the other parts of the generator or motor are assembled. The pole core pieces for the generator fields bolt to the inside of the frame ring as shown in Fig. 12-21. In many machines, especially the larger ones, these pole pieces are laminated in the same manner as are the armatures. In other machines, especially the smaller ones, the pole pieces are made in one piece.

Many generators, particularly those used in automobiles, have only two poles, one north and one south pole. A cross-sectional outline of such a generator can be seen in Fig. 12-20A. The field pole cores are usually shaped to fit snugly around the armature, as shown.

Most of the larger generators have more than two poles. Fig. 12-20B shows four magnetic field poles. Such a generator is called a four-pole generator. Note that the north and south poles are staggered alternately around the armature. Some of the very large generators that generate the power for the giant motors used in steel mills and other types of heavy industry have more than four poles. Six-pole generators are quite common in heavy industry; some of the very large machines have even more than six poles.

THE COMMUTATOR AND ITS BRUSHES

The commutator described earlier in this chapter is of the most elementary construction, but, although useful as a demonstrator it is not usable as part of a practical machine.

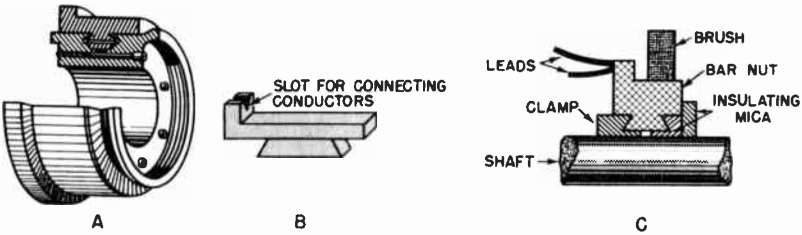


Fig. 12-22. The parts which go into the construction of a commutator.

From our study of the construction and operation of a generator, or motor, we have learned that the armature of a practical machine must have many more coils than the simple armatures shown in the illustrations. If such a practical armature has more coils, its commutator must have more segments than those shown previously. If it is a large machine, it will probably have a large number of commutator segments, similar to those shown in Fig. 12-22A. The physical construction of such a large commutator is also shown. The shape and construction of an individual segment is shown in Fig. 12-22B. Checking Fig. 12-22B with Fig. 12-22A shows how the individual segments of the commutator are held in place. Each of the segments is insulated from the others by mica insulation. One method of insulating the segments is shown in Fig. 12-22C. The clamp is a solid insulating material of some kind, usually mica. The brush riding on top of the segments of the commutator is also shown. The leads connected to the segment are the two ends of two separate coils imbedded in the slots of the armature.

Brushes which carry electrical current from the commutators of various DC generators and motors differ widely in their characteristics, construction, size, and appearance. (Most of them are from carbon, a few are made of copper.) The brushes used in the starting motors of automobiles are generally made of

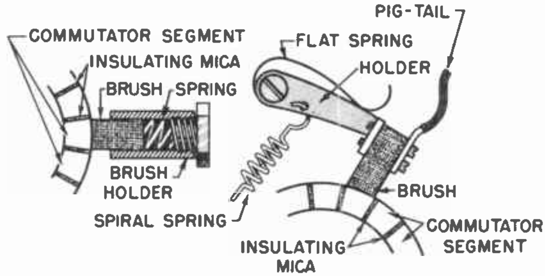


Fig. 12-23. How the brushes rest on the commutator. The brushes are held firmly against the commutator by spring tension. The individual segments of the commutator are separated from each other by insulating mica.

copper. Fig. 12-23 shows two types of carbon brush holders and how they rest on the face of the commutator.

THE MAGNETIC FIELD

In previous sections of this chapter, we have accepted the presence of a magnetic field without examining very closely its source. It is time that we give some attention to that field.

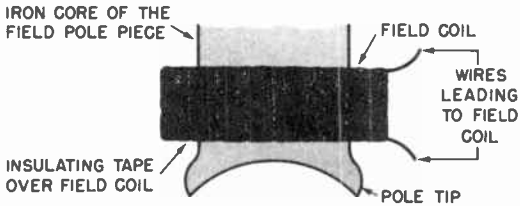


Fig. 12-24. How the field coil is mounted on the iron core.

The field of either a DC generator or a DC motor may consist of a simple permanent magnet or sometimes several permanent magnets. A few large generators have been built with permanent-magnet fields, and some are still in use. However, literally speaking, thousands upon thousands of small permanent-magnet generators and motors are being manufactured and used at present. For the most part, the pole pieces of DC generators and motors are magnetized by means of coils of wire through which a current flows. In that respect a generator field magnet is very similar to an ordinary electromagnet. Fig. 12-24 gives an idea of how such a coil looks when it is mounted on the pole piece. Sometimes the coil is actually wound right on the core of the machine. More often, however, it is wound to shape on a special coil-winding machine and then is wrapped with tape. Sometimes the tape is just ordinary friction tape, but generally it is a special tape used only for that purpose.

The coil of the field electromagnet may be wound with a few turns of very heavy wire, or it may be wound with many turns of very fine wire. This will depend upon its size, the manner in which it is to be energized, the voltage which will be used to energize it, and upon still other factors.

The magnetism created by the field coils will depend upon the ampere turns of their windings. The ampere turns, you will remember, are determined by the number of turns of wire on a coil and the amount of current that passes through it. A small current forced by a relatively high voltage through a large number of turns of fine wire has a magnetizing force equivalent to that of a large current forced through a few turns of heavy wire.

METHOD OF EXCITATION

Direct-current generators and motors are classed according to their field construction and connections as:

1. Separately excited (generators only).
2. Series wound.
3. Shunt wound.
4. Compound wound.

The electric current used to produce the magnetism in the field coils of a direct-current generator can be obtained from any suitable DC source.

If the current used in the field coils to "excite" the field is derived from some separate source, such as a battery or another generator, the generator is said to be "*separately excited.*" Generators used to generate large amounts of current for commercial purposes are often separately excited. There are certain advantages in such separate excitation which will receive more attention later.

Smaller generators, such as those found on automobiles and in small farm electric plants, are practically all "self-excited." In a self-excited generator, a small amount of the total current produced by the generator is fed back into the field coils of the generator and used to excite it.

The field coils of a generator may be self-excited in one of three ways. In one type the coils are connected so all of the current passes through the field coils. Such self-excitation is called "series excitation," and the generator is said to be a *series-wound* generator.

Fig. 12-25 shows how such a generator would be wound and the manner in which it would be connected to a load. An examination of the circuit shows that all the current produced by the

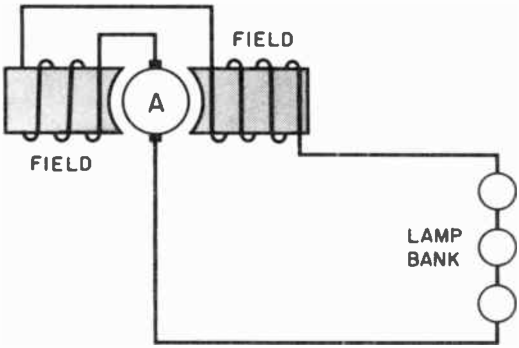


Fig. 12-25. Electrical circuit in a series generator. Note how the field coils obtain their exciting currents.

voltage generated in the armature must pass through the field coils before it can reach the lamp bank or load.

The voltage regulation (steadiness of voltage as load changes over its full range) of a series generator is not good since its field excitation depends entirely upon the generator load increasing as the load increases and decreasing as the load decreases. When the generator is driven at a constant speed, any increase or decrease of the load will result in its output voltage changing.

Another type of self-excited DC generator is called the *shunt-wound*. A diagram of the windings and connections of such a generator is shown in Fig. 12-26. The field winding of the generator is connected across the load shunting it. Thus, the full output voltage of the generator is across both the shunt windings and the load.

A good method of telling a series-wound from a shunt-wound generator is to examine the type of windings. Since the full-load current from a *series generator* must flow through the field windings, the wire used to wind series-wound field coils is usually very large and the winding has relatively few turns of this heavy wire.

In a *shunt-wound* generator, the full output voltage of the generator will be across the field. Unless the resistance of that field is kept quite high a large current will flow through it. For these reasons, the field coils of a shunt-wound generator are wound with a large number of turns of very fine wire.

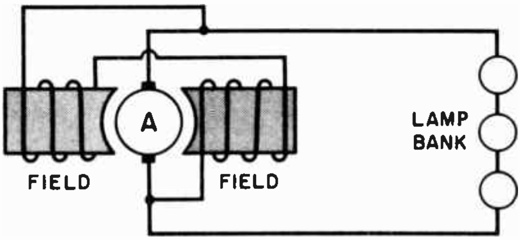


Fig. 12-26. Electrical circuits in a shunt generator. The field coils here are connected directly to the full output voltage of the generator.

The voltage regulation of a shunt generator is poor because an increase in load increases the voltage drop in the armature circuit and decreases the voltage applied to the field, thus reducing the generated voltage. The shunt generator is not used to any great extent except in automobiles, where the generated voltage is maintained at a fairly constant value by varying a resistance in the field circuit in a manner that will be explained later.

In addition to self-excited, series-wound, and shunt-wound DC generators, a fourth type, the *compound-wound generator,* is an interesting and very important type. The *compound-wound generator* combines the features of both the series- and the shunt-wound generator. It has both a series and a shunt winding on each of its fields. The shunt winding, made up of many turns of small wire, is connected in parallel with the armature. It functions to maintain a fairly constant field strength. The series winding, wound with comparatively few turns of large wire, is connected in series with the armature and generator load. This series winding is carefully designed so that it has exactly the right number of turns to offset the tendency of the output voltage to drop off as the strength of the shunt-field decreases with increasing load and to maintain the output voltage almost constant for any load within the rated limits of the generator.

The output voltage of any DC generator depends upon the following factors:

1. The speed with which the armature is rotated.
2. The strength of the magnetism in the field.
3. The physical construction of the machine itself; that is, the number of turns of wire on the armature, the dimensions of the armature, and several other things.

The speed of the armature rotation will control the output voltage of the generator to this extent:

1. The faster the armature is rotated, the more voltage the generator will produce.
2. The slower the armature is rotated, the less voltage the generator will produce.

The strength of the magnetic field, at any given speed, will affect the output voltage of a generator in the following manner:

1. The stronger the magnetic field, the higher will be the output voltage.
2. The weaker the field, the lower will be the output voltage.

Since DC generators are often operated at a wide range of speeds, as in the case of an automobile generator, and since the load on the generator will also often vary widely, it follows that some type of control must be provided to keep the output voltage fairly constant. It is not desirable to have the voltage high at one time and low at another.

One of the most common methods of regulating the output voltage of a DC generator is to control the strength of the field (magnetism). This can be done very easily by controlling the amount of current in the coils of the field magnets. One of the best ways to do this is to use a variable resistor in the field circuit of the generator. By varying this resistance, one can easily vary the amount of field current to increase or decrease the output voltage of the generator.

By selecting the variable resistance so that the normal setting is one-half the total resistance as shown in Fig. 12-27, one can either increase the resistance up to 50% above normal to reduce the voltage or can reduce it up to 50% below normal to increase the voltage. If this addition or reduction of resistance is made automatic, the voltage can be maintained at a fairly constant value over a wide range of operating speeds, and a wide variation in load (current drain).

It is fortunate that the output voltage can be controlled so readily, for it makes the DC generator readily adaptable for use in automobiles and other applications where the speed and load are subject to such wide variations.

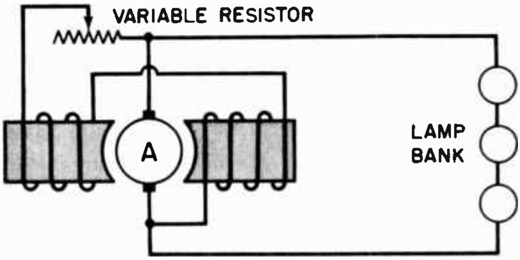


Fig. 12-27. The strength of the field magnetizing current in a shunt generator can easily be controlled by inserting a variable resistor in the field circuit.

Usually the output voltage of an automobile generator is controlled by a device called a "voltage regulator." It automatically cuts resistance into the field circuit of the generator when a large output is not needed, and it also cuts out that resistance when the demand on the electrical system increases.

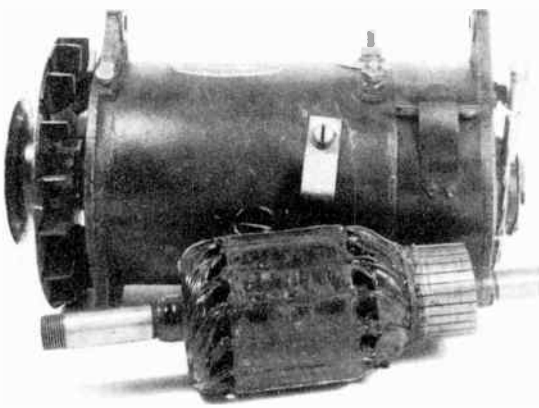


Fig. 12-28. An automobile generator. This is a common type of DC generator.

More DC generators are used in the electrical systems of automobiles than in all other applications put together. Fig. 12-28 shows what such a generator looks like. A generator in a modern automobile must withstand terrific abuse. Not only must it operate over a very wide range of speed and with a wide variety of loads, but it is also exposed to the terrific heat from the automobile engine, to abuse by the careless owner who neglects to service it regularly, and to outside temperatures ranging from sub-zero to near boiling. What a wonder that the generator does not give more trouble than it does. Its reliable performance is a

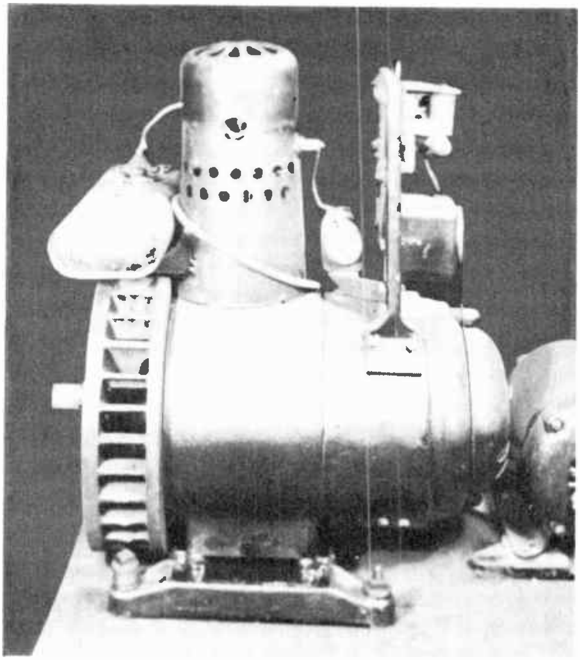


Fig. 12-29. A 32-volt electric generating plant intended for home use in remote areas where commercial power is not available.

tribute to the high degree of engineering design and craftsmanship which goes into the construction of the modern automobile generator.

Another type of DC generator which is still familiar to many persons on isolated farms, remote from commercial electricity, is the 32-volt electric plant. The Delco Electric Co. built tens-of-thousands of such farm electrical systems, many of which are still giving faithful service. The recent expansion of rural electrification is rapidly rendering them obsolete. Fig. 12-29 shows one of the older Delco systems still found in many rural localities and isolated areas of this country.

DC MOTORS

There are numerous places in industry where DC motors are still used. Such motors have a versatility that cannot be equalled by any type of AC motor yet invented. Many attempts have been made to design AC motors which could take over some of the special tasks still reserved for the DC motors, but without success.

One of the principal advantages of DC motors is the ease with which they can be controlled over a wide range of speeds. There are many places in industry where such a wide range of speeds is necessary. DC motors possess another tremendous advantage over most types of AC motors. This is their ability to start tremendous loads, loads that no AC motor of similar capacity could possibly start.

For the most part, it is only in industry that we still find large DC motors. Most of the motors found in our everyday lives, those on refrigerators, washing machines, power tools and the like, are AC motors. The starting motor used in our automobiles is the one big exception, for it is always a DC motor.

The physical construction of a DC motor is almost identical to that of a DC generator. In fact, almost without exception, a direct-current generator can be used as a DC motor or a DC motor as a DC generator. The above statement is correct but it deserves some modification. Although a DC motor or generator can be used as either a motor or a generator; a DC machine is usually designed to be only a motor or a generator and is not intended to function as both.

Perhaps you have used a DC generator to charge a storage battery. After you charged the battery for a period of time, and shut off the power to the AC motor, you were probably surprised to see the motor and generator continue to run. The generator had ceased to function as a generator and was being driven by the battery as a motor, thus driving the AC motor instead of being driven by it. In other words, the generator, which was designed for a generator, was then operating as a motor.

Types of DC Motors—All DC motors fall into three general types: the *series* motor, which is similar to a series generator; the *shunt* motor, which is similar to the shunt generator; and the *compound* motor, which is a cross between the series motor and the shunt motor with some of the best characteristics of each.

Fig. 12-30 shows the electrical connections for a series motor. Characteristics of this motor make it stand out from all other types. It is characterized principally by its enormous starting torque. At the instant of starting, a series motor is capable of

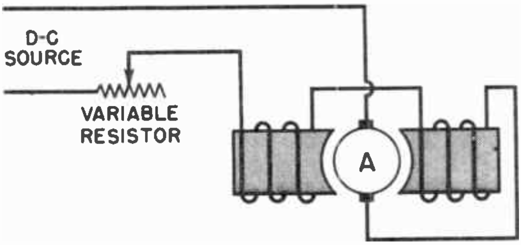


Fig. 12-30. A DC series motor can be controlled by inserting resistance in the circuits leading to the motor. The voltage drop across the resistance tends to reduce the voltage to the motor, thus slowing its speed.

exerting an enormous amount of energy (torque) to start a very great load. Because of this feature, the DC series motor has been adopted for use on streetcars, interurban trains, hoists, and the giant cranes used around steel mills and in heavy industrial applications. It can start a streetcar on a steep hill, where almost

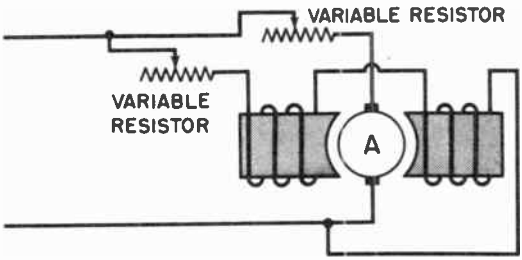


Fig. 12-31. Direct-current shunt motors can be controlled by inserting variable resistance in either the armature circuit or in the field circuit. Many shunt motors use variable resistances in both circuits to obtain even greater control than either alone can give.

no other kind of motive power—electric, steam, or animal could budge it.

This ability led to the adoption of the DC series motor as the standard starting motor for automobiles. In virtually every automobile today is a little series-motor, the sole purpose of which is to start the gasoline engine. That this little electric starter motor can start a big gasoline engine from such a small power source as a storage battery is a wonder, but its action is so reliable that we take it for granted and scarcely give it a thought. About the only time any of us become aware of the existence of this starting motor is when it fails to start the engine.

Fig. 12-31 shows the electrical connections for a DC shunt motor. The electrical connections for such a motor are essentially the same as those used with a shunt generator. In fact, almost any shunt generator could be used as a shunt motor.

The physical construction of the shunt motor differs from that of the series motor. In the series motor the wire in the field coils is very large, equal to or larger than the wire on its armature; while the wire used to wind the field coils of the shunt motor is quite small.

The shunt-wound motor will not start nearly so heavy a load as will the same size series motor; but it has a characteristic, ease of speed control over a wide range, that is very important. Its speed can be controlled over a wide range by varying the current through either the shunt fields or through the armature. Often variable resistors are placed in both the field and armature circuits of shunt motors, one serving to slow down the motor and the other to speed it up. In machine work, in production factories, and other places where it is necessary to operate machines at widely varying speeds, the DC shunt-wound motor has no equal. Where an absolutely stable speed is essential for the proper operation, as printing presses, the DC motor is usually selected.

A direct-current motor has a commutator and brushes just as does a DC generator. These brushes and the commutator sometimes require attention, as they gradually wear down until they must be replaced.

The starting motor of an automobile generally, uses copper brushes. Since the motor is not used more than a few seconds at a time, the copper brushes are not subjected to excessive wear. Being copper, they wear rather rapidly if subjected to much usage. Copper dust from them sometimes collects within the brush-rigging of the motor and partially short-circuits the commutator bars. Evidence of this trouble is sluggish action of a starting motor that has seen considerable service. Disassembling the motor and cleaning it with carbon tetrachloride will correct this trouble and make the (starter) motor work like new again.

Normally, the carbon brushes in the generator will wear down much more rapidly than the copper brushes in the starter. This is because the generator brushes are in constant use all the time the automobile is operating. The generator brushes should be replaced about every 10,000 to 15,000 miles. There is no economy in trying to get the last mile of wear out of them. It is wiser to replace them soon after they begin to show definite signs of wear. If they are left in too long, there is a possibility they will wear too much, cease to make good electrical contact with the commutator, and cause sparking to develop. If sparking develops, the generator will still operate, but the sparking will soon wear rough spots in the commutator. If this progresses too far, you will have to have the commutator "turned down" on a lathe to "true" it up again. Sparking causes low spots or "pits" to develop in the face of the commutator, which will be lower than the rest of the commutator, and the sparking will become progressively worse. Soon the brushes will be bumping up and down in the brush-holders, and the sparking will become so severe that there is danger of actually burning out the coils on the armature.

Probably the worst thing that can happen to a generator is to burn out one or more coils on the armature. There are several causes for this. Sparking is one, but not the most frequent. The most frequent cause of armature burn out is failure of the voltage regulator. If that occurs, there is virtually no control over the amount of current in the coils of the armature. Continuous use of the car, with such a heavy overload on the generator, causes the armature to get so hot that the solder which fastens the coils to the commutator bars can actually melt and fly out. Often the insulation on the conductors of the windings is burned off completely.

Chapter 13

AC GENERATORS AND MOTORS

WHERE ALTERNATING-CURRENT MACHINES ARE USED

Alternating-current generators are used to generate alternating voltage and current. The generators, which are more often called *alternators* than generators, are always driven by some type of prime mover. Such a prime mover may be a gasoline or diesel engine; it may be a steam turbine or steam engine; it may be a water turbine driven by a head of water from a power dam; or it may be something else, even a windmill.

In contrast to direct-current generators, alternators are nearly always built in large sizes, but there are a few exceptions to this, as in some of the late model 115 volt AC farm alternators. Generally speaking, the larger the size, the greater the operating economy. This is one of the reasons why most consumers prefer to buy their electric power from utility companies rather than to generate their own. The power companies with their larger machines can usually generate and distribute the electric power at less cost than the consumer could generate it.

We do not find any small counter-parts in alternators as we do in DC generators used in automobiles. Probably the nearest approach to such counter-parts are the relatively small alternators which are being installed in the newer railroad passenger cars to operate the fluorescent lamps and the passengers' electric shavers. Even so, these alternators are many times larger than DC generators in automobiles, and certainly they are not so numerous. Special types of alternators are used in some kinds of aircraft, but these are usually very special types.

Since most alternators are very large, there are many electricians who have never actually come into first-hand contact with one or perhaps even seen one. Except for those installed in large central generating plants, the only kind of alternators the electrical beginner is likely to find is one of small size which has been developed during recent years for use on the farm or in other isolated locations. Such a unit is shown in Fig. 13-1. Because the "high-lines" began spreading out through the rural areas about the same time these individual power plants were perfected, there are relatively few of them in general use. Probably the principal use of such power plants is for standby service—to take over in case something happens to the normal source of power. In remote areas when storms interrupt the commercial power, it may take a week or more to restore services; so these plants are often used to take over the load in case the regular power lines go out.

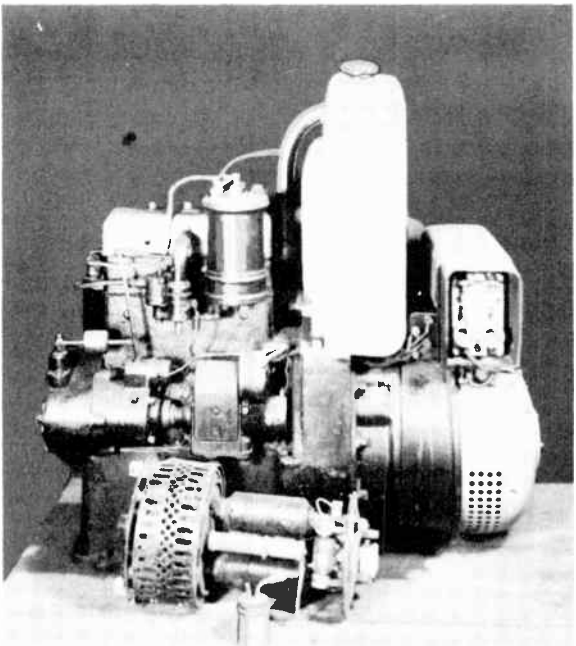


Fig. 13-1. A 110 volt alternator of the type that is sometimes used on farms.

The basic electrical fundamentals which make possible the generation of alternating current were described in Chapter 12. Fig. 12-12 and 12-13 show how the voltage is induced, first in one direction, within the coils of the revolving armature, and then in the other direction. For each pair of magnetic poles in this simple alternator, there will be two reversals of the voltage for every revolution of the armature. Since alternating current reverses twice during each cycle, our two-pole elementary machine will produce one complete cycle each time the armature turns through one revolution.

To carry this reasoning a little further, the armature would have to revolve 60 times in a second to produce an alternating current which had a frequency of 60 cycles, such as is commonly used in most of our homes. An alternator with only two magnetic poles would have to have the armature driven at the rate of 3600 revolutions per minute to generate alternating current with a frequency of 60 cycles per second.

There is a simple equation which can be used to determine the frequency produced by any alternating-current generator (alternator).

This equation is:

$$f = P \times \frac{N}{60}$$

where,

f = frequency (cycles per second).
P = number of pairs of poles of the alternator.
N = speed (revolutions per minute).

The 60 is derived from the fact that there are 60 seconds in one minute. All we need do to find the frequency is multiply the number of pairs of poles by the speed of the armature in revolutions per second.

Since it is desirable to tap off the alternating current which flows within the conductors mounted on the revolving armature, we do not use a commutator on an alternator. Instead, we use slip rings, which were described in the preceding chapter.

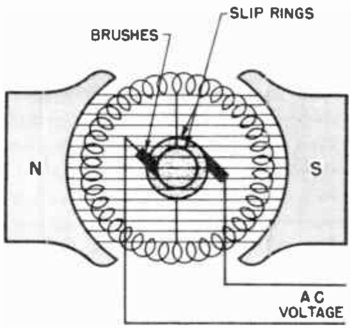


Fig. 13-2. How slip rings are used to pick up the current from a two-pole alternator.

The revolving armature used with an alternator is usually somewhat different from that used with a direct-current generator. Fig. 13-2 shows the action in an alternator. The coils of the armature are connected so they make a continuous circuit. As any coil rotates in the magnetic field, created by the field magnets, the voltages and currents will rise and fall and reverse within the rotating coil. The coil is tapped at two electrically opposite points, and these taps are connected to the slip rings. This is all clearly shown in the diagram. The voltage and the current flow which results from rotating the armature are transferred to the brushes which ride on the slip rings. The power is taken from the brushes to the external circuit.

Alternating current machines differ from their DC counterparts in still other ways. Most DC machines, you will remember, can be used either as generators or as motors. This is true despite the fact that they have been designed to operate as one or the other.

In AC machines, however, such is not the case. A few alternating current machines can be used as either an alternator or as a motor, but this certainly is not true for the majority. The more common types of AC motors, for example, could not be used as alternators. In fact, very few types of AC motors will function as generators.

There are far more AC motors in general use than there are DC motors, and there is a much greater variety of them. Direct-current motors are restricted to three general types; however, in the case of AC motors, there is a large number of basic types. Each type has been developed to meet some specific need.

In the industrial world we find such types of AC motors as: the three-phase induction motors, probably the most widely used of all; the wound-rotor motor; the synchronous motor; and several other types of heavy-duty motors. In addition, there are the smaller split-phase motors; capacitor motors; repulsion-induction motors; and a variety of combinations. The universal motor, which runs well on either AC or DC, is used to power such things as electric shavers; electric hand drills; food mixers; and similar small electrical devices. There are additional types of AC motors, such as the hysteresis motor, the shaded pole motor, and various miniature types.

Obviously, it is impossible to go into a detailed explanation of all these various types of motors in a text of this nature. Such detailed treatment may be found in a book written by authors dealing exclusively with motors and generators. Many of the motors mentioned are used only in industry and are installed and maintained by professional electricians. Still others are used only in commercially manufactured equipments and, for this reason, are seldom encountered.

Besides such specialized types, there are types of AC motors which many of us use every day. These are the motors which power our circular saws, drill presses, and other power machinery; they operate our refrigerators, washing machines, oil burners, coal stokers, and the many other things around our homes and businesses. An understanding of how these motors operate is useful to anyone in this age of electricity.

ALTERNATORS

The induction of a voltage in a conductor occurs when the conductor cuts across a magnetic field or when magnetic lines of force move to cut across a conductor. When a voltage is induced in a conductor, it makes little difference whether the conductor is moved or the field moves. Either action will induce the voltage.

Fig. 13-2 shows the principal components of one kind of alternator. There we see a pair of magnetic poles, a north and a south, between which a strong magnetic field exists. The coils of the armature are wound on the iron core (not shown) and revolve within this field. The armature revolves within the magnetic field in the same manner as does the armature in a DC machine. Actually, this type of elementary alternator would have an armature and winding as shown in Fig. 12-5 of Chapter 12; however, the "Gramme-ring" type of winding is used here and the steel core omitted to simplify the schematic drawing.

Instead of the voltage and current being tapped from the coil of the armature by means of a commutator as they were in the DC generator, here they are tapped by a pair of brushes riding on slip rings. The two slip rings are connected to the windings at positions diametrically opposite each other.

The voltage generated by such a machine will depend upon the winding, the speed with which the armature rotates, and the strength of the magnetic field. The frequency of this voltage will depend upon the speed with which the armature rotates and upon the number of pairs of poles.

Since the speed with which the armature rotates determines the frequency as well as the voltage of the alternator, it is not a general practice to vary the speed. It is usually held constant within close limits.

If the speed cannot be varied, any variation in the voltage generated by the machine will have to be corrected by varying the strength of the magnetic field. Any control over the output voltage must, therefore, be accomplished by changing the strength of the magnetic field.

In Fig. 13-3 we see the manner in which the field and the armature of a four-pole alternator are wound. The field poles are magnetized by causing direct current to flow through the field windings.

Because this machine has twice as many poles as the machine shown in Fig. 13-2, its armature would have to revolve only one-

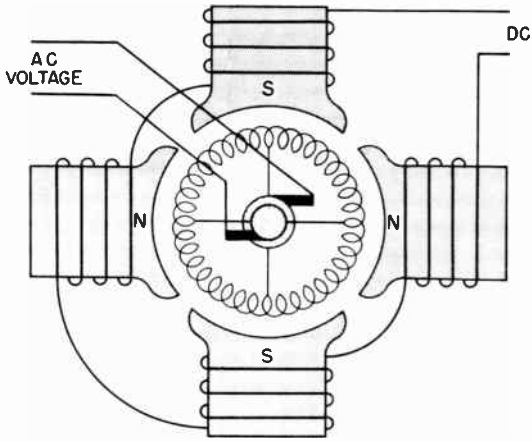


Fig. 13-3. A four-pole alternator with rotating armature.

half as fast to produce the same frequency. In the machine shown in Fig. 13-2, each part of the armature passes under the influence of one north pole and one south pole during each revolution of the armature to produce one complete cycle of generated AC voltage for each revolution of the armature. In the one shown schematically in Fig. 13-3, each part of the armature winding passes under the influence of a north pole twice and under the influence of a south pole twice during each revolution. Since it passes under the influence of these poles alternately, there will be two complete cycles of AC voltage produced for each revolution of the armature.

Instead of one pair of poles, as in Fig. 13-2, or two pairs, as in Fig. 13-3, alternators are often built with many pairs of poles. Whereas a machine with one pair of poles must have its armature revolving at the rate of 3600 revolutions per minute to generate 60 cycles per second. The same machine, with two pairs of poles, would have to revolve only 1800 revolutions per minute to generate 60 cycles per second. If the machine had three pairs of poles, it would have to revolve at only 1200 revolutions per minute to generate a voltage of 60 cycles per second. The frequency of the voltage generated by an alternator can be found by use of the equation which was given previously:

$$\text{Frequency} = \text{No. pairs of poles} \times \frac{\text{Speed in revolutions per minute}}{60}.$$

As the size of the machine increases, it is desirable to use more pairs of field poles. This permits the large machines to revolve at relatively slow speed, yet generate the same frequency as faster machines having fewer poles.

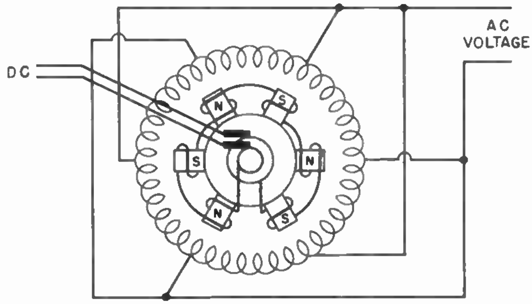


Fig. 13-4. A six-pole alternator with the armature wound on the stator, or frame, of the machine.

So far, we have spoken only of alternators which have revolving armatures. These represent the earliest types of alternators. Today, we do not find many alternators in which the armature revolves. Only a few of the smaller sizes are so constructed.

In modern alternators the armature is mounted stationary on the frame, and does not rotate. Instead, the field poles are mounted on the shaft and revolve inside the armature windings. Fig. 13-4 gives an idea of how the revolving fields rotate on a shaft inside the stationary armature.

The armature windings in which the AC voltage is induced are mounted on a stationary frame. Because these windings do not move, it is possible to use much larger and heavier wire than could be used if they were mounted on a rotating armature, as in the case of DC generators. It is also easier to wind many more turns on the stationary frame than on a rotating armature; therefore, a much higher voltage can be generated with a machine in which the armature is stationary instead of rotating.

There are other advantages in having the armature of an alternator stationary. Since there is no movable contact between the armature conductors and the lines leading to the external load, losses produced where the load current must pass from collector rings through brushes, are eliminated.

The field coils are energized with direct current. There will be as many pairs of poles as are necessary to give the desired frequency at the speed at which the machine is driven. Machines with twelve, sixteen, or even twenty-four pairs of poles are not uncommon. There are many machines in operation today which have fifty pairs of poles. Such machines turn slowly, requiring only 72 revolutions per minute to generate 60 cycles per second.

The direct current needed to energize the field coils is brought into the rotating member of the machine through a pair of slip rings. One of the slip rings is connected to the positive side of the DC source and the other to the negative side.

The diagram in Fig. 13-4 shows all the fields coils connected in series with each other. A machine, at least an experimental machine, could be designed to operate in this manner. However, the general practice is to connect each field coil directly to the slip rings. Because the coils are all connected in parallel, each coil has the full voltage of the DC source across it.

Alternators, with the field coils revolving within the armature as shown in Fig. 13-4 are being built in unbelievably huge sizes. The Commonwealth Edison Company in Chicago has such an alternator in their Fisk station capable of generating 100,000 kilowatts. At this writing they have under construction others which are even larger. Alternators, of even greater size are installed in the generating plant at the Grand Coulee Dam in the state of Washington.

Some of the very small alternators, especially those which have the armature revolving as in Fig. 13-3, often have a commutator mounted alongside the slip rings. When the alternator is so constructed, some of the voltage generated by the armature can be taken off the commutator in the form of direct current. This DC can then be used to energize the fields of the machine, causing it to operate as a self-excited alternator.

Such machines are relatively rare on the ground; but they have taken to the air by the thousands in our bombers, fighter planes, and commercial aircraft. Practically all airborne electronic equipment requires a source of one or three phase, 120 volt AC power. Among these are radio transponders, radio compass, radio jammers, radar search sets, and numerous others.

Machines that are a combination of a DC motor and AC alternator are known as *inverters*. They have a common armature which is equipped with both a commutator and slip rings. A small inverter, requiring 28.5 volts DC at 12 amps input and having an output of 115 volts AC, three-phase, 115 watts at a frequency of 400 cycles per second, is smaller in size and less in weight than the average automobile generator. A large inverter which requires 28 volts DC at 60 amperes puts out 115 volts AC at 10.4 amperes, single-phase, at a frequency which is variable from 800 to 1400 cycles. They are manufactured in capacities of 40 watts to 1500 watts approximately; for input voltages of 12, 24, and 28 volts DC; with output voltages of 80, 115, and 120 volts AC; and power outputs of 40 volt-amperes to 1500 volt-amperes. There are two standard output frequencies available, 400 and 800 cycles per second and two phases, single- or three-phase output. It should be mentioned here that the components used for stabilizing the frequency and output voltage over the range of input voltage normally encountered require an additional volume for their housing that amounts to about one-half the inverter's volume; and they weigh approximately one-fifth the inverter's weight. These regulating devices are housed in a cigar-box shaped metal box mounted on top of the inverter, which, in turn, sits on a flat base plate. This metal box also contains noise-supression networks for both input and output circuits, which filter out the electrical noise, commonly known as "hash," that is highly undesirable in electronic and radio circuits.

Quite a few gasoline engine driven alternators in the 10 to 50 kw sizes are found in telephone offices, telegraph offices, hospitals, radio stations, etc. Some of these alternators have been in constant readiness for use for many years, yet have never been used except for occasional tests. They stand ready to take over at a moment's notice should the regular source of power fail.

The telephone companies installed thousands of these auxiliary alternators in the early days of World War II. The army, the government, and the civil defense authorities were keenly aware of the importance of the telephone systems. They knew the chaos that would result if an enemy bomb should hit a central power generating station or otherwise disrupt electrical service. To prevent telephone service from being disrupted at the same time, and thus making matters even worse, alternators were installed for emergency standby service.

Other examples of the small self-excited alternators are those intended for use on farms and other remote places far from high-line power sources. Since it is a very simple matter to changeover from the small AC home generator to the power line when the high-line does reach the farm, alternating current generators of this kind are often preferred to the better known 32-volt DC systems. It is not so easy to changeover from 32-volt service because the insulation of such service is not usually suitable for 110 volt use, the 32-volt lamps cannot be used on 110 volts, and the 32-volt DC radios are difficult to convert for use on 110 volts AC.

Many farmers, resort keepers, remote summer hotels, and other places have an auxiliary alternating-current power plant at hand to take over in the event the regular source of power fails. Some of them are arranged to take over the load automatically in case of power failure and to operate so quickly that an uninitiated person is scarcely aware anything has happened to the regular source of power.

KINDS AND TYPES OF ALTERNATING CURRENT MOTORS

Since alternating current has become the predominant type of electrical power in this country, many kinds of motors have been invented to use that power. Many have been developed to meet specific needs and are used in only one or two applications. Others have characteristics which make them useful for many purposes.

In this book we shall examine the basic types of AC electric motors and find out how and why they run. We shall also examine the qualities which make some motors different from others.

By far the most important AC motor is the induction motor. Modifications of the induction motor are used for many purposes. Nearly all AC motors which operate from single-phase AC power are forms of the simple induction motor.

The Induction Motor—From a strictly physical point of view, an induction motor is very simple in construction. It consists of a metal frame, a shaft which rotates in a pair of bearings mounted in the frame, a rotor which is called a "squirrel cage" mounted on the shaft, and a magnetic field. A cut-away view of an induction motor is shown in Fig. 13-5. The horizontal shaft is clearly visible where it extends beyond the end-bell of the motor. The bearings at each end of the shaft can also be seen. The rotating member, mounted on the shaft, is sometimes called the "rotor" or the "squirrel cage." It can be seen near the center of the picture. Very close to the rotor, encircling but not touching it, are the magnetic field cores on which the field coils are wound.

Simplicity of construction is one of the things which has made the induction motor so universally popular. There is very little to get out of order in an induction motor. Because there is no electrical connection between the power source and the rotating member (rotor) of the motor, the chance of anything going wrong with the motor is greatly reduced.

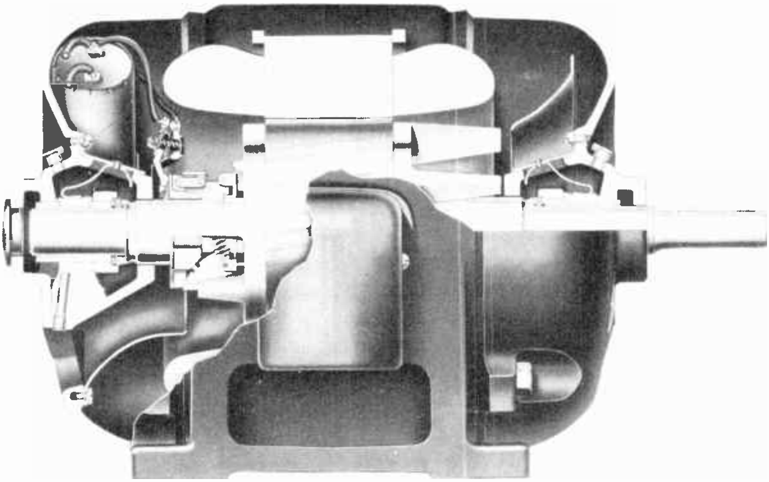


Fig. 13-5. Cutaway view of a single-phase capacitor motor. (Courtesy of General Electric Co.)

So long as the bearings are oiled occasionally and the motor is not seriously overloaded, the induction motor will run indefinitely with little or no additional attention. It has the added advantage that there is no danger of sparking since it doesn't have a commutator or slip rings. This makes it possible to use the motor in dusty or gaseous locations where other kinds of motors might touch off an explosion with their sparks.

Although an induction motor is physically simple in construction, its electrical action is quite difficult to understand. Many who have studied electricity do not fully understand just how the induction motor operates.

There are various types of single-phase induction motors. At one time, many two-phase induction motors were used, but today the two-phase induction motor is obsolete, it having been supplanted by the three-phase power now used almost entirely throughout the United States.

The induction motor is virtually a constant-speed machine and in this respect is somewhat like the direct-current shunt motor. The stationary member of the induction motor is called the *stator* and corresponds to the field structure of the shunt motor. The rotating member is called the rotor and corresponds to the armature of the shunt motor. The current in the armature windings of a direct-current motor is conducted to them through the commutator segments by way of the brushes. The current in the rotor windings of an induction motor is induced in them (by transformer action) by the alternating magnetic fields that are set up by currents in the stator windings. The operation of an induction motor is due to the interaction between the rotating magnetic field of the stator winding and the magnetic field which is produced by currents set up by induction in the rotor.

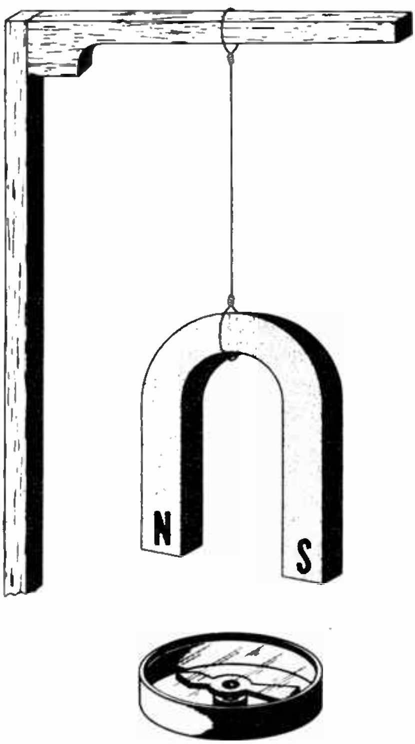


Fig. 13-6. An elementary demonstration to show the principle of a rotating magnetic field.

The principle of a rotating magnetic field can be shown by a horseshoe magnet suspended above a compass in the manner shown in Fig. 13-6. By spinning the magnet one can easily twist the string from which the magnet is suspended. If the horseshoe magnet is held stationary on the twisted string while the compass needle is placed directly beneath the ends of the magnet, we have a simple device for demonstrating a rotating magnetic field. When the horseshoe magnet is released, the twisted string will impart a torque to turn the magnet. The magnetic field produced by the revolving magnet will cause the compass needle to revolve with the rotating field and, in effect, we have a type of elementary rotating magnetic field motor. Although the rotor (compass needle) does not turn (revolve) because of a current due to induction, it does turn due to the rotating magnetic field produced by the turning permanent magnet. This illustration should convey some idea of a rotating magnetic field, although the rotating magnetic field in an induction motor is produced somewhat differently, as you will presently see.

In an induction motor the rotating magnetic field is produced by electromagnets instead of permanent magnets. The electromagnets (stator windings) of an induction motor are stationary; therefore, means must be provided to produce a magnetic field which rotates about the ends of the electromagnetic poles within the stator core.

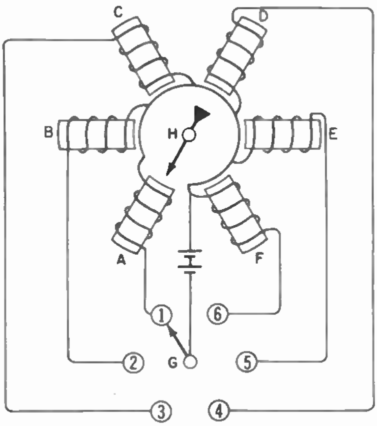


Fig. 13-7. A simple method to show how a rotating magnetic field can be produced.

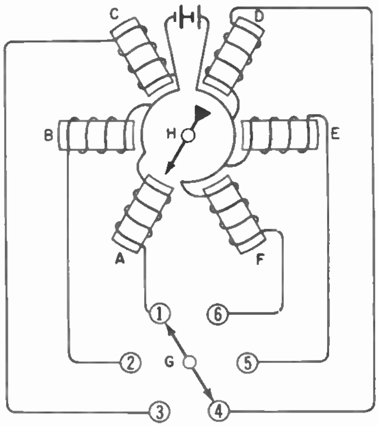


Fig. 13-8. This is a modified arrangement of Fig. 13-7 to show the principle of a rotating magnetic field.

A simple means of producing a rotating magnetic field by the use of electromagnets is shown in Fig. 13-7. In this instance, the rotor (magnetic needle) H will move from pole to pole as the controller arm G is moved from point to point on the contacts 1, 2, 3, 4, 5, and 6. The battery current energizes electromagnets A, B, C, D, E, and F one after the other as the moving controller arm G closes their circuits by touching contacts 1, 2, 3, 4, 5, and 6 in succession.

A more efficient means of producing a traveling (rotating) magnetic field is shown in Fig. 13-8 which depicts a modification of the circuit shown in Fig. 13-7. In this modified circuit, the rotor (magnetic needle) H follows the rotating magnetic field

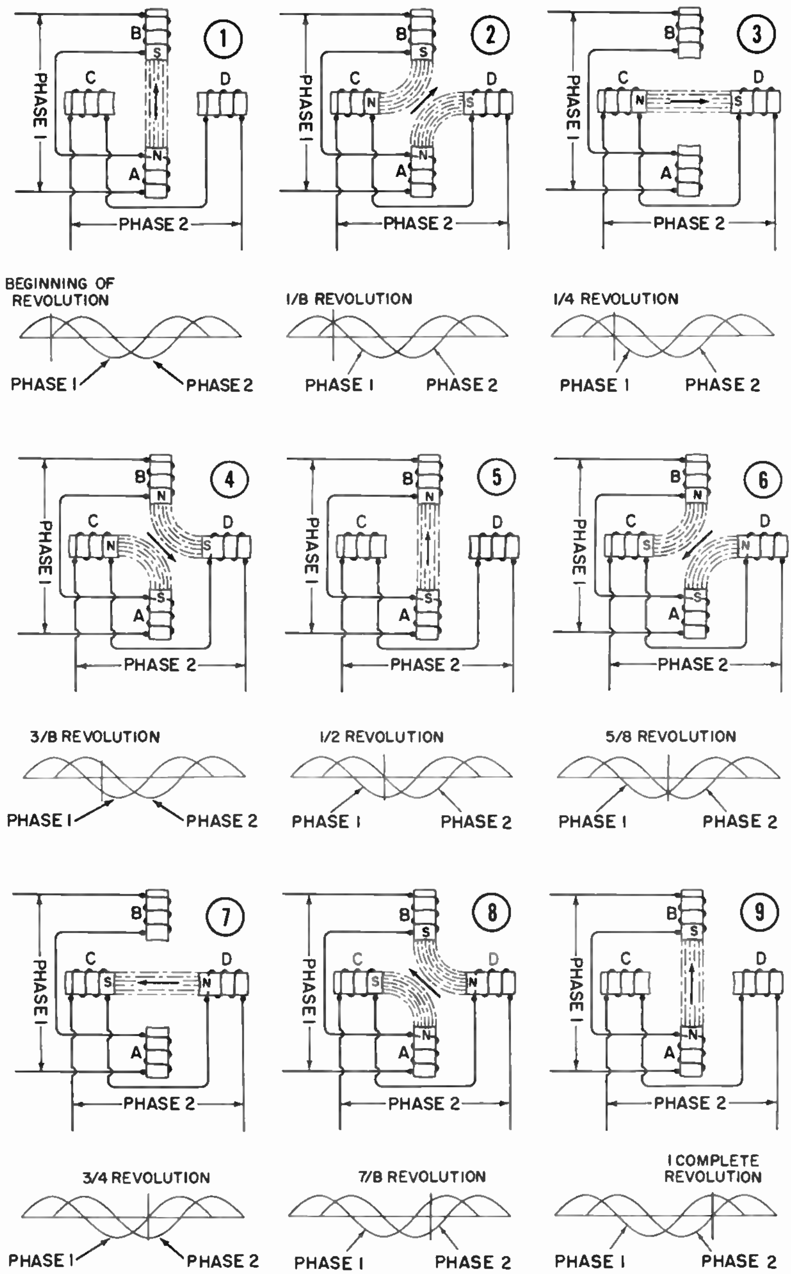


Fig. 13-9. Showing how a two phase current can produce a rotating magnetic field.

produced within the stator as controller arm G passes over contacts 1, 2, 3, 4, 5, and 6. In this modification, the battery current, instead of flowing through one electromagnet at a time, now flows through two diametrically opposite windings for each position of the controller arm.

The illustrations shown by Figs. 13-7 and 13-8 demonstrate how a magnetic field may be made to rotate about the poles of a motor stator without any physical movement of the electromagnets.

Each of the two schemes shown requires physical movement for shifting the current from winding to winding in order to make the magnetic field rotate. In an induction-motor stator, this shifting of the magnetic field is accomplished without physical movement by applying two or more currents that are out-of-phase with each other, or by means of two or more sets of stator pole windings, each of which produces a magnetic flux that is out-of-phase with the magnetic flux produced by the other set or sets of windings.

Fig. 13-9 shows how a two-phase current may be used to produce a rotating magnetic field. In a two-phase circuit the current in one phase is minimum (zero) at the same instant that the current in the other phase is maximum. For illustration, in Fig. 13-9 when phase 1 is maximum, phase 2 is minimum. You will note that there are 9 positions of the rotating magnetic field shown in Fig. 13-9. In position 1 the current in phase 1 is maximum but is zero in phase 2. The graph of the current wave is shown just below the stator in each of the 9 positions. From position 1 the strength of the current in phase 1 decreases as that in phase 2 increases until, at position 2, the currents in each phase are equal in value as shown. During the next one-eighth revolution ,the current in phase 1 decreases to zero, while the current in phase 2 increases to its maximum as shown in position 3 of the drawing.

Between positions 3 and 4 of the figure, the current of phase 1 increases while that in phase 2 decreases until, at position 4, the currents are equal but of opposite polarity causing the magnetic flux to shift to the position and in the manner shown in position 4 of the figure. From 4 to position 5, the current in phase 1 increases to a maximum, while the current in phase 2 decreases to zero. From position 5 to 6 the current of phase 1 decreases while the current of phase 2 increases until, at position 6, the currents are again equal and have the same polarity, producing a flux as shown in position 6. From 6 to 7, the current in phase 1 decreases to zero, while the current of phase 2 increases to maximum. The resultant flux for this condition is shown in position 7.

At position 8 the currents in the two phases are equal but of opposite polarity and so produce magnetomotive forces that are equal and opposite. The resultant flux shifts to the position shown in 8 of the figure. From position 8 to 9, the current in phase 1 increases to maximum and the current in phase 2 decreases to zero. This completes one cycle, position 9 being identical to the condition we had at the beginning of the cycle in position 1, this completing one revolution of the revolving magnetic field.

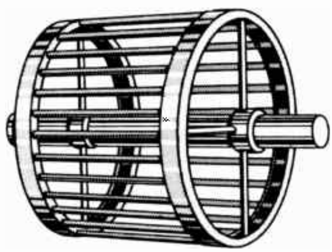


Fig. 13-10. An elementary squirrel cage rotor.

From the foregoing, it is easy to see how a compass needle would be turned or revolved in the rotating magnetic field produced by the two-phase stator; but commercial induction motors do not have a magnetic needle or other type of permanent magnet for their rotor. Instead, they have a rotor consisting of many bars of copper, aluminum, or other metals having good electrical conductivity; all short-circuited at their ends. Fig. 13-10 pictures a simple induction rotor structure made up of copper bars and shows how they are short-circuited together at their ends by copper rings. The appearance of this type structure has given it the name, "squirrel cage" rotor.

While an elementary squirrel cage rotor, such as shown in Fig. 13-10, would actually rotate if placed in a rotating magnetic fiield, it would not function efficiently. The turning torque of an induction motor depends on the amount of energy that is transferred from the stator field to the rotor by induction. The low efficiency of this elementary rotor permits it to receive very little energy from the stator field by induction; therefore, its turning torque is very small. The inefficiency of the elementary induction rotor shown in Fig. 13-10 is due to the great amount of reluctance the magnetic field encounters because no magnetic material is used for a rotor core to transfer the magnetic field flux through the rotor conductors.

To increase the efficiency of this energy transfer between stator and rotor, it is necessary to decrease the magnetic reluctance of the rotor structure to a minimum. This is accomplished by constructing the rotor of material which has a good magnetic conductivity (low reluctance) and imbedding the squirrel-cage conductors in it.

It is commercial practice to make induction rotors of laminated steel punchings. One type of rotor punching used in a squirrel-cage induction motor rotor is shown in Fig. 13-11. The rotor

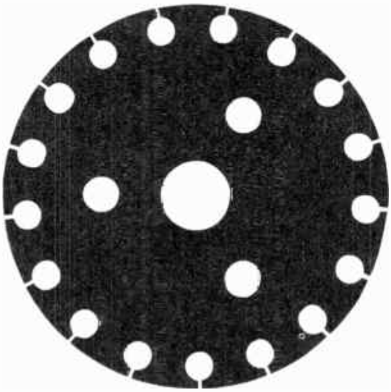


Fig. 13-11. A rotor punching for use in the rotor of an induction motor.

Fig. 13-12. A commercial type of squirrel cage rotor for an induction motor.

laminations are assembled into a stack to make a core of the desired thickness, and the rotor conductors are placed in the holes or slots of the punchings. The ends of the conductors are then short-circuited together, usually by conductive rings. Fig. 13-12 shows a squirrel cage induction rotor.

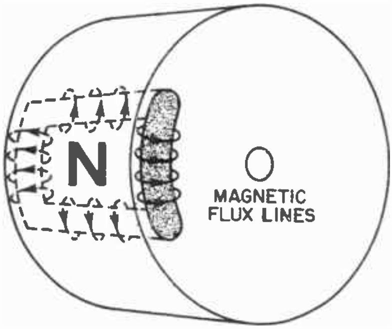


Fig. 13-13. How a current, induced in a short-circuited inductor of a squirrel cage rotor produces a magnetic field about itself.

To give some idea of how a voltage is induced in the squirrel cage rotor let us refer to Fig. 13-13. In this drawing, a phantom view shows two conductive bars imbedded within the rotor structure, their ends short-circuited. Actually, in any rotor, there are many conductive bars short-circuited together at their ends; but in this drawing only two bars are shown to simplify the structure so that the action occurring in any one closed circuit within the rotor can easily be seen. This short-circuited loop forms a single one-turn rotor coil in which an induced current will flow when the loop is placed within the influence of one of the pole pieces of the alternating-current stator.

The phantom view shows magnetic lines of force circling about this rectangular secondary. It is this interaction between the magnetic fiield produced by the rotor short-circuited (secondary)

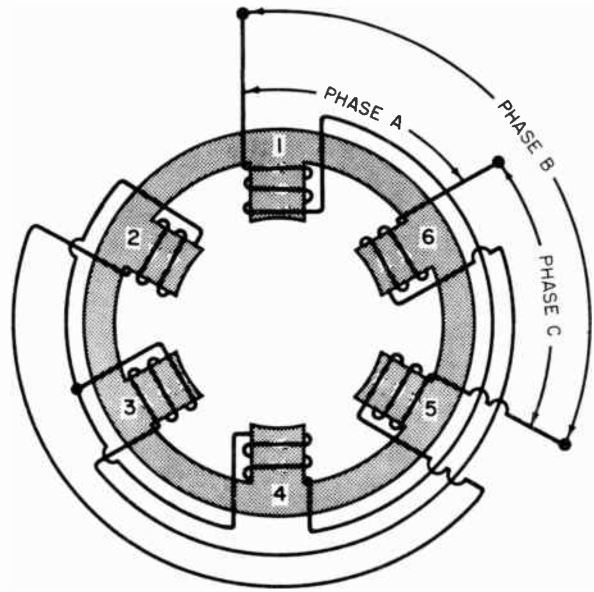


Fig. 13-14. The windings of a three-phase field, showing how the lead wires from the windings are brought out.

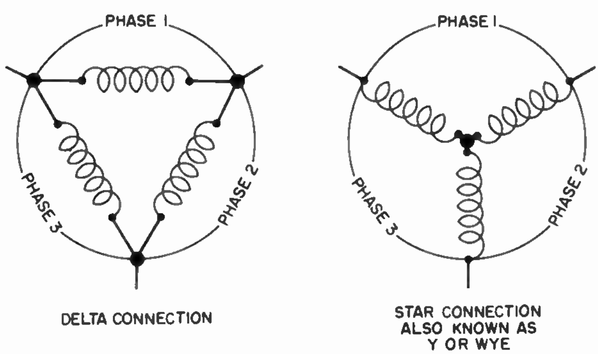


Fig. 13-15. Two methods of connecting a three-phase motor stator winding.

windings and the magnetic field produced by the stator (primary) windings that develops the rotor torque in all induction motors, single phase or polyphase.

A three-phase induction motor operates from a three-phase AC line. The three lines carrying the AC power connect to the field coils of the motor. The directions in which the field coils are wound and the manner in which the lead wires from the windings are brought out are shown in Fig. 13-14.

When the field coils are wound as shown in Fig. 13-14, the winding is known as a three-phase star-connected stator winding. In addition to being known as a "Star" winding, it is probably more often referred to as a "Wye" or simply "Y" connected winding. Fig. 13-15 schematically shows two methods of connecting a three-phase motor stator winding. In Fig. 13-15A, the windings of each of the three phases are delta connected; Fig. 13-15B shows the three windings star or wye connected. In a delta connection, the three windings form a triangle shaped like the Greek letter delta (Δ).

Fig. 13-16 show the motor stator field-polarity for certain instants of time with relation to the current change through the windings for one revolution of the magnetic field. The drawings show current direction and stator polarity for each one-sixth revolution of the rotating field. Below each stator is pictured the waveform of the three currents for the instant shown. The stator polarity is also indicated at the end of the stator poles for the instants of time at each one-sixth revolution of the magnetic field.

A study of the current values in the graph of Fig. 13-16A shows that the current of phase A is zero, while the currents of phase B and C are equal in value and opposite in direction; the resultant polarity of the field is as shown for this particular instant of time. If the direction of current of phases B and C through coils 2 and 5 are checked carefully it will be seen that the magnetomotive forces which they would produce separately would be equal and opposite at this particular instant of time because the currents are equal and opposite; therefore, poles 2 and 5 have zero magnetization at this instant.

Fig. 13-16B shows the direction of current flow through phases A and C one-sixth of a cycle later than that of Fig. 13-16A. At this instant the current flow is zero through phase B as shown by the graph of this figure.

Fig. 13-16C through G inclusive, show the progressive changes of field polarity that occur during the remainder of one complete revolution of the rotating magnetic stator field.

Although the polarities shown in the figures are all of equal strength or intensity for the instants of time represented, the

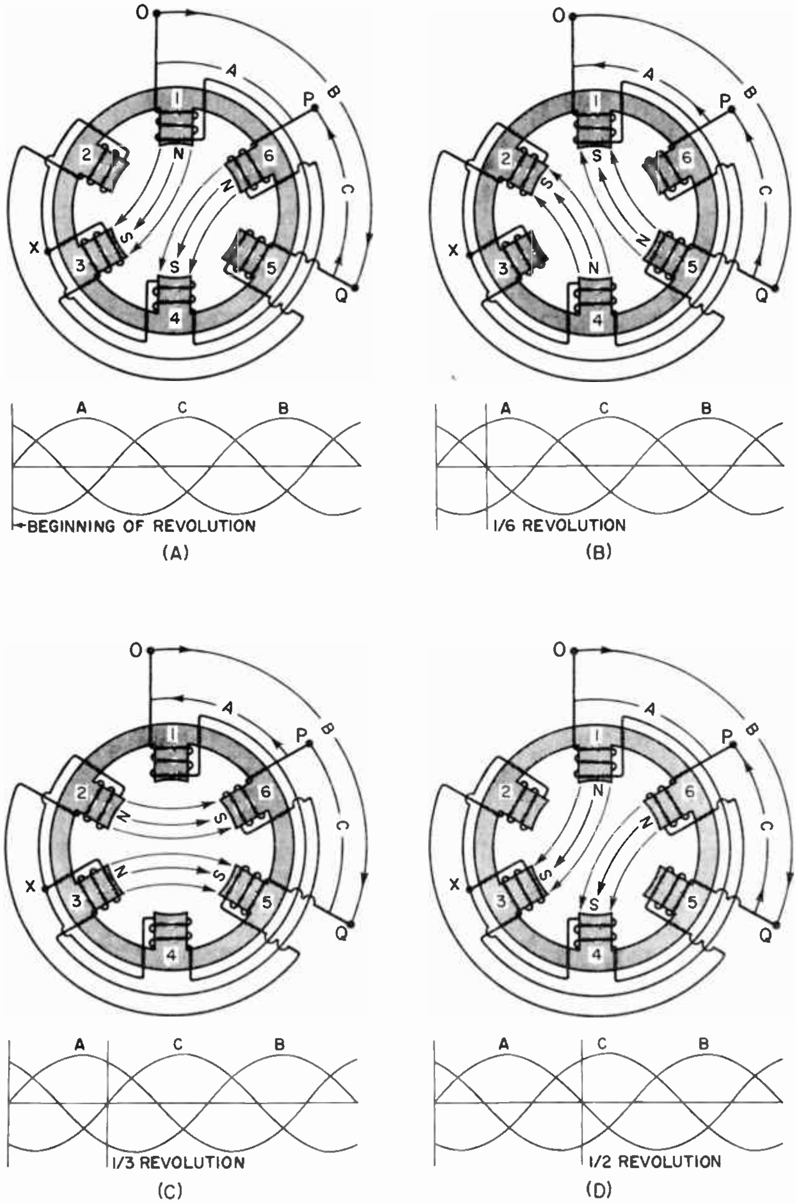
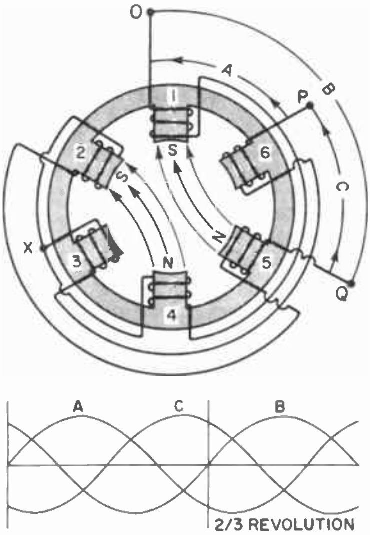
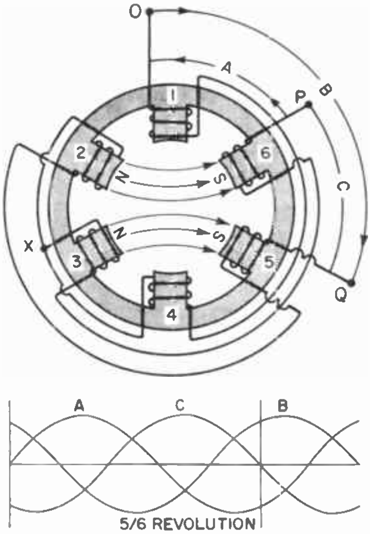


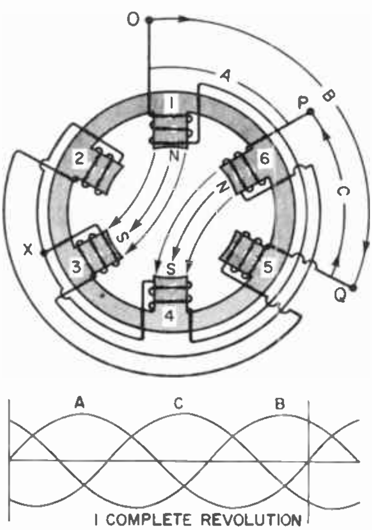
Fig. 13-16. How the rotating magnetic field shifts



(E)



(F)



(G)

or rotates within the stator of a three phase motor.

field strength of the various poles are changing constantly in the intervals of time between each one-sixth revolution of the field.

To further explain, let us (by means of illustration) subdivide the interval of time between the instants shown in Figs. 13-16A and 13-16B into three smaller intervals. The result of this subdivision first shows the field polarity at the beginning of the cycle. (See Fig. 13-17A.) Fig. 13-17B shows the individual magnetomotive polarities 1/18 (1/3 of 1/6) revolution later. Fig. 13-17C shows the magnetomotive polarities at the end of 1/9 revolution. Fig. 13-17D shows the polarity at 1/6 revolution of the field. An analysis of the change in field intensity and polarity is quite important and well worthwhile for the reader. The rotating magnetic field produced by a three-phase current is seldom thoroughly understood by even advanced students of electricity. During each revolution of the field the various stator poles are continually increasing and decreasing in strength as well as changing their polarity

In order to analyze more clearly how the rotating magnetic field is changing during the one-sixth revolution of the field shown by Fig. 13-17 let us trace the direction of current flow through the field winding for each separate and individual phase.

In order to compare the field polarities of the individual poles, we may take as a basis of comparison, the length of the ordinates* (of the three-phase sine waves) as current values at the instants shown. These values are shown at the upper left side of Figs. 13-17A, 13-17B, 13-17C, and 13-17D. The ordinate of phase A at the instant shown in Fig. 13-17A is zero. The ordinates of phases B and C are as shown; but in order to keep the letters indicating polarity at a reasonable size, only one-half the length of each ordinate is used, as indicated by the center division mark on each ordinate line shown at top of the figures. In other words, to keep our letters of reasonable size we have scaled the ordinates down by one half.

Figs. 13-17A and 13-17B shows the polarities and their proportional intensities that would be produced by each phase taken singly, at the instant shown, by the graph at the bottom of the figure below. Actually, it would be best to represent these polarities as magnetomotive forces because two unlike polarities can not exist in a single pole simultaneously such as shown at poles 2 and 5 of Figs. 13-17A and B. However, a single mag-

* An ordinate is the value that specifies distance in a vertical direction on an ordinary graph.

netic polarity may result if two magnetomotive forces are *unequal* and in opposite direction. The polarity in such instance would be the result of subtracting the smaller magnetomotive force from the larger.

The small letters (A, B, and C) in Figs. 13-17A, B, C, and D located beside the respective polarities indicates the current phase producing them. Since the magnetomotive forces produced by the currents in the windings of poles 2 and 5 at the instant shown in Fig. 13-17A are equal and opposite, the resultant polarity of the poles is zero. In other words, the magnetomotive forces cancel each other and poles 2 and 5 are left unmagnetized at this instant as shown in Fig. 13-17E.

If we subtract the magnetomotive forces produced by each phase through the windings indicated at Fig. 13-17B, the resultant polarity they produce is shown in Fig. 13-17F for the instant shown in the graph at the bottom of the figure for 1/18 rotation of the field.

In a similar manner the magnetomotive forces of the three-phase currents tend to produce polarities as indicated at Fig. 13-17C and D; however, when the magnetomotive forces produced by the instantaneous currents through the windings of the various poles are in each instance added or subtracted as the case may be, the resultant polarities are as indicated at G and H of Fig. 13-17 for the instant indicated by the graphs.

Our analysis of the magnetic field as it rotates shows that for each instant of flow of the three-phase current there is a constant shifting of the field and constant changing of magnetic intensity about each pole of the stator. This is shown clearly by Figs. 13-17E, F, G, and H. The windings on the various pole pieces of the motor have been so arranged that the changing currents cause a rotating magnetic field to be set up by the various pole pieces when the three-phase alternating current goes through its alternations. This magnetic field continues to rotate (shift) so long as the three-phase AC power is connected to the terminals of the field coils.

This rotating magnetic field plays a vital role in the operation of the three-phase induction motor. Due to the manner in which the currents flow in the three windings and the direction in which the coils are wound, the magnetic field is made to rotate around and around the poles. This rotation is due solely to a magnetic action. The invisible magnetic field rotates just as surely as though one could see it; however, no physical move-

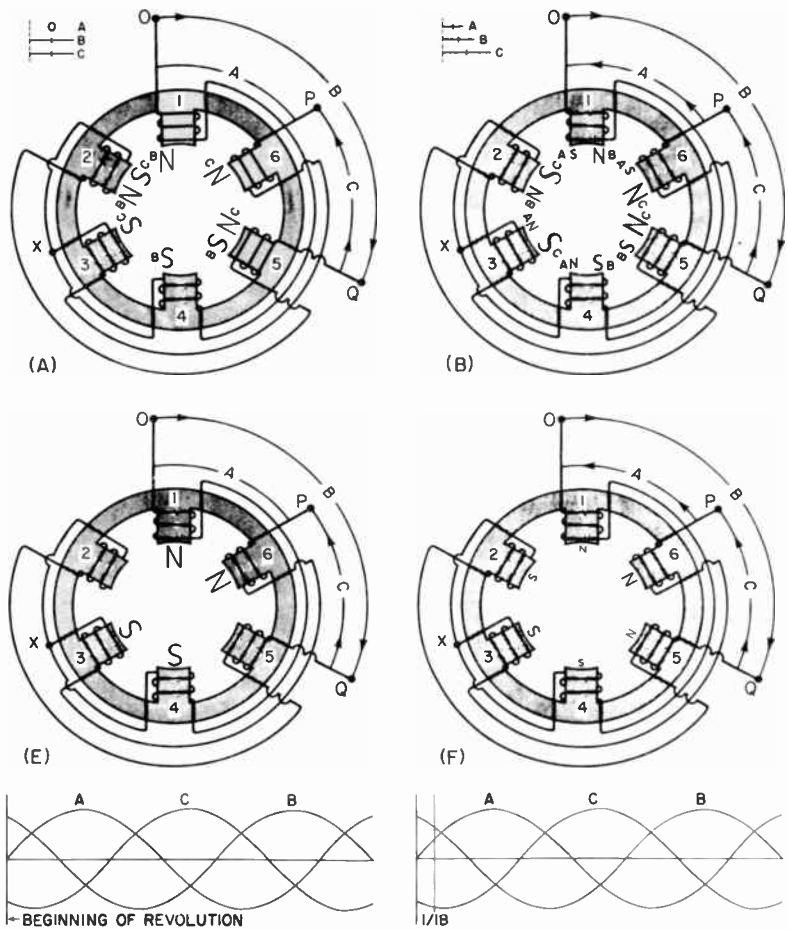
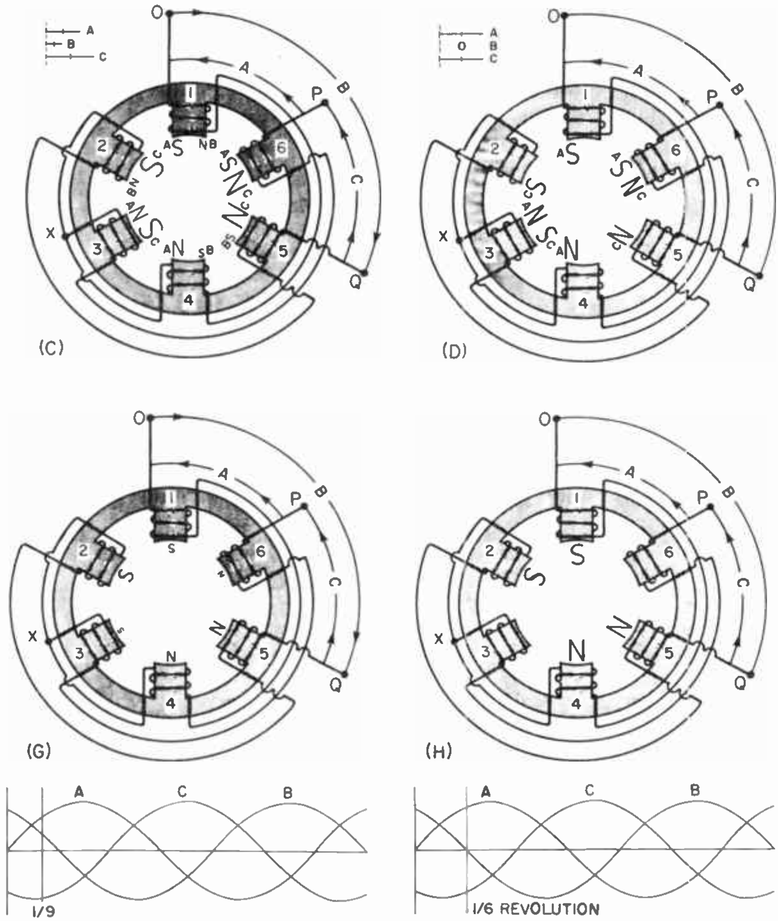


Fig. 13-17. Showing how the polarity of a three-phase

ment of the poles occurs, nor does the frame of the motor move. One important fact which should not escape our attention is that the lines of force within the magnetic field are constantly moving, moving in a revolving or rotating manner. If an electrical conductor is positioned within the magnetic field, a voltage will be induced within the conductor. If the conductor is part of a closed circuit, a current will flow.

Suppose we give our attention again to the squirrel cage shown in Fig. 13-10. If that squirrel cage were constructed of copper bars connected together at each end, we should have a circuit made of good electrical conductors closed at each end.



revolving field changes during one-sixth revolution of the field.

Now, if the squirrel cage were positioned inside the poles of the motor field shown in Figs. 13-14, 13-16, and 13-17 so the lines of force of the rotating magnetic field cut across the copper bars of the cage, a voltage would be induced within those copper bars. This induced voltage would cause a current to flow within the bars and through the end rings at the end of the bars.

The current that flows would be very large for two reasons. First, the large copper conductors would offer very low resistance. Second, the turns-ratio between that stator winding (primary) of many turns and the squirrel cage (secondary) winding of a single-turn would have a very large, step-down ratio; therefore, the short-circuited rotor bars would have heavy short-circuit currents flowing in them due to transformer (induction) action.

The rotating magnetic field would induce a voltage in the squirrel cage, and would cause a current to flow. This induced current would produce a magnetic field of its own, which would interact with the original rotating magnetic field. The result would be that the squirrel cage would revolve on its shaft in the same direction as the rotating magnetic field.

The squirrel cage could never rotate quite as fast as the magnetic field. If the magnetic field were rotating at 3600 rpm, the squirrel cage would rotate at about 3450 or 3500 rpm. If the magnetic field were rotating at 1800 rpm, the squirrel cage would rotate at about 1725 or 1750 rpm.

The speed of rotation of the revolving magnetic field in an induction motor may be found from the following equation:

$$\text{revolutions per minute} = \frac{120 \times \text{Frequency}}{\text{Number of motor poles}} \text{ or,}$$

$$\text{rpm} = \frac{60 \times \text{Frequency}}{\text{Number of pole pairs}}$$

where,

Frequency = cycles per second.

The speed of the revolving field in a two-pole induction motor operating on 60 cycles is:

$$\frac{120 \times 60}{2} = \frac{7200}{2} = 3600 \text{ revolutions per minute.}$$

This is known as the synchronous speed. The speed of the rotor of an induction motor is *ALWAYS* somewhat less than the synchronous speed of its rotating magnetic field.

The difference between the speed of rotation of the magnetic field and that of the rotor is called "slip." It usually amounts to from 5% to 10% of the speed of rotation of the magnetic field. It is this "slip" in rotor speed that produces the torque in an induction motor. If the rotor speed were exactly equal to that of the rotating field, the two would be in step and no voltage would be induced in the rotor conductors since they would not be in a changing magnetic flux, and consequently no current would flow in the rotor to produce torque.

In a motor it is desirable to have the best magnetic path possible between the pole pieces that are mounted on the frame of the motor. Since iron provides a good magnetic path, it is usually employed for that purpose. That is the reason the copper bars of the squirrel cage in Fig. 13-10 are imbedded in the iron "rotor" of the motor. Although the rotor of an induction motor is similar to the armature of a DC motor, they are by no means identical. They both rotate; and both do so under the influence of magnetic forces.

The appearance of the rotor of an induction motor can be seen if we examine Fig. 13-5. It is the rotating member which is mounted on the shaft. The copper bars of the squirrel cage, which are imbedded in the iron, can be seen in that photograph. The end rings are the heavy rings of metal at each end of the rotor which have large vanes extending from them. These vanes catch the air and aid in ventilating the motor.

The three-phase AC induction motor employs the principles involved in the operation of many other motors. Most of the single-phase motors which are used to power our refrigerators, oil burners, washing machines, and power tools are merely modifications of the three-phase induction motor. We shall discuss these types of motors in more detail a little later in this chapter.

The Synchronous Motor—A synchronous motor is an alternating-current motor which has a definite speed relation between its rotor and the frequency of the current applied to it. When every movement of one thing coincides exactly with every movement of another, then we say that their movements are synchronized. A synchronous motor is a motor which rotates at the same speed as the alternator (generator) that supplies its current, provided of course, that the motor and the alternator have exactly the same number of poles. At any rate, a synchronous motor will rotate at the same speed as the alternator that supplies its current, or at some multiple of that speed, depending upon the relationship of the number of poles of the alternator and motor.

Direct current is generally required for the field excitation of the synchronous motors used in commercial and industrial power application; however, there are millions of small synchronous motors which operate on single-phase alternating current.

Basically, a synchronous motor embodies many of the principles of other electric motors. Its wires, coils, and other parts are arranged to produce an interaction between two or more magnetic fields. This interaction, in turn, produces a torque which causes the rotating member to revolve.

This basic principle underlies the action of every type of electrical motor. It is the varying ways in which their coils are wound and the varying ways in which the magnetic interaction is set up that causes one motor to differ from another.

In the synchronous motor, a series of fixed magnetic fields are necessary. Those fields are generally produced by a series of rotating electromagnets mounted on the shaft. The rotating member of most AC machines is called the "rotor." This is true even when that rotating member could be classified as the "field" or as the "armature." Throughout the remainder of our discussion, the part that rotates will be termed the rotor. Fig. 13-18 gives an example of the use of the term, rotor.

The stationary part of most AC machines is called the "stator." This is true despite the fact that the stator winding could also be correctly called either the "field" or the "armature."*

These various ways of naming the parts of a motor sometimes tend to confuse the beginner in electrical work. However, a little experience soon shows that these names do fit very well.

Perhaps a brief review will prevent confusion. In the DC machines, the field poles are mounted on the frame of the machine. This means that the magnetic fields do not change their polarity during operation; they are permanently mounted and remain stationary. For these reasons, the term "field" in a DC motor or generator always refers to the stationary part mounted on the frame of the machine.

The part of a DC motor in which the magnetism is constantly changing from instant to instant is called the armature. The armature is almost always mounted on the shaft and rotates. All of this means, of course, that in a DC machine, the field is always permanently mounted on the frame and is stationary, while the armature is mounted on the shaft and rotates.

In AC machines, we have a different situation. The part of the machine in which the magnetism is changing from instant to instant, which roughly corresponds to the armature of a DC machine, may be mounted either in the frame or on the shaft. The same applies to the part of the machine in which the magnetic polarity does not change from instant to instant. It may

---

* The armature of a rotating machine is the member in which a voltage is generated or induced. The armature oftimes revolves, but in many instances it is the stationary member of the rotating electric machine.

be mounted either in the frame or on the shaft. To avoid confusion over terms it has become standard practice to refer to the stationary magnetic coils of an AC machine as the "stator" and to the rotating member as the "rotor."

There is yet another fact favoring the use of the terms "stator" and "rotor" in speaking of alternating-current machines. In the induction motor, you will remember, the alternating current from the power lines was applied to the coils wound on poles mounted on the frame of the machine. Since the coils of this magnetic field are stationary, they are properly called the "stator." The magnetism within the rotating member of the machine is not stationary. The rotor current is induced by the changing magnetic field of the stator. It is because of this fact that the current, and thus the magnetic polarity, of the rotor are always changing. In this case the term "rotor" applies very well, since the rotating member could hardly be thought of as the "field."

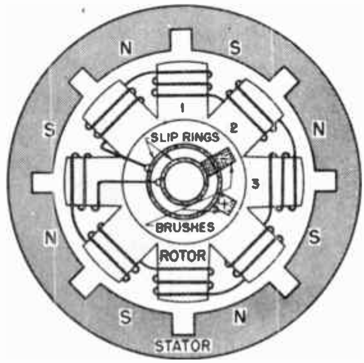


Fig. 13-18. The rotor and stator of a synchronous motor.

In the drawing in Fig. 13-18 the rotating member of the motor consists of eight poles. These poles are energized by direct current which is conducted to the pole windings by slip rings. The eight rotor poles shown are alternately north and south. Their polarity does not change from instant to instant as they revolve.

The eight rotating poles are mounted on a central shaft so they can freely rotate within the magnetic field of the stator. You will note there are slots in the frame of the motor. These slots are for the wires which create the magnetism in the stator poles when an alternating current is applied to the pole windings. The wires are not shown in the illustration. Instead, their magnetic polarity at some given instant is shown marked on the poles in the frame.

It should be kept in mind that the magnetism of the poles mounted in the frame will change from instant to instant as the alternating current changes from instant to instant. This means that the poles, marked "north" for the instant shown in the illustration, will change and become "south" an instant later when the current from the power line reverses its direction of flow. This action will continue, over and over, so long as the coils in the frame of the motor are connected to the line.

Note that the pole marked 1 on the rotor is midway between the N and the S poles of the frame in the illustration. It is quite obvious that the pole will be either "north" or it will be "south," depending upon the direction of the DC current flowing through the windings from the slip rings.

If the DC slip rings are connected so that pole is "north," there will be an interaction between it and the poles on the frame. The north pole of the rotor will be repelled by the north pole on the frame and will be attracted by the south pole on the frame. This means that the rotor will move, under the influence of the magnetic forces, to align itself with the south pole. Note also that a similar action is taking place with all the other poles around the rotor.

At that same instant pole 2 will be "south," if pole 1 is "north." Note also that there will be an interaction between pole 2 and the two adjacent poles on the frame. This interaction will also be such as to cause the rotor to move toward the right at that point or in a clockwise direction.

The rotor will move, but while it is moving, the current in the coils mounted on the frame is changing. By the time pole 1 on the rotor has moved in a clockwise direction until it is under the frame pole marked "south" that frame pole will be changing polarity. It will be north instead of south. Instead of it now attracting rotor pole 1, it will repel that pole.

The original momentum imparted to the rotor by the previous magnetic interaction will have carried pole 1 past the center of that frame pole, so that by the time the frame pole has changed polarity and starts repelling rotor pole 1, that interaction would keep the rotor continuing to move in a clockwise direction.

While that action is taking place between pole 1 and the adjacent frame poles, a similar action is taking place between each of the other rotor poles and its adjacent frame poles. The cumulative effect of all this magnetic interaction is to keep the rotor rotating in a clockwise direction so long as the current applied to the coils in the frame is alternating.

Now here is an interesting thing about a synchronous motor. The rotor will move the distance from one frame pole to another with each alternation of the applied AC voltage from the power line. It will move the distance of two frame poles during each cycle of the voltage from the AC power line. It will move exactly that distance—neither more nor less.

All of this means that the speed of the synchronous motor depends directly upon the frequency of the applied AC line voltage and the number of poles in the motor. Its speed is neither greater than that of the rotating magnetic field nor is it less. The synchronous motor is, in fact, a constant-speed motor. Its speed cannot be varied so long as the frequency of the AC supply current to the motor is constant.

The synchronous motor is not a self-starting motor. It has to be brought up to synchronous speed before it will lock in step with the magnetic field which is rotating around the stator of the motor.

There are many ways in which the synchronous motor can be started. A small DC motor may be used to bring it up to synchronous speed. A small induction motor may be used. These methods are used with some of the older and larger synchronous motors.

Most of the newer types of synchronous motors have squirrel-cage rotor bars imbedded in the face of the rotor poles. These rotor bars and their short-circuiting end-rings are often referred to as "amortisseur" or damper windings. In the case of poles 1, 2, and 3 shown in Fig. 13-18 the bars would be imbedded across the face of the poles, positioned parallel with the shaft. Fig. 13-19 shows how these bars are imbedded in the pole faces of a synchronous motor which has a larger number of poles.

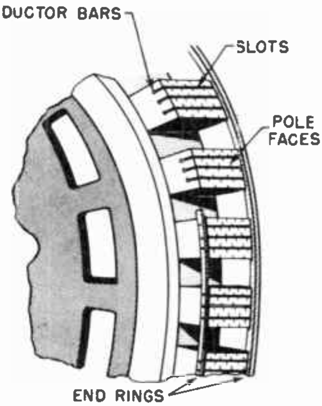


Fig. 13-19. How the squirrel-cage bars used to start the motor are imbedded in the faces of the poles on the rotor of a synchronous motor.

In starting the synchronous motor which has squirrel cage bars imbedded in the face of the pole pieces, the rotor poles are not energized by direct current. Instead the AC current is applied to the coils in the frame, the "stator" coils. The constantly changing AC current sets up a rotating magnetic field just as is always the case in any induction motor.

The rotating magnetic field will set up a current in the squirrel cage bars by induction. The interaction between the rotating magnetic field in the frame of the motor and the magnetism around the induction currents in the rotor bars causes the rotor to rotate.

The rotor will never reach synchronous speed as an induction motor; but it will almost reach synchronous speed. It will come close enough for the rotor to "lock in" at synchronous speed if the rotor poles are energized by direct current passed through their windings. Once the rotor is turning at synchronous speed, the speed of the rotating magnetic field in the stator, current will not be induced within the rotor bars of the motor and the motor will not be operating as an induction motor but will be running solely as a synchronous motor.

In industry, synchronous motors are usually quite large. In large sizes, they have some very difinite advantages over other types of motors. They can be run at full load for long periods of time; they have a corrective effect on the "power factor" of the power company's power lines; and in some cases, they are more economical to operate.

"Power factor" is something we have not touched upon in this book. It is a technical term and presents a subject of much concern to the power company and to the consumer of electrical power. It has to do with the problem of keeping the voltage and the current in an AC power line rising and falling together at exactly the same time. Alternating current has one disadvantage which must always be considered. This disadvantage is that some kinds of machines will tend to make the current lag behind the voltage in the line. This is not desirable. For that reason, both the power company and the user of power should always be alert to keep the current and voltage rising and falling together, for it is then that a line can deliver the greatest amount of power with the greatest efficiency.

There are some facts we should know about "power factor." At this time it will suffice to say: Power factor expressed as a decimal, such as 0.8 PF, means that only 8/10 of the power obtained by the equation power = volts × amperes would be doing useful work in the electrical device you were using; while the remaining 2/10 of the total power would be wastefully lost because the voltage and current were not in phase.

There is nothing about a resistance that can affect the power and prevent the voltage and current from rising and falling in step; and we have learned that when we have only resistance in the circuit, power is equal to volts times amperes. Now, for alternating current, the power equals volts times amperes times power factor (as a decimal fraction). It is easy to see that the power factor of a resistive load must be 1.00. The load formed by incandescent lamps is resistive; hence they have a PF of 1.00.

Devices, such as motors, which are not purely resistive, have power factors which differ from unity. Their power (in watts) may be found by multiplying volts times amperes times power factor.

One of the advantages of the synchronous motor is that it acts to keep the voltage and the current in an AC line working together. Technically this is known as keeping the voltage and the curent "in phase." This advantage is so great that sometimes *synchronous* motors are permitted to run idle on a line, doing no job except holding the voltage and current "in phase" with each other.

Synchronous motors are usually built either in very large sizes, running up into the hundreds of horsepower or, very small sizes, tiny fractions of one-horsepower. Relatively few are built in the range from one horsepower up to 50 horsepower.

Many tiny synchronous motors are used to power electric clocks. The synchronous motor always runs at exactly synchronous speed, and the frequency of electrical power is rigidly controlled at exactly 60-cycles per second; therefore, synchronous motors can be used for the accurate operation of clocks.

There is a difference in the physical construction of the motors used in electric clocks and those described here. Instead of having rotors the poles of which are energized with DC current, the small clock motor often uses a permanent magnet rotor, which is in the form of a toothed wheel with the teeth permanently polarized alternately north and south.

This is not to imply that only synchronous motors are used to power electric clocks. However, at one time virtually all the electric clocks in this country were operated by small synchronous motors. They were not self-starting and had to be started by giving a little knob on the back a quick twist.

The trend in recent years has been toward the use of hysteresis motors to power electric clocks. Basically speaking, the hysteresis motor is a modification of a regular synchronous motor. It is becoming rather popular as a synchronous motor, partly because it is self-starting, and partly because if power is interrupted, it will start again the instant current is restored.

Single-Phase AC Motors—It is probable that the theory and operation of single-phase motors will hold the greatest interest for beginners in the field of electricity. One of the reasons for this lies in the fact that there are so many of them. Another reason is that many single-phase motors may be found in an average home, whereas polyphase motors will rarely be seen there.

Nearly all household appliances use some form of single-phase motor as a source of power. Single-phase power is the only kind found in most homes.

Since single-phase power is available in nearly every home and polyphase power is not, it naturally follows that any motors used in the home must be single phase.

The motors which drive the compressors in our household refrigerators and freezers; those which operate the water-pumps at the wells in most rural areas, and the sump pumps in our basements; those which power our washing machines, automatic clothes driers, and the mandrel of automatic clothes ironers are all single-phase motors.

There are many other applications in our modern homes where single-phase motors are used. The oil or gas furnace uses a single-phase motor for power. In those homes using a stoker, the stoker is powered by a single-phase motor.

Into a somewhat different classification fall such electric-motor-powered gadgets as hand drills, food mixers, electric razors, and similar items. This last group uses single-phase motors of a slightly different type known as universal motors. The vacuum sweeper belongs in this last group also.

Single-phase motors can be classified according to their use, horsepower, or type. Generally speaking, single-phase motors may be classified in the following manner:

1. Resistance-start induction motors.
2. Capacitor motors.
3. Repulsion motors.
4. Universal motors.
5. Shaded pole motors.

Although this list is by no means complete, it incorporates the better known and most widely used types.

Induction Motors—The motors that are grouped into this general classification may be further subdivided. In general, all of the motors in this general classification operate in a somewhat similar manner once the motor has been started and brought up to speed. The ways in which they are started accounts for the principal differences between single-phase induction motors.

A single-phase induction motor, after reaching normal operating speed, operates in such the same manner as the two- and three-phase induction motors already described. That is, the polarity of the field is constantly changing as the AC voltage from the line goes through its alternations.

There is a difference, however. In the three-phase motor, we had the windings of the stator supplied from a three-phase power source, in which there were three different currents. These three-phase currents rose and fell continuously at successive and equally timed intervals around the stator, producing a continually (shifting) rotating magnetic field in the stator. This rotating magnetic field set up an induced voltage within the squirrel-cage bars of the motor, the current of which produced magnetic fields that interacted with the magnetism of the stator and caused the rotor to turn.

In the single-phase motor we also have a magnetic field that changes with each alternation of the single-phase AC power. Instead of rotating as one phase follows another, this magnetic field merely reverses itself with each alternation.

This action presents no particular difficulty once the rotor has been brought up to speed; in fact, if the rotor is turning at even a slow speed, the alternating magnetic field will keep the rotor turning. If the rotor is stationary, the magnetic field merely induces alternating currents in the rotor, which produce equal repulsive forces between the stator and rotor pole faces entirely around the face of the rotor. These forces are pulsating but produce no torque since they are balanced; therefore, there is no action to make the rotor turn.

The chief problem of operating a single-phase induction motor resolves itself into making the rotor start rotating. It is the variations found in the method of starting that makes one single-phase induction motor differ so greatly from another.

Repulsion Motors—A repulsion motor is a type of single-phase motor which enjoyed wide use at one time. In recent years, however, the repulsion principle of motor operation has been confined to the starting of single-phase induction motors. The repulsion motor is capable of exerting a powerful torque (twisting action) at low speeds; but its power output tends to fall off as the motor gains speed.

Although the single-phase induction motor does not have much torque at low speeds, it has considerable torque at high speeds. The repulsion motor was combined with an induction motor to produce a combinatoin motor capable of exerting powerful torque at low speeds for starting purposes and automatically switching over to induction motor action as the rotor approached full speed. This combination motor is the *repulsion-induction* motor mentioned in the preceding classification.

A repulsion motor acts on the principle that the induced magnetism of a coil or conductor will be repelled by the magnetism which originally induced it. This is where the motor got its name. It acts solely on repulsion between two like magnetic fields.

Universal Motors—A universal motor is one which can operate on either direct or alternating current. Basically, the universal motor is a series DC motor. The same current flows through both the stationary and the rotating members of the motor. You will recall that in our chapter on DC machinery we mentioned that the armature had to be laminated to prevent eddy currents building up there and overheating the core. In universal motors, both the rotor and stator are laminated, because alternating current flows in both if and when the motor is used on AC. In the DC machine, there was no alternating current flowing in the field; therefore, it was not necessary to laminate the field pole pieces.

Shaded-Pole Motors—The shaded-pole motor is a single-phase motor which is often used for fan service or in other applications requiring very little starting torque. It is a low starting torque motor built in fractional horsepower sizes for use in fans, phonograph record-players, and gear reduction drive devices for use in window displays and for similar purposes. The shaded-pole motor will be described in detail a little later in this chapter.

Some types of single-phase motors can be found for virtually every job requiring power. They can be and are used for almost every kind of work one can think of. Some single-phase motors find use in only one or two applications for which they are especially adapted. The shaded-pole motor, for example, often takes preference over other types of single-phase induction motors because of its low cost. We shall discuss in detail the operation of each of the several types of single-phase motors.

Operation of the Resistance-Start Motor—This motor is commonly called a "split-phase" motor, but it is sometimes referred to simply as a single-phase motor. These names are correct and accurate; but since they can be applied to various types of single-phase motors, they are not so descriptive as its real name, "resistance-start motor."

In a single-phase system, we have only single-phase power. Since single-phase power cannot give us the rotating magnetic field that is necessary to start the motor, we must somehow make that single-phase current act like a polyphase source of power. What we do is split the power from the line into two parts by a process known as phase-splitting. The power is allowed to flow through one circuit in the normal manner, but it is speeded or retarded slightly (phase shifted) through the other circuit or branch.

Without getting involved in a technical discussion, we shall point to the circuit shown in Fig. 13-20, where we see a resistance and a coil of wire connected in parallel with each other across an AC source of power.

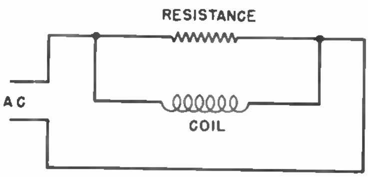


Fig. 13-20. Part of the current will flow through the resistance and part through the coil. That which flows through the coil will be retarded somewhat.

Strangely enough, alternating currents flowing through the two paths are going to act differently. The current will flow through that resistance unaltered, increasing at the same time the voltage is increasing across the circuit, reaching its maximum flow at the same time the voltage reaches its maximum strength, and beginning to fall at the same time the voltage begins to fall. The current will also reverse at the same instant that the voltage reverses. Thus, in the resistive branch of the circuit, the voltage and current are in phase with each other.

The situation will be somewhat different in the case of the current which flows through the coil. The coil exerts a peculiar influence over the current which causes it to lag slightly behind the voltage at all times. The current will rise in the circuit slightly after the voltage rises. It will reach its peak slightly after the voltage has passed the peak, and it will reverse itself a little after the voltage has reversed. The property of a coil that causes it to retard the flow of an alternating current is known as its *inductance.* The effect of inductance is very pronounced in transformers as well as alternating-current motors.

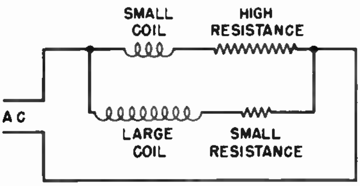


Fig. 13-21. Even though there is a resistance and a coil in each branch of the circuit there will be a splitting of the phase according to the amount of resistance and inductance in each branch.

If there are both resistance and inductance in the circuit, or in each circuit, as shown in Fig. 13-21, phase-splitting will still occur. The extent to which the flow of current will be retarded in each branch of the circuit will depend on the amount of inductance (larger or small coil) and the amount of resistance in series with it.

In Fig. 13-21, the upper half of the circuit has a small inductance and a large resistance. In that half of the circuit the current will not be retarded nearly so much as in the lower half of the circuit where the coil inductance is large and the resistance is small. To put this in other words, the current will flow in the upper half of the circuit almost in phase with the voltage, but in the lower half of the circuit the current will lag behind the voltage.

This action is known as "splitting the phase." It is a means often employed in electrical circuits used in alternating-current work. By thus "splitting the phase" of the single-phase current we have produced two currents that begin to resemble a two-phase AC current. If these two currents, which actually do not rise and fall at the same instants of time, are fed into two different field windings of a motor we can artificially produce a rotating magnetic field.

Fig. 13-22 shows how this principle can be applied to starting a motor on the power provided by a single-phase system. The current from the AC line is divided beyond points A and B. Part of it flows through the coils wound on the main field poles and part flows through the starting coils. A resistance is included in the circuit of the starting coils to limit the amount of current through that circuit to a safe value, since the inductance of that branch of the circuit is too small, by itself, to limit the current through the winding to a safe value. The resistance in the starting winding may be incorporated entirely in the starting winding by winding it with a small wire or it may consist of a separate resistance, in addition to the resistance of the starting winding, as shown in Fig. 13-22.

When a current starts flowing into the motor and reaches point A-B, it will divide. Since there is more resistance and less winding (inductance) in the starting winding than there is in the windings on the main field poles which have more coil turns (inductance), the current will flow through the starting circuit a little sooner than it will through the main winding.

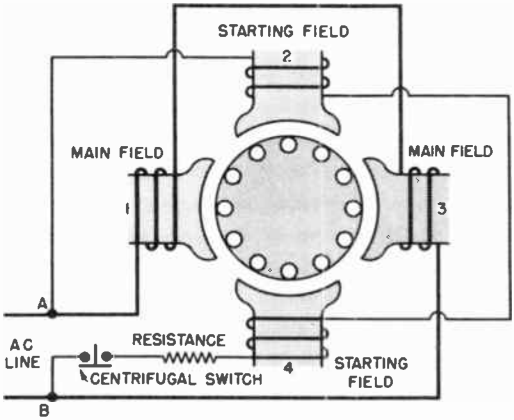


Fig. 13-22. How the phase-splitting principle can be applied to a single-phase motor.

This causes a magnetic field to build up in the starting field poles an instant before a field is built up in the main field poles. Thus, a magnetic field is built up first in the starting poles; then, an instant later, a stronger field is built up in the main poles. This produces a shift or movement of the magnetic field from the starting poles to the main poles. This movement of the magnetic field induces a voltage in the bars of the squirrel-cage rotor and imparts a twisting action to the rotor, causing it to start turning.

A moment later the current will reverse itself. The action will be repeated, the field first being built up in the starting winding; then, a moment later, a still stronger field is being built up in the main winding. As the sequence continues, one reversal follows another in rapid succession, and the rotor continues to turn faster and faster until it has reached normal operating speed.

Once the rotor attains operating speed, a pair of governor-weights in a centrifugal switch that is turned by the rotor axle opens the switch contacts. When the switch opens, the circuit to the starting winding is broken and the switch will remain open until the motor is disconnected from the line. As it slows down, the contacts reclose and are ready to start the motor at some future time.

Instead of the main and starting poles of the resistance-start induction motor being mounted on "salient"* poles as shown in Fig. 13-22, which resembles the construction of a DC machine, they are ordinarily placed on the stator of the motor in the form of "disrtibuted" windings, as shown in Fig. 13-23. Fig. 13-23 gives

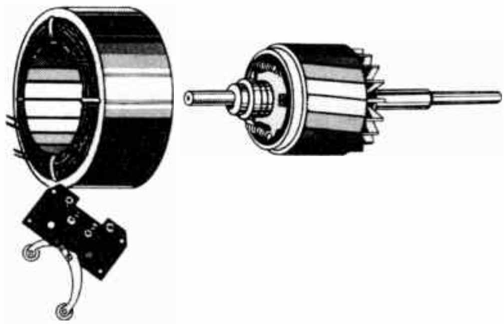


Fig. 13-23. The stator, rotor, and switch of a resistance-start induction motor.

a good view of the squirrel-cage rotor, the frame, the field windings, and the centrifugal switch of a resistance-start induction motor.

In the four-pole single-phase motor, probably the most popular of all in common use, there are four main poles and four starting poles. The four main poles are wound in the slots cut in the stator core, located so that one main pole is at the top of the frame, one at the bottom, and one equally distant at each side to the right and the left. These windings are wound with relatively large wire, which has low resistance, and they have a large number of turns.

The starting windings are positioned midway between these main poles. They are always wound with much smaller wire, which has a higher resistance than the large wire used on the main poles. There are not nearly so many turns of the small wire in the starting poles as there are turns of the heavy wire on the main poles. Thus, the starting winding has a high resistance and a small number of turns (low inductance), while the main wind-

---

* A salient pole consists of a separate radial projection of one single iron or steel pole piece and its own field coil. Salient pole structures are used extensively in the field systems of generators and motors.

ings have a low resistance and a large number of turns (high inductance). The current through the starting windings will be nearly in phase with that of the AC line, while the current through the main windings will lag considerably behind the line voltage and current. This difference in phase between these two currents accounts for the twisting motion which is imparted to the rotor in starting the motor, first causing it to start revolving and then bringing it up to speed.

Operation of the Capacitor-Start Motor—Some of the things which have been said about the resistance-start motor, apply equally to the capacitor-start motor. The biggest drawback to the use of the resistance-start motor is its low starting torque. The difference in the phase angle between the current which flows through the starting winding and that which flows through the main winding is not very great. Thus, the twisting torque applied to the rotor at starting is not very great.

This means that a resistance-start motor is not capable of starting a very heavy load. It is ideal for use in such appliances as driving a circular saw, a drill press, a lathe, and many other devices where the motor is not heavily loaded at starting. It is a rather inexpensive motor. The fact remains, however, that the resistance-start motor does not possess sufficient torque to start under a heavy load.

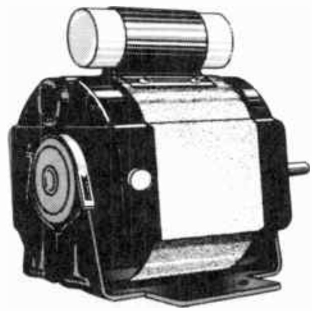


Fig. 13-24. A capacitor-start motor.

A motor used to operate a pump, a refrigerator compressor, or similar applications where the load is permanently connected to the motor must develop sufficient twisting action (torque) to get the load started from a standstill. This requirement imposses a severe demand on the motor's capabilities.

The capacitor motor was developed to provide a single-phase motor which could start while a heavy load was attached to it. An external view of a capacitor motor is shown in Fig. 13-24. The can on top of the motor houses the starting "capacitor."

Basically, a "capacitor" is a device which is capable of storing a charge of electricity. It is often used in alternating-current work to change the phase in one circuit of a split single-phase source.

We have explained that an AC current flowing through a coil of wire has a tendency to lag somewhat behind the voltage which causes it to flow. When an AC current is caused to flow in a circuit with a capacitor, the action is exactly opposite, with the current tending to lead the voltage which produces it.

The ability of a capacitor to store an electrical charge causes the current to flow somewhat ahead of the voltage when the capacitor is placed in an AC circuit. If a capacitor were substituted for the resistance in the starting circuit of Fig. 13-22 we would have a form of capacitor motor. The capacitor would be connected into the circuit as shown in Fig. 13-25.

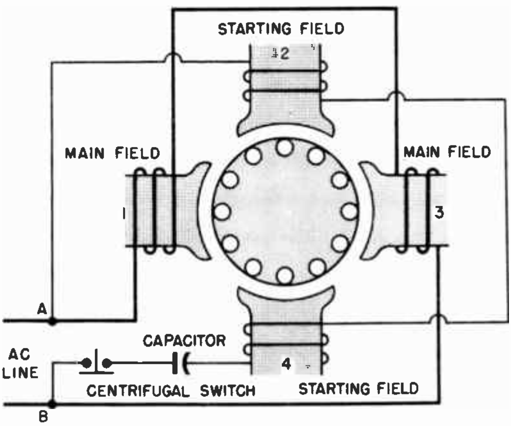


Fig. 13-25. The circuit of a capacitor-start motor, showing how the capacitor is connected in the starting winding circuit.

The principal purpose of having a resistance in the field winding of the resistance-start motor was to keep the current through that winding as nearly in phase with the line voltage as possible. No matter how much resistance is placed in that circuit, the current will not flow ahead of the line voltage; in fact, because of the coils (inductances) in the circuit, the current actually lags slightly behind the line voltage.

By placing a capacitor in the circuit as shown in Fig. 13-25, we can actually cause the current to flow through that winding slightly ahead of the voltage from the line. Although this may sound a little unreasonable, it is supported by sound electrical logic. Our causing the current to flow a little ahead of the voltage produces a much wider displacement of phase between the starting winding and the main winding.

By increasing the time interval between the instant when current starts flowing in the starting winding and the instant when it starts flowing in the main winding, we can produce a rotating magnetic field which induces currents in the rotor that impart a much more powerful twisting torque to it. Furthermore, because there is not so much resistance in the starting winding of a capacitor motor, we can permit a much larger current to flow there.

A capacitor motor can actually start an even heavier load than it can keep running at full speed. This powerful torque, developed by a capacitor motor at the moment of starting, makes it useful for many things. It can be used on refrigerators, pumps, compressors, or in any application where a heavy load must frequently be started from a standstill.

When the capacitor motor has attained full speed a centrifugal switch disconnects the starting winding, and it no longer has any effect upon the operation of the motor. Usually the capacitor intended for this type of service can withstand the presence of a heavy current for a short period of time, but it cannot operate for a long period of time without burning out. That is one of the reasons why an arrangement is provided for disconnecting the capacitor after the rotor has been brought up to full speed. Applications in which capacitor motors are required not only to start loads but also to continuously operate under heavy load use motors known as "capacitor start-capacitor run" motors. In this type of motor, a portion of the capacitance is automatically cut out of the circuit when the motor reaches approximately normal speed. The portion of the capacitor that remains in the circuit for continuous running is designed to withstand the presence of a heavy current continuously without being damaged.

Operation of the Repulsion-Induction Motor—The repulsion-induction motor has an armature and a commutator to which are connected the windings on the rotor or armature very similar to that of a DC motor.

The field coils, however, are much the same as those used on any other induction motor.

For starting this motor, a pair of brushes are connected across the commutator. To the casual observer, these brushes do not appear to be serving any purpose. They are connected together and short-circuit one side of the commutator to the other.

The field or stator coils of the motor produce an alternating magnetomotive force which induces a voltage and current within the armature of the motor, provided the armature brushes are in the correct position to allow the armature winding to be cut by the flux of the motor field. The position of the short-circuiting brushes determines the relative position of the armature poles with respect to the stator (field) poles. With the short-circuiting brushes in the position shown in Fig. 13-26, the armature winding is so connected that the center of its two poles are at right angles to the center of the two field poles. Therefore, no voltage is induced in the armature winding so long as the brushes

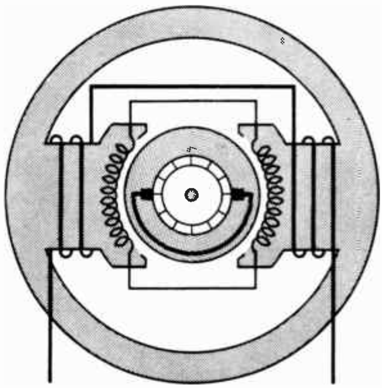


Fig. 13-26. There is no current flow through the armature (rotor) of a repulsion motor if the brushes are in the position shown.

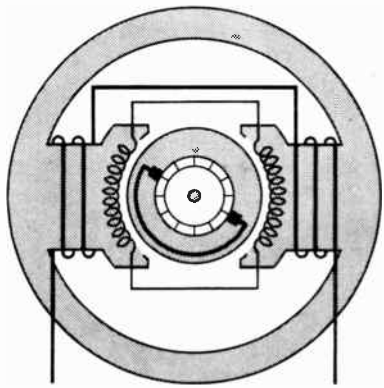


Fig. 13-27. The armature will rotate when the brushes are in this position.

remain in the position shown. If the brushes are shifted to a position at right angles to that shown in Fig. 13-26, the maximum current will be induced in the armature winding since the center of the armature poles are in exact alignment with the center of the motor's field poles. In this position the armature's induced voltage would be at a maximum but the armature would not turn because the repulsive action due to the interaction between the armature field and the stator field would produce a clockwise torque and a counter clockwise torque to each other. Shifting of the brushes from this position will produce a torque that will cause rotation of the armature. We see that there are two brush positions for this motor where no torque is produced. At one the brushes are at the position shown in Fig. 13-26, and at the other position the brushes are at right angles to that shown in this figure.

Since the pair of brushes are connected together across the armature winding, the voltage induced in the armature can be controlled from minimum to maximum by shifting the brushes on the commutator.

Fig. 13-27 shows the basic fundamentals underlying the action of a repulsion motor. The brushes are set slightly off center and thus produce the unbalance of current within the armature of the motor that gives rise to its starting torque.

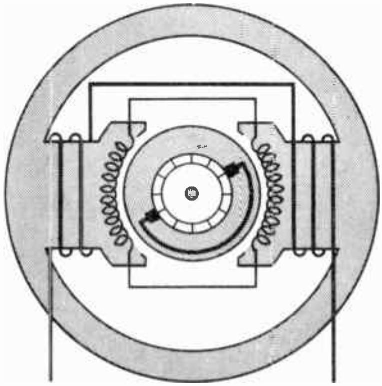


Fig. 13-28. When the brushes are in this position, the armature will rotate in the opposite direction to that of Fig. 13-27.

If the brushes are set on opposite sides of the commutator, the motor torque can be adjusted from minimum to maximum by adjusting the position of the brushes. If the brushes are shifted on the commutator from the position shown in Fig. 13-27 to that of Fig. 13-28, the armature will turn in the opposite direction.

When the motor comes up to speed, the brushes are usually raised so they no longer contact the commutator. This raising of the brushes actually has no electrical effect on the operation. It is done merely to save wear and tear on the brushes and commutator.

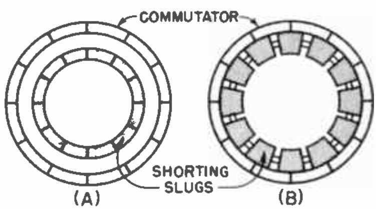


Fig. 13-29. The short circuiting "Necklace" which changes the armature of a repulsion induction motor into a squirrel cage rotor.

However, before the brushes are raised from the commutator, another mechanism has functioned to short-circuit all the segments of the commutator. Various motor manufacturers employ different methods to accomplish this, but the most common method is to use some kind of expanding ring to short-circuit the commutator segments. Fig. 13-29 shows such an expanding ring. The position of the ring is shown in Fig. 13-29A when the rotor is not turning. The short-circuiting slugs have been drawn away from the inside surface of the commutator so they cannot make contact. When the motor is at rest, these slugs are held away from contact with the commutator by a pair of coil springs. As the rotor approaches a speed approximately three-quarters normal running speed, a pair of pivoted "governor" weights develop sufficient centrifugal force to offset the tension of the springs and draw the shorting-slugs against the commutator while simultaneously lifting the brushes free of the commutator.

In Fig. 13-29B, the ring can be seen expanded so it contacts the inside of the commutator and short-circuits all the segments.

When all the segments of the commutator are short-circuited, the armature of the motor acts exactly like a squirrel-cage rotor and the motor operates as a straight induction motor.

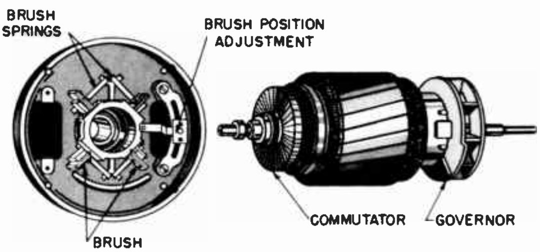


Fig. 13-30. The commutator of a repulsion-induction motor with the brushes and brush shifting mechanism.

The direction of rotation of the armature is controlled by the position of the short-circuiting brushes relative to their neutral mid-position, and is determined during the repulsion motor's starting period. Fig. 13-30 shows the essential parts of the brushes, the brush shifting mechanism, and the commutator.

The repulsion-induction motor is the most expensive of all single-phase motors. It is capable of starting tremendous loads and it is very difficult to stall. Generally, a repulsion-induction motor costs about fifty per cent more than a capacitor-start motor of equivalent horsepower, and a capacitor-start motor costs about fifty percent to seventy-five percent more than a resistance-start motor of equivalent horsepower.

The short-circuiting ring inside the commutator has proved to be the principal source of trouble in repulsion-induction motors. After the motor has had a considerable amount of use, breaks sometimes occur in the "necklace," as it is often called. When that occurs, the "necklace" has to be replaced.

This necklace often consists of nothing more than a continuous chain of interwoven copper links. It has sufficient spring tension to hold it away from contact with the inside of the commutator until the rotor attains about three-fourths normal speed. At that speed the pull of centrifugal force has offset its spring tension and permitted it to expand into contact with the commutator, shorting it out.

Operation of the Shaded-Pole Motor—Shaded-pole motors are a type of single-phase motors which operate on a somewhat different principle than those previously discussed. They are seldom made in sizes above a fractional horsepower, a 1/10 horsepower shaded-pole motor being a rather large one. They are made in sizes ranging down to 1/300th of a horsepower and even smaller.

Fig. 13-31 shows the basic structure of a shaded-pole motor. The poles of the motor have shallow slots usually running parallel with the shaft of the motor and cut in the pole faces.

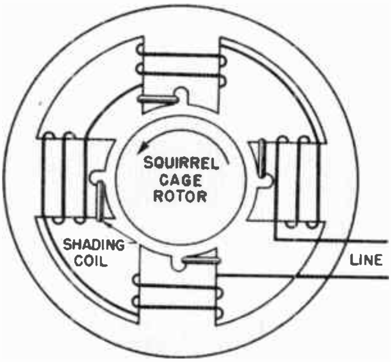


Fig. 13-31. A shaded-pole motor.

A single turn made from a heavy piece of copper lies in each slot and encircles a portion of the pole face. The illustration in Fig. 13-31 shows the shading ring encircling approximately one-half the pole face, but in commercial motors this portion of the pole encircled by the shading coil (inductor) amounts to considerably less than half the pole face. This single heavy turn of copper shown in Fig. 13-31, is known as the "shading coil." Actually, it is nothing more than a heavy copper ring.

This shading action is rather unusual. When a magnetic field is building up in the pole piece, the moving magnetic lines of force induce a current within the copper ring. That current flowing in the ring will then produce magnetic lines of force of its own. The magnetic lines of force produced by the current flowing in the shading coil (ring) oppose and partially cancel the flux in the shaded portion of the pole which originally produced the current in the ring. The net result is that the magnetism of the unshaded part of the pole piece is quite strong while that within the area shaded by the coil will be weak. An instant later, when the magnetism in the pole piece begins to change, the shading coil (ring) will begin adding magnetism of a polarity the same as that it opposed a moment earlier. The net effect is that as the magnetism rises and falls and reverses under the influence of the changing current from the line, a rotating effect is imparted to the magnetic field. This induces a voltage and current within the bars of the squirrel cage rotor which interact with the flux of the poles to impart a twisting torque to the rotor, starting it and bringing it up to speed. When it has attained normal operating speed, it operates as a straight induction motor.

Shaded-pole motors have long been used to power electric fans. Fans never have a heavy load at starting; it is only as they pick up speed that the load becomes heavy. Shaded-pole motors are ideal for this type of service, especially for the smaller sizes of fans. Shaded-pole motors have also been used to operate record players; however, hysteresis motors have taken their place in recent years.

Operation of the Universal Motor—In its basic construction, there is little to distinguish a universal motor from a small series DC motor. Inside the motor, however, several small differences become apparent. One, mentioned previously in this chapter, is that the field pole pieces are laminated. This is shown in Fig. 13-32.

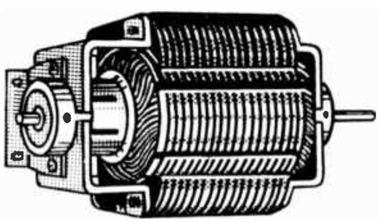


Fig. 13-32. A universal motor, showing the laminations in the field pole pieces.

One may wonder just how a series motor can operate equally well on either alternating current or direct current. There is nothing particularily mysterious about its performance.

A series motor rotates because of the interaction between the magnetic fields of the armature and the field poles. The same current flows through both the armature and the field. If the current flows through them in the direction shown in Fig. 13-33A the armature will rotate in the direction shown by the arrow. However, if the current is reversed as shown in Fig. 13-33B, the magnetism of both the field and the armature will be reversed. Because the polarity of both magnetic fields is reversed, the armature will continue to rotate in the same direction as before.

Note that it doesn't make any difference in which direction the current flows through such a motor. If the relationship between the magnetism of the armature and field is right, the armature will rotate in only one direction. Because the relationship between the two magnetic fields will remain the same, reversing the direction of the current through the motor will not change the direction of rotation.

The armature will rotate in only one direction regardless of the direction of the current flow. In fact, the only way to reverse the rotation of such a motor is to change the connections to the brushes of the motor. If the leads which are connected to the brushes are reversed, the motor will reverse its direction, but otherwise it will not.

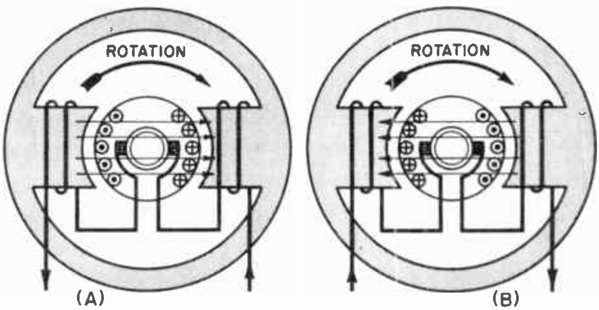


Fig. 13-33. The relationship between the direction of rotation of a series motor and the flow of current through the motor circuits.

Where the possibility exists that the motor may have to be operated on both AC and DC, the universal motor is the best type to use. It is often used to power small hand tools and appliances, such as electric hand drills and food mixers. As the speed of a universal motor drops, the torque will increase. This characteristic has proved very useful. In the case of electric hand drills, for example, the series motor exerts a very powerful torque when the load is increased sufficiently to slow down the motor. Thus, it is possible to pack a lot of power into a small space. In devices such as a hand drill, in which the operation is intermittent, there is little danger of overloading and thus overheating the motor. Since the duty cycle is small, the motor has ample cooling time during its off periods. The motors which we have studied in this chapter comprise about ninety-five per cent of all motors the beginner in electrical work is likely to meet during the first few years of his work.

For a more detailed discussion of all kinds of AC and DC motors and generators, it is suggested that you refer to another of the author's publications, entitled "Crow Rotating Electrical Machines." *

* Published by Universal Scientific Company, Vincennes, Indiana.

Chapter 14

CIRCUITS AND CONTROLS

THE NEED FOR CIRCUITS

If a friend walks up to your house and wishes to announce his arrival, instead of knocking he will probably look at the side of the door for a button to push. If your door is equipped with such a button, he will press it and stand back to wait for you to answer his ring. His pressing the button, thus sounding a bell, a gong, a buzzer, or a chime somewhere inside your home, notifies you that someone is at the door.

If you should live in an apartment building, you probably would not bother going all the way downstairs but would simply push another button conveniently located in your room; downstairs at the street door an electric lock would buzz and remain open to permit your friend's entry and then would relock after him.

In the "horse and buggy" days when people went calling, they simply doubled up their fist and rapped on the portal with their knuckles to announce their arrival. If, perchance, the home at which they were calling was equipped with the very latest thing in conveniences, the callers lifted the hinged member of the weighty new door-knocker and let go! It dropped with sledgehammer violence, delivering a mighty blow that could be heard not only throughout the house but all over the neighborhood.

Yes, in those days before electricity became man's servant, life had a certain directness and simplicity. The cause and effect for most things that occurred were right out in the open; but not so today! When you push the button of someone's door bell, you know that your action has caused a buzzer or bell to sound; but beyond that point what do you know? Do you understand how the bell is made to sound, where its power comes from, and why pushing the button has any effect? The lad who cleaned and filled kerosene lamps and trimmed the wicks knew where the light was coming from when he had light. Many people do not know what happens when we turn on the light switch, except that the lights go on.

Push buttons serve many purposes other than ringing door bells. In many of the larger homes where servants are employed, one or more push buttons are located in every room, out on the porch, and perhaps at a few strategic points here and there throughout the garden. These call buttons operate buzzers, lights, or the annunciator system in the servants' quarters. Very often the signaling system is arranged to permit the servants to reply to a call or acknowledge it in some manner.

In many rooming houses, apartment hotels, and some few of the older hotels, it is still possible to find systems of push buttons, bells, buzzers, and lights in use between the office and the rooms of the guests. Within recent years, telephones in each room have supplanted such elaborate systems of signals in rooming houses and hotels, and electronic intercommunication units have superceded them in the better homes.

The basic principles on which the operation of such systems is based have such wide applications that their study should prove both useful and profitable. The bank of pushbuttons on the busy executive's desk that are used to summon any employee in to his office; the burglar alarm systems which protect offices, businesses, stores, warehouses, and homes against pilfering; the alarm systems used in banks, currency exchanges, paymasters' offices, and similar places where large sums of money are frequently handled; and the complex system of lights and dials that tell on what floor the elevator is and informs the operator from which floor a summons has come—all are signaling systems.

Basically, any signal system consists of four essential parts: a source of voltage, a control or controls for the system, some form of indicating or signaling device, and the connecting wires and cables that link the other components together to form an operating system.

The source of power will depend upon the size of the system and its requirements. If it is a simple signaling system, the source may consist of a single dry cell, a battery, or a bell-ringing transformer.

The system's controls may take several forms. The most common control is a pushbutton. Other controls are key switches, pendant switches, keys, etc. The common forms of the indicating or signaling devices are buzzers, bells, lamps, annunciators, horns or klaxons.

THE ELECTRIC CIRCUIT

Electrical circuits have been thoroughly discussed in a previous chapter. We have learned why an electric circuit is necessary and just what constitutes an electrical circuit.

Fig. 14-1 shows a simple form of signaling circuit powered by dry-cell batteries. The four dry cells are connected in series to give a voltage of 6 volts to operate the bell. When the pushbutton is pressed, a complete electrical circuit is formed and current from the batteries flows through the bell, ringing it. At one time virtually all door-bell circuits, and many other signal circuits, used dry cells as their source of power.

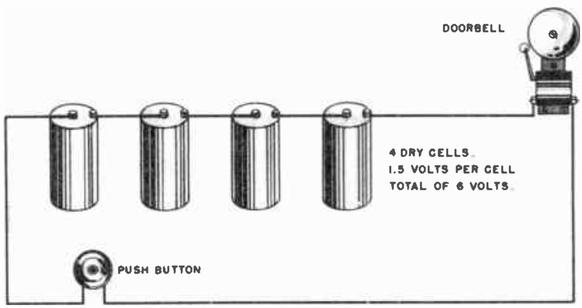


Fig. 14-1. A simple signal circuit powered from dry-cell battery.

The original cost of three or four such cells is not very great; nevertheless, it involves an outlay of cash. Dry cells do not last indefinitely. With moderate use they may last from six months to a year, and in some cases even longer; but, sooner or later they must be replaced. This means the purchase of new dry cells at least once a year, possibly more often. In addition to their cost, there is the trouble and bother of replacing them, plus the additional burden of having to remember that they require attention periodically.

A far superior source, one which has outmoded the dry cell in such applications, is the bell-ringing transformer. Since we have studied transformers previously, it will suffice to say that the bell-ringing transformer is a step-down transformer with a 115-volt primary that connects directly across the single-phase, 115-volt electrical power. Its secondary generally has a single voltage of from 6 to 8 volts; however, such transformers are available with multiple secondaries and tapped secondaries in voltages ranging all the way up to 24 volts. A voltage of between

6 and 8 volts has become standard for operating bells, buzzers, pilot lamps, annunciators, and other similar devices. In the signaling circuit shown in Fig. 14-2, the battery source of Fig. 14-1 has been replaced with a bell-ringing transformer.

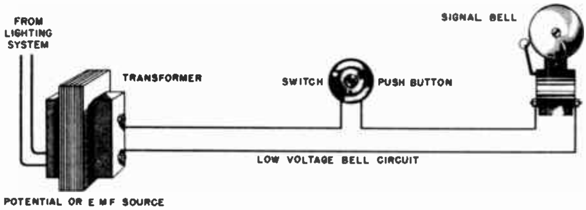


Fig. 14-2. A simple signal circuit powered from a transformer.

There are advantages and disadvantages to both the transformer and dry cells for use as a source. The dry cells have one advantage that the transformer cannot claim; they are independent electro-chemical sources of electrical power and, for that reason, can be used anywhere. The transformer, on the other hand, must always have a source of alternating-current electrical power to supply it, but it doesn't wear out and have to be replaced frequently. Where a source of electrical power is available, the transformer is preferable to batteries. In fact, the first cost of a small bell-ringing transformer is not so great as that of the four dry cells. In signaling systems, therefore, either a transformer or a battery of dry cells is used as the source that furnishes the power to energize the circuits.

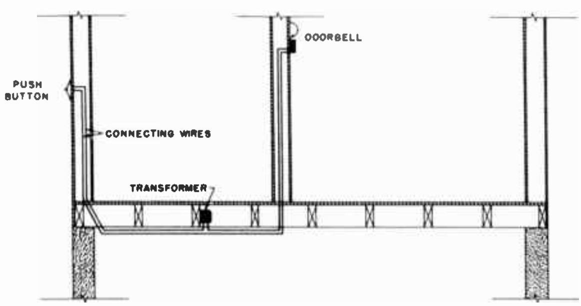


Fig. 14-3. How the wires are run to connect a door bell with its push-button control.

The controlling element in such a system is the switch, usually a push button. Fig. 14-3 shows a simple bell-button signaling circuit powered by a bell-ringing transformer. The house in which the system is installed is shown in cross-section view so the wiring may be seen. The push button is shown located on the outside of the house and is mounted in a position readily accessible to a visitor. The electric bell is located on one of the inside walls of the house. Its purpose is to produce a sound when the circuit is energized by someone pressing the push button outside of the house.

The three elements comprising the signaling system are shown connected together by the wiring. Since elementary circuits have already been studied, this circuit will be explained in a slightly more advanced manner than that of laborously tracing each wire from point to point throughout the system. Let's consider the circuit on a "cause" and "effect" basis. The effect that we wish to produce by pushing the push button is ringing the bell inside the house. Assume, for a moment, that the transformer is not part of the circuit and the bell is connected directly to the push button by two wires. We know the effect we wish to produce, and we know that pushing the push button will cause this effect. Nine out of every ten people who press the push button of your door bell have no idea of what takes place. To these nine, the cause is pressing the button and the effect is the ringing of the bell. In our assumed circuit, in which the transformer has been omitted, we have those two elements, the button and the bell, and we have connected the two of them together by means of wires. Assume that we provide the cause by pressing our finger down on the push button. Is the desired effect forthcoming? No, you would listen in vain for the sound of the bell. Since we desire only one effect and have the means of producing it, the electric bell, there must be something lacking in cause. Our body supplied the necessary physical energy to cause the bell to sound by the pressure we exerted on the push button. The energy that it did not and could not supply was a source of electrical energy, the missing cause.

In the simple signaling system which we have in a series circuit, all of the components of the circuit are connected in series with one another and the same current flows in every portion of such a circuit. We have no current flow in our circuit when we press the button, and the reason is simple; we have no source of electrical potential in the circuit to produce a current. Let us break into the circuit at any point and insert a source. This gives us a circuit like the one shown in Fig. 14-3, the source being in the form of a bell-ringing transformer, which supplies the missing cause.

Now press the push button; the bell will ring. Your act of pressing the button has supplied the necessary control or physical cause by electrically completing the circuit. The transformer supplies the necessary source or electrical cause that gives rise to a flow of current through the electric bell. This current energizes the electric bell to produce the desired effect, its ringing.

In a basic sense, this simple door bell circuit is no different from the important electrical circuits found in industry. Both incorporate a source of electrical power, a load which uses that power, and a complete electrical path through which the current can flow. The two circuits may differ in conductor size, voltage of the source, and amount of current used.

THE CONTROL ELEMENT

The control element in the door-bell circuit just described is a simple push button. We have prepared a sectional drawing of a push button so its mechanical and electrical construction and operation can be better understood. There are almost as many different types of push buttons as there are manufacturers who make them. Actually, there are probably more types than there are manufacturers since some manufacturers make many different types; however, the operation of all push buttons is basically the same.

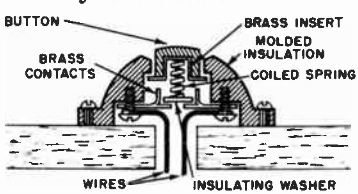


Fig. 14-4. Construction details of a push button.

The exterior of the push button is usually molded of plastic or other insulating material. This is shown in the drawing in Fig. 14-4 where the outer shell of the push button is clearly visible.

The conducting path can also be clearly seen. Note how the brass conducting insert that is a part of the button itself is held away from the other brass contacts by the action of the spring. Since the spring is resting on an insulating washer, there is no electrical contact between the spring and the two brass contacts. Until the push button is depressed, there should be no electrical connection between the two brass contacts.

However, when the button is pressed down with sufficient force to overcome the tension of the spring, the button will approach the brass terminals. If the pressure is sufficient, the button will be forced against the brass contacts so that the brass insert on the button will make an electrical connection between them, connecting them together electrically.

Such an electrical connection will exist only as long as there is sufficient physical pressure on the button. When the pressure is removed, the electrical contact is broken and the circuit is opened.

The push button can be connected into an electrical circuit by the use of the two secrews shown on the underside of the brass terminals. When one wire is connected to one of the screws and the other wire is connected to the other screw, a person can make an electrical connection between the two wires by pressing the button, but the connection between the wires will be broken at all other times.

Another type of switch for controlling signal circuits which enjoyed wide popularity at one time is shown in Fig. 14-5. It is not used much for its original purpose now, but variations of such a switch arrangement are used in higher voltage industrial circuits for many purposes. A variation of that type of switch is what is generally known as a "limit switch" and is used to limit some kind of action. In cases where a machine, such as a surface grinder, is moved physically in some manner, it is often desirable to provide some kind of automatic device to stop the movement; to reverse its direction; or to set into action some other activity. When the moving work piece touches the lever of a switch or when some portion of the machine comes in contact with it, similar to that shown in Fig. 14-5, the movement opens the circuit, closes it, or performs some other operation on it. The exact action which takes place depends upon the effect one desires to obtain.

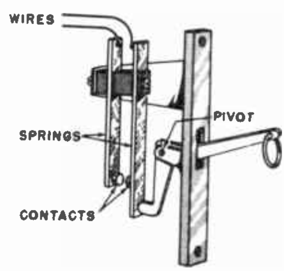


Fig. 14-5. A switch which could be used with a pull cord.

The action of the switch shown in Fig. 14-5 is self-explanatory. When the lever is pulled downward by the ring, it causes the other end of the lever to press against one leaf of the electrical contacts. Sufficient pressure will force the two contacts together. When they touch, the electrical circuit will be completed, and the switch will be in a closed position.

A different type of switch that can be used in some unusual circuits is shown in Fig. 14-6. This switch has three contacts with connecting wires brought out from each. The center wire is connected to the center contact, called the "common" contact, which is, or can be, common to two different circuits.

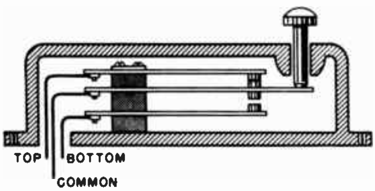


Fig. 14-6. A "leaf" or blade type two-contact switch.

The illustration shows the switch in its normal position with the center contact held up against the upper contact by the spring leaf's tension. This means that when the switch is in its normal position, the upper contact and the center contact are pressed together producing an electrical connection between the wires which are connected to the upper and center contacts. Any device that is desired to operate at all times, except when the switch button is depressed, may be connected between the top wire and the common (center) wire which are always electrically connected together except when the switch button is depressed.

There is a third electrical element in the switch, the lower contact. Normally there is no electrical connection between the lower contact and the center one. The center contact is held away from the lower contact and against the upper contact by the spring-leaf tension within the center contact blade.

When someone presses the button, but does not depress it all the way, the pressure will overcome the tension of the spring sufficiently to break the electrical contact between the center and the top contacts. That circuit will be broken and any electrical device in that circuit will cease to operate.

If additional pressure is exerted and the button depressed all the way, the center contact will make physical contact with the bottom contact and produce a good electrical connection between them. Any electrical device connected to that circuit would be operated by the act of pressing the button. This means that pressing the button can accomplish two things: It can *break* the circuit to the top contact and it can *make* the circuit to the bottom one.

Fig. 14-7 shows one way such a switch could be used. This is hardly a practical circuit, since lights in the home are seldom powered by batteries, but it is useful for understanding the action of the switch.

Fig. 14-7 shows a battery being used as the source of power for two lamps. One lamp is fastened to the ceiling inside the house and the other is fastened to an outside wall. When the switch, which is like the one in Fig. 14-6, is in the normal position, the light on the ceiling of the room will burn. Should the

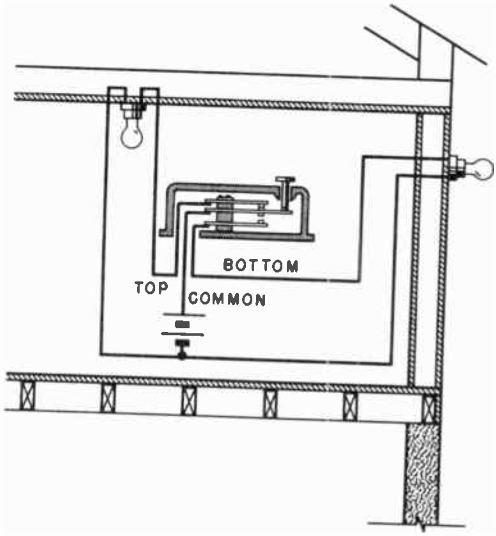


Fig. 14-7. How two lamps can be controlled from a single two-contact switch.

occupant wish to illuminate the yard outside the house so he could see what was going on out there and, at the same time, prevent anyone on the outside from seeing him, he could do so by pressing the button of the switch. Partially depressing the button opens the circuit to the lamp inside the room, and the lamp will go out. Depressing the button fully makes an electrical contact between the center contact of the switch which is connected to the battery and the lower contact which is connected to the lamp outside the building causing it to light. Thus, pressing a single push button will put out the lamp inside the house and light the lamp outside.

This same principle is employed for many other purposes, especially in various automatic operations. Fig. 14-8 shows a modified version of this principle. With some variations, it is widely used on automobiles today. Instead of the contacts being moved by the pressure of a person's finger, they are moved automatically by an electromagnet energized by the automobile generator. When the generator is not running the electromagnet is not energized and the contact is closed in the normal upper position. When the generator is running the electromagnet is energized, operating the switch so the contact is closed in the lower position. This electromagnetically operated switch is known as a relay, specifically a single-pole, double-throw relay (abbreviated S.P.D.T. relay).

When the engine is not running, and it is desirable to start it, the switch on the top of the starter is pressed. This completes the electrical circuit through that switch, the starter, the battery, and the two upper contacts on the three-way switch (relay). As soon as the engine starts the generator operates and ener-

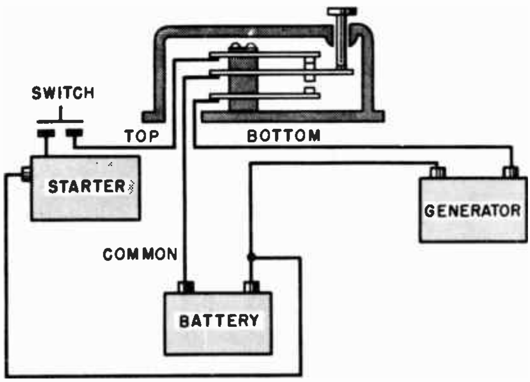


Fig. 14-8. How the principle of the two-contact switch can be applied to the automatic control of an automobile electric system.

gizes the switch electromagnet, and the middle contact of the relay is drawn downward, thus, making it impossible to energize the starter while the engine is running. This is a safety device to prevent the damage that could be caused by accidently energizing the starter while the engine is running. It functions to render the starter switch inoperative whenever the engine is running.

When the engine is not running, the circuit between the battery and the generator is broken since the central movable contact of the relay switch is not making electrical contact with the lower one. This makes it impossible for the battery to discharge itself through the motionless generator coils and run down while the engine is standing idle. However, as soon as the engine starts running and a voltage is built up within the generator, the center relay contact is drawn downward and makes electrical contact with the bottom one. This connects the generator to the battery and recharges it.

If you are familiar with the electrical wiring system of an automobile you are aware that this description has been oversimplified and that some vital parts are left out; but it serves to demonstrate how this particular kind of switch is put to actual use in a practical, everyday electrical circuit. There are many other types of "three-point" switches with which you will become familiar as you continue the study of electricity. Until that time, these examples will serve to acquaint you with the basic operating principles of this kind of switch.

Let us turn our attention to other interesting types of the simple push-button switches. Fig. 14-9 shows several types of push buttons that are in common use. Each type of push-button switch shown in Fig. 14-9 was developed to meet a specific need. You will probably recognize some of them from the illustrations; others are less familiar. The gang desk push button is merely a group of push buttons located on a common base where they will be handy for the busy executive. In most cases such ganged push buttons are used to communicate with any of several employees. The executive can summon any employee he wishes merely by pressing the button corresponding to that employee's office. They are available commercially as push-button blocks, in the gang desk push style in standard sizes with one to twelve buttons. This type with over twelve buttons is available only on special order, since the connector cable becomes too cumbersome and is not sufficiently flexible for normal desk-top use. They are available in fixed wall-box mounts as standard items in sizes having up to 240 buttons.

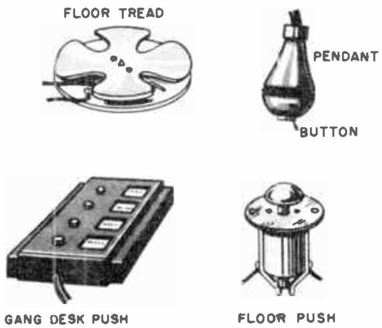


Fig. 14-9. Several types of low-voltage switches in common use.

The pendant push button, often called the "pearpush" because of its shape, has found considerable use in hospitals. It is convenient for the patients to use when they wish to summon a nurse.

The floor push-button switch has a variety of uses. It is often used in banks, paymasters' offices, and other places where money is handled. Being on the floor, it is within easy reach of the teller's foot in the event of a hold-up, and it can be used without the robber being aware an alarm has been sounded. In some homes employing a maid, one of these switches is placed beneath the dining table and used by the hostess or mistress to summon the maid. Other uses for such a switch are limited only by one's imagination.

The floor tread switch was once used widely as a warning or announcing switch and was placed under a carpet or door tread. This switch permits pressure on any side of the floor tread to make an electrical contact and thus operate a visual or audible signal. It has fallen into disuse in recent years, being displaced by the "electric eye" of the phototube; but there are still many applications in which the floor-tread switch can be put to good use.

DOOR SWITCHES AND ALARM SWITCHES

A switch which might be regarded as a variation of the push-button switch is known as a door switch and is designed to operate automatically when a door, a window, or other device upon which it is mounted is either opened or closed. Such switches are often found in small one-man operated stores and shops, in which the owner has his living quarters in a room adjoining the store or shop. The door switch is mounted on the door of the shop which leads to the street and permits the proprietor to be assured that should he go to his living quarters, he will know immediately if someone opens the door and comes into the shop from off the street.

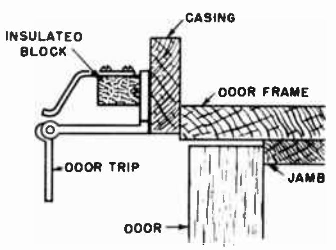


Fig. 14-10. Construction details of a door switch.

The constructional details of such switches vary widely; however, there are two requirements that must be met by all. It is essential that the contacts of the switch do not close when the door is closed and that they make contact with each other only when the door is open. Some are designed to maintain contact continuously while the door is open; others are designed to make only momentary contact as the door is opened. This second type warns the owner of the store of the presence of a customer but does not persist in continuous and annoying operation, should the customer forget to close the door.

The construction details of an automatic door switch operated by a trip action is shown in Fig. 14-10. The action is simple and should be easy to understand from the drawing. When the door is opened, it moves toward the left in the illustration. Opening the door engages the door trip, causing the metal hanging part of the trip to move toward the left also, in the direction of the door's movement. The movement of the trip causes its eccentric projection to raise and contact a metal arm which is mounted on an insulated block. Contact between the metal trip lever and the metal arm makes an electrical contact that closes the circuit to an electric alarm device such as a bell or buzzer. The method of mounting such a door switch on an entrance door is shown in Fig. 14-11.

The automatic door switch shown here is not the only type in general use. Several other types are used more widely. This type happens to show the essential features of such a switch better than one of the other more popular types.

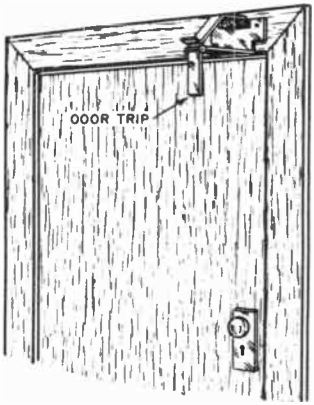


Fig. 14-11. How a door switch works.

The door switch of the type shown in Figs. 14-10 and 14-11 will sound an alarm only momentarily as the door is actually being opened. Another type of switch which can be more easily concealed is shown in Fig. 14-12. This switch will operate the alarm device during the entire time the door is open. The drawing makes the action of the switch self-explanatory. When the door is closed (Fig. 14-12A) a protruding plunger is pushed in, thereby breaking the contact between it and a little metal contact finger.

When the door is opened (Fig. 14-12B), the plunger is pushed out by a spring inside the small cylinder and a contact is made between the flattened end of the plunger and the metal arm.

This type of door switch has proved popular for use with alarm systems found in many business offices. It can be used to warn a person in an inner office that someone has entered the outer office. It has also found wide use in the automotive industry. When installed on the doors of an automobile it causes the dome light inside the car to turn on automatically when the door is opened. Some makes of automobiles have this type of switch installed in the front door to turn on a light under the dash panel that lights up the floor of the car as one gets in and out. One can conceive numerous uses for such a switch.

A type of automatically operated switch which can be attached to a window is shown in Fig. 14-13. If a person is interested in installing a simple, inexpensive burglar alarm system, this switch is useful. There are a number of objections to the use of this kind of burglar alarm system; but where simplicity and low cost are more important than absolute reliability, this type of switch is frequently used. There is nothing complicated about it.

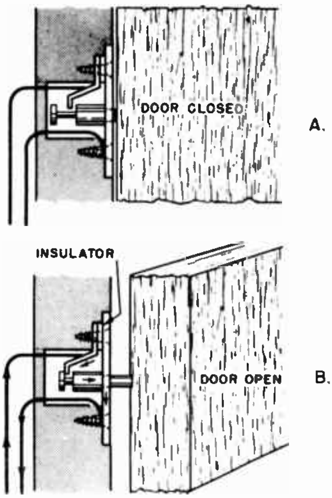


Fig. 14-12. A plunger-type door switch.

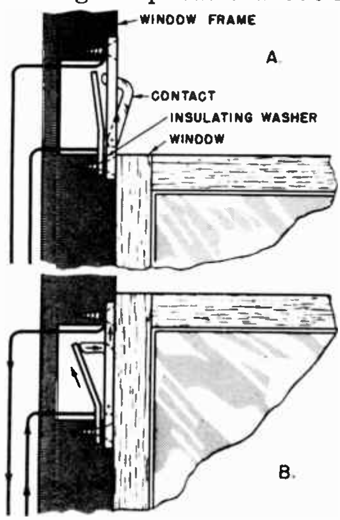


Fig. 14-13. A switch for use on windows in an alarm system.

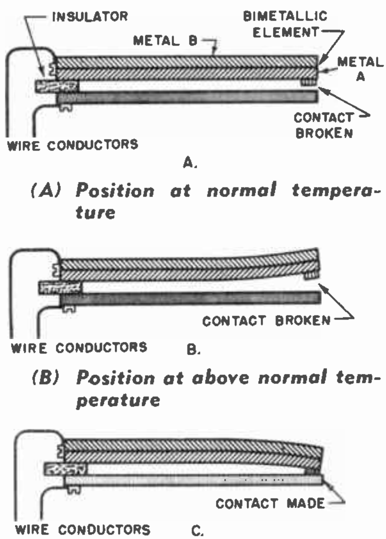
When the window is closed (Fig. 14-13A), the switch is open; there is no contact between its metal parts. If the window is raised (Fig. 14-13B) a contact arm, which normally extends into the track of the window, is pushed inward into the sash making electrical contact with another metal part. This closes an electrical circuit and sounds an alarm.

The principal objections to using this type of switch in a burglar alarm system are that the alarm does not sound if the wires are cut by a skillful burglar, and the alarm ceases to sound if the window is immediately lowered following an entry. A really good, and essentially foolproof, burglar alarm system is designed in such a manner that it cannot be put out of order by the cutting of any of the wires; and when an alarm is once sounded, will continue to sound until someone in authority turns off the master control.

OTHER KINDS OF AUTOMATIC ALARMS

When it is necessary to set up some method of controlling an electrical circuit automatically in response to some predetermined set of conditions, we usually can find a commercially developed switch or control for that purpose. One kind of automatic control switch, familiar to most of us, is the *thermostat* used in many of our homes to regulate the temperature. In their construction, thermostats vary widely, according to the tastes and ideas of the manufacturer; however, they all operate on the same basic principle. A thermostat is an automatic switch which opens or closes an electrical circuit in response to temperature changes.

Since the thermostat switch opens and closes an electrical circuit, there must be something inside it that moves. The movable element is a specially constructed strip of metal which is called bimetal.



(A) Position at normal temperature

(B) Position at above normal temperature

(C) Position at below normal temperature

Fig. 14-14. A bimetallic element used with temperature controls such as thermostats.

A bimetallic element is merely a strip of bimetal which is made of two dissimilar metals welded or otherwise bonded together. Such a bimetallic element is shown in Fig. 14-14.

A bimetallic element is made of two dissimilar metals which expand and contract a different amount per degree of temperature change. If the two pieces of metal are welded together or otherwise fastened rigidly together, as shown in Fig. 14-14, the entire element will bend when heat is applied to the combination. This is due to the fact that one of the metals, A, making up the bimetal strip has a greater linear expansion (changes its length more) for a certain rise or fall of temperature than does metal B. If the temperature rises 10 degrees, A lengthens a greater amount than B; and since the two metals are bonded together tightly, A is pulled over in the direction of B, making the strip bend. The two dissimilar metals are usually bonded together in such a way that the strip is practically flat at room temperature. As the temperature falls, the strip bends the other way.

Fig. 14-14A shows a bimetallic element used in a temperature control device such as a room thermostat when the temperature of the air surrounding it is what we will refer to as "normal." If the air surrounding it rises to a value higher than "normal" the bimetallic element will bend upward as shown in Fig. 14-14B. Fig. 14-14C shows the bimetallic element as it would appear when the temperature drops below normal.

If a bimetallic element is mounted on an insulating base as shown in Fig. 14-14 and a second metallic contact is also mounted on the same base, the combination can be used as an electrical switch which will respond to changes in temperature.

If this switch is placed in a case such as that which we know as a thermostat, the bimetallic element will bend as the temperature falls, until it will eventually touch the other metal (electrical contact) and, when the temperature has reached a certain point, will make an electrical connection between the two. This electrical contact can be used to close an electrical circuit and thereby turn on the gas to a furnace or start the electric motor in an oil burner or in a coal stoker. In any event, it can initiate the cycle of events necessary to create more heat and thus raise the temperature in the home.

After the temperature of the room has risen to some given level, the bimetallic element will become warmer, begin to bend, and thus begin to pull away from the other electrical contact. When this occurs, the electrical connection will be broken; the electrical circuit will no longer be closed; and the heating device will be shut off. No more heat will be supplied to the house until the temperature has fallen sufficiently to cause the bimetallic element to bend down once more, and again close the electrical contacts.

Many refinements, not mentioned here, are found in commercial thermostats. Arrangements are devised so the temperature can be maintained at a given level, and they can be adjusted to call for heat at a lower or higher temperature. Basically, however, the one essential element in a thermostat is a strip of bimetal equipped with electrical contacts.

In all of the thermostats discussed, the bimetal strip has been heated or cooled by the air surrounding it. There are other types of thermostatic controls in which the bimetal element receives heat directly from the object or device the temperature of which is being controlled. A good example of this is the thermostatically controlled electric soldering iron in which a bimetal switch receives heat directly from the iron. It breaks the circuit of the iron whenever the temperature of the iron exceeds a predetermined value. The thermostat remains open until the iron has cooled down to this predetermined value. As the temperature of the iron drops below that value, the thermostat contacts close, restoring the circuit and causing it to heat up again. This cycle is repeated over and over, with a result that the temperature of the iron remains reasonably constant at the predetermined value.

Thus, we see a thermostat is nothing more than an electrical switch which can close an electrical circuit and operate some device or initiate some action. The voltages used in conjunction with a thermostat control are similar to those used with door bells, push buttons, and the like, and they range from 8 to 24 volts. A thermostat is an automatic switch; the only difference between it and the automatic door switch is that the door switch operates under the influence of the physical movement of the opening door, while the thermostat operates under the influence of temperature changes.

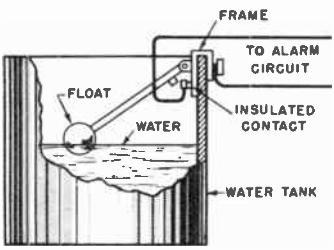


Fig. 14-15. A "Float" switch for controlling the level of water in a tank.

There are still other types of automatic controls. Probably one of the oldest is that originally used for warning of the rising or lowering level of water in a tank. The basic essentials of such an arrangement are shown in Fig. 14-15, where we can see the float which rests on the surface of the water, the contacts, and the connecting wires leading to the main circuit. This type of switch is known as a "float" or "liquid level" switch.

The float rests on the surface of the water and will rise as the water in the tank rises and will fall when the water in the tank falls. The contacts are the elements which make the actual electrical connections when the circuit is closed or opened. The float switch may operate in any one of a number of ways. Just how it operates depends upon the type of auxiliary equipment that it controls.

It could be arranged to control the pump which keeps the tank filled with water. In that case, when the water falls to a certain level, the contacts will close and start the pump operating to force water into the tank. When the water has reached a level where the float has lifted sufficiently to break the electrical contact, the switch will open and stop the operation of the pump motor.

Instead of directly controlling a pump motor, the switch could control a pilot lamp or some other warning device. If the water level drops below a predetermined value, the float will then permit the electrical contacts to close, lighting a warning lamp to indicate that the water level in the tank is low.

The operation of the system could be reversed and used to warn against overfilling the tank. The lamp, in this case, would remain lighted all the time during which it was safe to add water to the tank. When the water in the tank exceeded a predetermined level, the rising float would cause the contacts to separate and break the electrical circuit. The lamp would go out, warning that the level of the water was approaching the top of the tank. Thus, by arranging the switch to make instead of break the electrical contact as the float rises, we can reverse the action of the warning system. In this fashion a lamp could be caused to flash on when the level of the water approached the top of the tank; or instead of a lamp, a bell could be used to sound a warning when the water level rose high enough to cause closure of the electrical contacts.

While it is very interesting to try to find out all the things that can be done with electrical switches, it is probably even more interesting to see how many of these same things can be done automatically. It is due in large measure to our inventive ability and skill in thinking up gadgets and automatic devices that electricity has become so useful to us as a nation. We are often spoken of abroad as a nation of gadgeteers; but it is these very gadgets that have given us a standard of living far above that of any other nation on earth.

Automatic controls regulate the temperature in our homes even on the coldest days and maintain it more steady than could the most watchful human fireman. Automatic electrical controls regulate the air conditioning in our stores, theaters, offices, and even in our homes. Automatic control circuits maintain the temperature within our refrigerators at a pre-selected level and even automatically defrost the units.

There are available electrical and electronic systems that will automatically turn on the lights inside our garage, open the garage doors, and even light the grounds surounding our homes, as our car swings into the driveway at night. Automatically controlled circuits safe-guard every foot of track over which our high-speed trains run and provide automatic signals to let the engineer know if each new block of track over which he must travel is clear of other trains. If he should miss seeing their warnings or ignore them, they even function to apply the air-brakes and automatically stop the train. A veritable maze of traffic signals, blinkers, warning lights, electric signs, and other automatically operated devices guide, break up and regulate the stream of vehicular traffic in our cities and on the nation's highways. In many of our newer automobiles, automatic electrical circuits have taken away much of the strain and work of driving. They shift gears; dim the headlights; raise and lower the top; open and close the windows; and operate the overdrive.

These are only a few of the many places where automatic electrical circuits take over and make living safer, less arduous, and more enjoyable. You can probably think of dozens of others.

THE COMMON VIBRATING DOORBELL

The operating details of an electromagnet will not be discussed in this chapter, since they were explained in detail in another chapter. Essentially, an electromagnet is a device in which a piece of soft iron becomes a magnet whenever an electric current flows through a coil of wire surrounding it. Fig. 14-16 illustrates the essential elements of an electromagnet.

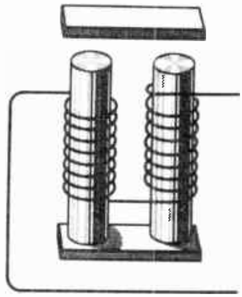


Fig. 14-16. Basic construction of an electromagnet.

A vibrating doorbell is operated by an electromagnet. The electromagnet used in most common door bells is similar to the one illustrated in Fig. 14-16.

The operation and action of a door bell is shown diagrammatically in Fig. 14-17. In Fig. 14-17A we see each element of the bell named. The electromagnet attracts a second piece of soft iron called an *armature,* so-called because it is fairly free to move. Under normal conditions the armature is held away from the electromagnet by the tension of the spring. When the spring holds the armature away from the electromagnet, an electrical contact on the upper part of the armature makes electrical contact with a stationary contact mounted on the frame of the door bell. The frame of the door bell is not shown in the diagram except as a general outline in the form of a dotted line.

The extreme upper end of the movable armature carries a round steel clapper. The striking of the clapper against a hemispherical hollow piece of metal produces the sound we hear when the bell rings.

When the switch is closed, current will flow through the coils of the electromagnet as shown in Fig. 14-17B. The electromagnet

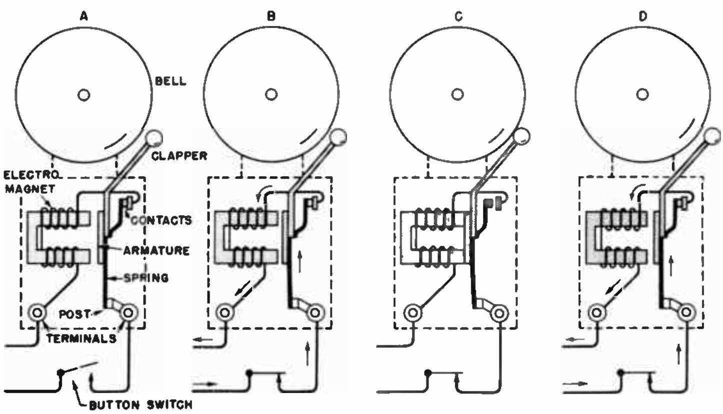


Fig. 14-17. How a vibrating bell works.

will then attract the armature causing it to move toward the electromagnet. The electrical contact mounted on the armature will then move away from the stationary contact mounted on the frame. As the pull continues, the armature will break the electrical connection between the two contacts shown in Fig. 14-17C. When the electrical connection is broken, the current ceases to flow in all parts of the electrical circuit including the coils wound on the electromagnet. When the current ceases to flow through the coils, the electromagnet ceases to be magnetized and no longer attracts the movable armature.

When the armature is no longer attracted by the electromagnet, it will move away from it due to the pull of the spring and will close the two electrical contacts. This is shown in Fig. 14-17D.

When the electrical connection is re-established by the closure of the two contacts, the current starts flowing again. This is also indicated in Fig. 14-17D.

The instant current starts flowing, the electromagnet will again attract the movable armature, which will again move toward the electromagnet and break the connection between the two contacts. This cycle of events repeats itself over and over with great rapidity.

This action of the armature buzzing back and forth striking the bell with the clapper every time it moves toward the bell, will continue as long as the push button is depressed and the electrical circuit remains closed.

THE SINGLE-STROKE BELL

Sometimes the continuous ringing of the vibrating door bell is undesirable because of the clamor it makes. A slight change in the construction of the vibrating bell will convert it to a single-stroke bell so that it makes only one stroke each time the push button is depressed and does not persist in ringing as does the vibrating type.

One type of single-stroke bell is shown diagrammatically in Fig. 14-18. A study of the drawing will disclose that practically the only difference between the single-stroke bell and the vibrating bell is that it lacks the pair of contacts which are constantly making and breaking during the ringing of the vibrating bell.

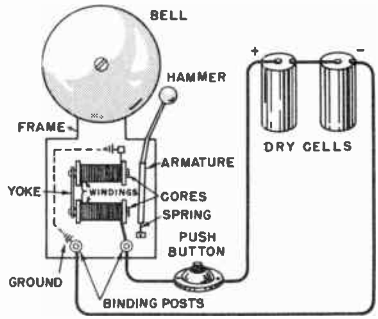


Fig. 14-18. Wiring details of a single-stroke bell.

In the single-stroke bell, the connection from the source of power and the controlling push button is made directly to the coils of the electromagnet. When the push button is pressed, the electromagnet will be energized and attract the armature, but the attraction of the armature will not break the circuit as it did in the vibrating bell. Instead, as long as the push button is depressed, the electromagnet will remain energized and the clapper will remain pressed against the bell. The armature will not move away from the electromagnet until the circuit is broken by the releasing of the push button.

THE BUZZER

The buzzer is very similar in its operation to that of the vibrating bell, except that it has no bell and there is no clapper on the end of its movable armature. This results in the buzzer producing a buzzing sound when operating instead of the clamorous ringing we have with the operation of a door bell.

Buzzers usually serve the same purposes as door bells. They are used to announce the presence of someone at an entranceway or the desire of an executive for the presence of an employee or for some similar purpose. Where the noise level is normally low as it is in some offices and in many homes, the sound of a buzzer is more desirable than the strident ringing of a bell. The buzzer has a muted sound, readily audible to a person near it but too low to annoy anyone elsewhere in the vicinity.

In factories where the noise level is high, and in home locations where the signal must be audible over a considerable distance, the bell is superior to a buzzer. Sometimes a door bell will be located in a basement and a buzzer in the kitchen or living room. Thus, the occupant regardless of what part of the house he is in, is informed of someone's presence at the door. With only a buzzer in the kitchen it might not be possible for a person in the basement to hear the signal.

DOOR CHIMES

Another type of signaling device widely used in the home, which has points of superiority over both the door bell and the buzzer, is the electric door chime sometimes called the door gong.

The electric door chime employs what is called a plunger magnet, which is constructed similar to an ordinary electromagnet; but its operation is somewhat different. Fig. 14-19 shows a cross-sectional view of a plunger magnet. Normally, the movable iron plunger inside the coil of wire is held partially outside the coil by the action of a spring. When current is passed through the coil of wire, electromagnetism will be produced and the iron plunger will be pulled into the coil.

The action of the door chime is shown very clearly in Fig. 14-20. When a source of voltage controlled by a push button is connected to terminals A and B, the chime will be ready for action. When someone at the front door presses the push button the electromagnet will be energized. This will cause the iron plunger to jump violently to the right, strike the metal tube at the right sharply, and produce a low musical note. The spring will then exert its influence to jerk the plunger back toward the left, overshooting its normal position enough to strike the metal tube on the left. This striking produces a second musical tone having a slightly different pitch from the first. The two-tone chime has a very pleasant sound.

In some types of chimes the strength of the spring is not sufficient to give the plunger a return stroke until after the electromagnet has been cut off by the release of the push button, thus cutting off the current. In that case, one musical note is sounded when the push button is first pressed, and a second when the finger is removed from the push button. Most door chimes are designed to sound two musical notes when the push button is operated.

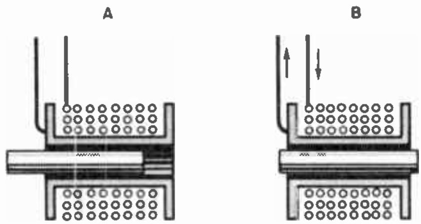


Fig. 14-19. Construction details of a plunger magnet.

This type of chime may be arranged to announce the presence of someone at the rear door as well. A third connection for wiring to the chime is shown at terminal C. This makes it possible to connect a second electrical circuit to the chime from a back door push button, and have sufficient distinction between the sounds to indicate which push button had been operated.

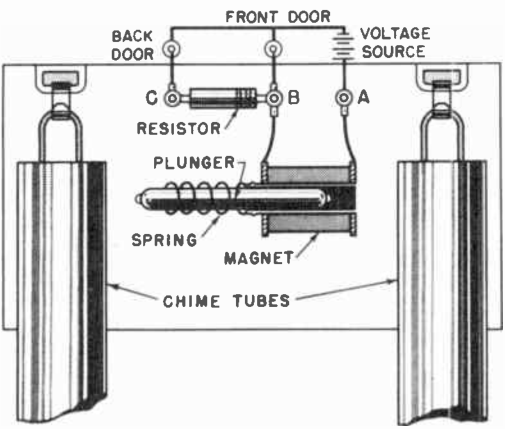


Fig. 14-20. How a door chime works.

If the back door push button is connected between terminals A and C, a pressure on the push button at the back door will energize the coils of the electromagnet and produce magnetism. The resistor in the circuit, reduces the amount of current passing through the electromagnet coil and hence reduces the magnetic pull on the plunger. Instead of jerking the plunger all the way to the right with sufficient force for it to strike the right-hand tube, the spring will stop it short. Thus the plunger will not touch the metal tube on the right and no sound will be produced. However, as soon as the push button at the back door is released, the electromagnet will free the plunger, permitting the stretched spring to return the plunger to its normal position. The abrupt pull of the spring on the feed plunger causes it to overshoot its normal position and sharply strike the tube on the left, sounding a note.

The resultant effect is simply this: When the front door push button is pressed, there will be two distinct musical notes sounded by the chime as the plunger strikes first one of the metal tubes, then the other; but when the rear door push button is pressed, only one note will be sounded. Usually, its sound will not be so loud as that from the front door.

This description of a door chime is not intended to cover all such chimes now on the market. There are variations both in construction and operation from the type shown here. Basically, however, they all are much the same. Some have only one metal tube for sounding the musical note, while others may have three, four, or even five.

WIRING FOR SIGNAL CIRCUITS

Most of the circuits described in this chapter refer to low-voltage systems where the voltage is usually from 6 to 10 volts. In no case, is it more than 25 volts. Special inexpensive types of wire are on the market for use with such circuits. Since this wire does not have the heavy insulation associated with the wires used in higher voltage circuits, it should never be used for handling the voltage and power present in house lighting circuits. To do so creates a serious fire hazard. However, it is very useful for wiring signal circuits such as we have described. Fig. 14-21 shows several types of wire used in this kind of work. The single-conductor wire usually comes in small rolls or on metal spools. The common name for it is "annunciator wire," so called because of its original wide use in annunciator systems. Where two wires are run in parallel with each other, such as between the transformer and the push button, the twisted pair wire or the duplex wire is widely used because of the additional convenience it affords.

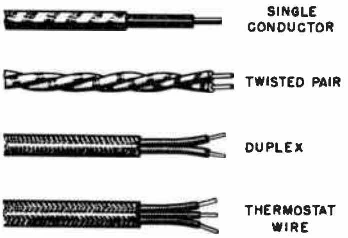


Fig. 14-21. Types of door-bell wire.

Many thermostat circuits, to achieve additional control advantages, use three wires instead of only two. Such thermostats have two separate sets of contact points instead of only the single pair described. The extra pair of contacts requires an extra wire for the proper operation of the circuits. Although the three-wire, low-voltage thermostat cable was developed to meet a specific requirement, it has come to be used widely in other applications.

Where the wires pass through walls or floors, it is always a good practice to provide them with extra protection. These low-voltage signal-circuit wires should also be protected against contact with the higher-voltage house-wiring circuits. Fig. 14-22 shows how porcelain tubes and woven looms can be used to protect the signal wires. They should always be run along the joists beneath the floor in such a manner that they are not likely to be damaged by objects coming into contact with them, and thus breaking the insulation or even the wires themselves. The wires can be fastened to the joists with *insulated* staples, as shown in Fig. 14-22. These staples are inexpensive, yet hold the wires in place and make a neat and safe installation.

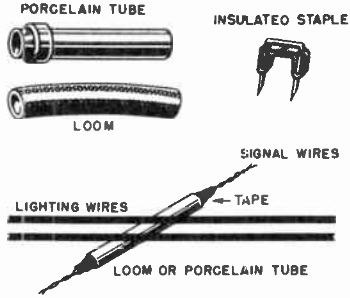


Fig. 14-22. An insulated staple, loom, and porcelain tube.

THE WIRING LAYOUT

The circuit for an electrical signal system is often very simple, consisting of a battery of dry cells or a transformer, a push button, and a door bell, chime, or buzzer all connected in a series circuit. A series circuit, as we have already learned, is one where all the current in the circuit flows through all parts of the circuit. Opening the circuit at any point will effectively interrupt the circuit and cause all current to cease flowing.

There are other instances where a more elaborate system is either necessary or more convenient. In Fig. 14-23 we see a single bell-ringing transformer acting as the source of voltage for three separate signal circuits. In the diagram we see the lower door bell being controlled by a push button located at the front door.

In addition to the bell operated from the front door push button, there is a second bell located near the first bell, but it is operated and controlled by a second push button at the back door.

In addition, for the convenience of the occupants, there is a third push button which operates a buzzer. No particular effort has been made to designate a location for the buzzer or for the push button controlling it. It might be a buzzer located in the kitchen with its push button in the master bedroom, dining room,

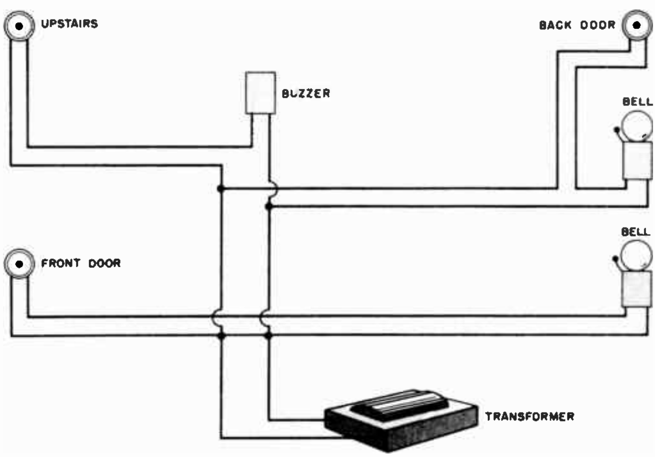


Fig. 14-23. A typical door bell signal system used in a better home.

living room, or some other room. The exact location is of little importance for our purpose which is to show how three separate and distinct signal systems can be operated from a single source.

Very often a single door bell is adequate, with its operation controlled from both the front and the rear door. This method of operation does not indicate whether the signal is coming

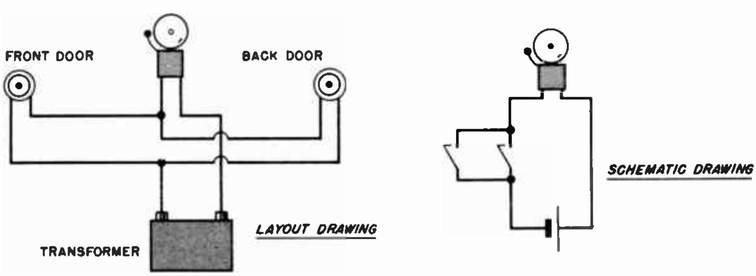


Fig. 14-24. A door bell controlled by two pushbuttons.

from the front or the rear door, but sometimes that is not important. Fig. 14-24 shows how a single bell can be controlled from either of two locations. The pictorial drawing shows how the wiring extends from the transformer, which acts as the source of power, to the bell, and hence to the push buttons in the two locations. The electrical essentials of such a circuit can be seen more clearly and understood better, by a study of the schematic drawing in the same illustration. The schematic shows how a circuit can be completed between the source of power and the bell if either of the two switches is closed. The schematic of the circuit is electrically identical to its pictorial. For the sake of simplicity, we have substituted a battery in the schematic drawing for the transformer shown in the pictorial drawing. The electrical action is the same.

The method of laying out a return-call system is shown in Fig. 14-25. Here we have a circuit which makes it possible for a person to press push button *B* and cause the buzzer *B* to sound. This might be used by a person on the first floor to signal a person on the second floor or at some other remote location. If the person on the second floor hears the buzzer, he can acknowledge the fact by pressing his own push button, switch *A*, which will ring the bell *A*, located near switch *B*.

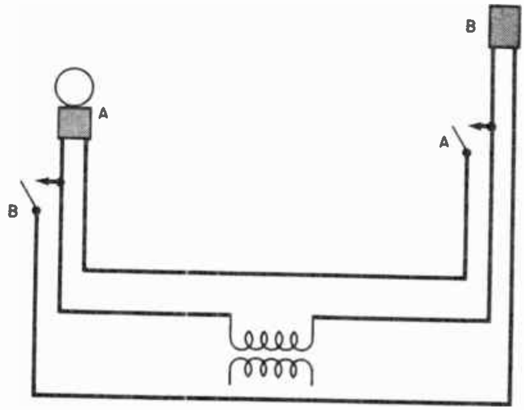


Fig. 14-25. A return-call system circuit.

To better understand the mechanics of such a system, suppose we consider the installation in Fig. 14-26. The wiring for such a system would follow the schematic circuit of Fig. 14-25 in all details. From Fig. 14-26 it is easy to see how a person in one part of a house can signal a person in another part. An understanding of the operation of the system may be obtained more readily from studying the pictorial installation drawing than it can from a study of the schematic.

While we have used push buttons, bells, and buzzers to demonstrate the operation of this type of circuit, the electrical principles which are found in this circuit have many other applications. A variation of the return-call system of circuits is that used in so many apartment buildings for communication between the entrance lobby of the building and the apartment units. Many such apartments have a lobby accessible from the outside which contains mail-slots. No stranger, without a key, can enter the main building from the lobby unless someone within the building admits him. Usually each mail slot has the name of the occupant and apartment number on a little name plate beside it, along with a push button by means of which a visitor can signal his presence.

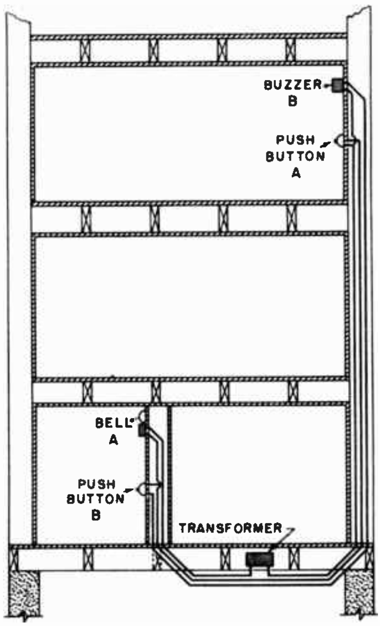


Fig. 14-26. The method of wiring a return-call system.

A visitor presses the push button of the apartment he intends to visit. If the person living in the apartment is home and wishes to admit the visitor, he can release the electric lock on the entrance door leading to the stairway of the building by pressing a push button within his apartment. Many such systems have the added convenience of an intercom which permits the occupant of the apartment to talk with the visitor before admitting him.

Fig. 14-27 shows how such a system works in a building where there are only three apartments. The same system, with additional circuits, could be used in a six-apartment building or in a building with any number of apartments.

In the schematic wiring diagram for this building, we see a rather elaborate system of signaling. There are push buttons at the front door for each apartment; a return system from each apartment which can control the door opener on the door between the lobby and apartments; and a buzzer in each apartment operated by a push button at the rear door.

To demonstrate how this system operates, suppose a visitor enters the front hall lobby and wishes to visit apartment No. 1.

He presses the push button in the hallway corresponding to the No. 1 apartment. When that push button is pressed, the bell in the No. 1 apartment rings. This action can be better understood by tracing the circuit, which connects from the transformer to the bottom side of the No. 1 push button; from the upper side of that push button to the bell; through the bell to the common line, which extends from the upper side of the transformer; and through that common line back to the transformer. Thus it can be seen that pressing the No. 1 button in the front hall completes the circuit and rings the bell in the No. 1 apartment. The occupant of No. 1 apartment can then admit the visitor by pressing the switch shown in the drawing, for this switch operates the electric door opener.

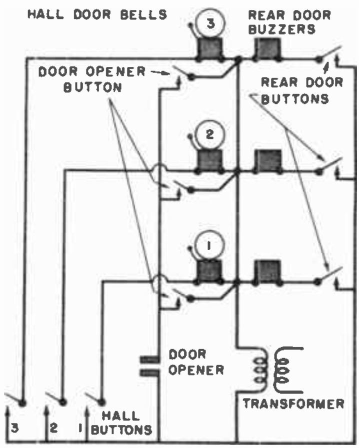


Fig. 14-27. A signal system commonly used in apartments.

If a visitor comes to the back door of the No. 1 apartment, he will press the rear door push button, which will sound the

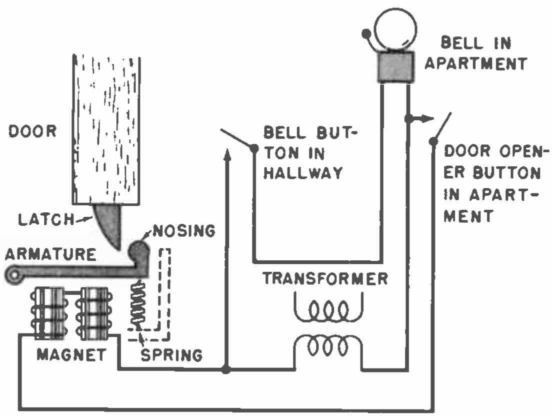


Fig. 14-28. Operating details of a door opener.

buzzer in the apartment. It is necessary to trace the circuit to that buzzer to understand what occurs when the push button is pressed at the rear door. Pressing that button completes the circuit from the upper side of the transformer, through the buzzer, through the closed switch, and back to the lower side of the transformer. Remember, that one transformer is the source of power for the operation of this entire signal system.

The circuits for each of the bells and buzzers in the other apartments, and also the circuit for the operation of each door opener should be traced to give you a better insight into the operation of parallel circuits. The electrical principles explained here apply equally well to the higher voltage circuits used to supply light and power to our homes, offices, stores, and businesses.

You are probably interested in learning just how an electric door opener operates. Fig. 14-28 shows the electrical and mechanical details of such an opener. When the push button in the apartment is pressed, it completes a circuit from the transformer through the push button and back through the coils of the door opener to the transformer. Pressing the push button causes the transformer to send current through the coil of the door opener's electromagnet, the magnetism of which attracts the movable armature which normally keeps the door locked. As long as the armature is attracted by the electromagnet, the door is unlocked and can be opened by a push from the outside.

ANNUNCIATOR CIRCUITS

Most of us who have entered the nurses' office in a modern hospital, ridden in an elevator, or been around the manager's office in a small hotel have seen some type of annunciator system in operation. Basically the purpose of an annunciator system is two fold. First, it functions as a regular signal system to indicate that something is wanted; and second, it gives some form of visible indication to show who it is wanting the service.

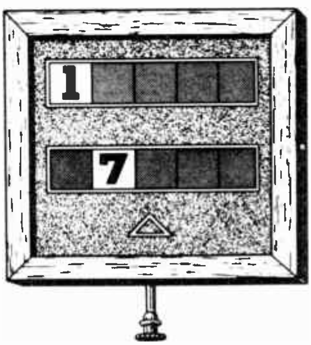


Fig. 14-29. The type of annunciator often used in rooming houses and small hotels.

In hospitals each patient can ring for a nurse by pressing a push button near his bed. Pressing the button produces a signal in the nurses' quarters in the form of a muted buzzer, a light, or a subdued single-stroke chime. At the same time the signal is given, a little indicator button drops down on the annunciator board to show the nurse which patient has called her and from what room the call comes.

There are many types of annunciators in common use. Fig. 14-29 shows a common type used to indicate from which room a call has come. Fig. 14-30 shows still another type. There are probably more than a dozen other types and as many shapes. Some annunciator boards require only four drops, as they are called, to handle the needs adequately, while other boards may require fifty or more; however, the electrical principles are the same for all.

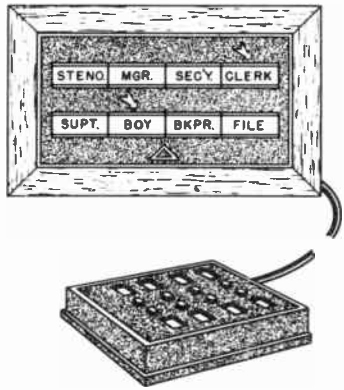


Fig. 14-30. A type of annunciator used in offices and places of business.

Reduced to its basic simplicity, the mechanism and electrical operation of an annunciator drop is shown in Fig. 14-31. When the switch marked "contact" is closed a current is caused to flow through the coil on the iron core of the electromagnet. The flow of the current through the coil of wire energizes the electromagnet and causes it to attract the iron (steel) armature. As the armature is moved downward by the magnetic pull, the lever arm turns on the pivot, releasing the "drop," which falls to the position shown by the dotted outline.

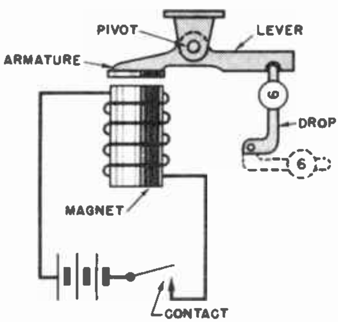


Fig. 14-31. Operating details of an annunciator drop.

The drop will remain in the "dropped" position until it is manually returned (reset) to its normal position. Only a momentary contact at the switch contacts is needed to cause the annunciator drop to fall.

The wiring of a four-position, or four-drop annunciator, is shown in Fig. 14-32. This type of annunciator is often used in homes where several servants are in attendance. With the advent of modern housekeeping aids and the difficulty of obtaining house servants, the need for this type of annunciator is not so great as it once was, but it is still used in many of the larger homes.

The annunciator indicator is usually located in the kitchen or in the servants' quarter. The push buttons from which the calls are made are placed in convenient locations, which may include the dining room, the living room, the parlor, any of the bedrooms, the front door, and the rear door. Instead of using a bell for the signal, one could arrange a lamp which would remain lit until extinguished by the person answering the summons.

Note that in this circuit the bell rings when any one of the push buttons is pressed, but it rings only as long as the button is

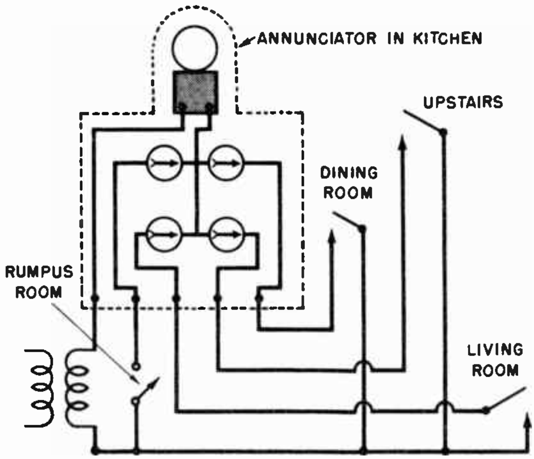


Fig. 14-32. A four-drop annunciator which would be suitable for use in a home.

depressed. The annunciator could be arranged so that the bell continues to ring until it is shut off by the person answering the summons. The source of power is the transformer shown in the lower left corner of the drawing.

Still another application of the annunciator would be in an elevator. Fig. 14-33 shows how an annunciator is installed in the car of an elevator to show the operator from which floor a summons has come. When a passenger wants to use the elevator, he presses a push button near the elevator door on whatever floor he is standing. Pressing the push button rings a bell or lights a lamp on the annunciator board within the car. At the same time it drops an indicator, or lights a lamp behind a number, and thus shows the operator on what floor the passenger is waiting. By raising a little control button under the annunciator board as shown in Fig. 14-29, the operator of the elevator can restore the annunciator to normal, making it ready for the summons of the next passenger. If the operator should be outside the elevator cab when someone rings, a glance at the annunciator when he returns will inform him of the call and tell him the floor from which it came.

Many of the newer elevators have annunciator systems which represent a radical improvement over the simple types shown

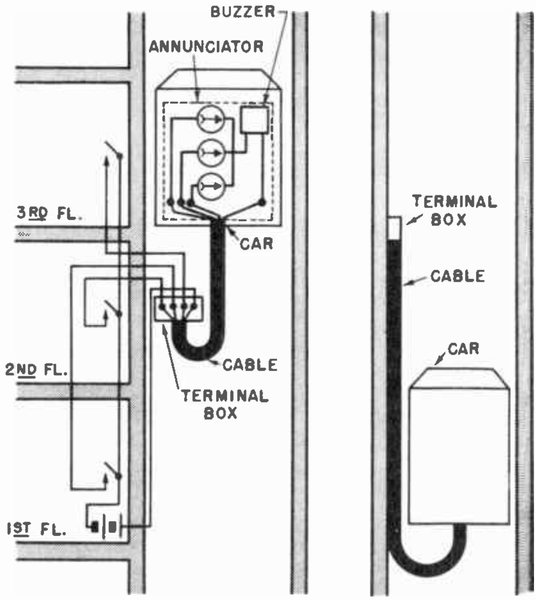


Fig. 14-33. How an annunciator system would operate in an elevator.

here. Many of those systems are tied-in with the operation of the elevator itself. In such systems, pressing the button near the door of the elevator shaft on any floor is sufficient to bring the elevator directly to that floor and cause it to stop there. Despite the fact that such systems are much more complicated, many of them are merely enlargements upon the systems described here, their underlying electrical principles being the same.

THREE-WAY SWITCHES

In Figs. 14-6 through 14-8, the operation of switches having more than two contacts was studied and applications in which such switches are used were described. There are still other applications in which the use of such switches can provide increased effectiveness in the control of an electrical circuit.

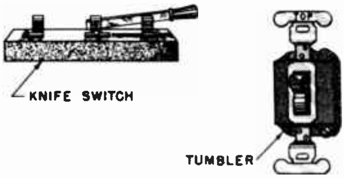


Fig. 14-34. A single-pole double-throw knife switch and a three-way tumbler or toggle switch.

In Fig. 14-34 we see a single-pole double-throw knife switch. This type of switch can be used for a variety of purposes, one of which is to control the operation of a lamp from either of two locations. The wiring connections for such an operation is shown in Fig. 14-35.

The advantage offered by the use of this switch in the circuit of Fig. 14-35 is that the light can be turned on or off from either of two locations. For example, it might be highly desirable to have a lamp located where it will light a stairway. A person, wishing to ascend the stair, could turn the light on with the switch located at the foot of the stairway, ascend the stair safely, and turn out the light with the switch located at the head of the stairway. Obviously, a person would not want to go all the way back downstairs to turn off the light he had switched on to permit his safe ascent. This method of wiring permits a person to turn the light on downstairs, climb the stairs, and turn it out at any time. The light can be turned on either from upstairs or downstairs, whichever is desired.

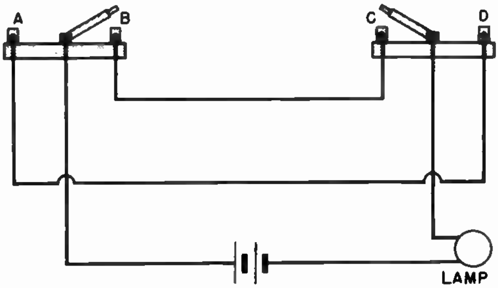


Fig. 14-35. How two single-pole double-throw knife switches can be connected to control a lamp from either of two positions.

Another useful application for this method of wiring is the control of the garage lights. A switch inside the house will turn the garage lights on or off, and another switch in the garage will also turn them on or off, thereby providing a very flexible control. In this manner, the lights in the garage can be turned on before one leaves the house to go to the garage. This is particularly desirable where a person must take the car out at night, for it not only serves to relieve their uneasiness, but actually offers a safeguard against any chance of an intruder being hidden in the darkness. If the yard lights are on the same circuit, walking to the garage is much safer and more convenient.

Furthermore, when one drives into the garage, the lights in both the garage and the yard can be turned on at the same time before the head lights are extinguished, and kept burning until the person enters the house. Once inside, he can turn off both lights.

Often the lights in the living room, the kitchen, or the dining room are controlled from two locations. One can enter the room through one door, turn on the lights so things can be seen, then leave by another door, and there turning the lights out.

Our using knife switches in Fig. 14-35 instead of regular three-way toggle or snap switches, permits the wiring circuits which control the operation of a lamp from either of two locations to be understood more easily.

In Fig. 14-35 neither switch is closed. Thus the light is not burning. If the switch on the left is closed by making the blade contact terminal B and the switch on the right is closed by making the blade contact terminal C, the lamp will light. A circuit would then be complete from the battery to the lamp, from the lamp to the blade of the switch on the right from the terminal at C to the terminal of the other switch at B, and finally back through the blade of the switch on the left to the battery.

Suppose, then, that the blade of the switch on the left is moved from terminal B to terminal A. The lamp will no longer burn because the circuit is broken. We know that the lamp would burn if we returned the switch blade to terminal B, because it was burning in that position a few moments before.

Even with the switch blade at the left contacting terminal A, the lamp can still be made to burn. This can be done by moving the blade in the other switch from C to D.

Let us see how this can be done. If the left switch blade is contacting terminal A and the right switch blade is contacting terminal D, the circuit will be complete from the battery through the lamp, through the blade of the switch to terminal D, then back through the connecting wire to Terminal A, and through the switch blade back to the battery, a complete and closed circuit.

The lamp will burn. Opening either switch would cause the lamp to go out, because doing so would break the circuit.

Knife switches such as illustrated in Fig. 14-34 and 14-35 would not be used to control the operation of a lamp from either of two locations because for such circuits to properly function, the person operating the switch would each time have to throw the switch blade from one switch terminal completely over onto the other terminal. In other words, the switches in such a circuit must always be closed in one position or the other; otherwise, the circuit will not function. Each switch in this type of circuit must *always* be closed in one position or the other.

Under actual operating conditions requiring three-way switches, the toggle type of switch sometimes called a "tumbler" switch, is generally used because this type of switch is constructed so that the instant the switch blade is removed from one switch terminal, it automatically (by spring action) snaps into contact with the other switch terminal.

Fumbling around for a knife switch in the dark is not generally recommended. When we want to control a lamp, it is better to use a switch where there is no danger of making an accidental contact with a piece of electrically charged metal.

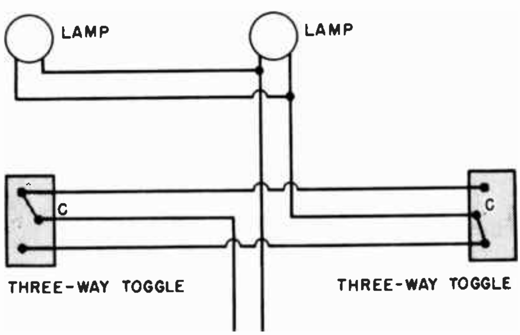


Fig. 14-36. How two three-way toggle switches can be used to control two lamps from two different positions.

That is the reason the toggle or tumbler switch (Fig. 11-34) is used widely. The action of both types of switches is the same. Note the three screws on the switch by means of which electrical contact can be made to the three elements of the switch. That is the reason they are so often called "three-way toggle" switches.

In Fig. 14-36 we see how a pair of three-way toggle switches can be used to control two different lamps. This could be an arrangement such as we described in the case of the garage and yard lamps controlled from two locations.

Each of the two switches has one terminal which is called the common terminal, marked "C" in the drawing. On the switches themselves the common terminal is usually a different color from the other two. It is always marked in some distinctive manner to make the wiring of the switches easier.

The common terminal is always in contact with one or the other of the other two terminals, but only with one. This means that if the common terminal in both switches is in contact with the upper terminal in both switches, the two lamps will light. If the common terminals are in contact with the two lower terminals, both lamps will light. If one common terminal is in contact with an upper terminal and the other common terminal is in contact with a lower terminal, as shown in the illustration, neither of the lamps will light.

There are many variations of this method of wiring. Similar circuits are used in automobiles, aircraft, and many other places.

Chapter 15

PRACTICAL WIRING AND ELECTRICAL APPARATUS

WIRING RULES AND REGULATIONS

Electricity has come to be one of man's most faithful and useful servants. People have long known that electricity can be dangerous and destructive if it is not carefully and properly handled. Hundreds of persons have had their lives snuffed out in an instant because of their own or someone else's carelessness in handling electricity. Nobody knows how many hundreds of millions of dollars worth of property have gone up in smoke from fires resulting from improper electrical wiring. (See Fig. 15-1.)

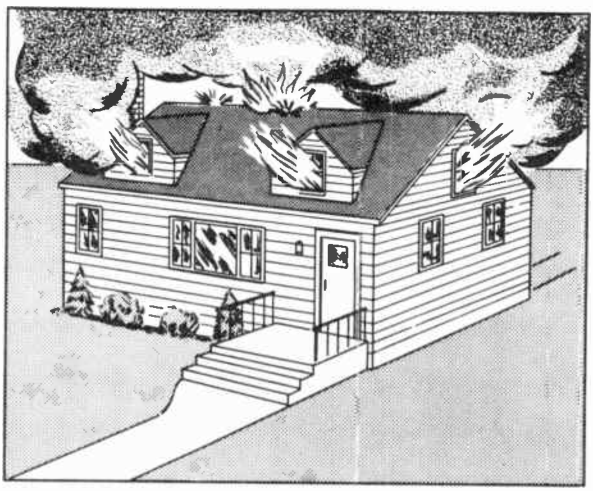


Fig. 15-1. Many fires are caused every year by improper electrical wiring.

From facts like these, one might be inclined to think of electricity as too dangerous to use and that we should turn to other sources for our light, heat, and power. Reasoning of that kind ignores one important factor concerning the use of electricity: its danger comes from careless and improper handling.

Many persons and many large companies are greatly interested in making electricity safe to use. Among these are the electrical manufacturers. They contribute large sums of money to the support of a large testing laboratory which constantly runs tests on electrical apparatus of all kinds to determine if it is electrically safe and to see that it will not bring harm to its users nor be a source of fire hazard. Companies who write fire insurance probably are the most concerned of all groups. They are vitally interested in reducing all possible sources of fire hazards to a minimum and in doing everything that they can to prevent fires. The fire underwriters, the companies who write such fire insurance, have banded together for mutual assistance to aid in preventing fires. They have created an organization called The National Board of Fire Underwriters which has offices located in several principal cities in the United States. The National Board of Fire Underwriters, together with the electrical manufacturers, support the Underwriters' Laboratories, the great laboratory the sole duty of which is to test and inspect the design and construction of all types of electrical equipment and materials to make certain their use does not constitute a fire hazard. A seal or stamp of approval of the Underwriters' Laboratories is the user's best guarantee that the piece of electrical apparatus he is buying is as safe as modern science can make it. No manufacturer can place the Underwriters' Laboratories' stamp of approval on his product unless it has been tested by the laboratory and has met with approval. A sample of the product bearing their stamp is periodically tested by the laboratory to make certain the manufacturer is maintaining the required standards.

The Underwriters have done more than this. In cooperation with state and municipal electrical inspectors, and with fire prevention bureaus, as well as with the electrical manufacturers, the Underwriters have borne the major portion of the expense of preparing an electrical code which tells how all kinds of electrical apparatus shall be made and how all kinds of electrical wiring shall be installed. More than this, they have also gone to the expense of revising the code and keeping it up to date as new knowledge and new equipment have come into existence.

The electrical code prepared by the Board of Fire Underwriters is called the National Electrical Code. A copy of the code can be obtained by writing The National Board of Fire Underwriters, 222 West Adams Street, Chicago, Illinois, or by writing to them at one of their other offices.

The National Electrical Code is considered the standard code for electricians throughout the United States. To lend emphasis to its value, many states and cities have incorporated the National Electrical Code into their statutes or ordinances, copying the code word for word. The Board of Fire Underwriters have a way of making the code effective. Should any community be so unwise as to refuse to accept the minimum standards set down by the code, the members of the Board can refuse to provide fire insurance for any of the buildings in that locality. There is no record that any community has been forced to accept the provisions of the code. It has been prepared at great expense by hundreds of experts, and only a very foolish person would reject its provisions. However, the Board could use very strong persuasion to make it accepted if that were necessary.

The National Electrical Code is known as a code of minimum standards. This means that any kind of wiring or any kind of electrical apparatus that does not meet those standards is not considered good enough for anyone to use. Nevertheless, there is no reason why any city, state, or other community cannot adopt even more stringent standards than those required by the code. Many cities have done so. The code, for example, permits what is known as "open wiring" in which the wires in a home or other buildings are carried throughout the building on porcelain knobs or cleats and through porcelain tubes. Many cities now bar all forms of open wiring and insist that all wires carrying more than 50 volts be enclosed within pipes or other metal conduits or enclosures.

SERVICE ENTRANCE

The act of furnishing electricity to a customer by an electrical utility is often referred to as "electrical service." This term probably came into existence in the early years of electricity because of the anxiety of the utilities to emphasize their desire to "serve" their customers, to provide "service." Almost anything connected with their contact or relation with customers was referred to as "service."

In time all the wires, fuse boxes, cabinets, meters, switches, and anything else closely connected with providing service to a customer came to be grouped under the loose term "service equipment." The service equipment included the heavy wires between the power company's line pole and the customer's build-

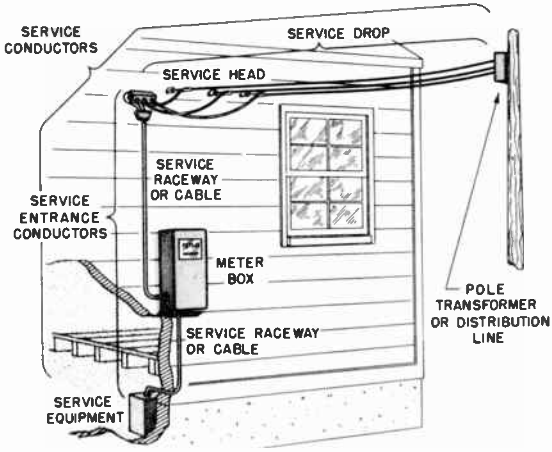


Fig. 15-2. The principal parts of an electrical service entrance.

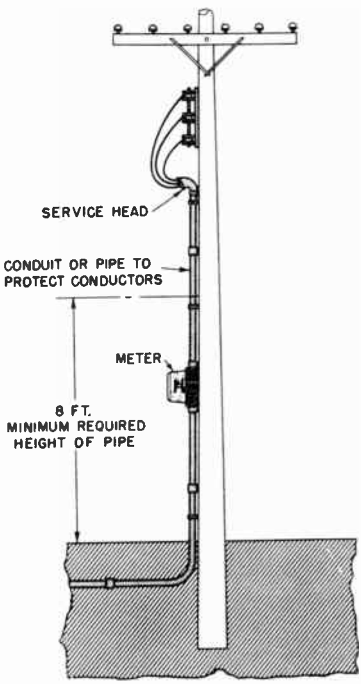


Fig. 15-3. A meter on a pole for an underground service.

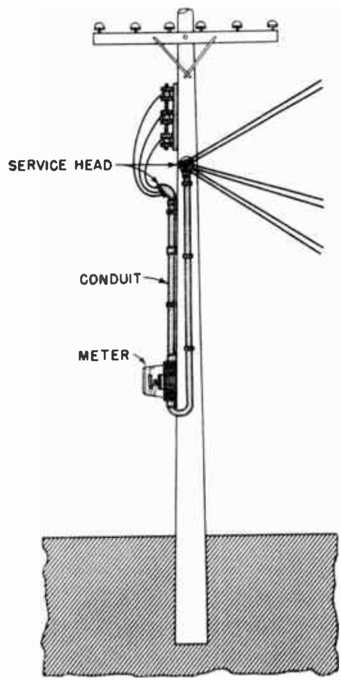


Fig. 15-4. A meter on a pole for an overhead service.

ing, the heavy wires from that point down the side of the building to the meter, the meter, and usually the main switch and the fuse cabinet. Now the general inclusive name "electrical service" is more commonly used and generally accepted. This remains true even though much of the wiring which was originally part of the utility company's service must now be provided by the customer. Fig. 15-2 indicates the various parts included in the service equipment needed for the wiring of a house.

Fig. 15-3 shows how an outside meter is often placed on a "meter pole" on a farm. The meter pole is usually centrally located so wires can spread out from the pole to the house, barn, well, and other farm buildings. Such an arrangement usually makes a saving in the amount of wire needed to take electricity to all parts of the farm. It also makes individual wires shorter, thus reducing the resistance in any given circuit and lessening the power losses in the wires.

Fig. 15-3 shows the wires going underground from the meter pole to the other buildings. This is done on many of the larger farms where a multiplicity of wires between the meter pole and the farm buildings would be unsightly. A more common method is to have the wires spread out in every direction from the top of the meter pole to the various buildings. Such an arrangement is shown in Fig. 15-4.

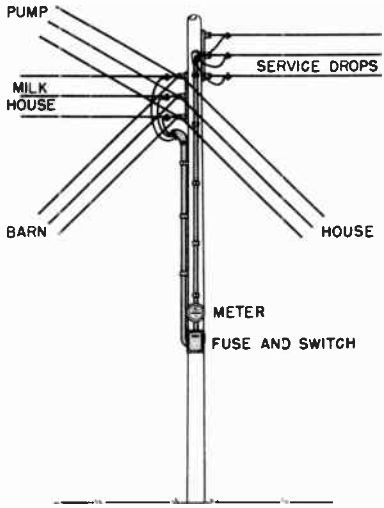


Fig. 15-5. The main fuse and main switch are often located on the meter pole.

Sometimes the electric service conductors are provided with fuses, or with fuses and a main switch, just after the power passes through the meter on the power pole. The location of the cabinet containing the fuses and the switch is shown in Fig. 15-5.

Anyone who has ever had any wiring done which involved bringing in a new electrical service has no doubt been confused by the seemingly peculiar terminology of the wires and other equipment involved. Such confusion occurs in the wiring of a house but is even greater on a farm or with any other type of rural electrical wiring.

The wiring usually includes reference to "service drops," "service conductors," "service entrance," "service equipment," and other similar terms. The confusion generally arises from the fact that there is some overlapping in the exact meaning of these terms, and in some instances either of two names could be applied to the same wires with equal accuracy.

Generally speaking, the term "service conductors" can be applied to all the conductors between the point where a connection is made to the power company's transformer and the location of the main switch and fuse cabinet. All of these wires are quite large. The National Electrical Code specifies they shall not be smaller than No. 6, although the neutral wire may be No. 8. The No. 8 wire is, of course, a little smaller than No. 6.

The more common practice is to use the term "service conductors" to apply to those wires which run from outside the service

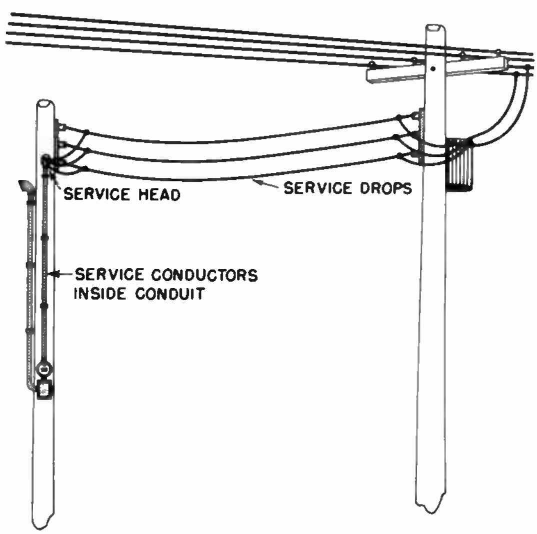


Fig. 15-6. The location of the service conductors, the service drops, and the service head in an overhead service to a meter pole.

head at the top of the meter pole to the fuses and main switch. In nearly every locality the customer must pay for the installation of these conductors.

The power company or other utility installs the service drop wires. The "service drops" are clearly shown in Figs. 15-2 and 15-6. They are the wires which take the power from the transformer or the power company's power pole to the meter pole or to the customer's building. They may be connected to the power pole or to the customer's building by what are called "service attachments" or by screw-type wire-holder insulators. The wire-holder insulator is generally preferred because it is easy to install. It consists of a large ceramic insulator which has a large screw protruding from its base. Fig. 15-7 shows how such an insulated wire-holder is installed and how the service drop is connected to it.

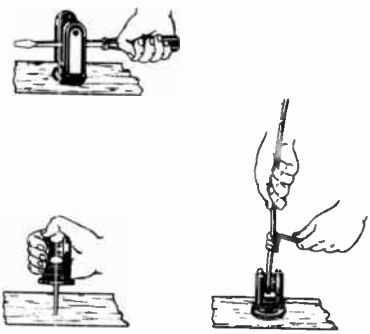


Fig. 15-7. The service attachment is fastened to a pole or building, and the service drops are connected to it.

In virtually every community the customer installs the insulated wire-holder or the service attachment. The service attachment consists of three large insulators mounted on a metal base. The insulated wire-holders or the service attachment are mounted on the pole or the building near the service head. The insulators on the service attachment are located eight inches apart. If the individual wire-holders are used, they must be mounted exactly eight inches apart and in a straight line. They may be mounted either vertically or horizontally, whichever best suits the local conditions.

Most of the private power companies furnish the customer with the wire-holders or the service attachment without charge; then the customer installs them. The REA co-operatives and other public power companies usually charges the customer for them.

After the insulated attachments are installed and the other wiring has been properly completed, the power company makes the connection between the company's power pole and either the meter pole or the building. In brief, the utility company installs the service drops at its own expense making the connection to the insulated attachments already installed by the customer.

The customer then assumes the job of installing all the necessary wiring from the service head into and throughout the building. From the power company's point of view, it is the customer who handles the details of such wiring, but in practice the customer usually hires an electrician to do the actual work.

Before going any further into a description of the steps to be taken in making an electrical installation, a few words of explanation are in order. In most cities and villages where the municipality has a regular electrical inspector, the power company will not install the service drop through which electrical service can be supplied until the customer or the customer's electrician presents an electrical permit issued by the city or village. In many rural areas, the county or some other authority often has the responsibility of issuing such permits. Many cities and villages will not issue a permit to any person except a licensed electrical contractor. This makes it impossible for the average householder to install his own electrical service equipment. An electrical contractor must be hired to do the work before the power company will make the connection for the electrical service. No one should make any attempt to install electrical service wiring and equipment without first making certain he can do so legally. In the rural areas the regulations are often much different. So long as the service wiring and the other wiring meets the approval of the power company's inspector, the company does not care who does the work. Anybody who is handy with tools and who has a reasonable knowledge of electrical wiring can wire his own home including the installation of the electrical service equipment.

The customer makes an electrical connection to the power company's "service drop" by running service conductors up close to the point where the service drop wires are fastened to the service attachment. In Figs. 15-5 and 15-6 the service drop ends at a service attachment mounted near the top of a meter pole. The service conductor wires which make the actual connection to the service drop enter a "service head," which is mounted on the upper end of a piece of "conduit." A conduit is a metal pipe used to enclose the service conductors and protect them against mechanical damage. In Fig. 15-2 the "service head" is mounted on the side of a building, only a short distance from the service attachment which anchors the service drops. Here, again, the service head is mounted on the upper end of a length of conduit.

In many of the cities, villages, and suburban areas, the meter is mounted in a "meter cabinet" as shown in Fig. 15-2. According to present rules, the meter must be mounted outside the building and must be protected by such a cabinet. Most of the privately owned power companies furnish the meter cabinet without charge, but some of the co-operative and public power companies require the customers to pay for it.

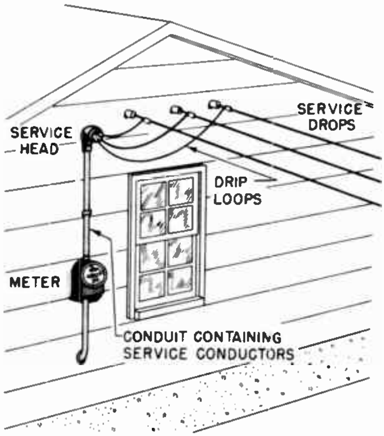


Fig. 15-8. The location of a meter on the side of a building when a meter pole is not used.

In the rural areas, the meter is nearly always mounted as shown in Figs. 15-5 and 15-6, or as shown in Fig. 15-8.

In Fig. 15-8 the meter is mounted directly on the side of a house. If the house is in a rural area but is not exactly a farmhouse surrounded by a group of farm buildings, it is often more desirable to mount the meter directly on the side of the house instead of on a meter pole. However, when there is a group of scattered farm buildings, all of which require electric power, the meter pole arrangement is more practical. The exact method of mounting the meter will depend on which is the more practical from the standpoint of both the customer and the power company.

The meter in Fig. 15-8 is a different kind of meter from the one mounted inside the meter cabinet shown in Fig. 15-2. Because of

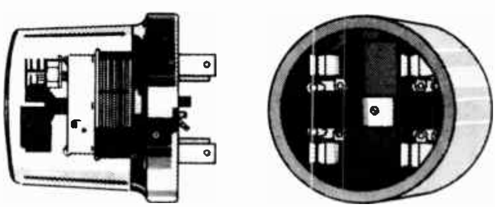


Fig. 15-9. A glass-enclosed type of outdoor meter suitable for mounting directly on a pole or outside wall without a protective cabinet.

the convenience of having the meter outside the house rather than inside, as was once the universal practice, new types of glass-enclosed water-tight meters have come into widespread use.

Such a meter, with the base upon which it is mounted, is shown in Fig. 15-9. The base is to the right of the illustration. The base, also sometimes called the "socket," is mounted directly on the meter pole or on the side of a building. It is fastened securely with heavy wood screws or other required fasteners. All the electrical connections are then made to the meter base. Usually there is a threaded opening in the top and another in the bottom of the base. A conduit is fastened to the meter base with threaded connections, thus making a water-tight junction. After it has been put in place, the service conductors are pulled in through the conduit and are fastened to the specially prepared connectors inside the base of the meter. After all the electrical connections have been completed, the main part of the meter is fastened onto the base.

The exact method of fastening varies with different kinds of meters. Some are fastened on by a metal band which surrounds both the meter and its base and are then clamped in place; others are fastened on with special type screws, still others are held in place in other ways. In every case, however, provision is made for the power company to seal the meter so it cannot be opened or tampered with without breaking the seal.

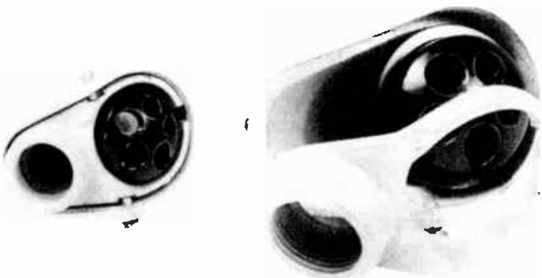


Fig. 15-10. An electrical service head.

The service head at the top of the conduit which encloses the service conductors is a device which serves to protect the insulation of the conductors where they emerge from the conduit and to prevent rain and other weather elements from entering the conduit. Fig. 15-10 shows what one type of service head looks like. The main shell of the service head is made of metal. Most of them are constructed so that the top of the shell is demountable, thus making it possible to put the top of the head in place after the wires have been installed. The part of the head through which the conductors emerge to the outside is made of insulating material. Sometimes it is porcelain, but in recent years there has been a strong tendency to use pressed fiber or plastic instead of porcelain. The fiber and plastic are more rugged and not so easily broken through rough handling. Some of the service heads have three partially closed openings through which the wires can emerge; others have four and five such openings partially closed with thin pieces of fiber or plastic. When the service is installed, the openings needed are fully opened with a knife or screwdriver so the wires can slip through easily.

The base of the service head is fitted with screw threads so the head can be tightly screwed on the end of a piece of pipe conduit. The heads are made in standard sizes to fit on standard sizes of pipe. The smallest is intended to fit a piece of ½-inch pipe. Other common sizes will fit a ¾-inch pipe, a 1-inch pipe, or a 1¼-inch pipe. They also come in larger sizes, but the sizes mentioned here are the ones in general use. They will handle all normal electrical installations in the average home or on the average farm. A 1-inch service head will handle three No. 6 conductors, but if either No. 4 or No. 2 conductors are used, it will be necessary to have a 1¼-inch service head. It will handle three No. 2 conductors.

The heavy electrical conduit, called "rigid conduit," is very similar to ordinary water or gas pipe. The fact is that water pipe is often used for an electrical conduit, although such use is not generally recommended. Water pipe is always galvanized, while gas pipe is finished with a black finish that is not particularly resistive to rust or corrosion. Both water pipe and gas pipe are sold in standard 21-foot lengths.

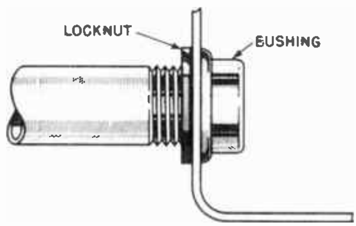


Fig. 15-11. How locknuts and bushings are used to fasten rigid conduit to a switch box or other metallic enclosure.

Rigid electrical conduit comes only in 10-foot lengths instead of the 21-foot lengths of water and gas pipe. Furthermore, rigid electrical conduit is galvanized on the outside to protect the iron against corrosion and is varnished or lacquered on the inside to provide added protection to the conductor insulation.

The rigid conduit is connected by locknuts and bushings to switch boxes, convenience outlet boxes, fuse cabinets, and other electrical metal enclosures. The bushing is located on the inside of the enclosure as shown in Fig. 15-11, while the locknut is on the outside of the box. In making such a connection, the locknut is first placed on to the end of the conduit, and then the end of the conduit is pushed through the hole in the cabinet or other enclosure. Finally the bushing is placed on to the end of the conduit and tightened.

Fig. 15-12. A reamer for reaming burrs from conduit.

Whenever a piece of rigid conduit is cut, the ends of the conduit should be carefully reamed out with a reamer such as that shown in Fig. 15-12. The reason for the reaming can be seen by examining Fig. 15-13. Cutting the conduit will nearly always leave a little "lip" or burr

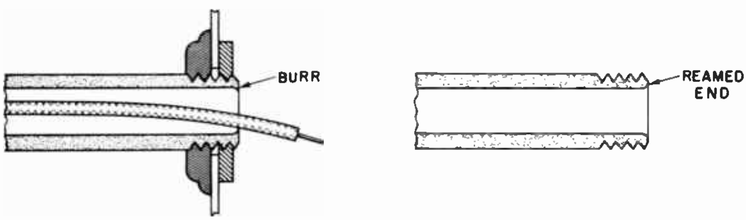


Fig. 15-13. End of conduit before and after reaming.

on the inside at the point where it is cut. The reamer cuts off the burr and lessens the danger of damage to the insulation on the conductor.

In addition to the regular rigid electrical conduit, which is similar to ordinary water pipe, there is another kind of electrical metallic conduit. Its correct and official name is Electrical Metallic Tubing, but it is commonly referred to in the electrical trade as "thinwall" conduit or just plain "thinwall."

Thinwall conduit comes in the same nominal sizes as rigid electrical conduit. The inside dimensions of the two types are the same. This means that if a run of rigid conduit will carry wires of a certain size and quantity, thinwall conduit will do the same.

As its name implies, thinwall conduit is much thinner than rigid conduit. It is so thin, in fact, that the National Electrical Code will not permit it to be threaded.

Thinwall conduit is fastened by friction connectors, such as those shown in Fig. 15-14, to switch boxes, convenience outlet boxes, and other metal enclosures. The coupling is used to connect two lengths of conduit to make a single continuous run; the connector, to connect a length of conduit to a metal box, such as those used for holding switches or convenience outlets; and the angle connector, to make right-angle connections to a box.

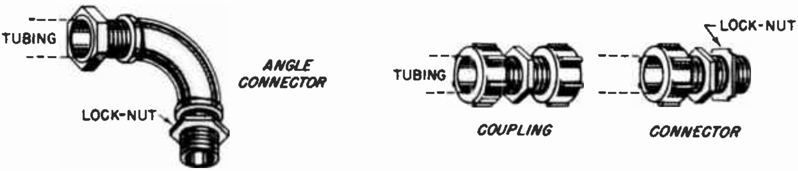


Fig. 15-14. Fittings used with thin-wall conduit.

Generally speaking, thinwall conduit can be used every place that rigid conduit can be used. There are however, a few exceptions. Some localities do not permit thinwall to be used outdoors for enclosing service entrance conductors while others readily permit such use. In hazardous locations such as gasoline filling stations, chemical factories, and similar places where there are corrosive fumes, the use of thinwall conduit is often prohibited.

However, because of the ease with which thinwall can be cut and installed, it has practically superceded the use of rigid conduit wherever its use is permitted. Since no threading is necessary, it is much easier to prepare thinwall for installation.

Both rigid conduit and thinwall conduit are used to enclose the service entrance conductors between the service head and the meter. When thinwall conduit is used, a connector, such as that shown in Fig. 15-14, is installed on the upper end of the conduit. The locknut is removed and the service head is screwed directly on to the end of the connector. At the lower end of the conduit, a similar connector can be used, again with the locknut removed. The connector can be screwed directly into the threads of the meter socket or base.

If the meter is installed in a meter box or cabinet, as shown in Fig. 15-2, a specially prepared "knock-out" at the side of the cabinet can be punched out. The connector can then be inserted through the hole and the locknut installed. Thus, a locknut is necessary for making connection to a cabinet or box; but it is not necessary for making connection to a service head or meter socket base.

After the conduit is installed, the lower end is fastened to the meter or its cabinet and the upper end is connected to the service head, it is then fastened rigidly to the pole or the side of the building. It is strapped tight by the use of clamps similar to those shown in Fig. 15-15.

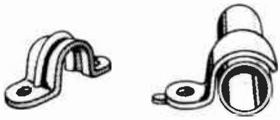


Fig. 15-15. Clamps for strapping conduit to a wall or post.

Finally, the conductors are pulled in through the conduit and the electrical connections made inside the meter. Often, by pushing the conductors down from the upper end at the service head one can put them through the conduit. If the conduit enclosing the service conductors is long, it may be impossible to push the conductors through the conduit, in which case the conductors will have to be "fished" through.

There are several ways to "fish" a conductor through a conduit. It is easier to push a length of small wire through a conduit than it is to force a length of large wire through the same conduit. Often it is possible to push a length of small wire through the conduit, and then use it to "fish" or pull the larger conductors through. An even better method employs what professional electricians refer to as a "fish tape." A fish tape is a piece of narrow flexible steel tape, thin and narrow enough to turn and twist its way following the contours of the conduit; yet rigid enough to be pushed through a great length of conduit. The fish tape comes in a variety of sizes and in lengths ranging from 25 feet to 100 feet.

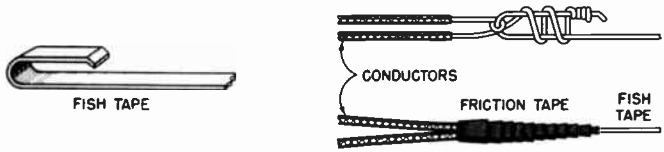


Fig. 15-16. How conductors are fastened to fish tape for pulling.

If electrical fish tape is available, it can be pushed through the conduit; then the ends of the conductors can be fastened to the end of the fish tape. Fig. 15-16 shows how the conductors can be fastened to the end of the fish tape.

There is another kind of service conductor which has come into wide use in the last few years. It is used almost exclusively in many rural areas, particularly on farms. This is a special service-entrance cable which combines in one cable everything needed to bring in the power. Fig. 15-17 shows how such a cable is constructed. It is a braided, insulated cable, quite heavy and larger than the largest automobile-battery cable. The outer braid of this cable is usually greenish gray in color.

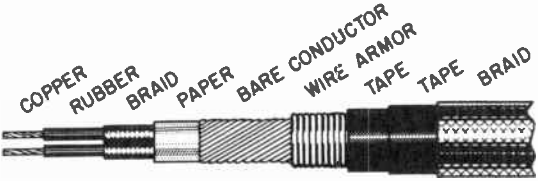


Fig. 15-17. Construction of service-entrance cable.

At the center of the cable is a pair of heavy conductors, each insulated from the other. These are the two "hot" conductors which serve to bring in the two hot leads from the service drop. They are rarely smaller than size No. 6, for they must be heavy enough to handle a large amount of current. Wrapped around the two inner conductors and protected from them by a heavy layer of insulating paper or fiber, is a twisted braid of wires. These wires serve a dual purpose: they provide mechanical protection to the inner conductors and their insulation; and they serve as the neutral conductor of the three-wire Edison system which usually supplies electric power to the customer.

The service-entrance cable can be connected to the service head by a water-tight connector such as that shown in Fig. 15-18. The connector is constructed so that the cable will pass through the hole in the rubber bushing inside the connector. When the packing nut is tightened, the bushing will pack tightly around the cable and make a water-tight fit. A similar connector is used where the service-entrance cable enters the meter base or the cabinet of the meter box. A water-tight fit is likewise necessary at that point.

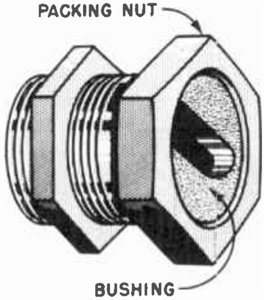


Fig. 15-18. A water-tight fitting for use outdoors with service-entrance cable.

The service-entrance cable also connects the meter with the fuse cabinet and main switch. This is true, whether the fuse cabinet is located on the pole near the meter as in Fig. 15-5, or is inside the house as in Fig. 15-2.

SERVICE ENTRANCE EQUIPMENT

Speaking from a strictly technical standpoint, the service-entrance equipment probably includes all that we have discussed so far plus the fuse cabinet, the meter, and the main switch.

The purpose of the main switch is to provide a means whereby all the electrical power can be quickly cut off at one point. There are many reasons why such a provision is both necessary and convenient; however, the principal reason is to comply with the National Electrical Code. The National Electrical Code makes the use of such a switch mandatory, because it is highly important in the case of fire to be able to shut off all electrical power at one point. With a main switch, in case of fire, it would not be necessary to search for all the many switches which control electrical power on the premises. It is much better to have one centrally located master switch, a "main" switch, which when opened cuts off all the power.

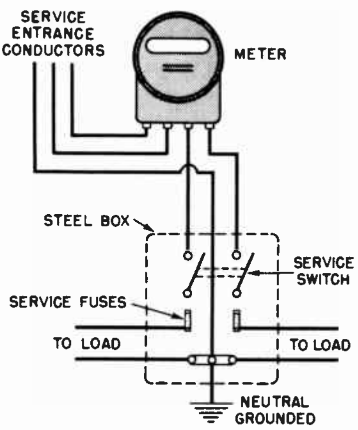


Fig. 15-19. Electrical connections to a meter, a switch, and a main fuse.

Often the "main switch" and the main-fuse cabinet are located together. In fact, in the modern types of electrical equipment, they are often combined in one cabinet so that removal of the main fuses automatically opens the circuit; and thus the holder for the main fuses acts as the main switch. One of the older methods uses a so-called "safety switch" with fuses.

Such switches are operated from the outside by a handle which moves the switch blades. The wiring is much like that shown in Fig. 15-19. The neutral is never fused. According to the rules of the National Electrical Code, it cannot be fused.

A connection is usually made between the neutral wire inside the fuse box and some ground connection. It is a good idea to make this connection, even though there is also another ground outside at the meter.

A more modern method known as a "dead-front" fuse box is shown in Fig. 15-20. When the front of the fuse box is opened, no live electrical contacts that might be touched accidentally are exposed. This provides much greater safety for the person changing a fuse, especially if it happens to be dark. When the handle of the fuse holder, which is marked "main," is pulled out, the

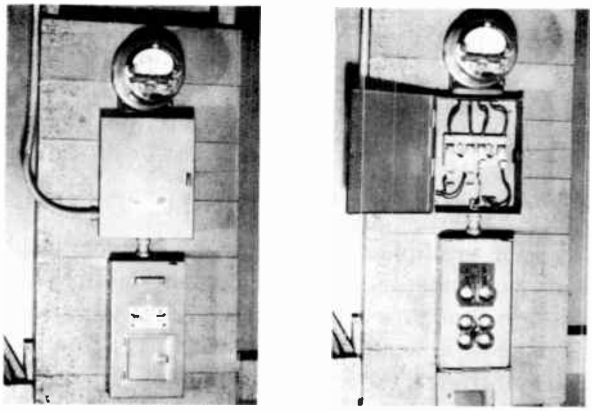


Fig. 15-20. A service entrance installation.

fuses are disclosed and can then be changed. The act of pulling the fuse holder from its socket also breaks the circuit, and thus serves as the main switch. This is the most favored type of main switch and fuse cabinet now in general use.

In addition to the main fuse, most fuse cabinets installed inside a building have provision for the branch circuit fuses. These are small plug-type fuses which provide protection for the individual circuits. If the main fuse cabinet is mounted on the meter pole, as in Fig. 15-5, it does not contain the fuses for the branch circuits.

When the main fuse cabinet is mounted inside the building, it is usually convenient to have the branch circuit fuses mounted in the cabinet with the main fuse.

When the main fuse is mounted on the meter pole, a different arrangement is usually more satisfactory. The main fuse is there to provide protection against an overload so great that it will overheat the main service conductors. Such an overload rarely occurs; some main fuses have been in constant use for many years without ever blowing. However, since they do provide that protection should the occasion arise, they are needed. They can also function as the main switch if they are of the proper type.

It would not be practical to mount the individual branch circuit fuses on the meter pole with the main fuse, since their purpose is to protect the branch circuits against an overload. There are many reasons why such an overload can occur; and almost every person using electrical power has had the experience of having a branch circuit fuse blow out. It would be most inconvenient to have to make a trip out to the meter pole to replace one of these fuses. They go out at the most inconvenient times, at night, on rainy nights especially, and during snowstorms. No, it certainly would not be convenient to go out-of-doors to change such fuses.

For that reason the branch circuit fuses are almost always placed in some convenient location within the building where those circuits are used, such as in the house or in the barn.

GROUNDING THE ELECTRICAL SYSTEM

The matter of grounding the electrical system has been discussed in previous chapters in considerable detail. This will not be repeated, but the matter of grounding is so important that we should like to show how an electrical system is actually grounded at the service entrance.

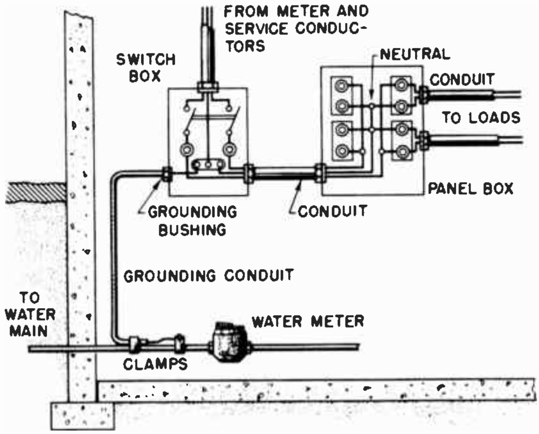


Fig. 15-21. A practical method of grounding an electrical system.

Fig. 15-21 shows how the conductors come in from the meter to the main switch box, which also contains the main fuse. This box isn't one of the more modern types, but is shown in order that the details can be made more clear.

The ground wire is connected to the neutral wire inside the fuse-switch box. The connection is usually made here before the service conductors go into the branch circuit fuse cabinet. If the main fuse and the branch circuit fuses are all in the same cabinet, the ground wire is also connected here.

The ground wire is connected to a water pipe if there is one available that lies underground for a considerable distance. If there is no such pipe, a grounding rod must be driven to make the ground connection.

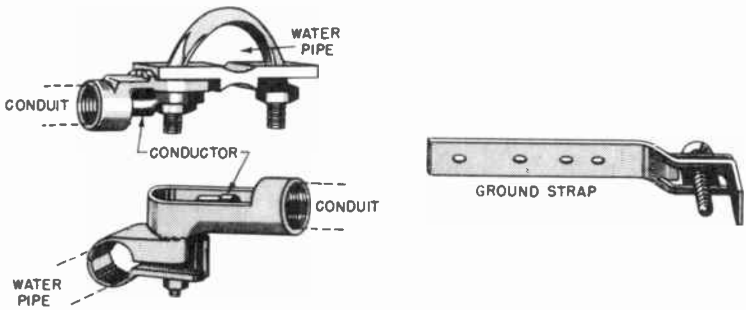


Fig. 15-22. Types of ground clamps and straps.

The grounding wire is fastened to the water pipe or ground rod by means of a grounding clamp. There are a variety of such grounding clamps, but they all serve the same purpose, that of providing a solid and secure electrical and mechanical connection to the pipe or rod. Fig. 15-22 shows two types of pipe clamps and a ground strap, all of which are used to tie the grounding wire to the ground pipe.

WIRING INSIDE BUILDING

There are several methods of wiring recognized and approved by the National Code. Among them are: the "open wiring" method in which the wires are strung on porcelain knobs and cleats and not enclosed in a metal enclosure; the armored cable method in which the wires are enclosed within a spiral metal band by the manufacturer of the wire cable; the thinwall conduit method; and the rigid conduit method. There are other methods of wiring inside buildings, particularly one which uses non-metallic sheathing.

Despite the fact that open wiring is still approved by the National Electrical Code, it has been outlawed so extensively that there is little point in discussing it here. It probably will not be long before this method is outlawed by the National Electrical Code.

We have already discussed the use of rigid conduit in detail. Essentially, it consists of rigid conduit used as an enclosure for the conductors joining one outlet box to another. The conduit is connected to the boxes in the manner shown in earlier illustrations in this chapter, and the junctions between one circuit and another are made inside metal boxes as shown in Fig. 15-23.

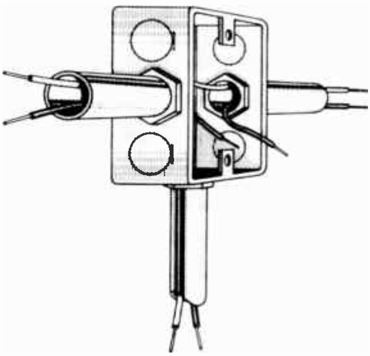


Fig. 15-23. How a junction box is used to make a connection to a branch circuit enclosed with rigid conduit.

The use of rigid conduit can be managed by the average handyman so long as its use is confined to the outside of a building where the conduit is used to enclose the heavy service conductors. It is not recommended for any person who is not well equipped with the tools suited to that kind of work. To install rigid conduit requires the same kind of tools as a plumber needs to install a system of water pipes. The method of running the conduit from one switch box or outlet box to another is shown in Fig. 15-24. Only a portion of the conduit system is shown, just enough to clearly illustrate the type of work involved.

Installing a wiring system with thinwall conduit is far easier

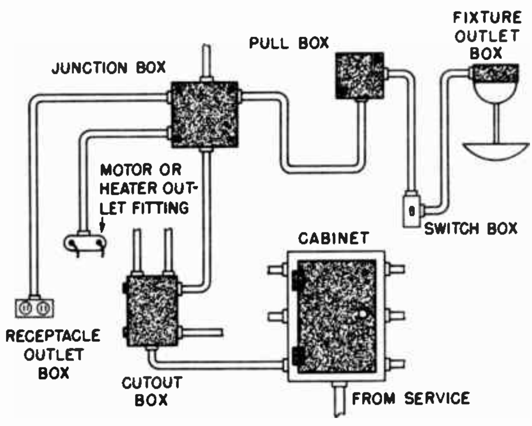


Fig. 15-24. How rigid conduit is run from one box to another in an electrical wiring system.

than with rigid conduit. Although installation with thinwall does require special types of tube bending gear, they are not particularly expensive.

We have previously explained how thinwall conduit is connected to switch and outlet boxes and how the connections are made by use of special compression-friction connectors and couplings. It is not difficult to use the connectors. The thinwall conduit is easily cut with a hacksaw. Despite all this, there are easier methods of wiring for the person who is satisfied with a good, substantial, safe electrical installation, yet one which is, perhaps, not absolutely the best method in use.

For the person who is not regularly in the electrical business, yet is called upon to do a certain amount of wiring occasionally, it may be wise to use armored cable, or the non-metallic sheathed cable. Either of these will provide a good, safe, and easy installation; one that meets all the provisions of the National Electrical Code. There are a few localities, especially in some of the larger cities, where neither of these methods may be used on new buildings under construction. Most localities recognize and approve them for making electrical extensions or for rewiring old buildings.

WIRING WITH ARMORED CABLE

Armored cable consists of two or more insulated electrical conductors which are enclosed within a heavy steel protective armor. The appearance of armored cable is shown in Fig. 15-25.

Fig. 15-25. A length of armored cable and one of the fiber bushings which are used to protect the conductor insulation.

The insulated conductors are wrapped into a tight bundle in a heavy covering of tough insulating paper. Over the heavy paper is wound an interlocking spiral of steel armor, making a continuous protective covering for the conductors. The interlocking steel spiral makes the cable flexible; therefore, it is possible to pull the cable through small holes in joists, inside of hollow walls, and around rather sharp curves. Furthermore, once the cable has been pulled from one point to another, both wires for the circuit are there and it is not necessary to go back for the other wire, as is so often the case with other types of wiring.

The cable is fastened to the metal switch boxes, junction boxes, and convenience outlet boxes by using special types of connectors which have been developed especially for armored cable. They are shown in Fig. 15-26. Before the connector is fastened on the armor of the cable, an insulated fiber bushing, such as that shown at the right side of Fig. 15-25, is inserted under the end of the steel cable and over the heavy paper. It provides protection to the insulation on the conductors and prevents them from possible damage should there be a sharp edge at the cut end of the armor.

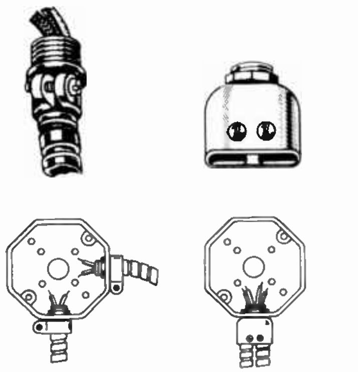


Fig. 15-26. Connectors used with armored cable and how they are used.

In preparing the armored cable for making a connection to a switch box or other metal enclosure box, one should cut the armor about eight inches from the end. Care should be exercised in making such a cut. A hacksaw can be used to cut across the spirals of the armor, if it is held at an angle of about 30° to the cable. A few strokes of the hacksaw are usually sufficient to cut a fairly deep slash in the steel armor, yet not enough to cut into the insulation covering the wires inside. When the armor has been slashed, it can usually be broken by bending or by applying some pressure with a heavy pair of electrician's pliers. If the armor is twisted back and forth a few times, it will break. Then the short piece of armor can be pulled off the end of the cable, and the two conductors will be exposed.

The fiber insulating bushing is then slipped over the conductors, but under the armor. This covers any sharp edge and protects the insulation on the conductors against any damage. After this has been done, one of the connectors (shown in Fig. 15-26) is slipped over the end of the cable and tightened into place.

Some connectors are tightened by a single set screw; others have two screws. Furthermore, some of the connectors take only one cable, while others take two.

The flexibility and ease with which armored cable can be handled make it a favorite with many wiremen, especially with the handymen who do wiring only occasionally. Fig. 15-27 shows how the cable can be used to wire a ceiling lamp. Two types of boxes are shown in the illustration.

Fig. 15-28 shows how easy it is to fish armored cable through the walls of an existing building. By using two or more fish tapes, or merely pieces of wire with a hook on the end, a means can be provided for making an attachment to the end of a length of cable. When pulled, the cable will follow wherever the wire or tape can go.

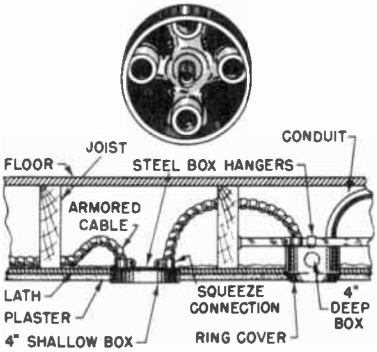


Fig. 15-27. Armored cable can be run from box to box. It can be easily fished through the hollow spaces within the walls and above the ceiling.

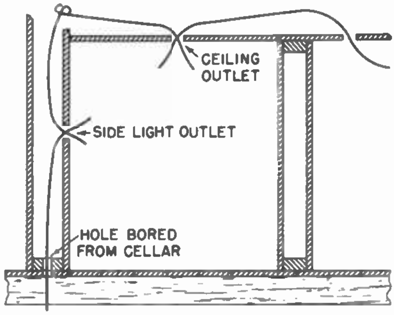


Fig. 15-28. Armored cable can be fished from outlet to outlet through the walls by using fish tapes and "snakes".

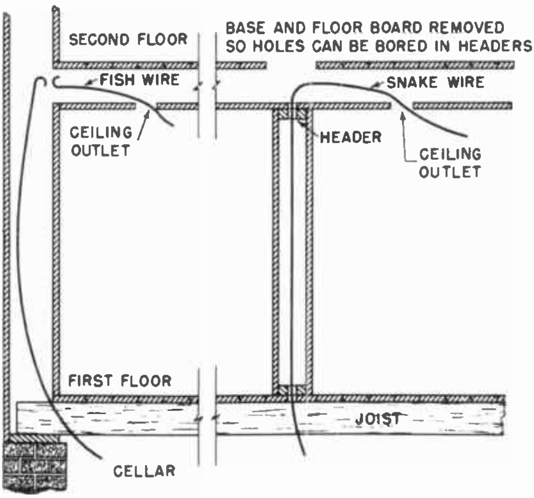


Fig. 15-29. It is often possible to fish armored cable through wall spaces without making holes in the wall or removing baseboard.

Fig. 15-29 shows other examples of fishing armored cable through the walls of a building. One of the things that makes it useful is the ease with which it can be shunted around obstructions. In Fig. 15-30 we see how an obstruction blocks the passage of the feeler "mouse" which is often used to test a wall to see if it is clear. Such obstruction will prove almost insurmountable for most methods of wiring, but it is no particular problem with armored cable.

After locating the cross-stud of Fig. 15-30, shown in greater detail in Fig. 15-31, the electrician bores a hole upwards at an angle of 45° and a second hole downward at the same angle. This provides a hole through which the cable can be pulled and passed on downward. This illustration presupposes the obstruction is near a door so the surface hole can be covered by the door

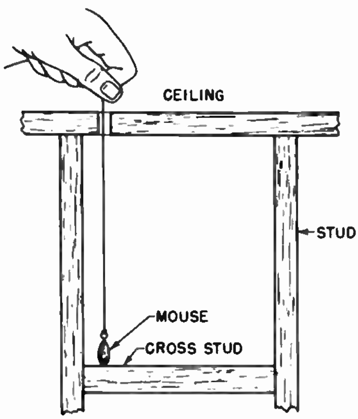


Fig. 15-30. How obstructions within a wall can be located.

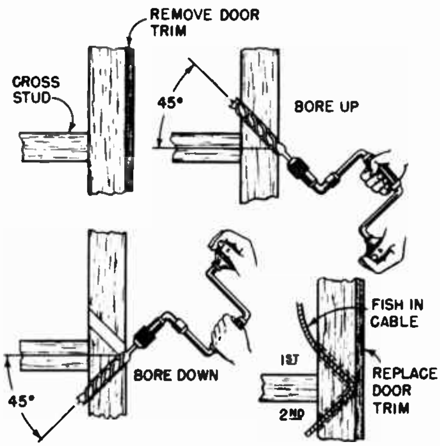


Fig. 15-31. Bypassing an obstruction without seriously marring the wall.

trim. However, it would be almost as simple if the door trim were not there. In that case it would be necessary to make a small hole in the plaster before boring the two holes. After the holes had been bored and the armored cable passed through, the hole in the plaster can be refilled, and if it is carefully done, one can scarcely detect where the cross-stud had been bypassed and the plaster broken.

WIRING WITH NON-METALLIC SHEATHED CABLE

Wiring with non-metallic sheathed cable is much the same as wiring with armored cable. There is one difference. The metal armor of the armored cable acts as a solid metallic ground to bond the entire electrical system into a completely grounded system.

This acts to ground every switch box, outlet box, and other parts of the system. Then, should a short-circuit occur anywhere between one of the "hot" conductors and a switch box or between one of the conductors and an outlet box, the fuse protecting that circuit would blow and would warn of trouble. A non-metallic sheathed cable wiring system does not always have such a bonded ground. It is true that some non-metallic cable have a special bonding wire inside the cable so the entire system can be deliberately grounded, but not all cables have it.

Non-metallic sheathed cable can be used nearly everywhere that armored cable can. The conductors in a non-metallic cable do not have the same amount of mechanical protection the conductors in an armored cable have. Such extra protection is not always important.

The non-metallic cable is connected to outlet boxes and switch boxes with connectors which are similar to those used with armored cable. The non-metallic cable consists of a pair of conductors covered with a heavy wrapping of paper as shown in Fig. 15-32. The heavy protective paper is, in turn, enclosed within a heavy braided covering of tough fibrous material which is highly resistive to abrasion and to flame.

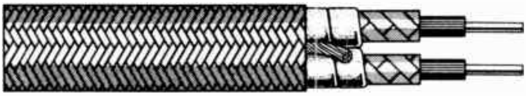


Fig. 15-32. What non-metallic sheathed cable looks like.

The non-metallic cable can be fished through open walls in the same manner as armored cable. Many electricians prefer non-metallic to armored cable. There are two ways in which it is definitely superior. For one thing there are no sharp edges at the end of its protective covering to damage the insulation of the conductors. Therefore, there is no possibility of a short circuit developing. This is truly an important point because the possibility of damage to the conductor insulation is ever-present when one is using armored cable. Constant care will prevent such damage and render its possibility remote, but that matter of constant care must be exercised. Carelessly installed armored cable can cause trouble, but the armored cable is mechanically stronger.

The other advantage of non-metallic cable is that it can be used safely around barns and milk houses. The presence of cows and horses around barns and milking houses brings the constant threat of corrosive fumes from the animal excretions. These fumes can seriously damage and even destroy the covering of armored cable. Sometimes under severe conditions, it will be eaten away in less than a year. For that reason most localities forbid the use of ordinary armored cable around barns and milkhouses. However, permission to use a special type of armored cable known as lead-sheathed armored cable is given to the farmer. It is a special type which has been developed for use in damp places or in places where corrosive fumes are present.

Non-metallic sheathed cable is not affected by the fumes and other corrosive materials and can be used without any other protective covering. This makes non-metallic sheathed cable a favorite with farmers.

Non-metallic cable has another advantage. In damp places, the metal on armored cable will deteriorate quickly and will soon leave the conductors without any protection. This prohibits its use outdoors or where it will be subjected to dampness. It is true that the lead-sheathed type of armored cable can be used in damp places and in places where it will be subjected to the weather, but this lead-sheathed type is quite expensive and is not generally favored for ordinary wiring activities. The non-metallic cable can be used in damp places where armored cable would soon rust away.

Both armored cable and non-metallic cable come in a variety of sizes. The most common size is two-conductor size 14 wire, which will handle 15 amperes of current without overheating and, when used on branch circuits, is protected with a 15 ampere plug fuse.

The next most commonly used size is No. 12 wire, with two conductors in a single cable. This size was originally intended to handle 20 amperes of current for operating ironers, toasters, and other ordinary electrical apparatus. In many rural areas served by co-operatives operating under the REA, No. 12 wires are required even on the 15-ampere circuits, because the heavier wire will handle the load with less heating and with less voltage drop in the lines.

For some of the heavier loads, such as heavy-duty water pumps and hammer mills, even larger size wires are available in both armored cable and non-metallic cable. No. 10 wire, capable of handling 25 amperes of current, is used for that purpose. Two such conductors in a single cable are fairly common.

It is also possible to obtain both types of cable with three wires, used in three-way switching circuits.

INSTALLING SWITCH BOXES

The National Electrical Code requires electrical switches used in homes and other buildings to be enclosed within metal boxes. Such "switch boxes" can be purchased at most hardware stores and at all electrical supply houses. Most of the large national mail order houses can also supply the boxes at a very nominal price.

The metal box encloses the switch and prevents the spread of flame should anything go wrong with the electrical wiring.

There are many types of switch boxes, and usually each is installed in the manner best suited to its type. This variety provides a special type of box to fit the circumstances and conditions where it is to be used.

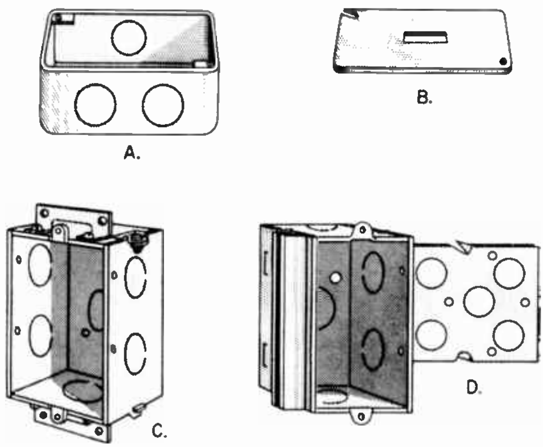


Fig. 15-33. "Switch boxes" used to enclose switches and convenience outlets.

Fig. 15-33 shows three types of switch boxes. The slightly oval box (Fig. 15-33A) is one which can be easily mounted on the surface of a wall, bench, or other similar place. The slotted cover (Fig. 15-33B) is first fastened tightly to the switch by means of screws, and then the cover is fastened on to the box with other screws. A variation of this type of box is often called the "handy" box in the electrical trade. This model is so constructed that the switch can be directly connected to the center of each end of the handy box; this is similar to the tapped holes in the other two boxes shown in the illustration. While these boxes are usually referred to by the general name "switch boxes," they are equally useful for the installation of convenience outlets.

The other two boxes shown in Fig. 15-33, are usually imbedded within the wall so the switch or outlet will be flush with the surface of the wall. One of the boxes (Fig. 15-33C) has a pair of "ears," one at the top and the other at the bottom. These are used to fasten the box to the plaster lath in the wall or to whatever else is most convenient at that particular location.

The box shown in Fig. 15-33D has a perforated flange extending to one side. It is welded to the body of the box. Its presence makes fastening the box to an upright stud in the wall much easier. Once the exact location is decided upon, the flange is placed against the stud and the front tapped smartly with a hammer. The short "spike," which is a part of the flange, penetrates the wood of the stud and holds the flange and box securely until it can be more firmly anchored by nails or wood screws.

The switch box shown in Fig. 15-33D is used almost universally on "new" construction. New construction, in this sense, means buildings which are under construction. To use the box with the flange in an old building in which the walls have already been plastered and are intact would mean serious damage to the walls. The box shown in Fig. 15-33C is adapted for both new or old construction.

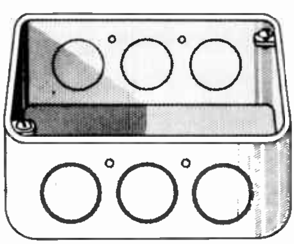


Fig. 15-34. The useful "1900" box. It is four inches square.

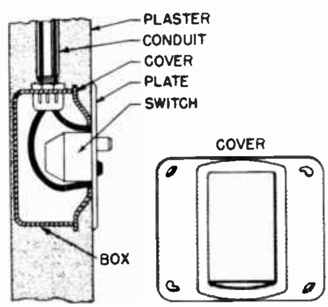


Fig. 15-35. How a "1900" box can be fitted with a cover and used as a switch box.

Another kind of metal enclosure for switches and convenience outlets is a large 4-inch square metal box like that in Fig. 15-34. That type of box is known throughout the electrical trade as a "1900" box, and is the workhorse of the electrician, it being used for many things. Switches and outlets cannot be mounted directly on this kind of box as was done with the boxes shown in Fig. 15-33. Instead, a switch-box cover is used for the purpose of mounting the switch or convenience outlet as shown in Fig. 15-35. The detail drawing shows how a switch would be mounted on the cover.

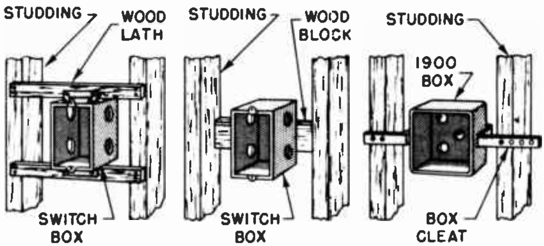


Fig. 15-36. Methods of mounting switch boxes.

The square-corner type of switch box with mounting ears can be placed directly on the lath in a house which is to be plastered. Other methods of mounting the box are shown in Fig. 15-36. It can be mounted on a wood block fastened between the studs, but behind the box; or it can be mounted on a regular metal box cleat, which is much better known as a "bar hanger." The square-corner boxes and the "1900" box can be mounted on either the bar hanger or the wooden block; however, the "1900" box cannot be mounted on the lath.

The square-corner switch box is useful in mounting a switch in a wall which has already been plastered. Once the exact location for the switch or convenience outlet has been determined, a hole can be made in the plaster. Care must be taken in making the initial hole. A very small hole can be punched in the wall with a screwdriver, and then the hole can be enlarged to the size of the switch box. The position of the hole must be such that the upper ear of the box will fit over a lath above the box and the lower ear will fit over a part of the lath below the box. One whole lath will have to be cut out directly behind the box. The details for making the hole and fitting the box to it are shown in Fig. 15-37.

After the initial hole is made with a screwdriver to find the exact location of the lath, the hole is enlarged. This must be done carefully to prevent having the hole too large and ending up with an unsightly job.

The middle lath behind the box will have to be cut out. It must be located directly in the center of the hole. When it is located carefully, there will be plenty of lath left above and below for anchoring the box with wood screws. If the hole is made a little too high or a little too low, there is danger of not having enough

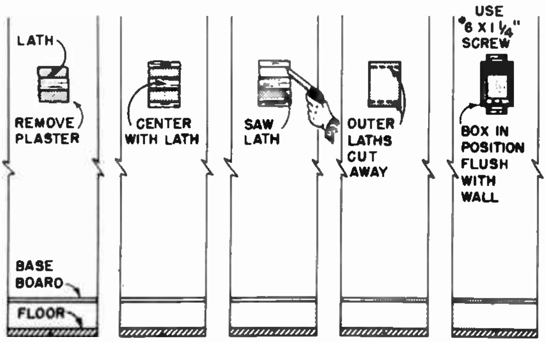


Fig. 15-37. Preparing a hole in the lath for a switch box.

lath either above or below the box for anchoring the wood screws which hold it in place.

WIRING UNDER PLASTER

Usually the first work a novice electrician has to undertake is that of making extensions. The term "extensions" means the adding of switches or outlets to an existing electrical installation.

In wiring the modern home, every effort is made by the elec-

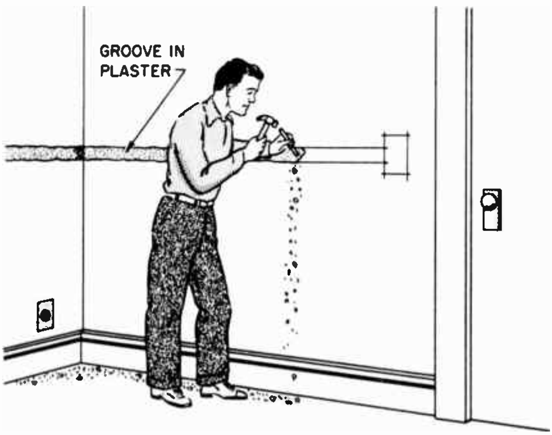


Fig. 15-38. Grooving plaster to make an electrical extension.

trical contractor to put in switches and outlets in all the places where they are likely to be needed. It is always much easier and less expensive to put in such switches and outlets when the building is being constructed than it is to do it later.

Many of the older homes were not wired so carefully. The result is that many home owners feel the need of new switches or new convenience outlets. Then comes the problem of installing them.

One method of making such an extension would be to cut a groove in the plaster, as is shown in Fig. 15-38, to provide a place to anchor the conduit or armored cable. The groove would have to be cut from an existing outlet, or from the lamp or outlet the switch is intended to control.

This method is followed by many electricians, and sometimes there is no alternative but to cut the groove in the plaster. However, skilled electricians try to avoid grooving out the plaster because it entails considerable work and leaves messy surroundings after the job has been finished. Many times, armored cable can be run from one location to another without cutting a groove,

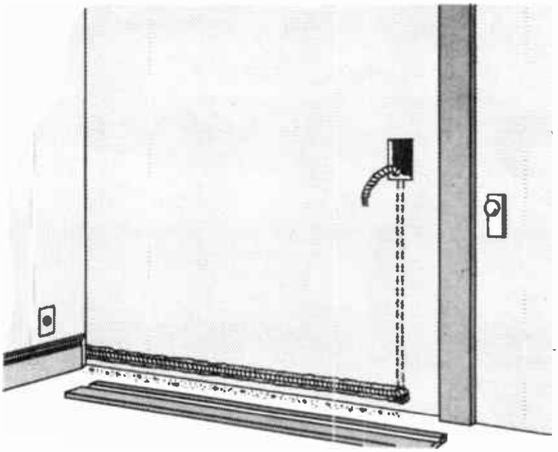


Fig. 15-39. How armored cable can be used for making an electrical extension without damaging the visible plaster.

One method of running the wiring from one location to another is to use armored cable. Instead of the groove being cut as it is shown in Fig. 15-38, it is cut in the plaster behind the baseboard, which has been removed for that purpose. The armored cable will fit snugly in that groove and often does not have to be stapled or anchored in any other manner. (See Fig. 15-39.)

At a point directly below the opening for the switch box, a small hole is cut through the plaster behind the baseboard. The armored cable is passed through that hole, and then pulled up to the opening for the switch box. The cable is completely concealed behind the plaster, and no visible part of the plaster is damaged or disturbed.

A skillful electrician can install such an extension for either a switch or for a convenience outlet without disturbing any part of the visible plaster. Then there is no need to call in a plasterer and a decorator.

When working with switch boxes, whether the job is an extension or is so-called "new" work, one must leave sufficient lengths of wire extending inside the box to make the wiring job easy and convenient. It is recommended that eight inches be left for the purpose of making the connection. Perhaps it will be a little more than is needed, but the excess can be cut off with a pair of pliers. It is always better to have a little more wire than is needed than not to have enough.

Sometimes it is necessary to make a connection between two or more wires inside a switch box or inside a "1900" box. Fig. 15-23 shows one example of such an occasion. Actually the need for making such splices arises in the majority of boxes.

There are several ways a splice can be made between two wires. By far the best, the simplest, and the easiest is the ordinary "pigtail" splice, also called the "rat-tail" splice. Fig. 15-40 shows how the splice is made. It consists merely of twisting the wires together until they make a tight connection.

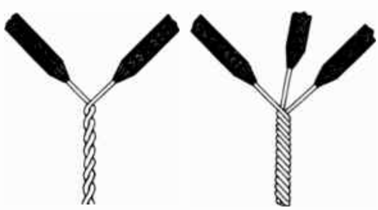


Fig. 15-40. How to make a rat-tail splice.

Once that is done, the splice should be soldered to exclude the air and prevent further oxidation; then it should be carefully taped. If it is not soldered, the copper begins to oxidize after several years. The oxide makes a high resistance between the wires and heat develops.

INDEX