Electronics

Radio

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DIRECT CURRENT MEASURING INSTRUMENTS

ASSIGNMENT 11

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In 1833 Lord Kelvin wrote these words . . .

I often say that when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind. It may be the beginning of knowledge but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be.

These are certainly appropriate words for the electronics industry, for a great deal of the progress in the development of this industry can be traced directly to the availability of suitable **measuring instruments.**

Striking perhaps closer to home, the electronics technician is completely dependent upon his measuring instruments, for only by measuring various currents, voltages, and resistances, can he determine any source of trouble. The automobile mechanic, for example, can see or feel that a certain part is worn or broken and needs replacing, but it is usually impossible to tell by looking or feeling whether or not an electronic component, such as a resistor, is acting properly. Consequently, we must measure the current or voltage drop in such a resistor, and perhaps its resistance value, to definitely establish the source of trouble.

There is some confusion among electronics technicians as to the proper name for electrical measuring equipment. An **instrument** has been defined by the American Institute of Electrical Engineers as "a device for measuring the present value of the quantity under observation," whereas, a **meter** has been defined as "a device for measuring and registering the total sum of an electrical quantity with respect to time." Thus, by these definitions, milliammeters, ammeters, voltmeters, wattmeters, and similar devices measuring the current, voltage, or power **at a given instant** are properly called instruments, whereas, the familiar watt-hour meter, which measures the quantity of electric energy taken over a period of time, is properly called a meter. The average electronics technician, however, frequently refers to any of his instrument-type test equipment as a meter, and this procedure will be followed here.

The Effects of Electricity

We have learned that an electric current is a slow progression of electrons passing a point in a circuit, with 6.28×10^{18} electrons per second constituting a current of one ampere. However, rather than count these electrons in order to measure the current, we take the easy way out and measure the **effects** of an electric current or voltage rather than the current or voltage itself.

There are a number of different effects that an electric charge or an electric current can produce. For example, we learned in our study of dry cells and batteries that when certain chemicals are brought together, electricity was produced. Consequently, there is a connection between chemical action and electricity.

We also learned in our study of magnetism, that an electric current will produce a magnetic field; this would be a magnetic effect.

The ordinary electric toaster or flat iron is an example which shows that electricity can produce a heating effect.

In our study of static electricity, we learned that like electric charges have a repelling effect; whereas, unlike electric charges have an attracting effect. These effects are called the electrostatic effects.

Electricity, then, under the proper conditions, will produce four entirely different effects; **chemical, magnetic, heating,** and **electrostatic.** If we measure the amount, or value, of any one of these effects, for all practical purposes we will have the same information as though we had measured the electric current or charge itself.

There are, in common use today, two basic kinds of electricity known as direct current and alternating current. In this assignment we will study only the instruments and meters designed to measure direct current, and then we will adapt some of these for alternating current in a later assignment.

Direct Current Instruments

Almost without exception, every instrument for measuring an electric charge or current consists of two parts, one movable and one stationary. The force which determines the amount of motion of the movable part is determined by the amount of the electric current being measured, and, in most cases, this force is the result of a **magnetic effect**. Most instruments have two magnetic members, one of which must be variable in strength. Either of these members may take the form of a permanent magnet, a temporary or induced magnet, or a wire carrying a current.

In certain other types of instruments, the moving member is caused to move by the expansion of a piece of wire heated by an electric current. In still another type, the moving force is brought about by the electrostatic attraction of two oppositely charged plates, one of which is free to move toward the other. But in every case, the moving member drives a pointer across a scale which can be calibrated in terms of volts or amperes.

In 1820, Hans Christian Oersted discovered the phenomenon upon which the modern meters, which are used to measure current, operate. He noticed that a compass needle, when placed near a wire carrying an electric current, moved from its original direction, as shown in Figure 1. The larger the current, the greater was the deflection and large currents made the compass needle stop at nearly right angles to the wire. Also, if the current were reversed, the needle deflection would be in the opposite direction.

The underlying principle of this instrument is the fundamental law of magnetism which we have already studied. **Like magnetic poles repel.** The current flowing through the wire sets up a magnetic field around the wire. This magnetic field interacts with the magnetic field of the compass needle. Since the compass needle is free to rotate, the repulsion between its magnetic field and the magnetic field of the wire causes the compass to be deflected from north.

This was the skeleton of an instrument mechanism, but a great many improvements have been made on it.

In our study of magnetism, we learned that we could increase the magnetic field around a wire, with a given amount of current flowing through the wire, if we wound the wire in the form of a coil. Such an instrument is shown in Figure 2. The advantage of this instrument over the crude one of Oersted's is that a smaller amount of current is required to produce a certain amount of deflection of the compass needle. To illustrate this, let us assume that in Oersted's instrument, a current of 10 amperes would have to be flowing through the wire to produce a 15 degree deflection of the compass needle. In the instrument of Figure 2, one ampere of current flowing through the coil might produce this same 15 degree deflection of the compass needle. The instrument in Figure 2 is said to be **more sensitive** than the one in Figure 1.

The instrument illustrated in Figure 2, which is called a "tangent galvanometer", can be quite accurate when used properly but has the disadvantage that its performance involves the earth's magnetic field, which varies from place to place, in both direction and magnitude. The use of this instrument is a rather complicated process, and for this reason it is used for demonstration purposes only.

The D'Arsonval Movement

In 1888, Arsine D'Arsonval, a Frenchman, applied these same principles to a slightly different instrument. This type of instrument is called a D'Arsonval movement, and modifications of this basic movement are in almost all modern electrical instruments.

A working sketch of the D'Arsonval movement is shown in Figure 3 and a phantom-type photograph of such an instrument is shown in Figure 4. A permanent magnet of an alloy, such as tungsten steel, cobalt steel, or aluminum-nickel-cobalt (alnico), produces a strong magnetic field, and there is mounted in this field, a coil of fine wire which is pivoted and free to move. Thus, in this instrument, the coil moves while the magnet is stationary, permitting the use of a much stronger magnetic field than that of the earth. Again, it can be seen that the instrument operates because an electric current is passed through the turns of wire. The relative positions of the permanent magnet and the moving coil may be seen in Figures 3 and 4.

Polarity of the permanent magnet is shown in Figure 3. When no current is being passed through the coil, it is held in the position shown by the two small spiral springs, one at either end of the coil. These springs also serve to conduct the current to and from the coil.

When current is passed through the coil it becomes an electromagnet, the polarity of its field being indicated by the dotted arrow in Figure 3. The repulsion by the two N-poles and also by the two S-poles produces a rotation of the coil in a clockwise direction. The coil rotates until the actuating force of magnetic repulsion is balanced by the restoring force of the two springs. As the coil rotates, a pointer attached to it moves up a scale. This scale may be calibrated to indicate the amount flowing through the coil.

The phantom-view photograph of Figure 4 illustrates some of the improvements in the modern instrument, compared to the basic unit illustrated in Figure 3. In Figure 4, we see that soft iron pole pieces have been added to the magnet to concentrate the magnetic field in the region surrounding the coil. To increase this effect, a cylindrical piece of magnetic material has been placed inside the moving coil. This magnetic core is stationary, and does not rotate with the moving coil. The coil rotates in the small circular gap between the pole pieces of the magnet and the cylindrical core. The magnetic field in the region is very strong. This makes the instrument more sensitive.

The moving coil is wound on a small aluminum frame. In addition to providing a light form on which to wind the coil, this aluminum frame acts to **dampen** the meter movement. Without this **dampening action,** the meter will oscillate. That is, when a current is passed through the meter, the pointer will swing up-scale and pass the proper point. Then it will come to a stop and swing down-scale past the proper point, come to a stop and swing up-scale again. This back and forth action will continue, with the pointer stopping closer to the correct reading each time, until finally it stops on the proper point. Anyone wishing to make a reading with the undamped meter will have to wait for it to stop "swinging around" the proper point (oscillating) before making the reading. In the **damped** meter, the pointer will swing more slowly and come to rest at the proper point without oscillation. This damping action occurs because the aluminum frame forms a complete loop or turn. As it moves through the magnetic field, a current will be set up in the frame, and the magnetic field set up by this current will oppose the motion. This makes the pointer move more slowly, and it will not swing past the proper point.

The V-shaped part which may be seen in Figure 4, directly in front of the moving coil, is the zero adjustment of the meter. As this part is moved it varies the pressure produced by the spiral spring seen in the front of the coil in Figure 4. This will cause the pointer to move slightly about its zero position. This adjustment is made by turning the small screw which may be seen directly below the meter face in Figure 5. By turning this zero adjusting screw, the meter pointer may be made to fall exactly on zero when no current is flowing through the instrument.

Figure 5 shows a typical panel mounting meter which will measure currents up to one milliampere.

The D'Arsonval instrument can be made extremely accurate, very sensitive and reasonably rugged. Tests made at the National Bureau of Standards have shown that, after a half-century of constant use and no repairs, they still yield results within 0.5 percent of the accuracy guaranteed by the manufacturer.

The sensitivity of such an instrument depends on the strength of the permanent magnet and the number of turns of wire which are put on the moving coil. Instruments have been made using more than 2000 turns of copper wire having a diameter less than one third the diameter of a human hair. Sensitivity is a measure of **how small** a current produces full scale reading on the meter. Thus, a meter that gives a full scale reading when one milliampere of current is flowing through it is ten times as sensitive as one which requires 10 milliamperes of current for full scale deflection.

So sensitive can the modern permanent-magnet moving-coil type of instrument be made, that, in one portable type, a current of only five millionths of an ampere produces full-scale deflection on a scale approximately 6 inches in length. Ordinarly, a person with moist fingers can drive the pointer across the scale merely by touching the terminals. Yet, sensitive as this instrument is, it can be constructed to be very portable. Such instruments are often made in small cases with a carrying handle, and can be carried to the equipment to be tested without damage to the instrument as long as reasonable precaution is observed in handling.

D-c meters are made with a wide variety of sensitivities. A great majority of them are made with a sensitivity of one milliampere for full scale deflection. We shall see later in this assignment that it is possible to use a meter to indicate a higher value of current than that for which it is designed by using shunt resistors.

The full-scale current sensitivity of other popular meters are 10 mA., 500 μ A. and 50 μ A.

The moving coil in all meters is made of wire (usually copper) and, of course, has some resistance. The resistance of the coil is called the **internal resistance** of the meter.

Meter Accuracy

All meters lack perfection, but for the average practical work extreme accuracy is not required, and 5% accuracy is usually satisfactory. Meter inaccuracies may be due to several causes. For one thing, the meter cannot be calibrated perfectly. The scales are printed from a drawing which is based on a typical meter of the type considered. However, not all bearings, springs, magnets, and coils are exactly alike and slight variations in responding to the same current will result. The same current, therefore, may give slightly different readings on several similar meters. The meter accuracy also depends upon errors due to the associated resistors used with the meter, and to the width of the pointer. Most responsible meter manufacturers will guarantee their products to be accurate to within plus or minus 2% when it leaves the factory, and to hold its accuracy to within plus or minus 5% with reasonable care in the field.

Now that we have seen how direct-current meters operate, let us learn the proper way to read a meter.

Reading a Meter

In order to obtain as accurate a reading as possible from a meter, we must be careful to place our eye directly in front of, or above the pointer. Figure 6 shows what might happen if we do not do this. Since the meter pointer is normally between one sixteenth and one eighth of an inch away from the scale, an inaccurate reading will result if we look at the meter from an angle, as illustrated.

Expensive, highly-accurate laboratory type measuring instruments usually have a mirror built into the scale; and to properly use such an instrument, we place our eye so that the image of the pointer in the mirror is directly behind the pointer itself, or until we can no longer see the image of the pointer because the pointer itself is in the way.

Study the enlarged meter scale shown in Figure 7. The 0, 1, 2, 3, 4 and 5 are the numbers which would appear on the meter scale. The numbers printed above the scale do not appear on an ordinary meter scale, but are included in the figure to aid in learning to read a meter. If various readings on this scale can be correctly read, you should have no difficulty with other meter readings.

When the pointer stops on any of the marked divisions, 1, 2, 3, 4, or 5, the reading will simply be the printed number for that division line.

When the pointer stops on one of the small unmarked divisions, note the value of the marked divisions on either side, then figure out the value of the mark under the pointer just as you would figure out the value of one of the marks between the inch marks on a ruler.

In Figure 7, note that there are 5 small divisions between each marked division, therefore each small division is equal to 2 tenths of one milliampere. Thus, if the pointer were to stop on the first small division above the 2, the correct reading would be 2.2 mA. If the pointer were to stop on the third division above the 4, the correct reading would be 4.6 mA.

If the pointer stops half way between two small division marks, figure out the value of the two small divisions, then read a value half way between them. For example, if the pointer were to stop half way between the first and second small divisions above 1 on the meter scale shown in Figure 7, the correct reading would be 1.3 mA., since the first mark above 1 is 1.2 mA. and the second mark above 1 is 1.4 mA.

If a pointer does not fall directly on a division mark, it is entirely adequate, in electronic work, to estimate the reading. Study the meter scale shown in Figure 7 until you are satisfied that you can read the meter correctly with the pointer at any given position on the scale.

How to Use a Current Meter

If we wish to measure the current flowing in a circuit, the current meter (ammeter or milliammeter) should be connected in **series** with the circuit. This is illustrated in Figure 8. If we wish to measure the current flowing in the circuit consisting of the battery and resistor shown in Figure 8(A), the circuit should be broken and the meter inserted in series with the circuit. Two methods of doing this are illustrated in Figure 8(B) and 8(C). In either case we would obtain the same reading on the meter. Figure 8 also indicates the proper way to connect a meter regarding polarity. The (+) terminal of the meter should be connected to the side of the circuit which connects to the (+) of the source, and the (—) terminal of the meter should be connected to the side of the circuit which connects to the (—) of the supply.

Two precautions must be observed in using current indicating meters. Current indicating meters (ammeters and milliammeters) should **never be connected across the source of potential.** Currents higher than that for which the meter is designed should never be passed through a meter. The coil of a meter is made of small wire, and if a current greatly in excess of that for which the meter is designed is passed through the coil, it will become hot and the wire will melt, ruining the instrument. Also, a current greatly in excess of the proper full scale current will cause the pointer to swing so hard against the right hand stop (see Figure 4) that the pointer will be bent or broken.

The ideal ammeter should have little or no internal resistance, since it is inserted into the circuit in series, and any resistance it might have will be added to the circuit resistance, reducing the series current flowing in the circuit. For instance, let us take a practical example. Suppose we have a 2 ohm resistor connected across a 2 volt battery, as in Figure 9(A). Ohm's Law tells us that 1 ampere of current will flow in this circuit.

$I = \frac{E}{R} = \frac{2}{2} = 1$ amp. Now suppose we try to measure this current by inserting in the circuit an ammeter which has an internal resistance of 4 ohms, as shown in Figure 9(B). The two resistances (the 2 ohm resistor and the 4 ohm meter) are in series and would add up, giving us a total resistance of 6 ohms in the circuit. This would limit the current flow to 1/3 ampere. $R_T = R_1 + R_2 = 6\ \Omega \quad I = \frac{E}{R} = \frac{2}{6} = \frac{1}{3}$ amp.

The meter would indicate only 1/3 ampere of current flowing in the circuit, when, without the meter in the circuit, as in Figure 9(A), there was 1 ampere of current. This error resulted from the internal resistance of the meter. To eliminate this error, the internal resistance of the meter should be very low. A typical 0 to 5 ampere ammeter has an internal resistance of 0.03588 ohms. If this meter were used to measure the current in the circuit of Figure 9, the current would be just **slightly less** than one ampere, and as far as the reading on the meter could be determined would be one ampere.

The internal resistance of ammeters is usually only a fraction of an ohm, since ammeters are used in low resistance circuits. Milliammeters and micro-ammeters have higher internal resistance because the moving coil is wound of very small wire. The higher internal resistance of these low current meters does not cause an appreciable error in the amount of current which will flow in a circuit when they are added in series, because they are usually used in circuits containing high values of resistance. To illustrate this point, let us assume that we have a circuit similar to the one shown in Figure 9(A), except a 2000 ohm resistor is used in place of the 2 ohm one. The current which would flow would be 1 mA. ($I = \frac{E}{R} = \frac{2}{2000} =$ .001 A or 1 mA.). Now let us assume that, as in Figure 9 (B), a current meter, for example a O — 1 mA. meter, with internal resistance of 100 ohms is added in this circuit. Under these conditions the total circuit resistance will be 2100 ohms. ($R_T = R_1 + R_2 = 2000 + 100 = 2100$). The current which would flow after the meter was added would be .00095 or .95 mA.

($I = \frac{E}{R} = \frac{2}{2100} =$ .00095 A or .95 mA.). This value of current, .95 mA., is very close to the 1 mA. which would have been flowing in the circuit if the meter had not been added. Thus, we can say that the addition of the meter to the circuit has not upset the circuit conditions. If this same meter were to be connected in a circuit with a 200 volt supply and a 200,000 ohm resistor, the error which results will be even less.

The internal resistance of some typical current meters are, for a 0 — 1 mA. meter, 100 ohms, for a 0 — 500 microammeter, 200 ohms. The internal resistance of meters made by different manufacturers will not be the same. For example, the internal resistance of a 0 — 1 mA. meter by one manufacturer is 100 ohms, while the internal resistance of a 0 — 1 mA. meter made by another manufacturer is 70 ohms.

Direct-Current Milliammeters

Direct-current milliammeters are of very great importance in electronics because in this field the currents to be measured are often very small. This is particularly true in vacuum-tube and transistor circuits.

The ordinary direct-current milliammeter consists essentially of a permanent-magnet moving-coil instrument of the D'Arsonval type. In the more sensitive of these meters (those having full-scale readings of 30 milliamperes or less), the entire current to be measured passes through the moving-coil, and the sensitivity is controlled by the size of the wire and the number of turns. In the larger sizes of these meters (those measuring more than 30 milliamperes), only a part of the current is passed through the movement and the remainder of the current is "shunted", or by-passed, around it. A shunt is merely a resistor of the proper low value placed in parallel with the meter movement. The proper design of these shunts is very important to the electronics technician, for this knowledge will enable him to use the same basic instrument to measure a wide range of currents.

To understand the action of a shunt resistor, study Figure 10 (A).

This circuit consists of a battery, resistor R, two milliammeters M_1 and M_2, and a shunt resistor R_s. Resistor R_s is called a shunt resistor since it is connected in parallel with the meter M_2, and shunts part of the current around M_2. In the circuit, notice that the total current flowing is 10 mA. as indicated by M_1. **However, only 1 mA. of current is passing through M_2.** The other 9 mA. of current being shunted around M_2 by the resistor R_s. To state this in another way, nine times as much current flows through the shunt resistors as through the meter M_2.

Notice that the current flowing through M_1 is 10 mA., while the current flowing through M_2 is only 1 mA. If the combination of R_s and M_2 were to be connected in another circuit, as shown in Figure 10 (B), and one mA. of current is indicated on the meter, then we would know that the total current flowing in the circuit is 10 mA. (One mA. through M_2 and nine times as much or 9 mA. through the shunt resistor.) M_2 could be a 0 to 1 mA. meter, and used in this fashion, it indicates that 10 mA. of current is flowing in the circuit when it reads 1 mA. The range of the 0 to 1 mA. meter, when used with the shunt resistor R_s, is 0 to 10 mA. If the meter indicates .5 mA. of current, then the total current would be .5 X 10 or 5 mA. Likewise, a reading of .2 mA. indicates a total current of 2 mA. in the circuit under test. A current of .2 mA. flows through the meter and 1.8 mA. flows through R_s.

Let us apply our knowledge of Ohm's Law to find the ohmic value of R_s required to increase the range of the 0 to 1 mA. meter in Figure 10 to a 0 to 10 mA. meter. Let us assume that we know that the internal resistance of M_2 is 100 ohms. Examine Figure 10 (A) again. R_s and M_2 are in parallel. The current flowing through M_2 is 1 mA. Its internal resistance is 100 ohms. We can apply Ohm's Law and find the voltage drop across M_2.

$E = I \times R$

$E = .001 \times 100$ (the current through the **meter** times the **meter** resistance.)

$E = .1$ volt.

The voltage across the meter is .1 volt. The meter and the shunt resistor are in parallel, therefore, they have the same voltage drop across them. Thus, there is a .1 volt drop across the shunt resistor R_s. Figure 10(A) shows that the current through R_s is 9 mA. when the current through M_2 is 1 mA., so we have all we need to find the resistance of R_s. We know the voltage across it, and the current through it. Let us put these values in Ohm's Law.

$$R_s = \frac{E_s}{I_s} = \frac{.1}{.009}$$ (Remember current must be in amperes, so we change 9 mA. to .009 amperes.)

$R_s = 11.1$ ohms.

Thus, we find that if we connect a shunt resistor of 11.1 ohms across the 0 to 1 mA. meter with internal resistance of 100 ohms, we will increase the range of the meter to 0 to 10 mA.

As an example illustrating the practicality of shunt resistors, suppose we find that we cannot afford to purchase a wide assortment of meters, but decide to purchase a 0 to 1 milliammeter movement and shunt it for the various currents we want to measure. We decide that if we have a meter which, by means of a switching arrangement, has full-scale ranges of 1 mA., 5 mA. and 25 mA., this will be sufficient. Since the greatest sensitivity needed is 1 mA., we should buy a 1 mA. movement and shunt it for the larger current ranges. The milliammeter which we obtain has an internal resistance of 105 ohms, so the problem is to design shunts for the 5 mA. and the 25 mA. ranges.

The first thing to do in any problem of this type is to draw a diagram of the circuit, and indicate on it all the known quantities. This has been done in Figure 11, where I_T is the total full-scale current to be measured, I_M is the full-scale current through the meter (1 mA. for a 1 mA. meter, etc.), and I_S is the current to be by-passed by the shunt. R_M is the meter resistance (in this case, 105 ohms) and R_S is the resistance of the shunt which we want to find. We see that our circuit is a simple parallel resistance circuit, and, for the 5 mA. range, I_T (the total current) would be 5 mA., I_M (the current through the meter) would be 1 mA. and I_S (the current through the shunt) would be the difference between the total current and the current through the meter. In this case I_S would be 4 mA. $(5 - 1 = 4)$.

Since the voltages are the same across each branch of a parallel circuit, if we find the voltage across the meter branch, we will have the voltage across the shunt branch. Ohm's Law says that the voltage is equal to the current (in amperes) times the resistance (in ohms). To find the voltage across the meter, we substitute the known values in this formula.

$E_m = I_m \times R_m$ (Remember that only 1 mA. flows through the meter.)

$E_m = .001 \times 105$

$E_m = 0.105$

The voltage drop across the meter is .105 volt when a full scale current of 1 mA. is flowing through it. The shunt resistor is connected in parallel with the meter, so it has the same voltage drop across it, or .105 volt. We know that the current through the shunt should be 4 mA., or .004 amp.

Since we know the voltage and the current, we can find the resistance.

$$R_s = \frac{E_s}{I_s}$$

$$R_s = \frac{.105}{.004} = 26.25 \text{ ohms}$$

Therefore, if we placed a resistance of 26.25 ohms in parallel with our 105 ohm, 1 mA. meter, and caused 5 mA. to go through the combination, 1 mA. would go through the meter and 4 mA. would be shunted around it. Likewise, if we caused only half as much current to go through the combination, only half as much current would go through each branch and the meter would read only half-scale. This could be marked 2.5 mA. on the meter scale. If we caused one-fifth as much current to go through the combination, only one-fifth as much current would go through each branch and the meter would read one-fifth scale. This could be marked ⅕ of 5 or 1 mA. on the meter scale, and so on.

We can determine the resistance of the shunt for the 25 mA. range in the same manner. In this case I_T (the total current) would equal 25 mA. and I_S (the current through the shunt) would be 24 mA. since, with the same 1 mA. meter, I_M (the full scale current through the meter) would remain 1 mA. The voltage drop across the meter when full scale current of 1 mA. flows through the meter is the same as in the previous example, since the current and resistance are the same (.105V). The voltage drop across the shunt would still be 0.105 volt. Since the current through the shunt is now 24 mA. or 0.024 ampere, the resistance of the shunt will be $R_s = \frac{E_s}{I_s} = \frac{0.105}{0.024} = 4.375$ ohms.

If we connect a 4.375 ohms resistor in parallel with the meter, there will be a total of 25 mA. of current flowing in the circuit when 1 mA. is passing through the **meter.** Therefore, we could put a scale on the meter which reads 25 mA. for full scale deflection; 12.5 mA. for ½ scale deflection, etc.

Of course we do not need a shunt for the 1 mA. range of our meter since we are using a 0 — 1 mA. meter.

By using a switch to connect the shunts across the meter as desired, we have a milliammeter with three ranges; 1 mA., 5 mA., and 25 mA. The complete circuit is shown in Figure 12.

With the switch in Figure 12 in the position shown, the 26.25 ohm shunt is connected in parallel with the meter, and a full scale reading on the meter would indicate 5 mA. of current flowing in the external circuit. When the switch is turned to the 25 mA. position, the 4.375 ohm shunt is connected across the meter, and a full scale deflection on the meter indicates 25 mA. of current flowing in the external circuit. When the switch is turned to the 1 mA. position, there is no shunt across the meter and a full scale reading of the meter would indicate 1 mA. of current flowing in the external circuit. This same method may be used to find the value of the shunt resistors for any meter.

To find the value of shunt resistors, it is only necessary to know the internal resistance of the meter, the full scale current of the meter, and the desired full scale indication.

It is not possible to increase the sensitivity of a meter. For example, it is not possible to shunt a 0 to 1 mA. meter so that a full scale deflection can be obtained with less than one mA. of current flowing in the external circuit. This is because 1 mA. of current must flow through the moving coil to produce the necessary magnetic field to move the pointer to full scale.

We have seen how we could use one milliammeter, and by employing the proper value of shunt resistors use this one meter to read a wide range of currents. It is also possible to use a milliammeter to indicate a wide range of voltage values.

D-C Voltmeters

If we had a 0 to 1 mA. milliammeter with an internal resistance of 100 ohms, the voltage drop across it for full-scale deflection would be $E = IR = 0.001 \times 100 = 0.100$ volt, or 100 millivolts. Such being the case, the scale of the millliammeter could be divided into millivolts instead of milliamperes, and the milliammeter would then become a millivoltmeter. Thus, mechanically and electrically, there is no difference between a millivoltmeter and a milliammeter.

Full scale reading on this meter would be 100 mV, half scale reading 50 mV, one fourth scale reading 25 mV. etc.

We have just seen how a milliammeter could be used to measure small voltages, and was then called a millivoltmeter. In the example given, a voltage of 100 millivolts applied to the meter would cause exactly one milliampere of current to flow through the 100 ohm internal resistance of the instrument. This current meter may be used to measure voltages up to 100 mV. or 1/10 of a volt. An applied voltage of 50 mV. or 1/20 of a volt will cause the current to be only ½ of a milliampere, and the meter pointer will only move to the center of the scale. However, the voltages we will wish to measure in most radio and television circuits will be between 1 volt and several thousand volts, so we will need some way to extend the range of this millivoltmeter.

We will first consider how to make this meter read up to 10 volts at maximum deflection. If the meter can be made to do this, we will also be able to read other voltages which are less than 10 volts. Suppose we now connect a resistor in series with the meter as shown in Figure 13. Notice that we connect the resistor in **series** with the meter, rather than in parallel with it as we did in the case of the ammeter. How large should this resistor be, so that when we are measuring a voltage of 10 volts, the meter pointer will move only to its extreme right hand position, but not beyond? For a full scale deflection of the meter, there must be a .1 volt drop across the meter. Since we have 10 volts, the difference, or 9.9 volts, must be dropped in the resistor. Since we are using a 0 to 1 mA. instrument, the current in the circuit must be 1 mA. when the needle shows full-scale deflection. Since the resistor and meter are in series, this 1 mA. of current will also flow through the resistor. The series resistance, R_s, is equal to the voltage dropped in it, divided by the current through it, or $R_s = \frac{E_s}{I_s} = 9.9/0.001 =$ 9,900 ohms. The series resistor used with a milliammeter to make a voltmeter is called a **multiplier resistor.**

By connecting a resistor of 9900 ohms in series with the milliammeter, we have made a voltmeter which will indicate that the total voltage applied to the circuit is 10 volts, when the meter pointer moves to a full scale position. Also, a half scale reading of the meter indicates 5 volts applied, and a 1/10 scale reading indicates 1 volt applied. Since a 10,000 ohm resistor will represent an error of only one percent, we would use this size multiplier resistor in a practical circuit.

To provide a **group** of voltage scales, the same procedure of calculation would be employed. For example, for a 50 volt range, the multiplier resistor would be found to be 49,900 ohms. This is calculated in the following manner. The voltage drop across the meter would be 1/10 volt for full-scale deflection. This leaves 49.9 volts to be dropped across the multiplier resistor. The current through the resistor will be 1 ma.

Applying Ohm's Law we have: $R_s = \frac{E_s}{I_s} = \frac{49.9}{0.001} = 49{,}900$ ohms.

In a practical circuit we would use a 50,000 ohm resistor.

For a 100 volt range, the voltage drop across the multiplier resistor would be 99.9 volts. The resistance would be found to be 99,900 ohms

$(R = \frac{E}{I} = \frac{99.9}{.001} = 99{,}900)$.

For a 500 volt range, we could employ the same method, and find that the proper value of multiplier resistor would be 499,900 ohms. (500,000 would be used.) A selector switch could be used to choose between these various ranges, giving us a circuit as illustrated in Figure 14.

Using the procedure followed above, it is possible to convert any milliammeter to a voltmeter of any desired range higher than that of the instrument alone. We do not have to confine ourselves to a 0 to 1 mA. meter to do this. A 0 to 2 mA. or 0 to 10 mA. meter could be used just as easily as far as our computations are concerned. To illustrate this point, let us find the value of the multiplier resistor required to convert a 2 mA. meter with an internal resistance of 70 ohms into a voltmeter with a full scale reading of 15 volts.

When 2 mA. is flowing through the meter, the pointer will be deflected full scale. The voltage drop across the meter with this current can be found by Ohm's Law. $E_m = I_m \times R_m = .002 \times 70 = 0.140$ volt. This leaves 14.86 volts to be dropped across the multiplier resistor $(15 - .14 = 14.86)$. We know the voltage drop across the multiplier resistor (14.86V) and the current through it (2 mA.). To find the resistance we apply Ohm's

Law. $R = \frac{E}{I} = \frac{14.86}{.002} = 7430$ ohms. The circuit is shown in Figure 15.

The sensitivity of a voltmeter is expressed in "ohms per volt" and is equal to the total resistance of the meter and series resistor divided by the number of volts indicated at full-scale deflection. For example, if a 0 to 10 volt voltmeter has a combined resistance of 10,000 ohms, the sensitivity

would be 1000 ohms per volt, $(\frac{10{,}000}{10})$. From Ohm's Law we would

find that the instrument requires 1 mA. of current for full-scale deflection

$(I = \frac{E}{R} = \frac{10}{10{,}000} = .001$ A.). In a similar manner, if a 0 to 10 volt

voltmeter had a total resistance of but 1,000 ohms, the sensitivity would be 100 ohms per volt and it would require 10 mA. to move the needle to full scale deflection. This shows that the higher the resistance of the voltmeter for any given range, the greater the sensitivity. For measuring voltages of circuits where very small currents only can be taken from the circuit, voltmeters having a sensitivity of 20,000 ohms per volt are popular.

In all cases, a voltmeter should be connected across the source of potential. One precaution should be observed in using a voltmeter, and that is to make sure that a voltage is never applied which is higher than the full scale voltage of the range in use. For example, if an unknown voltage is to be measured, it is advisable to first use the highest voltmeter scale to find the approximate voltage, and then to use a range which will give a reading near the center of the scale.

When using a voltmeter, the + terminal of the meter should be connected to the + side of the voltage under test, and the — side of the meter to the — side of the applied voltage.

The High Resistance Ohmmeter

A milliammeter may also be used to measure the value in ohms of a resistance. If we were to take the 0 to 1 mA., 100 ohm, milliammeter we have been using and connect it in series with a 4½ volt battery and a 4,400 ohm resistance, we would have the circuit shown in Figure 16. If we ignore the resistance of the wires and the internal resistance of the battery, the total resistance of the circuit would be 4,500 ohms, which is the sum of the meter resistance and the fixed resistor. A 4½ volt battery in this circuit would make the current in this circuit equal to 0.001 ampere or 1 mA., and this current would cause the meter pointer to stop at the extreme right hand position of the scale. ($I = \frac{E}{R} = \frac{4.5}{4500} = .001$ ampere.)

If we were to change the circuit of Figure 16 by breaking the series circuit at some point and putting terminals at each end of the wire at this break, we would have the circuit of Figure 17. We can connect two wires known as "test leads" at these two terminals. If these two terminals were shorted, that is, connected together with a short piece of wire having almost no resistance, the meter pointer will swing to the right end of the scale. Since, for all practical purposes, the wire which is connected between the test lead terminals, has zero resistance, we could mark this point on the extreme right hand end of the scale "0". An ohmmeter scale is shown in Figure 18. Now let us leave these terminals open by removing the shorting piece of wire. Under these conditions we are actually measuring the resistance of the air between the terminals, but since this resistance is very high, running into many millions of ohms, we may consider it infinite (the greatest possible value). The symbol ∞ (an eight lying on its side) represents infinity, and since the pointer in this case will be all the way to the left, its normal position, we can mark this point infinity. (See Figure 18).

If, now, we were to measure a resistor having a resistance of exactly 4,500 ohms by connecting it between the terminals of Figure 17, the total series resistance of the circuit would be 9000 ohms. ($4500 + 100 + 4400 = 9000$). The current would be reduced to just half of its full scale value, or ½ mA. Thus, the .5 mA. point on the meter scale could be marked "4,500 ohms", since the resistance connected **between the test leads** is 4500 ohms. Likewise, if we were to measure the resistance of a 1,000 ohm resistor by placing it between the test leads or terminals, we would have a total circuit series resistance of 5,500 ohms. (The 4,500 ohms of the meter and series resistor plus the 1000 ohm resistor under test.) Since the battery has a voltage of 4½ volts, the current in the circuit and through the meter will be $\frac{4.5}{5,500}$ or 0.00082 amperes or 0.82 mA. We can, therefore, mark 1000 ohms on our meter scale at this point. (Notice that the scale is calibrated in resistance between the test leads.) Any number of other points can be obtained in the same way. Several more points are shown in Figure 18.

An ohmmeter scale is spread out at the right for low resistance values and is very congested at the left for extremely high resistance values. An ohmmeter, such as that of Figure 18, can be used to measure resistances up to about 500,000 ohms; after that the total space of the scale remaining before the infinity mark, is so small that no accurate reading is possible. To read higher resistance values with some degree of accuracy, the meter movement must be very sensitive or else a higher voltage (series battery and fixed series resistor) must be used. For example, an ohmmeter of the type of Figure 17 can be made to read 45,000 ohms in the center (with correspondingly higher readings at the left) if the series resistance is made equal to 45,000 ohms and a 45-volt battery is used.

In most practical ohmmeters, the meter resistance is so low compared to the series resistor, that its value is ignored. Besides, this series resistor is usually made variable in order to permit adjustment to be made for the varying output voltage of the battery due to its age, and then it is easy enough to compensate for the meter resistance.

After the scale of the meter has been calibrated in ohms, it is a very simple matter to read the ohmic value of a resistor directly from the meter scale. All that has to be done is to connect the resistor between the test leads and read the resistance value directly on the calibrated scale. In commercial ohmmeters, the battery, and series resistor (part of which is variable) are located inside the wooden or plastic case.

Multimeters

Since it is possible to use a single milliammeter in conjunction with suitable resistors and batteries, to read current, voltage, and resistance, most test instruments are manufactured as multimeters.

In these multi-meters, some sort of switching arrangement is provided so that the single milliammeter can be used to read several values of current, voltage, and resistance.

Figure 19 shows a multimeter circuit which uses three current ranges similar to Figure 12, the voltmeter section shown in Figure 14, and the ohmmeter shown in Figure 17.

To use this meter to read current, one of the test leads would be connected to the terminal marked "Common" and the other test lead connected to the terminal marked "MA". The desired current range can be selected by turning the current range switch to the desired position.

To use the voltmeter section of this meter, one of the test leads should be connected to the terminal marked "Common", and the other to the terminal marked "Volts". The voltage range selector switch is rotated to obtain the desired range. The mA. switch would have to be in the 1 mA. position to use either the voltage or resistance ranges of the meter.

To measure resistance with this meter, one of the test leads should be connected to the terminal marked "Common", and the other to the terminal marked "Ohms".

In the meter shown in Figure 19, two rotary selector switches are shown. In many meters, these two switches will be combined, and controlled by one shaft.

Typical Commercial Multimeters

Figure 20 is a photograph of a typical pocket-sized volt-ohm-milliammeter which is almost a necessity for electronics service work. A unit, somewhat similar to this will be supplied you, to build and use throughout this training program. Notice in the illustration, that the meter incorporates scales for reading various values of voltage, current in milliamperes, and resistance in ohms. This meter scale has been re-drawn in Figure 21 for greater clarity. The rotary switch, used for the selection of the scale to be employed, is marked with the multiplication factor and an indication as to whether it is related to voltage, current, or resistance. Let us suppose that we are measuring voltage and our knowledge of the circuit and our previous experience leads us to believe that we might expect to find a d-c voltage of about 45 volts. We would turn the rotary switch to the "75 V. D.C." position and connect the test leads from the two terminals in the meter to the source of voltage. If there is a d-c voltage present which has a value between 0 and 75 volts, the pointer will indicate somewhere on the scale. Our next problem is to read this exact voltage.

The first thing to do is to look at the extreme right row of numbers of the scales of the meter and find the number which goes into 75, once, or ten times, or a hundred times. The number in this case is 75. Read the values indicated by the pointer, by making reference to this middle lower scale (the one that has numbers 0, 25, 50 and 75). Since we have assumed that the voltage we are reading is 45 volts, the meter pointer will stop just to the left of the "50" on the scale. This is between "25" and "50", we know that our unknown voltage lies between 25 volts and 50 volts, and also closer to 50 volts than to 25 volts. Notice that there are 10 small marks between 25 and 50. Since this part of the scale represents 25 volts, each of these marks would represent 25/10 or 2.5 volts. If our pointer were to rest on the second mark to the left of the 50 volt mark, we would read this as 45 volts; if it were to rest on the first mark to the left of the 50 volt mark, we would read it as 47½, if it were to rest on the first mark to the right of the 50 volt mark, we would read it as 52½ volts; and so on.

Suppose we wanted to use this meter to check a voltage which was supposed to be about 350 volts d.c. Looking over the positions and ranges available on the rotor switch, we see one marked "300 V. D.C." and one marked "1500 V. D.C.". Obviously the one marked "300 V. D.C." will not be satisfactory, so we turn the switch to the 1500 volt range and connect our test leads to the voltage source. Next we look for the proper set of numbers on the scale, but we do not find a set ending in 1500. However, we do find a set ending in 15 and it is a simple matter to mentally add two zeros to whatever reading we obtain on this scale. Notice that there is a basic difference of 5 volts for each ten divisions, so each division would represent a reading of .5 volts on the 15 volt range and 50 volts on the 1500 volt range. If our unknown voltage source has a voltage of 350 volts, the pointer will stop 3 divisions to the left of the 5 volt mark on the scale, and we would read this as 350 volts.

Notice that if we wish to measure a-c voltages with this multimeter, we would read them on the center scale rather than the lower scale, but everything else would remain the same.

There are two ranges of resistance on this meter, an "R × 1" range, and an "R × 100" range. If we were measuring a 50 ohm resistor, we turn the switch to the "R × 1" range and touch the test leads together. If the test leads are shorted together, we would, of course, be measuring zero resistance and the meter pointer should read on or near 0, at the extreme right hand side of the top or ohms scale. If the pointer does not stop at exactly zero, we can turn the "adj. ohms" knob below the selector switch until it does, and then our meter will be properly adjusted for resistance readings **on this scale.** In doing this, we vary the size of the series resistor to compensate for the aging of the battery. We can now connect the test leads across the unknown resistor, and if this resistor has a resistance value between 0 and 10,000 ohms, the pointer will indicate this value directly. Notice how hard it is to accurately read the values at the extreme left end of the scale. To read resistances higher than 1,000 ohms (1M), we would probably go to the "R × 100" scale. Again, we would have to "zero" the meter by the "adj. ohms" knob with the test leads shorted before making a reading. Suppose we want to measure a 4,500 ohm resistor. We would zero the meter with the switch in the "R × 100" position and connect the test leads to the resistor. The pointer will stop at the 45 ohm line on the ohms scale of the instrument, and we would multiply this 45 ohms reading by 100 to get the 4,500 ohm, correct reading.

This meter has two d-c milliampere ranges, 0 to 15 mA. and 0 to 150 mA.

To read current, the selector switch should be rotated to the desired range and the reading taken using the bottom scale on the meter.

Figure 22 shows the schematic diagram of the meter shown in Figure 20. The symbol marked "rectifier" is the symbol for a device which has the property of changing a-c current to d-c current. We have said that the D'Arsonval instrument will operate only on direct current, so to measure a-c voltages we must change the a-c to d-c. We will study a-c meters in another assignment in this training program.

Summary

This assignment has presented a large amount of information about d-c meters. It has explained the fundamentals of operation of the almost universally used d-c meter—the D'Arsonval type. It has shown that this meter operates on the principle of the opposing forces of two magnetic fields. One of these fields is produced by a permanent magnet and the other field is produced by the current flowing through the turns of wire in a coil which is pivoted between the poles of the permanent magnet.

It has also pointed out that it is possible to use a current meter to indicate higher values of current than that for which it is designed by using shunt resistors of the proper value connected in parallel with the meter. Likewise, it is possible to use a current meter to read voltage by using a multiplier resistor in series with the meter. Resistance values can be read by using a battery and series resistance in conjunction with the meter.

It has been demonstrated that it is possible to use one meter, in conjunction with a suitable switching arrangement, resistances, and batteries to form a multimeter. Multimeters are sometimes called volt-ohm-milliammeters, since they will perform the functions of each of these meters. Since only one meter movement is used in a multimeter, such an instrument is much cheaper than individual meters for each use would be.

We have also learned to read the scales of a meter and how to estimate the reading if the pointer does not fall directly on a calibrated division, and what scale to use on a multimeter.

Multimeters are used very widely in the testing and repairing of electronics equipment, and for this reason, a technician should have a thorough knowledge of the principles of the operation of a multimeter.

In the next assignment, we will study the subject of resistance in detail, and will learn other ways of measuring resistance.

"HOW TO PRONOUNCE . . ."

(Note: the accent falls on the part shown in CAPITAL letters.)

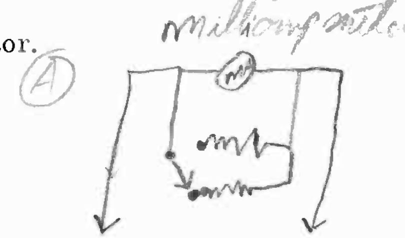
D'Arsonval	(de-ARE-son-val)
infinity	(in-FINN-uh-tee)
oscillate	(OSS-sill-late)
rectifier	(RECK-tuh-fie-er)
tangent	(TAN-jent)

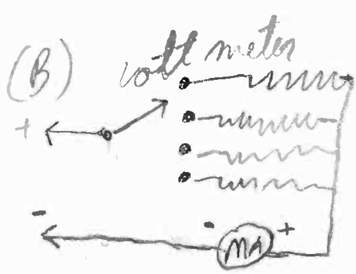
Test Questions

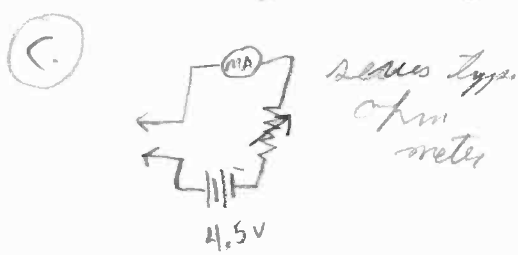
Be sure to number your Answer Sheet Assignment 11.
Place your Name and Associate Number on **every** Answer Sheet.

Submit your answers for this assignment immediately after you finish them. This will give you the greatest possible benefit from our personal grading service.

1. What are three effects of electricity?
2. What two things do the spiral springs in a D'Arsonval meter do?
3. Should a milliammeter be connected in series with a circuit, or across the voltage source?
4. What would happen if too large a current is passed through the coil of a D'Arsonval type meter?
5. The movement of the pointer in a D'Arsonval type meter depends upon the action of two magnetic fields. Where are these two fields obtained?
6. Is the shunt resistor, which is used to increase the current range of a milliammeter, connected in **series** with the meter, or in **parallel** with the meter?
7. Is the voltmeter multiplier resistor, which is used to increase the range of a d-c millivoltmeter, connected in **series** or in **parallel** with the meter?
8. On the type of ohmmeter discussed in this assignment, is the 0 ohms point on the scale at the left end or the right end?
9. If one is to obtain a correct resistance reading, there must be a variable series resistor (zero adjust) in the ohmmeter circuit. Why?
10. Draw the schematic diagrams for the following meters:
    (a) Milliammeter with shunt resistor.
    (b) Voltmeter with multiplier resistor.
    (c) Ohmmeter (basic circuit).







HOW TO COMPUTE THE VALUE OF A SHUNT RESISTOR

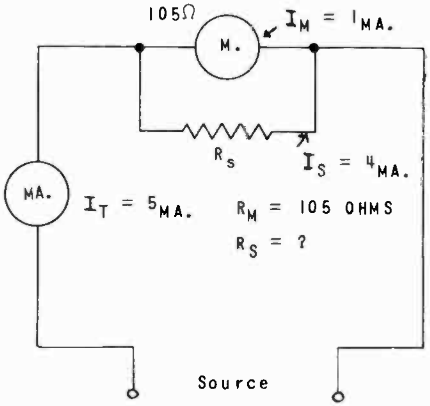


FIGURE 11

USING ONE METER TO INDICATE THREE CURRENT RANGES

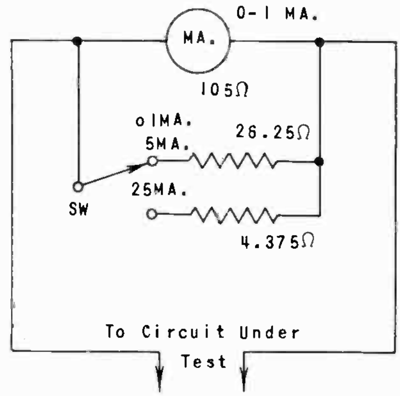


FIGURE 12

MAKING A MILLIAMMETER ACT AS A VOLTMETER

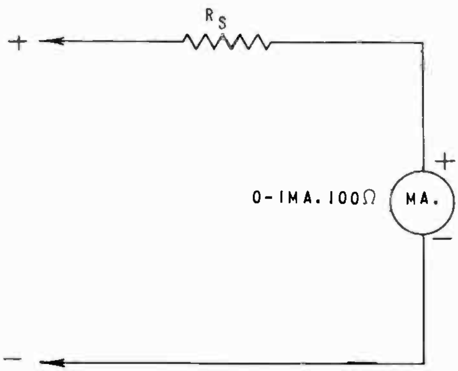


FIGURE 13

USING ONE METER TO INDICATE FOUR VOLTAGE RANGES

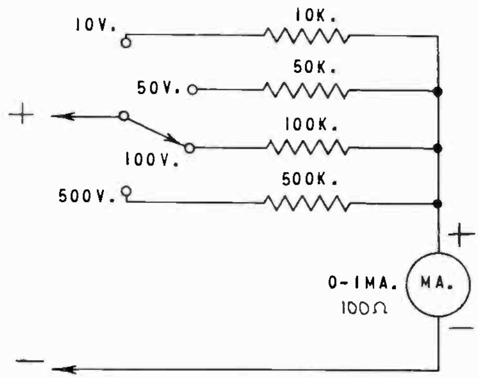


FIGURE 14

A VOLTMETER USING A 2 MA. METER

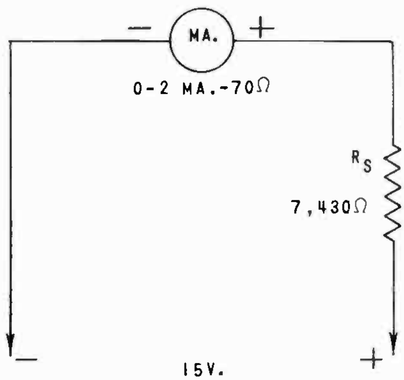


FIGURE 15

EXPLANATORY CIRCUIT

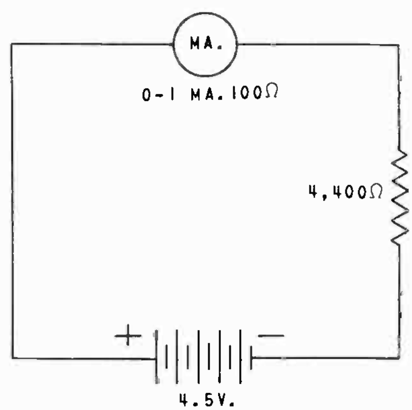
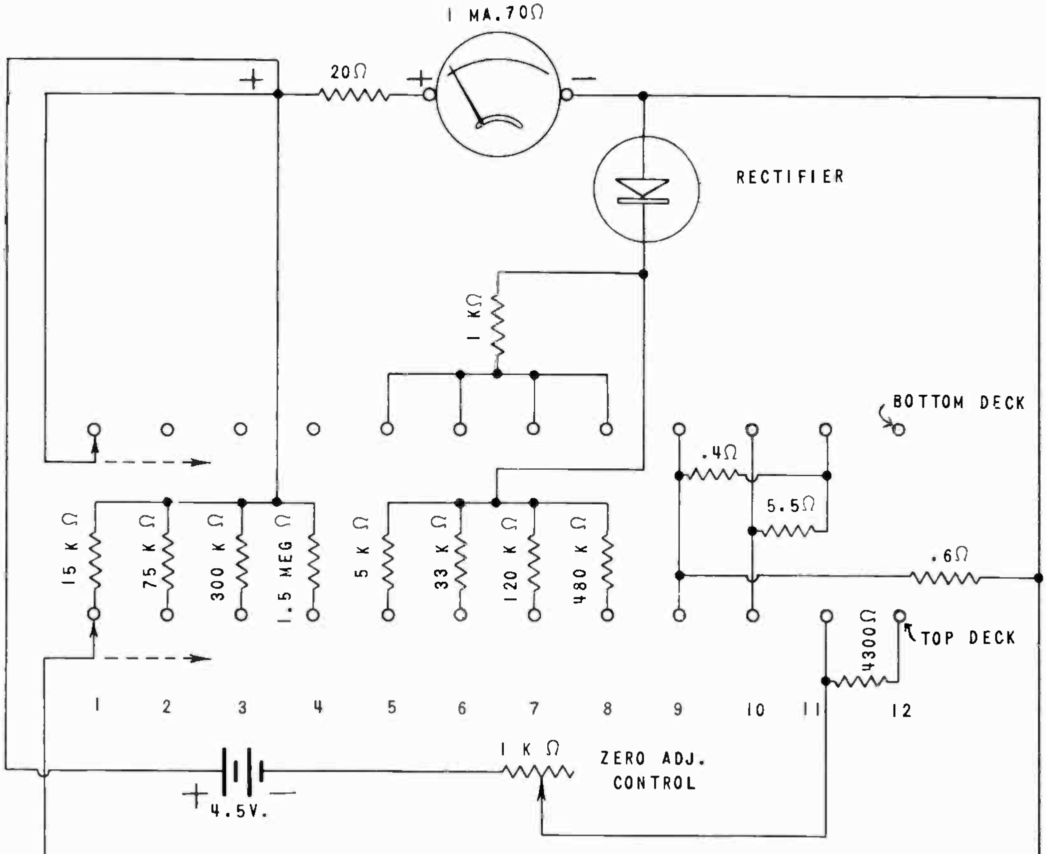


FIGURE 16

SCHEMATIC DIAGRAM OF MULTIMETER SHOWN IN FIGURE 20



L E G E N D

SWITCH POSITION	RANGE	SWITCH POSITION	RANGE
1	15 V.D.C.	7	300 V.A.C.
2	75 V.D.C.	8	1500 V.A.C.
3	300 V.D.C.	9	150 MA.
4	1500 V.D.C.	10	15 MA.
5	15 V.A.C.	11	R x 1
6	75 V.A.C.	12	R x 100

Ω = OHMS
K = 1,000
MEG = 1,000,000

RED JACK

BLACK JACK

FIGURE 22

BASIC HIGH-RESISTANCE OHMMETER CIRCUIT

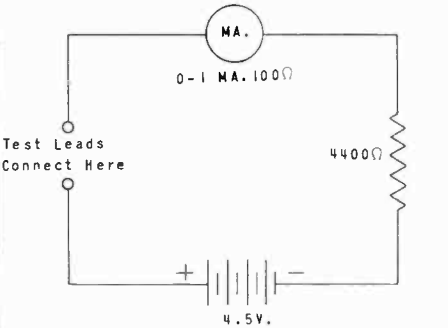


FIGURE 17

OHMMETER SCALE FOR CIRCUIT OF FIGURE 17

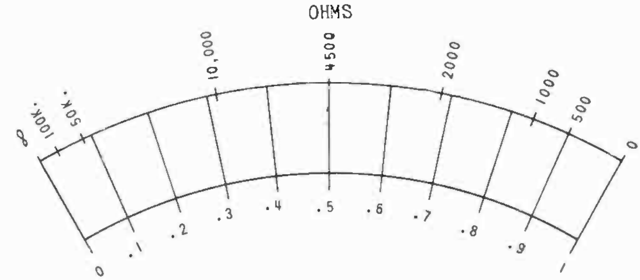


FIGURE 18

A MULTIMETER CIRCUIT WITH 3 CURRENT RANGES, 4 VOLTAGE RANGES, AND 1 RESISTANCE RANGE

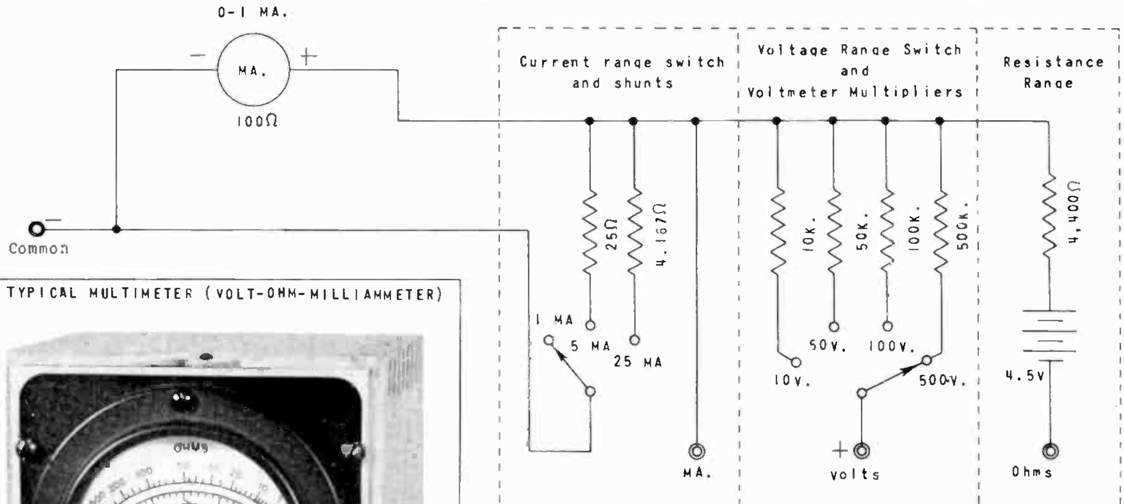


FIGURE 19

TYPICAL MULTIMETER (VOLT-OHM-MILLIAMMETER)

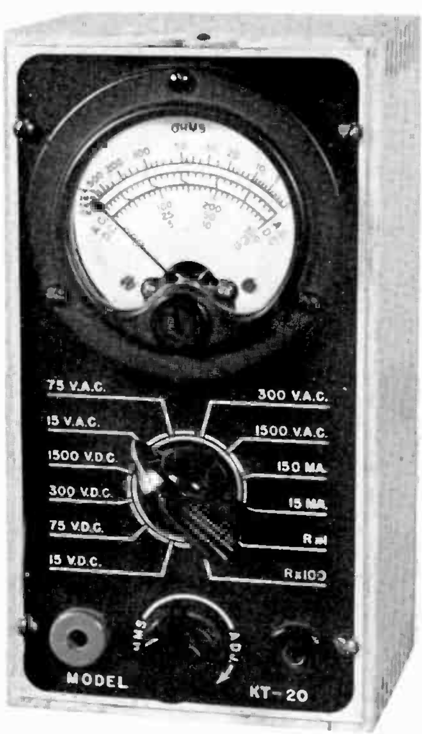


FIGURE 20

SCALE OF MULTIMETER OF FIGURE 20

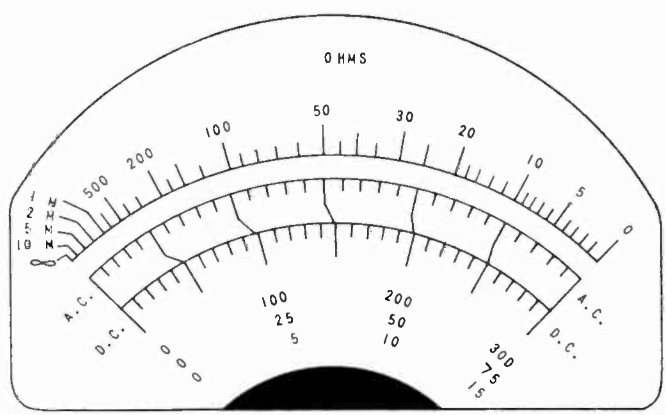


FIGURE 21

HOW TO LOOK AT A METER

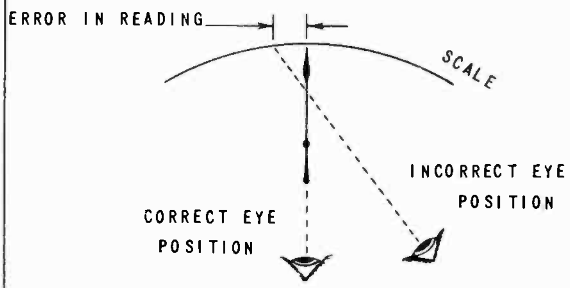


FIGURE 6

HOW TO READ A METER

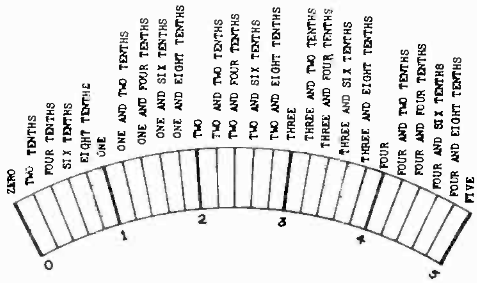


FIGURE 7

HOW TO CONNECT A METER IN A CIRCUIT

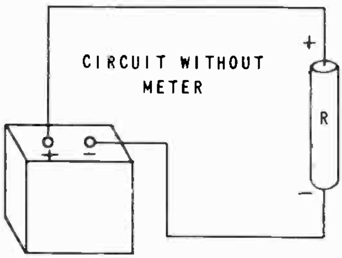


FIGURE 8-A

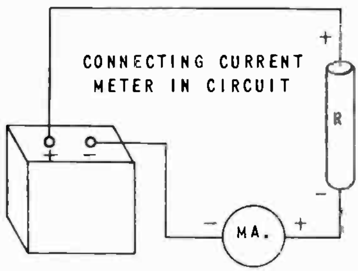


FIGURE 8-B

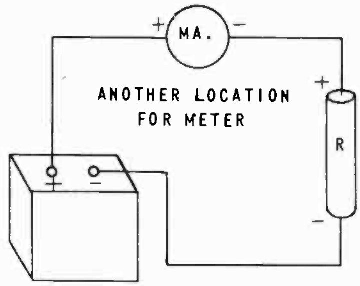


FIGURE 8-C

ILLUSTRATING THAT LOW INTERNAL RESISTANCE IS REQUIRED OF A CURRENT METER

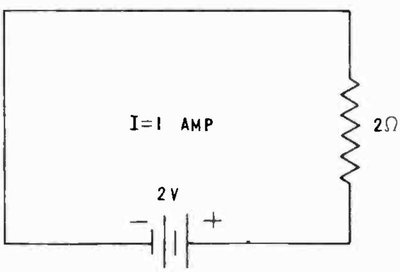


FIGURE 9-A

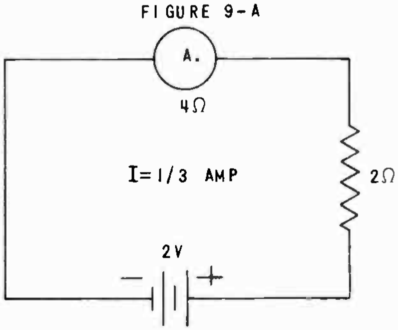


FIGURE 9-B

CIRCUITS ILLUSTRATING ACTION OF A SHUNT RESISTOR

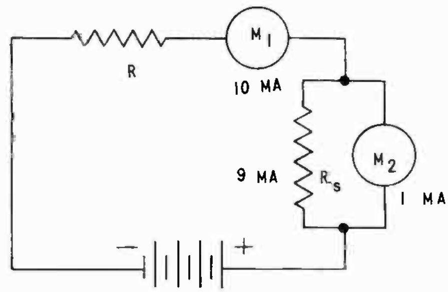


FIGURE 10-A

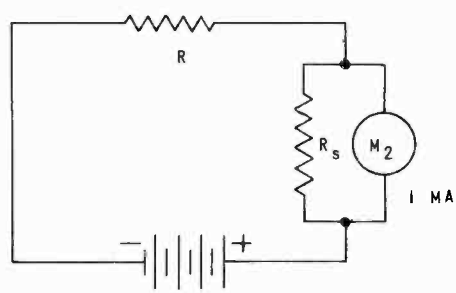


FIGURE 10-B

OERSTED'S EXPERIMENT

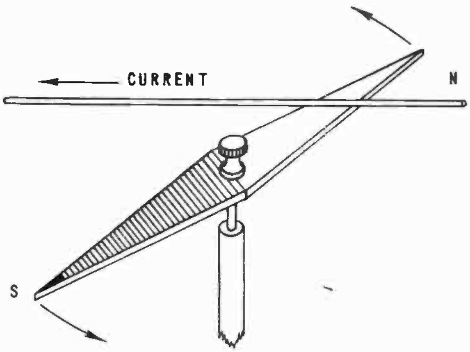


FIGURE I

IMPROVING THE SENSITIVITY
OF OERSTED'S "METER"

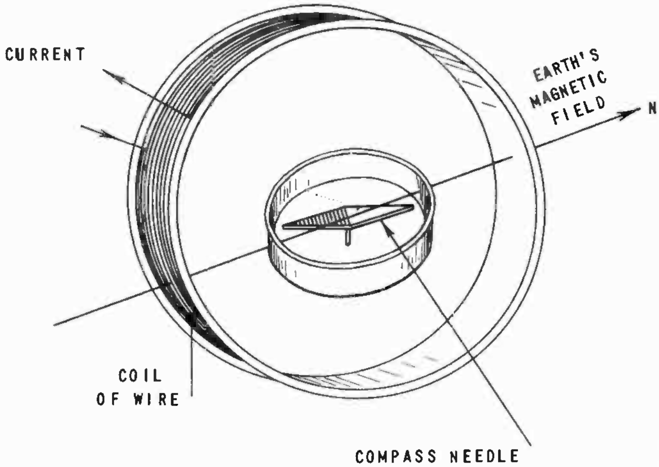


FIGURE 2

SKETCH OF D'ARSONVAL MOVEMENT

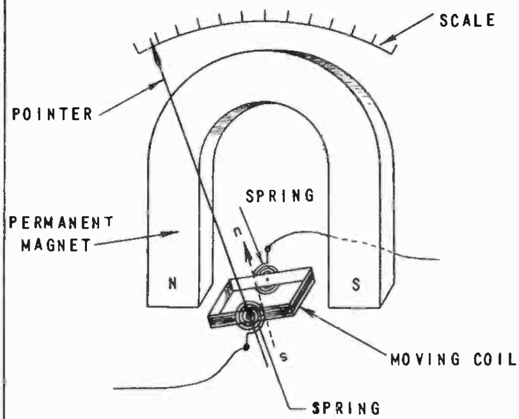


FIGURE 3

PHANTOM VIEW OF D'ARSONVAL MOVEMENT

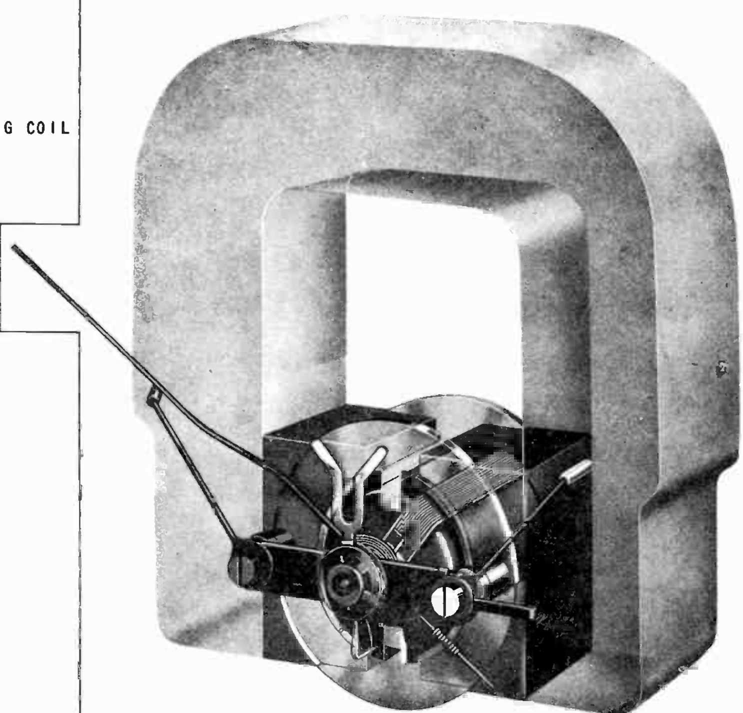


FIGURE 4

A ONE MILLIAMPERE
PANEL-MOUNTING METER

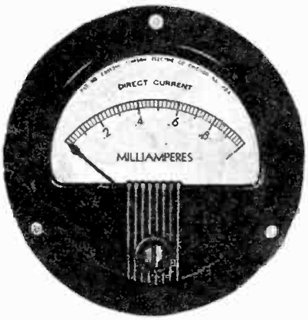


FIGURE 5