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INDUCTANCE

Capitol Radio Engineering Institute
Washington, D. C.

718D

INDUCTANCE

FOREWORD

Inductance is one of the three components (the others are capacity and resistance) present in *every* electrical and radio circuit. The effect of inductance is manifest *every time the current in a circuit varies*. That variation may be the 120 cycles/second ripple in the output of a 60-cycle full-wave rectifier or it may be the 6×10^8 alternations per second in the output circuit of a 300-megacycle oscillator. The effects of a given amount of inductance, however, would be vastly different in the two cases.

Inductance is a circuit component which may be visualized. The power plant electrician may think of inductance in terms of a heavy iron core wound with thousands of turns of wire; the commercial radio operator probably thinks of twenty or thirty turns of copper tubing on an insulating form in a radio transmitter or in terms of one of the r.f. coils in a receiver. Both of these concepts are correct, but as one goes up in frequency, inductances become more and more simple. In the broadcast band, for example, the inductive effect of a hundred feet of straight wire is appreciable—and at 300 mc/s an inch of straight wire connecting circuit elements becomes something which must be taken into consideration. It is the effect of inductance which causes the current at high radio frequencies to travel only on the surface of a conductor. By the proper use of a few turns of wire on a small form, the distributed capacity of tube and wiring in a television video amplifier may be compensated for and the frequency response thus extended by millions of cycles per second.

By means of inductive coupling the elements of a vacuum tube may be raised to a white heat during evacuation simply by placing the tube within a coil-carrying high-frequency current. By inserting inductance in a circuit, the alternating current in the circuit can be made to lag behind its voltage. Inductance is used in conjunction with capacity to provide radio frequency tuning or resonating to a given frequency.

This technical assignment is extremely practical, because it gives you *facts, figures, and applications*. It is the first of a series dealing with this interesting subject.

E. H. Rietzke,
President.

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INDUCTANCE

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IT HAS BEEN SHOWN THAT THE CURRENT CAUSED TO FLOW THROUGH A CONDUCTOR BY A VOLTAGE IMPRESSED ACROSS THE CONDUCTOR DOES NOT NECESSARILY RISE AND FALL IN UNISON WITH THE VOLTAGE. THE CURRENT HAS THREE ALTERNATIVES; IT MAY BE IN PHASE WITH THE VOLTAGE, THE CONDITION IN A CIRCUIT CONTAINING ONLY RESISTANCE; THE CURRENT WILL LAG BEHIND THE VOLTAGE WHEN THE CIRCUIT IS AN INDUCTIVE CIRCUIT; THE CURRENT WILL LEAD THE VOLTAGE WHEN THE CIRCUIT CONTAINS A PREPONDERANCE OF CAPACITY.

IN THE CASE OF A CIRCUIT MADE UP OF RESISTANCE ONLY, THE CONDITION IS EXPRESSED SIMPLY BY OHM'S LAW, AND THE CURRENT AT ANY INSTANT IS A DIRECT FUNCTION OF THE VOLTAGE AT THAT INSTANT.

IN EITHER THE INDUCTIVE OR CAPACITIVE CIRCUIT THAT IS NOT THE CASE. THE CURRENT MAY BE NEAR ITS ZERO VALUE WHEN THE VOLTAGE IS AT MAXIMUM, OR VICE-VERSA.

THIS LESSON WILL DEAL WITH THE EFFECTS OF INDUCTANCE IN THE CIRCUIT. ONE OF THE MOST COMMON MISTAKES IN MANY TEXTS IS THAT OF TRYING TO EXPLAIN TOO MANY OF THE INDUCTIVE EFFECTS BY MEANS OF MECHANICAL ANALOGIES. FOR AN EXPLANATION OF SOME OF THE MORE SIMPLE AND ELEMENTARY PHENOMENA OF INDUCTIVE CIRCUITS THE MECHANICAL ANALOGY MAY BE USED. THE MECHANICAL ANALOGY, HOWEVER, WILL NOT EXPLAIN MANY OF THE MOST IMPORTANT PHENOMENA ASSOCIATED WITH INDUCTANCE, AND THE DANGER IN THE USE OF THE MECHANICAL ANALOGY IS THAT THE STUDENT MAY DEPEND TOO MUCH UPON IT TO EXPLAIN PHENOMENA WHICH CANNOT BE ADEQUATELY EXPLAINED IN THAT MANNER. THE PHENOMENA OF INDUCTANCE ARE FULLY EXPLAINABLE BY THE RELATIONS BETWEEN MAGNETISM AND ELECTRICITY--THAT IS, BETWEEN MAGNETIC FIELDS AND CURRENT CARRYING CONDUCTORS.

GENERATOR ACTION AND INDUCTANCE: THE BASIC THEORY OF INDUCTANCE CAN BE

EXPLAINED VERY SIMPLY BY A REFERENCE TO GENERATOR ACTION AS DISCUSSED IN AN EARLIER LESSON. IT HAS BEEN SHOWN THAT GENERATOR ACTION REQUIRES MOTION. THE MOTION MAY BE EITHER THE MOVEMENT OF CONDUCTORS ACROSS A MAGNETIC FIELD OR THE MOVEMENT OF A MAGNETIC FIELD ACROSS ONE OR MORE CONDUCTORS, BUT IN ORDER TO HAVE GENERATOR ACTION MOTION IS ESSENTIAL. A NUMBER OF CONDUCTORS STATIONARY IN A STATIONARY MAGNETIC FIELD WILL GENERATE NO E.M.F. REGARDLESS OF THE NUMBER OF CONDUCTORS OR THE DENSITY OF THE FIELD. IF, HOWEVER, THE MAGNETIC FIELD IS CAUSED TO MOVE IN ANY MANNER PAST THE CONDUCTORS, A DIFFERENCE OF POTENTIAL WILL BE GENERATED BETWEEN THE ENDS OF THE CONDUCTORS.

THE MOVEMENT OF THE MAGNETIC FIELD MAY BE CAUSED BY MECHANICALLY MOVING FIELD POLES PAST THE CONDUCTOR AS IN A ROTATING FIELD ALTERNATOR, OR THE FIELD WINDINGS AND THE CONDUCTOR TO BE CUT MAY BE STATIONARY AND THE FIELD CAUSED TO EXPAND AND CONTRACT PAST THE CONDUCTOR DUE TO A VARIATION OF CURRENT IN THE WINDINGS OF THE FIELD. THE LATTER METHOD IS USED IN ALL TYPES OF TRANSFORMERS AT RADIO, AUDIO AND COMMERCIAL POWER FREQUENCIES.

IN EXPLAINING THE CONDITIONS ASSOCIATED WITH AN ELECTRO-MAGNETIC FIELD, IT HAS BEEN SHOWN THAT THE DENSITY OF THE FIELD, FOR A GIVEN NUMBER OF TURNS AND A CONSTANT PERMEABILITY OF THE SURROUNDING MEDIUM, VARIES DIRECTLY AS THE CURRENT THROUGH THE TURNS. IF THE CURRENT THROUGH A CONDUCTOR IS INCREASED, THE MAGNETIC FIELD DUE TO THAT CURRENT WILL INCREASE IN DENSITY, AND IN INCREASING WILL EXPAND OUTWARD FROM THE CONDUCTOR, THE PLANE OF ROTATION OF THE FIELD BEING AT RIGHT ANGLES TO THE CONDUCTOR.

IF THE CURRENT IN THE CONDUCTOR IS DECREASED, THE MAGNETIC FIELD WILL DECREASE IN DENSITY, CONTRACTING IN TOWARD THE CONDUCTOR.

IF, IN BOTH OF THE ABOVE CASES, THE DIRECTIONS OF THE CURRENT FLOW ARE THE SAME, THE POLARITY OF THE FIELD AND ITS DIRECTION OF ROTATION WILL BE THE SAME WHETHER THE FIELD IS EXPANDING OR CONTRACTING. THE DIRECTION OF MOTION OF THE CONTRACTING FIELD, HOWEVER, WILL BE THE REVERSE OF THE DIRECTION OF MOTION WHEN THE FIELD IS EXPANDING.

THIS IS SHOWN IN FIGURE 1, (A) AND (B), IN WHICH THE ARROWS ALONG THE HORIZONTAL PLANE INDICATE THE DIRECTION OF MOTION OF THE FIELD. THE DIRECTIONS OF ROTATION OF BOTH FIELDS ARE THE SAME BECAUSE THE DIRECTION OF CURRENT FLOW THROUGH THE CONDUCTOR IS THE SAME IN BOTH CASES. IT IS APPARENT THAT WHEN

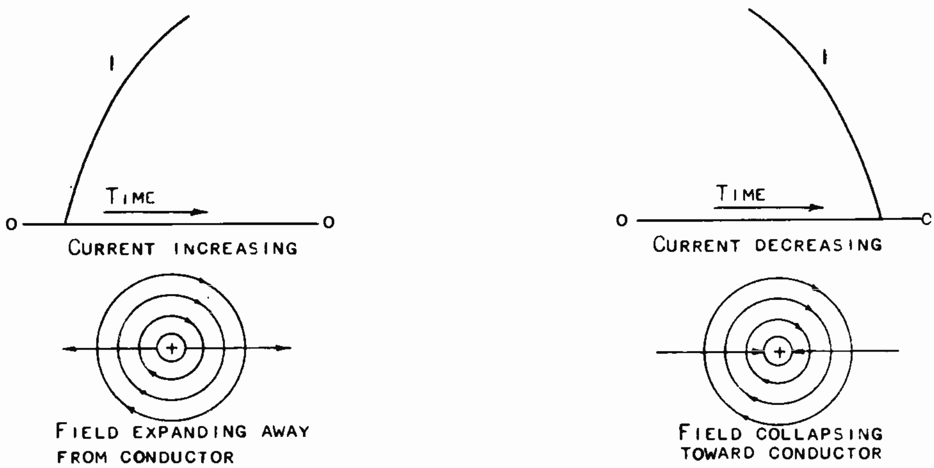


FIG. 1(A) FIG. 1(B)

A CURRENT FLOWS IN A CONDUCTOR AND RISES AND FALLS IN AMPLITUDE, THERE IS ESTABLISHED A MAGNETIC FIELD AND MOTION. THE ONLY OTHER FACTOR NECESSARY FOR GENERATOR ACTION IS A CONDUCTOR TO BE CUT BY THE MOVING MAGNETIC FIELD.

IN FIGURE 2 IS SUPPLIED THE CONDUCTOR, B, WHICH IS TO BE CUT BY THE EXPANDING AND CONTRACTING FIELD AROUND A.

FIG. 2(A) FIG. 2(B)

IN 2(A) THE FIELD IS EXPANDING, CUTTING CONDUCTOR B FROM LEFT TO RIGHT. IN 2(B) THE FIELD IS COLLAPSING, CUTTING CONDUCTOR

B FROM RIGHT TO LEFT. CONDUCTOR B HAS NOT MOVED AND THE POLARITY OF THE FIELD HAS NOT CHANGED, BUT THE DIRECTION OF MOTION OF THE FIELD HAS BEEN REVERSED. ACCORDING TO THE THEORY OF GENERATOR ACTION THIS WILL PRODUCE A POLARITY REVERSAL OF THE VOLTAGE GENERATED, OR INDUCED, ACROSS CONDUCTOR B WHEN THE DIRECTION OF MOTION OF THE MAGNETIC FIELD REVERSES; AND IF CONDUCTOR B HAS BEEN FORMED IN THE SHAPE OF A CLOSED CIRCUIT, THE CURRENT FLOW THROUGH THIS CLOSED CIRCUIT WILL ALSO REVERSE. THIS LEADS UP TO THE BASIC LAW OF INDUCTIVE CIRCUITS WHICH STATES THE CONDITION OF REVERSED CURRENT IN THE SECONDARY CIRCUIT, B, FOR A VARIATION OF CURRENT IN THE PRIMARY CIRCUIT A.

Lenz

LENZ'S LAW: LENZ'S LAW STATES THE DIRECTION OF THE INDUCED E.M.F. IS SUCH THAT IT TENDS TO SET UP A CURRENT THE MAGNETIC FIELD OF WHICH ALWAYS OPPOSES ANY CHANGE IN THE EXISTING FIELD.

LENZ'S LAW DOES NOT STATE THAT THE FIELD OF THE INDUCED CURRENT ALWAYS OPPOSES THE FIELD OF THE INDUCING OR PRIMARY CURRENT; IT ALWAYS OPPOSES ANY CHANGE IN THE FIELD OF THE EXISTING CURRENT. THE WORD "CHANGE" IS THE MOST IMPORTANT WORD ASSOCIATED WITH THE PHENOMENA OF INDUCTANCE AND WHEN USED WITH INDUCTANCE ALWAYS IMPLIES A CHANGING CURRENT. THE EFFECTS OF INDUCTANCE IN A CIRCUIT ARE DUE TO CURRENT VARIATIONS AND ARE NOT RELATED TO VOLTAGE VARIATIONS EXCEPT FOR THE EFFECT OF THE VOLTAGE VARIATIONS ON THE AMPLITUDE OF THE CURRENT.

SINCE THE FIELD AROUND ANY CONDUCTOR DEPENDS FOR ITS DENSITY AND POLARITY UPON THE CURRENT IN THE CONDUCTOR, WHEN ONE SPEAKS OF THE MAGNETIC FIELD ONE ALSO SPEAKS OF THE CURRENT CAUSING THAT FIELD. ACCORDING TO LENZ'S LAW, THE DIRECTION OF CURRENT IN CONDUCTOR B, FIGURE 2(A), MUST BE SUCH THAT ITS FIELD OPPOSES ANY CHANGE IN THE FIELD OF CONDUCTOR A, THE PRIMARY CONDUCTOR. THE FIELD AROUND CONDUCTOR A IS EXPANDING, THEREFORE, IT MUST BE INCREASING IN DENSITY. TO OPPOSE THIS INCREASE, (CHANGE), THE FIELD AROUND CONDUCTOR B MUST BE IN OPPOSITION TO THAT OF CONDUCTOR A. TO BE IN OPPOSITION TO THE FIELD OF A, THE FIELD OF B MUST BE CAUSED BY A CURRENT OF OPPOSITE DIRECTION TO THE CURRENT IN A.

IN FIGURE 2(B) THE FIELD AROUND A IS COLLAPSING, THAT IS, DECREASING IN DENSITY. THIS COLLAPSE IS ALSO A CHANGE, SO IN ORDER TO MAKE LENZ'S LAW VALID, THE ROTATION OF THE FIELD AROUND B MUST BE IN SUCH A DIRECTION AS TO OPPOSE THE DECREASE IN THE FIELD OF A AND THEREFORE MUST BE OF THE SAME POLARITY AS THE FIELD OF A. FOR THE TWO FIELDS TO BE OF LIKE POLARITY, THE TWO CURRENTS MUST BE IN THE SAME DIRECTION.

THE CURRENT IN A, DURING THE TWO CHANGES, HAS VARIED IN AMPLITUDE BUT NOT IN DIRECTION. THE CURRENT IN B HAS VARIED BOTH IN AMPLITUDE AND IN DIRECTION, BEING OPPOSITE TO THE CURRENT IN A WHEN THAT CURRENT WAS RISING AND IN THE SAME DIRECTION AS THE CURRENT IN A WHEN THAT CURRENT WAS DECREASING IN AMPLITUDE. IT WILL BE NOTED THAT THE INDUCED VOLTAGE, AND THEREFORE THE CURRENT, IN THE SECONDARY CONDUCTOR IS DIRECTLY DUE TO A CHANGE OF CURRENT IN THE PRIMARY CONDUCTOR. THIS METHOD BY WHICH POWER IS TRANSFERRED FROM ONE CIRCUIT TO ANOTHER BY MEANS OF INDUCTION IS CALLED MUTUAL INDUCTION.

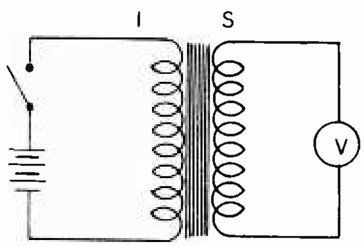
THE SIMPLE PHENOMENON OF MUTUAL INDUCTION IS THE BASIC MEANS BY WHICH NEARLY ALL POWER TRANSFER OCCURS IN RADIO COMMUNICATION. FROM THE VOLTAGE GENERATED ACROSS THE ARMATURE TURNS IN THE GENERATOR SUPPLYING POWER TO THE TRANSMITTER, TO THE RECEIVING ANTENNA THOUSANDS OF MILES AWAY BEING CUT BY THE MOVING MAGNETIC COMPONENT OF THE RADIATION FIELD, THE EFFECTS OF MUTUAL INDUCTION ARE MANIFEST TO SOME DEGREE. IT IS FOR THAT REASON VERY ESSENTIAL THAT THE RADIO ENGINEER BE ABLE TO VISUALIZE WHAT IS ACTUALLY TAKING PLACE WHEN CIRCUITS ARE COUPLED TOGETHER INDUCTIVELY.

THE ENGINEER WHO IS ABLE TO VISUALIZE WHAT IS TAKING PLACE IN A CIRCUIT—EVEN IF TO ONLY A VERY FUNDAMENTAL EXTENT—WILL FIND THE STUDY OF RADIO INFINITELY MORE INTERESTING, AND HE WILL BE MUCH MORE LIKELY TO QUICKLY DIAGNOSE TROUBLE CORRECTLY THAN THE ENGINEER WHO MERELY KNOWS THE MATHEMATICS AND THEORY OF THE CIRCUIT WITHOUT HAVING THE ABILITY TO VISUALIZE ITS OPERATION.

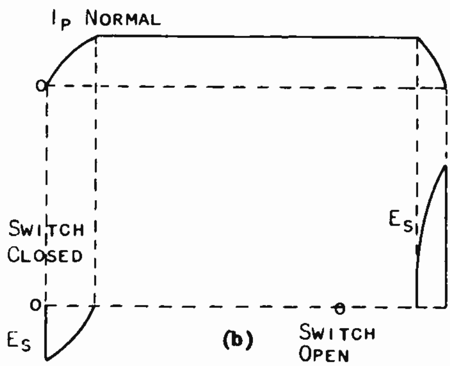
INDUCED VOLTAGE: SINCE THE INDUCED VOLTAGE ACROSS THE SECONDARY IS CAUSED BY A VARIATION OF CURRENT IN THE PRIMARY, IF THE PRIMARY CURRENT RISES TO A

CERTAIN AMPLITUDE AND MAINTAINS THAT LEVEL, THERE WILL BE A VOLTAGE INDUCED IN THE SECONDARY ONLY WHILE THE CURRENT IS ACTUALLY RISING. IF THE SWITCH IN THE PRIMARY CIRCUIT IS SUBSEQUENTLY OPENED AND THE CURRENT IN THE PRIMARY BROUGHT TO ZERO, THE FIELD IN COLLAPSING WILL CUT THE SECONDARY CONDUCTORS IN THE OPPOSITE DIRECTION AND THERE WILL AGAIN BE A VOLTAGE INDUCED ACROSS THE SECONDARY CONDUCTORS, BUT OPPOSITE IN DIRECTION TO THAT INDUCED WHEN THE SWITCH WAS CLOSED AND THE FIELD EXPANDED TO ITS STEADY VALUE.

THIS WILL BE THE CONDITION IF A D.C. VOLTAGE IS APPLIED ACROSS THE PRIMARY OF A TRANSFORMER, AND IS SHOWN IN FIGURE 3. WHEN THE SWITCH IS CLOSED THE INDICATOR ON THE VOLTMETER WILL DEFLECT IN SUCH A DIRECTION AS TO SHOW A VOLTAGE OPPOSITE TO THAT ACROSS THE PRIMARY. THE INDICATOR WILL DEFLECT TO SOME PEAK VALUE AND THEN GRADUALLY DROP TO ZERO AS THE CURRENT IN THE PRIMARY REACHES ITS



(a)



(b)

FIG. 3.

NORMAL AMPLITUDE WHICH WILL BE LIMITED ONLY BY THE RESISTANCE OF THE CIRCUIT AND THE VOLTAGE OF THE BATTERY. WHEN THE SWITCH IS OPENED THE INDICATOR OF THE VOLTMETER WILL DEFLECT IN THE OPPOSITE DIRECTION OR IN SUCH A DIRECTION AS TO INDICATE A VOLTAGE ACROSS THE SECONDARY OF THE SAME POLARITY AS THAT ACROSS THE PRIMARY. THE SECOND DEFLECTION WILL REACH A GREATER AMPLITUDE THAN THE DEFLECTION CAUSED WHEN THE PRIMARY CIRCUIT WAS CLOSED. THIS IS BECAUSE THE CURRENT IN THE PRIMARY FALLS OFF MORE RAPIDLY WHEN THE SWITCH IS OPENED THAN IT RISES WHEN THE SWITCH IS CLOSED. THE REASON FOR THIS WILL BE EXPLAINED LATER IN THIS LESSON.

THE IMPORTANT POINTS TO REMEMBER HERE ARE THAT A VOLTAGE IS INDUCED ACROSS THE SECONDARY ONLY WHEN THE FIELD OF THE PRIMARY CHANGES, AND THAT THE AMPLITUDE OF THE VOLTAGE ACROSS THE SECONDARY DEPENDS ALSO UPON HOW RAPIDLY THE CHANGE TAKES PLACE.

WHEN A SOURCE OF ALTERNATING CURRENT IS CONNECTED ACROSS THE PRIMARY THE AMPLITUDE OF THE CURRENT IN THE PRIMARY IS CONTINUALLY CHANGING--RISING AND FALLING AND REVERSING IN DIRECTION; AND SO LONG AS THE CURRENT IS CHANGING, A VOLTAGE IS INDUCED ACROSS THE SECONDARY CONDUCTORS. WHEN THE CHANGE OF CURRENT IS MOST RAPID THE GREATEST DIFFERENCE OF POTENTIAL IS INDUCED ACROSS THE SECONDARY. THE RATE OF CHANGE OF THE CURRENT IS EXPRESSED IN "AMPERES PER SECOND."

THE PRINCIPLE AS SHOWN IN FIGURES 3(A) AND 3(B) IS MADE USE OF IN THE SPARK COIL. WHEN THE VIBRATOR CONTACTS OPEN THE PRIMARY CIRCUIT SUDDENLY, THE FIELD AROUND THE PRIMARY COLLAPSES RAPIDLY, INDUCING A HIGH VOLTAGE ACROSS THE SECONDARY. THE INDUCED VOLTAGE MAY BE MADE ADDITIONALLY HIGHER BY HAVING A GREATER NUMBER OF TURNS IN THE SECONDARY THAN IN THE PRIMARY.

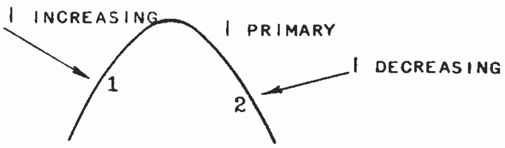
IF A UNIFORM RISE AND FALL OF PRIMARY CURRENT IS MAINTAINED, THE INDUCED VOLTAGE ACROSS THE SECONDARY WILL BE EQUAL TO THE PRIMARY VOLTAGE TIMES THE RATIO OF THE SECONDARY TURNS TO THE PRIMARY TURNS. IF THERE ARE TEN TIMES AS MANY TURNS IN THE SECONDARY AS IN THE PRIMARY, THE SECONDARY VOLTAGE WILL BE TEN TIMES AS GREAT AS THE PRIMARY VOLTAGE. THIS STATEMENT ASSUMES PERFECT COUPLING, I.E., COUPLING IN WHICH ALL OF THE MAGNETIC LINES OF FORCE AROUND ALL OF THE PRIMARY TURNS CUT ALL THE TURNS OF THE SECONDARY. THIS CONDITION IS PRACTICALLY OBTAINED IN IRON CORE TRANSFORMERS AT COMMERCIAL POWER FREQUENCIES. IT IS NOT OBTAINED IN RADIO FREQUENCY TRANSFORMERS WHERE THE COUPLING IS LOOSE AND WHERE THE VOLTAGE ACROSS THE CIRCUIT IS A FUNCTION OF SEVERAL FACTORS. FOR THE PURPOSE OF STUDYING THE EFFECTS OF INDUCTANCE IT WILL BE ASSUMED THAT WHERE COUPLING IS MENTIONED, THE COUPLING IS EQUAL TO THAT OF THE IRON CORE POWER TRANSFORMER UNLESS OTHERWISE STATED. THE REASON FOR THE TURNS RATIO FACTOR IS SIMPLE AND IS FULLY EXPLAINED IN THE EQUATION FOR THE AVERAGE VOLTAGE OF A GENERATOR. WITH GIVEN FLUX DENSITY

AND FIELD VELOCITY, THE GENERATED VOLTAGE IS A DIRECT FUNCTION OF THE NUMBER OF CONDUCTORS CUT BY THE FIELD.

IN THE ABOVE EXPLANATION INVOLVING MAGNETIC FIELDS, IT MUST NOT BE UNDERSTOOD THAT THE INDUCED CURRENT IN THE SECONDARY ACTUALLY OPPOSES THE CHANGE OF CURRENT IN THE PRIMARY. THE DIRECTION OF THE INDUCED CURRENT IS SUCH THAT IF IT WERE INDUCED DIRECTLY INTO THE PRIMARY TURNS THEMSELVES, IT WOULD BE IN SUCH A DIRECTION AS TO OPPOSE ANY CHANGE IN THE INDUCING CURRENT.

CONSIDER THE INDUCED CURRENT IN THE SECONDARY: WHEN THE CURRENT IN THE PRIMARY IS RISING THE CURRENT IN THE SECONDARY IS IN THE OPPOSITE DIRECTION, THEREFORE, IF THE SECONDARY CURRENT COULD BE MOVED OVER INTO THE PRIMARY TURNS, IT WOULD OPPOSE THE RISE OF THE ORIGINAL PRIMARY CURRENT. WHEN THE PRIMARY CURRENT IS FALLING OFF THE SECONDARY CURRENT IS IN THE SAME DIRECTION AS THE PRIMARY CURRENT, AND IF TRANSPOSED OVER INTO THE PRIMARY TURNS WOULD ADD TO THE ORIGINAL PRIMARY CURRENT AND TEND TO PREVENT IT FROM FALLING OFF.

THE PRIMARY AND SECONDARY CURRENTS AS REFERRED TO IN THE PRECEDING PARA-



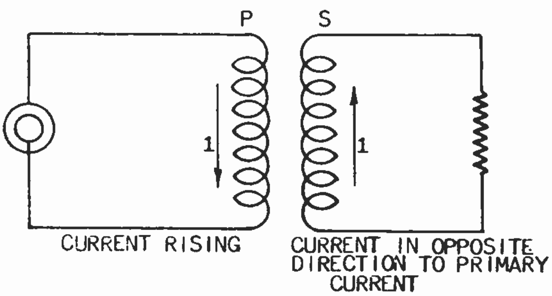


FIG. 4(A).

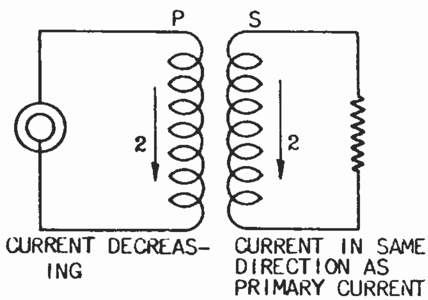


FIG. 4(B).

GRAPH ARE SHOWN IN FIGURES 4(A) AND 4(B). IN 4(A) THE PRIMARY CURRENT IS INCREASING IN AMPLITUDE; IN 4(B) IT IS DECREASING BUT THE DIRECTION OF CURRENT FLOW IS THE SAME IN BOTH CASES. THE DIRECTION OF THE SECONDARY CURRENT, HOWEVER,

HAS REVERSED.

IN FIGURE 5 IS A CROSS-SECTION OF A SINGLE LAYER COIL. ALL TURNS ARE PARALLEL AND CLOSE TOGETHER. IF AN ALTERNATOR IS CONNECTED ACROSS THE TERMINALS OF THIS COIL THERE WILL BE A CURRENT CONTINUALLY RISING AND FALLING AND REVERSING IN DIRECTION THROUGH THE TURNS OF THE COIL. CONSIDER A SINGLE TURN. AS THE CURRENT RISES IN THE TURN IT CAUSES A MAGNETIC FIELD TO EXPAND AT RIGHT ANGLES TO THE TURN. THIS EXPANDING MAGNETIC FIELD CUTS ALL OF THE OTHER TURNS AND INDUCES ACROSS THEM A VOLTAGE WHICH TENDS TO FORCE A CURRENT THROUGH THE TURNS IN SUCH A DIRECTION AS TO OPPOSE THE RISE OF THE EXISTING CURRENT WHICH IS CAUSED TO FLOW BY THE VOLTAGE OF THE ALTERNATOR. SINCE THE CURRENT DUE TO THE ALTERNATOR VOLTAGE IS RISING SIMULTANEOUSLY IN ALL TURNS OF THE COIL, THE MAGNETIC FIELD AROUND EVERY TURN CUTS EVERY OTHER TURN INDUCING A VOLTAGE IN ALL THE TURNS IN SUCH A DIRECTION AS TO OPPOSE THE RISE OF THE ORIGINAL CURRENT.

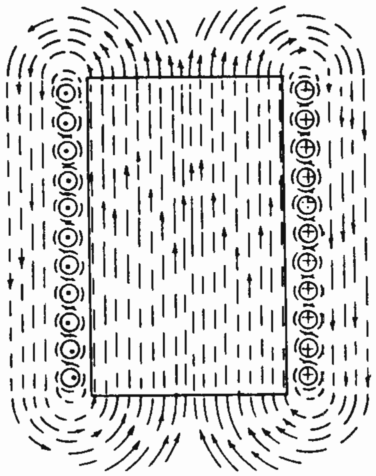


FIG. 5.

AFTER THE CURRENT THROUGH THE TURNS HAS FINALLY REACHED ITS MAXIMUM VALUE IT STARTS TO DECREASE. AS THE CURRENT BEGINS TO DECREASE IN AMPLITUDE THE MAGNETIC FIELD STARTS TO CONTRACT TOWARD ITS INDIVIDUAL TURNS. THUS THE FIELD OF EVERY TURN, IN CONTRACTING, WILL CUT EVERY OTHER TURN, AND A VOLTAGE WILL BE INDUCED ACROSS THE TURNS IN SUCH A DIRECTION AS TO <u>OPPOSE THE DECREASE OF THE ORIGINAL CURRENT</u>. (SEE LENZ'S LAW.)

IT WILL BE SEEN THAT EACH TURN IN THE WINDING ACTS SOMEWHAT AS A SECONDARY WITH ALL OF THE OTHER TURNS ACTING AS PRIMARY TURNS. EACH TURN ALSO ACTS AS A PRIMARY WITH ALL OF THE OTHER TURNS ACTING AS SECONDARY TURNS.

<u>CURRENT LAG</u>: SINCE THE INDUCED CURRENT IS ALWAYS IN SUCH A DIRECTION AS TO OPPOSE THE <u>CHANGE</u> IN THE EXISTING CURRENT, IT IS EVIDENT THAT THE CURRENT IN THE

COIL WILL NOT RISE AS RAPIDLY AS IT OTHERWISE WOULD IF THE INDUCED CURRENT WERE NOT PRESENT. NEITHER WILL IT FALL OFF SO RAPIDLY. A CURRENT LAG HAS THEREFORE BEEN INTRODUCED INTO THE CIRCUIT.

THE INDUCED VOLTAGE FOR A GIVEN NUMBER OF TURNS DEPENDS UPON HOW RAPIDLY THE CHANGE IN THE EXISTING CURRENT AMPLITUDE TAKES PLACE, AND IS VERY CLEARLY SHOWN IN THE COMMON INDUCTION COIL USED FOR IGNITION PURPOSES IN SOME INTERNAL COMBUSTION ENGINES. See FIGURE 6.

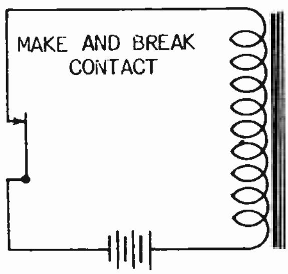


FIG. 6.

THIS SYSTEM IS MERELY A COIL HAVING A VERY LARGE NUMBER OF TURNS WOUND ON AN IRON CORE, AN ARRANGEMENT FOR OPENING AND CLOSING THE CIRCUIT, AND A BATTERY. AS THE CIRCUIT IS CLOSED A STEADY SOURCE OF E.M.F. IS APPLIED TO THE TERMINALS OF THE COIL. IF THE COIL POSSESSED ONLY RESISTANCE THE CURRENT WOULD RISE INSTANTLY TO A VALUE EQUAL TO THE VOLTAGE DIVIDED BY THE RESISTANCE. THE CURRENT TRIES TO DO THIS. BUT AS IT TENDS TO RISE VERY RAPIDLY THE MAGNETIC FIELD EXPANDS AROUND EACH TURN CUTTING EVERY OTHER TURN. THE HIGH PERMEABILITY OF THE SURROUNDING MEDIUM, DUE TO THE IRON CORE, ALLOWS A STRONG FIELD TO BE BUILT UP AROUND THE TURNS, WHICH EXPANDING AND CUTTING THE OTHER TURNS, INDUCES A VOLTAGE ACROSS THE COIL WHICH TENDS TO OPPOSE THE INSTANTANEOUS RISE OF THE EXISTING CURRENT TO ITS MAXIMUM VALUE. THIS IS SHOWN IN FIGURE 3(B) IN WHICH THE PRIMARY CURRENT IS SEEN TO BE RISING GRADUALLY AND NOT INSTANTLY. THE VOLTAGE IS AT ITS MAXIMUM VALUE THE INSTANT THE CONTACT IS CLOSED, BUT THE CURRENT LAGS AND REACHES ITS MAXIMUM VALUE, EQUAL TO E/R, MORE SLOWLY. WHEN THAT VALUE IS REACHED, THE FIELD, NO LONGER EXPANDING, REMAINS STEADY, THEREFORE CEASING TO CUT ADJACENT TURNS.

POWER HAS BEEN EXPENDED IN EXPANDING THE MAGNETIC FIELD AND THIS POWER CONTINUES TO EXIST IN THE FORM OF MAGNETIC FLUX AROUND THE TURNS AS LONG AS CURRENT FLOWS IN THE TURNS. WHEN THE CIRCUIT IS OPENED, HOWEVER, THE APPLIED VOLTAGE DROPS TO ZERO AND THE CURRENT ALSO TRIES TO FALL OFF INSTANTLY. IF THE CIRCUIT

CONTAINED ONLY RESISTANCE THE CURRENT WOULD INSTANTLY REACH ZERO VALUE WHEN THE SWITCH WAS OPENED. HOWEVER, THERE EXISTS CONSIDERABLE ENERGY IN THE FORM OF A MAGNETIC FIELD SURROUNDING THE COIL. THAT ENERGY CANNOT BE THROWN AWAY, OR NEGLECTED. AS THE CURRENT TRIES TO DROP TO ZERO THE MAGNETIC FIELD COLLAPSES AND CUTS ALL THE TURNS OF THE COIL INDUCING A VOLTAGE ACROSS THE COIL IN SUCH A DIRECTION AS TO MAINTAIN THE ORIGINAL CURRENT FLOW. THE CURRENT CAUSED BY THE INDUCED VOLTAGE CONTINUES TO FLOW FOR A CERTAIN LENGTH OF TIME AFTER THE CIRCUIT HAS BEEN OPENED AND IS SHOWN BY THE SPARK AT THE SWITCH CONTACTS WHEN THE SWITCH IS OPENED.

AMPLITUDE OF INDUCED VOLTAGE: IT HAS BEEN STATED THAT ORDINARILY A HIGHER VOLTAGE IS INDUCED WHEN THE CIRCUIT IS OPENED THAN WHEN IT IS CLOSED. THIS IS TRUE ONLY IF THE CIRCUIT IS OPENED VERY RAPIDLY. THERE IS A CERTAIN DEFINITE AMOUNT OF ACTUAL ENERGY OR POWER EXISTING IN THE MAGNETIC FIELD AROUND THE COIL. AS THE CIRCUIT IS OPENED THAT ENERGY IS EXPENDED IN HEAT IN THE SPARK AT THE SWITCH CONTACTS. HOWEVER, IF THE CIRCUIT IS OPENED VERY GRADUALLY THE CURRENT WILL FALL OFF SLOWLY DUE TO IONIZATION OF THE AIR BETWEEN THE CONTACTS. THE IONIZED AIR WILL FORM A COMPARATIVELY LOW RESISTANCE PATH FOR THE CURRENT, THE RESISTANCE INCREASING AS THE SWITCH IS OPENED WIDER, UNTIL THE CURRENT FINALLY REACHES ZERO. UNDER SUCH CONDITIONS THE EXISTING CURRENT DOES NOT TRY TO FALL TO ZERO IMMEDIATELY BUT DECREASES IN VALUE MORE SLOWLY. THE MAGNETIC FIELD THEREFORE COLLAPSES SLOWLY CUTTING THE TURNS OF THE COIL SLOWLY AND INDUCING ONLY A COMPARATIVELY LOW VOLTAGE ACROSS THE TURNS. IF, HOWEVER, THE SWITCH IS OPENED TOO RAPIDLY FOR IONIZATION TO TAKE PLACE TO ANY GREAT EXTENT, THE CURRENT TRIES TO FALL OFF ALMOST INSTANTLY CAUSING A VERY RAPID COLLAPSE OF THE MAGNETIC FIELD WHICH IN TURN INDUCES A VERY HIGH VOLTAGE ACROSS THE TURNS, CAUSING AN INTENSE SPARK OF SHORT DURATION BETWEEN THE SWITCH CONTACTS BUT PRACTICALLY NO IONIZATION, AND THEREFORE NO PROLONGED ARC. IN THAT CASE THE SPARK WILL LAST ONLY LONG ENOUGH TO DISSIPATE IN HEAT ALL THE ENERGY THAT EXISTED IN THE MAGNETIC FIELD.

IN MANY CIRCUITS WHICH ARE HIGHLY INDUCTIVE AND WHICH CARRY VERY LARGE CURRENTS, THE SWITCH CONTACTS ARE OPENED IN OIL TO PREVENT IONIZATION AND A VERY

PROLONGED ARC WHICH WOULD QUICKLY MELT THE SWITCH CONTACTS. ON MANY LARGE INDUCTANCES WHICH ARE LIKELY TO BE SUBJECTED TO VERY LARGE AND SUDDEN CURRENT FLUCTUATIONS OR SURGES WHICH WOULD CAUSE EXTREMELY HIGH INSTANTANEOUS VOLTAGES TO BE BUILT UP, THE INDUCTANCE COIL HAS CONNECTED ACROSS IT A SAFETY GAP SO ADJUSTED THAT THE GAP WILL BREAK DOWN BEFORE A VOLTAGE SUFFICIENTLY HIGH TO DAMAGE THE INSULATION OF THE COIL IS REACHED. SUCH A GAP IS VERY OFTEN USED ACROSS THE WINDINGS OF ANTENNA COUPLING TRANSFORMERS IN MEDIUM AND HIGH POWER RADIO TRANSMITTERS, WHERE BY SOME ADJUSTMENT THE CURRENT VARIATIONS MAY BE ALLOWED TO EXCEED A SAFE AMPLITUDE AND THE INSULATION OF THE WINDINGS OR THE INSULATION TO GROUND MIGHT OTHERWISE BE DAMAGED.

SELF-INDUCTANCE: A CIRCUIT POSSESSING THE ABOVE CHARACTERISTICS IS SAID TO POSSESS SELF-INDUCTANCE OR SIMPLY INDUCTANCE. INDUCTANCE IS THE PROPERTY OF A CIRCUIT WHICH TENDS TO OPPOSE A CHANGE IN THE EXISTING CURRENT AND IS MANIFEST ONLY WHEN THE CURRENT IS CHANGING. THE INDUCTANCE OF A COIL DEPENDS UPON THE SHAPE OF THE COIL, ITS LENGTH, DIAMETER, NUMBER OF TURNS, SPACING BETWEEN TURNS, AND THE CHARACTER OF THE SURROUNDING MEDIUM. ANYTHING WHICH WILL TEND TO INCREASE THE DENSITY OF THE MAGNETIC FIELD PRODUCED BY A GIVEN CURRENT THROUGH A COIL, WILL INCREASE THE INDUCTANCE OF THE COIL. FOR EXAMPLE, AN AIR CORE COIL HAS CERTAIN INDUCTANCE. IF AN IRON CORE IS INSERTED WITHIN THE COIL, THE INDUCTANCE WILL BE INCREASED BY MANY TIMES.

INDUCTANCE OF STRAIGHT WIRE AND "SKIN-EFFECT": IT MUST NOT BE THOUGHT THAT A CONDUCTOR MUST BE FORMED IN THE SHAPE OF A COIL IN ORDER TO POSSESS INDUCTANCE. WINDING A GIVEN LENGTH OF WIRE INTO A COIL OF SMALL DIAMETER WILL INCREASE THE INDUCTIVE EFFECT OF THAT LENGTH OF WIRE; BUT IF THAT PIECE OF WIRE WERE STRETCHED PERFECTLY STRAIGHT AND ISOLATED IN SPACE IT WOULD STILL POSSESS INDUCTANCE. THIS IS DUE TO THE FACT THAT AS THE CURRENT IS RISING AND FALLING THROUGHOUT A CONDUCTOR THE FIELD WILL BE EXPANDING AROUND AND THROUGH THE CONDUCTOR. IT MUST BE REMEMBERED THAT THE MAGNETIC FIELD AROUND A CONDUCTOR IS SIMPLY THE SUM OF BILLIONS OF MAGNETIC FIELDS EACH DUE TO THE MOVEMENT OF ONE ELECTRON THROUGH THE

CONDUCTOR. IF AN ELECTRON NEAR THE CENTER OF THE CONDUCTOR IS MOVING, THE FIELD DUE TO THAT MOVING ELECTRON MUST EXPAND OUTWARD, THROUGH THE REST OF THE CONDUCTOR, THEREBY CUTTING THE CONDUCTOR AND INDUCING A VOLTAGE ACROSS THE CONDUCTOR WHICH WILL TEND TO PREVENT THE CURRENT CHANGE. THE CONTRACTING FIELD OF THAT ELECTRON WILL ALSO CUT THE CONDUCTOR WITH CORRESPONDING INDUCTIVE EFFECTS.

ELECTRONS MOVING NEAR THE SURFACE OF THE CONDUCTOR WILL CAUSE EXPANDING AND CONTRACTING FIELDS THAT CUT THE CENTER OF THE CONDUCTOR CAUSING INDUCED CURRENTS THROUGH THE CONDUCTOR. THIS EFFECT IS ONE OF THE PRINCIPAL REASONS WHY AT RADIO FREQUENCIES A LOWER RESISTANCE, AND THEREFORE A LOWER LOSS CIRCUIT, CAN BE OBTAINED BY USING A HOLLOW TUBING THAN BY USING A SOLID CONDUCTOR OF THE SAME DIAMETER. <u>AT HIGH RADIO FREQUENCIES THE CURRENT NORMALLY TRAVELS ONLY ON THE SURFACE OF THE CONDUCTOR; THE HIGHER THE FREQUENCY THE LESS THE PENETRATION OF THE CURRENT BELOW THE SURFACE</u>. THIS IS CALLED THE HIGH FREQUENCY "SKIN EFFECT." IF THE CONDUCTOR HAS A SOLID CENTER, EDDY CURRENTS ARE INDUCED INTO THE CENTER OF THE CONDUCTOR, DOING NO USEFUL WORK BUT EXPENDING POWER IN HEAT INSIDE THE CONDUCTOR. THIS POWER SHOWS UP AS AN INCREASE IN THE RADIO FREQUENCY RESISTANCE OF THE CIRCUIT. SO THAT EVEN THOUGH THE ACTUAL CROSS-SECTION OF COPPER IN THE TUBING IS LESS, THE ACTUAL RADIO FREQUENCY RESISTANCE OF THE CIRCUIT MAY BE CONSIDERABLY REDUCED. IN A SIMILAR MANNER THE RADIO FREQUENCY RESISTANCE OF STRANDED WIRE IS LOWER THAN THAT OF A SOLID WIRE CONSISTING OF THE SAME AMOUNT OF COPPER BECAUSE THE SURFACE AREA OF THE STRANDED WIRE WILL BE GREATER THAN THAT OF THE EQUIVALENT SOLID WIRE.

WHILE AT LOW FREQUENCIES A SHORT STRAIGHT CONDUCTOR IS USUALLY THOUGHT OF AS BEING PRACTICALLY NON-INDUCTIVE, THAT IDEA MUST BE REVISED WHEN WORKING WITH THE ULTRA-HIGH FREQUENCIES NOW BECOMING USEFUL IN RADIO WORK. AT MOST FREQUENCIES, EVEN AS HIGH AS FIVE OR SIX THOUSAND KILOCYCLES, A STRAIGHT WIRE A FEW INCHES LONG MAY BE CONSIDERED A DEAD SHORT IF PLACED ACROSS A CIRCUIT. HOWEVER, AT FREQUENCIES AROUND SIXTY THOUSAND KILOCYCLES, (5 METERS), AND ABOVE, A STRAIGHT PIECE OF WIRE TWO OR THREE INCHES LONG CAN BE USED FOR A RADIO FREQUENCY CHOKE

AND WILL HAVE AN INDUCTIVE REACTANCE, (TO BE EXPLAINED LATER), OF MANY OHMS. (A STRAIGHT PIECE OF No. 16 WIRE ONE INCH LONG HAS AN INDUCTANCE OF .0134 μH. THIS IS ENOUGH TO IMPOSE SERIOUS LIMITATIONS IN CERTAIN TYPES OF PRECISION APPARATUS.)

THIS MAY BE VERY SIMPLY EXPLAINED BY REMEMBERING THAT INDUCTANCE MANIFESTS ITSELF WHEN THE CURRENT CHANGES, AND THE MORE RAPID THE CHANGES THE GREATER ARE THE EFFECTS OF INDUCTANCE. IN THE INDUCTION COIL THE INDUCTIVE EFFECTS ARE GREATER WHEN THE CIRCUIT IS OPENED RAPIDLY THAN WHEN THE SWITCH IS OPENED VERY SLOWLY DRAWING A PROLONGED ARC. AT SIXTY THOUSAND KILOCYCLES THE CURRENT COMPLETES SIXTY MILLION CYCLES EVERY SECOND. REFERRING TO THE SINE CURVE IT IS SEEN THAT FOUR COMPLETE CHANGES, (ZERO TO MAXIMUM OR MAXIMUM TO ZERO), TAKE PLACE IN EACH CYCLE. AT SIXTY THOUSAND KILOCYCLES THE CURRENT MAKES TWO HUNDRED FORTY MILLION COMPLETE VARIATIONS EVERY SECOND. AT THAT INCONCEIVABLY RAPID RATE OF CHANGE A SMALL AMOUNT OF INDUCTANCE MAY HAVE A VERY CONSIDERABLE EFFECT.

CHOKE COILS: THE PROPERTY OF INDUCTANCE WHICH TENDS TO PREVENT A CURRENT CHANGE THROUGH IT IS MADE USE OF IN THE DESIGN OF "CHOKE COILS" FOR ALL PURPOSES AND AT ALL FREQUENCIES. WHEREVER IT IS DESIRED TO PASS A DIRECT CURRENT AND AT THE SAME TIME TO PREVENT FLUCTUATIONS IN THAT CURRENT, AN INDUCTANCE IS INSERTED IN SERIES IN THE CIRCUIT. IF THE INDUCTANCE IS SUFFICIENTLY LARGE, RAPID CURRENT FLUCTUATIONS CANNOT TAKE PLACE AND THE CURRENT COMES THROUGH THE CIRCUIT IN A PRACTICALLY STEADY STATE. AN EXAMPLE OF THIS IS IN THE FILTER REACTOR USED IN THE OUTPUT CIRCUIT OF A RECTIFIER. THE LOAD CURRENT FROM THE RECTIFIER IS NORMALLY PULSATING, BUT IF A SUFFICIENTLY LARGE INDUCTANCE IS PLACED IN THE LINE THE PULSATIONS CANNOT TAKE PLACE RAPIDLY THROUGH THE INDUCTANCE AND THE OUTPUT CURRENT COMES THROUGH WITH THE PULSATIONS SMOOTHED OUT. (CHOKE COILS WILL BE DISCUSSED IN DETAIL IN A LATER LESSON.)

THE NUMBER OF CYCLES OF VARIATION OF THE CURRENT PER SECOND, (THE FREQUENCY), DOES NOT HAVE ANYTHING TO DO WITH THE INDUCTANCE OF THE CIRCUIT. THE EFFECTS OF THE INDUCTANCE, HOWEVER, VARY DIRECTLY AS THE FREQUENCY.

UNIT OF INDUCTANCE: THE UNIT OF INDUCTANCE IS THE HENRY. A COIL HAS AN INDUCTANCE OF ONE HENRY WHEN A CHANGE OF CURRENT OF ONE AMPERE IN ONE SECOND WILL CAUSE AN AVERAGE INDUCED VOLTAGE OF ONE VOLT ACROSS THE COIL.

THE HENRY IS A VERY LARGE UNIT AND IN RADIO THIS UNIT IS ENCOUNTERED ONLY IN THE AUDIO FREQUENCY CIRCUITS OF RECEIVERS AND TRANSMITTERS, AND IN POWER SUPPLY FILTERS. IN LOW RADIO FREQUENCY CIRCUITS THE MILLIHENRY, (1/1000 HENRY), IS USED, AND AT THE INTERMEDIATE AND HIGH RADIO FREQUENCIES THE COMMON UNIT IS THE MICROHENRY, (ONE MILLIONTH OF ONE HENRY).

FROM THE DEFINITION OF THE UNIT OF INDUCTANCE, THE HENRY, IT IS APPARENT THAT WHAT ACTUALLY TAKES PLACE IN A COIL WHEN THE CURRENT CHANGES IS NO DIFFERENT THAN WHAT OCCURS IN A GENERATOR. WHEN THE CURRENT CHANGES AT THE RATE OF ONE AMPERE PER SECOND, IF THE COIL HAS AN INDUCTANCE OF ONE HENRY, ONE VOLT WILL BE INDUCED ACROSS THE WINDING. IT HAS BEEN SHOWN IN AN EARLIER LESSON THAT ONE VOLT IS GENERATED WHEN 10^8 MAGNETIC LINES OF FORCE ARE CUT PER SECOND. THEREFORE, WHEN A CURRENT VARIATION OF ONE AMPERE PER SECOND CAUSES AN INDUCED E.M.F. OF ONE VOLT, THERE MUST BE SUFFICIENT TURNS AND A SUFFICIENT DENSITY OF MAGNETIC FIELD TO CAUSE 10^8 LINES OF FORCE TO BE CUT EACH SECOND.

INDUCTANCE CALCULATIONS; COIL DESIGN: HOW THE VARIOUS FACTORS OF TURNS, SHAPE, AND PERMEABILITY OF THE SURROUNDING MEDIUM ENTER INTO THE CALCULATION IS SHOWN IN THE FOLLOWING EQUATION EXPRESSING THE INDUCTANCE OF A COIL:

$$L = \frac{1.26\ N^2 \cdot A\ \mu}{10^8 \cdot l} \qquad \text{(EQUATION 1)}$$

(THIS EQUATION MAY BE USED FOR A LONG SOLENOID, A VERY COMPACT COIL, OR WHERE THE MAGNETIC PATH IS THROUGH IRON.)

WHERE L = INDUCTANCE IN HENRIES.

N = NUMBER OF TURNS

A = AREA ENCLOSED BY A SINGLE TURN IN SQUARE CM.

l = LENGTH OF WINDING IN CM.

μ = PERMEABILITY OF CORE

THE FACTOR 10^8 ENTERS INTO THE CALCULATION AS EXPLAINED ABOVE. THE GREATER THE AREA ENCLOSED BY EACH TURN THE GREATER THE AMOUNT OF FLUX CONTRIBUTED TO THE

TOTAL BY THAT TURN. THE GREATER THE LENGTH L OF THE COIL FOR A GIVEN NUMBER OF TURNS, THE MORE WIDELY SEPARATED THE TURNS WILL BE AND THEREFORE THE WEAKER THE FIELD OF EACH TURN CUTTING THE OTHER TURNS. IT WILL BE SEEN THAT THE INDUCTANCE OF THE COIL IS A DIRECT FUNCTION OF THE AREA AND AN INVERSE FUNCTION OF THE LENGTH OF THE WINDING. THERE IS ALSO A DIRECT RELATION BETWEEN THE INDUCTANCE AND THE PERMEABILITY OF THE CORE. SINCE THE MAGNETIC PERMEABILITY OF IRON MAY BE SEVERAL THOUSAND TIMES GREATER THAN THAT OF AIR, IF A CORE OF HIGH PERMEABILITY IS USED THE DIMENSIONS OF THE WINDING MAY BE VERY GREATLY REDUCED OVER WHAT IS REQUIRED FOR AN AIR CORE AND STILL MAINTAIN A LARGE VALUE OF INDUCTANCE. FOR THAT REASON, AT LOW FREQUENCIES WHERE LARGE VALUES OF INDUCTANCE ARE REQUIRED, THE CORES OF REACTORS, TRANSFORMERS, ETC., ARE MADE OF IRON, OR MORE COMMONLY, STEEL.

THE FACTOR N^2 HAS BEEN LEFT UNTIL LAST BECAUSE IT IS A FACTOR OF VERY GREAT IMPORTANCE. N REPRESENTS THE NUMBER OF TURNS ON THE COIL. AS A CURRENT RISES AND FALLS THROUGH THE TURNS, THE MAGNETIC FIELD GOES THROUGH CERTAIN VARIATIONS OF DENSITY. IT HAS BEEN SHOWN THAT THE MAGNETIZING FORCE H VARIES DIRECTLY AS THE NUMBER OF AMPERE TURNS. THEREFORE WITH A GIVEN CURRENT AMPLITUDE THE TOTAL AMOUNT OF MAGNETIC FLUX WILL BE A DIRECT FUNCTION OF THE NUMBER OF TURNS. IF THE NUMBER OF TURNS ON THE COIL IS DOUBLED, ALL OTHER CONDITIONS BEING UNCHANGED, THE TOTAL MAGNETIC FLUX WILL BE DOUBLED.

THIS LEADS TO ANOTHER CONDITION. WITH A GIVEN VARIATION OF MAGNETIC FLUX THE VOLTAGE GENERATED OR INDUCED WILL BE A DIRECT FUNCTION OF THE NUMBER OF TURNS BEING CUT. FOR A GIVEN FLUX VARIATION, IF THE NUMBER OF TURNS IS DOUBLED, THE INDUCED VOLTAGE WILL BE DOUBLED. NOW WITH EACH TURN ACTING AS BOTH A PRIMARY AND A SECONDARY, AND WITH BOTH TOTAL MAGNETIC FLUX AND TOTAL VOLTAGE PER UNIT FLUX BEING DIRECT FUNCTIONS OF N, (THE NUMBER OF TURNS), THE COMBINED EFFECTS MUST BE A PRODUCT OF THE TWO FACTORS AND THE TOTAL INDUCED VOLTAGE FOR UNIT CURRENT VARIATION IN AMPERES PER SECOND MUST BE A FUNCTION OF N^2. THEREFORE, WITH A COIL OF GIVEN AREA, LENGTH, AND CORE PERMEABILITY, IF THE TURNS ARE DOUBLED

L will become four times as great; if the number of turns is reduced to one-quarter, the inductance will be reduced to one-sixteenth, etc.

Equation 1 is not at all difficult to use. Consider the following coil: 1000 turns having a mean diameter of 2.5 inches with a length of winding of 3 inches. Permeability of steel core, including airgap, at the flux density at which it is designed to operate, 250. What is the inductance in Henries? First, convert the dimensions from inches to cm. Diameter = 2.5" = 2.5 x 2.54 = 6.35 cm. Length of winding = 3" = 2.54 x 3 = 7.62 cm. The mean turn area = πr^2; r = 6.35/2 = 3.18 cm. Then A = 3.14 x 3.18^2 = 31.4 cm^2. The formula,

$$L = \frac{1.26\ N^2\ A\ \mu}{10^8\ l}$$

becomes,

$$L = \frac{1.26 \times 1000^2 \times 31.4 \times 250}{10^8 \times 7.62} = \frac{99 \times 10^8}{7.62 \times 10^8}$$

L = 13 Henries

The actual inductance of this coil will, of course, vary somewhat with the current through the winding due to the change of permeability with flux density.

This equation is very useful in radio where it is necessary to design audio frequency choke coils, filter reactors, etc. It may be used in conjunction with magnetic circuit calculations--as discussed in an earlier lesson--to obtain a coil having not only certain magnetic characteristics but also some specified value of inductance. An example of where such combined features are required is the field winding of a dynamic reproducer in a modern broadcast receiver. Such a winding is ordinarily required to perform three functions: First, to supply the required magnetic flux density in the airgap in which the voice coil moves; second, to act as a filter reactor of the required inductance for the power supply; third, to form the first voltage divider resistance in the power supply output.

To satisfactorily perform these three functions several factors must be balanced against each other. First, the number of turns must be such that, combined with the plate current load of the receiver, IN is correct to produce the

REQUIRED FLUX DENSITY IN THE AIRGAP; SECOND, N MUST BE SUCH THAT COMBINED WITH THE OTHER COIL DIMENSIONS AND μ OF THE CORE, THE INDUCTANCE IS CORRECT FOR ITS FUNCTION AS A FILTER REACTOR; THIRD, THE SIZE OF WIRE MUST BE SUCH THAT IT WILL, HAVE THE NECESSARY RESISTANCE FOR ITS THIRD FUNCTION AND AT THE SAME TIME SAFELY CARRY THE LOAD CURRENT OF THE RECTIFIER.

CONSIDERABLE INGENUITY IS REQUIRED IN SUCH A DESIGN PROBLEM. SEVERAL COMBINATIONS OF COIL DIMENSIONS, NUMBER OF TURNS, AND WIRE SIZE MUST BE TRIED, IF NO APPROXIMATE FIGURES ARE AVAILABLE, AND THE COMPLETE PROBLEMS WORKED OUT. WHEN A FAIR APPROXIMATION OF REQUIRED VALUES IS REACHED, THE CORE SHOULD BE BUILT UP WITH THE ACTUAL GRADE OF STEEL TO BE USED, MEASUREMENTS MADE TO CHECK THE ACCURACY OF THE CALCULATIONS, AND THEN CORRECTIONS MADE TO BRING ALL THE FACTORS TO THE PREDETERMINED SPECIFICATIONS.

IN THE ADJUSTMENT OF A RADIO TRANSMITTER CIRCUIT WHERE THE COILS ARE USUALLY WOUND ON A FORM WITH A MAGNETIC CORE OF AIR, VARIATIONS OF L ARE ORDINARILY MADE BY MOVING A TAP FROM ONE TURN TO ANOTHER. IF IT IS DESIRED, IN ORDER TO OBTAIN A LOWER FREQUENCY, TO DOUBLE THE INDUCTANCE CONNECTED INTO THE CIRCUIT, THE NUMBER OF TURNS SHOULD BE INCREASED BY $\sqrt{2}$ OR 1.41 TIMES. TO OBTAIN 3 TIMES AS MUCH INDUCTANCE, THE TURNS SHOULD BE INCREASED BY $\sqrt{3}$ TIMES, ETC.

THE INDUCTANCE FORMULA GIVEN AS EQUATION 1, WHEN USED WITH AN AIR CORE WINDING ASSUMES A COIL LENGTH OF AT LEAST 10 TIMES THE COIL DIAMETER. FOR MOST RADIO COIL PURPOSES A LENGTH OF AT LEAST 10 TIMES THE DIAMETER WOULD BE VERY INCONVENIENT. THEREFORE THE FORMULA FOR THE INDUCTANCE OF A SINGLE LAYER COIL AS GIVEN BELOW (EQUATION 2) IS MORE PRACTICAL. THIS FORMULA TAKES INTO CONSIDERATION A FORM FACTOR K WHICH IS A FUNCTION OF DIAMETER/LENGTH. TABLES GIVING THE VALUE OF K FOR DIFFERENT RATIOS OF DIAMETER/LENGTH MAY BE FOUND IN VARIOUS ELECTRICAL TEXTS AND HANDBOOKS. ONE SUCH TABLE IS GIVEN ON PAGE 283 OF THE BUREAU OF STANDARDS CIRCULAR 74. A PARTIAL TABLE IS GIVEN BELOW. THE EQUATION

$$L = \frac{.03948\ A^2N^2}{B}\ K \qquad \text{(EQUATION 2)}$$

WHERE A = RADIUS OF COIL MEASURED FROM THE AXIS TO THE CENTER OF ANY WIRE

N = NUMBER OF TURNS IN WINDING

B = LENGTH OF COIL

K = CONSTANT WHICH IS A FUNCTION OF $\frac{2A}{B}$

L = INDUCTANCE IN MICROHENRIES

(DIMENSIONS OF A AND B ARE IN CENTIMETERS)

THIS FORMULA DOES NOT TAKE INTO CONSIDERATION THE SIZE AND SHAPE OF THE CROSS-SECTION OF THE WIRE. HOWEVER, FOR MOST PRACTICAL PURPOSES IT IS SUFFICIENTLY ACCURATE. THIS IS PARTICULARLY TRUE AT RADIO FREQUENCIES WHERE HIGH FREQUENCY SKIN EFFECT AND OTHER CONDITIONS, THE EFFECTS OF WHICH ARE EXTREMELY DIFFICULT TO CALCULATE, TEND TO LIMIT THE ACCURACY OF FURTHER CORRECTIONS.

TABLE

VALUES OF K FOR USE IN EQUATION 2.

$\frac{\text{DIAMETER}}{\text{LENGTH}}$	K.	$\frac{\text{DIAMETER}}{\text{LENGTH}}$	K.
.1	.9588	1.75	.5579
.2	.9201	2.00	.5255
.3	.8838	3.00	.4292
.4	.8499	4.00	.3654
.5	.8181	5.00	.3198
.6	.7885	6.00	.2854
.7	.7609	8.00	.2366
.8	.7351	10.00	.2033
.9	.7110	12.00	.1790
1.0	.6884	15.00	.1527
1.25	.6381	20.00	.1236
1.50	.5950	30.00	.0910

(VALUES IN BETWEEN THOSE LISTED MAY BE DETERMINED BY INTERPOLATION.)

THE VALUE OF K EXTENDS OVER WIDE LIMITS. WHERE THE RATIO OF DIAMETER/LENGTH IS LESS THAN .1 THE CONSTANT MAY BE TAKEN AS UNITY WITHOUT APPRECIABLE ERROR. WHEN THE DIAMETER AND LENGTH ARE EQUAL, K = .6884; WHEN THE DIAMETER/LENGTH EQUALS 2, K = .5255; WHEN DIAMETER/LENGTH EQUALS 6, K = .2854, ETC. IT WILL BE SEEN THAT WITH A SINGLE LAYER COIL ON A CORE OF UNIT PERMEABILITY, TO OBTAIN THE MAXIMUM INDUCTANCE FOR A GIVEN AMOUNT OF WINDING, THE COIL SHOULD BE SHORT AND OF LARGE DIAMETER. A COIL SHAPE VERY COMMONLY USED IN RADIO IS ONE IN WHICH THE LENGTH OF THE WINDING IS 2.5 TIMES THE DIAMETER. THIS IS A DIAMETER/LENGTH RATIO

OF .4 AND THE VALUE OF K IS .8499.

EQUATION 2 IS ALSO QUITE EASY TO USE. CONSIDER THE FOLLOWING R.F. COIL. DIAMETER = 1.4", LENGTH OF WINDING 1.4", N = 60 TURNS. THE EQUATION,

$$L = \frac{.03948\ A^2N^2}{B} K$$

WHERE $\frac{2A}{B} = 1$, $K = .6884$

$A = 1.4/2 = .7" = 2.54 \times .7 = 1.78$ CM.

$B = 1.4" = 2.54 \times 1.4 = 3.56$ CM.

$$L = \frac{.03948 \times 1.78^2 \times 60^2 \times .6884}{3.56} = 87\ \mu H.$$

EQUATION 2 MAY BE REARRANGED TO FIND ANY OTHER FACTOR. FOR EXAMPLE, TO DESIGN A COIL TO HAVE A GIVEN INDUCTANCE WHEN DIAMETER AND LENGTH OF WINDING HAVE BEEN SELECTED. HOW MANY TURNS WILL BE REQUIRED?

$$N = \sqrt{\frac{BL}{.03948\ A^2\ K}} \qquad \text{(EQUATION 3.)}$$

IT IS SUGGESTED THAT THE STUDENT MAKE INDUCTANCE CALCULATIONS FOR A NUMBER OF RECEIVER COILS THAT MAY BE AVAILABLE IN ORDER TO GAIN FAMILIARITY WITH THE USE OF THIS FORMULA.

THE WRITER WOULD LIKE TO BRING OUT AT THIS POINT THE FACT THAT IN COIL DESIGN—JUST AS IN ALL OTHER DESIGN WORK—SOME FACTORS MUST BE ARBITRARILY TAKEN AS A STARTING POINT. AS AN EXAMPLE, IN THE USE OF EQUATION 3, IN ORDER TO FIND THE NUMBER OF TURNS REQUIRED FOR A GIVEN AMOUNT OF INDUCTANCE, IT IS NECESSARY TO FIRST ARBITRARILY SELECT THE DIMENSIONS, DIAMETER AND LENGTH, OF THE WINDING. AFTER THIS HAS BEEN DONE IT IS NECESSARY TO SELECT A SIZE OF WIRE WHICH, <u>INCLUDING THE INSULATION</u>, WILL ALLOW THE CALCULATED NUMBER OF TURNS WITHIN THE ARBITRARILY SELECTED LENGTH OF WINDING. IF THIS RESULTS IN TOO SMALL A WIRE SIZE SO THAT THE RESISTANCE MAY BE EXCESSIVE, IT WILL BE NECESSARY TO SELECT A WINDING OF GREATER DIMENSIONS AND AGAIN MAKE THE TURN CALCULATIONS.

AN ENGINEER WHO HAS AN ORIGINAL COIL DESIGN PROBLEM FOR WHICH DATA ON OPTIMUM DIMENSIONS, SHAPE, WIRE SIZE, ETC., ARE NOT AVAILABLE, USUALLY MAKES A NUMBER OF COIL CALCULATIONS OVER A CONSIDERABLE RANGE OF DIMENSIONS AND SHAPES, PLOTS

THE DATA IN THE FORM OF CURVES, AND THEN BUILDS UP THE COILS TO EXPERIMENTALLY VERIFY THE CALCULATIONS. THIS ALSO ALLOWS THE ACTUAL R.F. RESISTANCE AND DISTRIBUTED CAPACITIES OF THE VARIOUS COILS TO BE MEASURED AND PLOTTED SO THAT FACTS ARE OBTAINED WHICH ARE EXTREMELY DIFFICULT TO CALCULATE WITH ANY GREAT DEGREE OF ACCURACY.

ENGINEERS DOING DESIGN ENGINEERING ORDINARILY HAVE ACCESS TO TABLES, CHARTS AND CURVES WHICH HAVE BEEN ACCUMULATED DURING PREVIOUS DESIGN WORK BY THEMSELVES OR OTHERS. IF SUCH DATA ARE NOT AVAILABLE IT IS NECESSARY TO MAKE NUMEROUS CALCULATIONS, EXPERIMENTALLY VERIFY THE RESULTS, AND THEN FROM THE ACCUMULATED DATA SELECT THE ARBITRARY VALUES THAT BEST SUIT THE PROBLEM AT HAND.

AFTER ALL THE DATA HAVE BEEN ACCUMULATED THE SELECTION OF ARBITRARY VALUES WILL ORDINARILY BE LARGELY INFLUENCED BY CIRCUMSTANCES. FOR EXAMPLE, IN THE DESIGN OF A BROADCAST RECEIVER COIL, IF THE SPACE AVAILABLE DEFINITELY LIMITS THE COIL TO A DIAMETER NOT TO EXCEED .75 INCH AND A LENGTH OF NOT MORE THAN 1.5 INCHES, IT IS NECESSARY TO BUILD THE BEST COIL <u>THAT WILL GO INTO THAT SPACE</u>, REGARDLESS OF WHAT THE DATA MAY INDICATE AS THE BEST SIZE AND SHAPE. MANY FACTORS ENTER INTO A DESIGN PROBLEM, NOT THE LEAST OF WHICH MAY BE COST, AND IT IS THE JOB OF THE DESIGN ENGINEER TO TURN OUT THE BEST POSSIBLE PRODUCT TO SUIT THE CONDITIONS PRESCRIBED.

SUPPOSE IT IS DESIRED TO EMPLOY THE SAME DIAMETER OF COIL FORM AS USED IN THE 87 μH INDUCTANCE CALCULATED ABOVE, TO WIND A COIL TO HAVE INDUCTANCE OF 200 μH. THE COIL IS TO HAVE A DIAMETER/LENGTH RATIO OF .4. IN OTHER WORDS THE LENGTH OF THE WINDING IS TO BE 2.5 TIMES THE DIAMETER. THE DIAMETER WAS GIVEN AS 1.4" OR 3.56 CM SO THAT IN THE FORMULA A = 1.78 CM. LENGTH IS 2.5D SO THAT B = 3.56 x 2.5 = 8.9 CM. FOR $\frac{2A}{B} = .4$, K = .8499. TO FIND THE NUMBER OF TURNS REQUIRED AND THE MAXIMUM SIZE OF ENAMEL COVERED WIRE THAT CAN BE USED. USING EQUATION 3:

$$N = \sqrt{\frac{BL}{.03948\ A^2K}} = \sqrt{\frac{8.9 \times 200}{.03948 \times 1.78^2 \times .8499}}$$

$$N = \sqrt{\frac{1780}{.106}} = 129 \text{ turns.}$$

The length of the winding in inches is 1.4 x 2.5 = 3.5 inches. The allowable space per turn is 3.5 /129 = .0271 = 27.1 mils per turn. Allowing 1 mil per turn for the thickness of the enamel, the wire diameter must not exceed 26.1 mils. Reference to a copper wire table shows that No. 22 wire has a diameter of 25.3 mils, well within the limit, and that No. 21 has a diameter of 28.5 mils, considerably too large. Thus the best size of wire in this particular case will be No. 22.

<u>EFFECT OF IRON CORE SATURATION</u>: It will be seen that Equation 2 does not take into consideration the current in the turns. Neither does Equation 1 <u>directly</u>. However, in Equation 1 the permeability (μ) is a factor. So long as an air core coil is used μ remains constant, (unity), regardless of the current amplitude. When an iron core is used that is not true. By definition, magnetic permeability is equal to B/H. In an earlier lesson it was shown that the B-H curve, the slope of which, B/H, represents μ, flattens out for large values of H due to magnetic saturation of the iron, and correspondingly reduces μ for large values of H which are due to large current in the turns.

In radio transmitters and receivers a common use for iron core reactors is in the filters of high voltage rectifiers, the inductance being used to smooth out the ripple or fluctuations in the rectifier output current. Such an output usually consists of a large direct current with a component of amplitude variations at a constant frequency, the amplitude variations being what it is desired to suppress. If the D.C. component of current is sufficiently small so that, flowing through the turns of the reactor, H is far below the value required for saturation, μ will be high and a large value of inductance will oppose the fluctuations. If, on the other hand, the D.C. component of current is so large that the core is saturated, μ will be almost negligible and, since the high permeability of the core was depended on to develop a large value of L, (see Equation 1), the fluctuations of current will cause little change in the flux density in the already saturated core and very little inductive opposition will be offered to the current variations.

Thus an iron core coil will have a specified value of inductance <u>only</u> when carrying a current which is below a specified maximum value. This must be carefully taken into consideration when designing or selecting an iron core reactor for a specific use.

<u>INDUCTANCES IN SERIES AND IN PARALLEL</u>: In considering the case of inductances connected in series, it is necessary to know whether or not there is any coupling between them. For example, consider the arrangement as shown in Figure 7. L_1 and L_2 are connected together, the turns are in the same direction in

$L_1 = L_2$

Fig. 7.

both coils, the spacing between the coils is very short so that essentially L_1 and L_2 may be considered as a single coil having twice the number of turns and twice the length of winding. The effective resulting inductance L will be a function of several factors.

First, L increases as N^2 so that from this consideration alone L should equal $4L_1$ or $4L_2$. However, from Equation 2, doubling the length of the coil doubles factor B, so that this will divide the total inductance due to the factor N^2 by 2. On the other hand, the increased length for the same diameter increases factor K which counteracts to some extent the increase in B. Thus L will be greater than $L_1 + L_2$.

If the two coils are so wound on a common iron core that essentially all the flux of L_1 cuts all the turns of L_2, and vice-versa, then the effects of K and B may practically be neglected and, if $L_1 = L_2$, $L = 4L_1$ or $4L_2$ in accordance with N^2.

If the coils are widely spaced, shielded, or in any way arranged so that none of the flux of one cuts the turns of the other, then $L = L_1 + L_2$. Such an arrangement is shown in Figure 8.

If, in Figure 7, the winding of either coil is reversed so that the field of

L_1 IS OF OPPOSITE POLARITY TO THE FIELD OF L_2, EACH FIELD COUNTERACTS TO SOME EXTENT THE FIELD OF THE OTHER AND L IS <u>LESS</u> THAN $L_1 + L_2$.

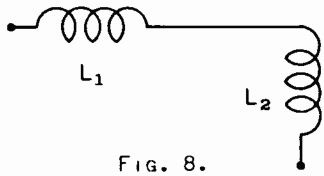


FIG. 8.

THUS IN THE CASE OF INDUCTANCES IN SERIES, THE TOTAL INDUCTANCE CAN EQUAL THE SUM OF THE INDIVIDUAL INDUCTANCES, WHERE THERE IS NO COUPLING BETWEEN COILS, OR CAN BE LESS THAN OR GREATER THAN THE SUM OF THE INDIVIDUAL INDUCTANCES, DEPENDING UPON THE AMOUNT AND POLARITY OF THE COUPLING BETWEEN COILS. WITH TWO IDENTICAL COILS, THE TOTAL INDUCTANCE MAY BE ANYWHERE BETWEEN PRACTICALLY ZERO AND PRACTICALLY FOUR TIMES THAT OF ONE COIL, DEPENDING UPON THE MUTUAL INDUCTANCE OR COUPLING. THIS WILL BE DISCUSSED IN DETAIL IN A FOLLOWING LESSON.

INDUCTANCES ARE SELDOM CONNECTED IN PARALLEL. HOWEVER, IF TWO OR MORE INDUCTANCES ARE CONNECTED IN PARALLEL AND SHIELDED FROM EACH OTHER, THE TOTAL INDUCTANCE IS CALCULATED JUST AS FOR RESISTANCES IN PARALLEL.

$$L = \frac{1}{\frac{1}{L_1} + \frac{1}{L_2} \text{ ....., ETC.}}$$

WORK EACH PROBLEM AFTER COMPLETING THE PAGES INDICATED AFTER THE PROBLEM.

1. FIND THE INDUCTANCE OF THE PRIMARY COIL FOR A TRANSFORMER HAVING 1000 TURNS. THE LENGTH OF THE MAGNETIC CIRCUIT IS 125 CM, THE AREA IS 1900 SQUARE CM, AND THE PERMEABILITY OF THE IRON IS 4500. (PAGE 22)

2. YOU WISH TO INCREASE THE INDUCTANCE OF AN IRON CORE COIL BY 4.5 TIMES. HOW MUCH SHOULD THE NUMBER OF TURNS BE INCREASED? (PAGE 22)

3. FIND THE INDUCTANCE OF A COIL 35 CM LONG, 20 CM IN DIAMETER, HAVING 200 TURNS OF WIRE, WITH AN IRON CORE OF 4000 PERMEABILITY. (PAGE 22)

4. AN AIR CORE COIL 20 CM LONG, 10 CM IN DIAMETER, CONTAINING 2000 TURNS HAS HOW MUCH INDUCTANCE? (PAGE 22)

5. HOW MANY TURNS WOULD BE REQUIRED FOR AN AIR CORE COIL TO HAVE AN INDUCTANCE OF 30 μH IF THE DIAMETER IS 24 CM, ITS LENGTH IS 4 CM? (PAGE 22)

6. THREE COILS OF 50, 270, AND 80 μH RESPECTIVELY, ARE CONNECTED (1) IN SERIES AND (2) IN PARALLEL. DETERMINE THE TOTAL INDUCTANCE FOR CASES (1) AND (2). (AT END OF ASSIGNMENT)

ANSWERS

1. 862 HENRIES

2. 2.12 TIMES AS MANY TURNS

3. 18.09 HENRIES

4. .1615 HENRIES

5. 8.59 TURNS

6. (1) 400 μH

   (2) 27.6 μH

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INDUCTANCE

EXAMINATION

Underline all correct answers.

1. (A) Lenz's Law has a practical application in dealing with:
   - (a) Generators.
   - (b) Capacitors.
   - (c) Transformers.
   - (d) Resistances.
   - (e) Incandescent d.c. lighting circuits.
   - (f) Inductors.
   - (g) Motors.

   (B) The fundamental factor in the relationship expressed by Lenz's Law is:
   - (a) The theory of electro-magnetism.
   - (b) The magnitude of induced EMF.
   - (c) The effect of change of magnetic flux.

   (C) In an inductive circuit, the current which flows due to an induced EMF (has no bearing upon, tends to oppose, tends to aid) the change in the magnetic field.

   (D) The primary of a radio receiver power transformer is supplied from a d.c. source by a potential low enough to prevent burning out the primary. A zero-center d.c. meter which will read both positive and negative voltages without reversing the leads is connected across the secondary. If the meter indicates a positive voltage at the instant the switch is closed, it will indicate (positive, negative, practically zero) voltage ten seconds after the switch is closed. It will indicate (positive, negative) at the instant the switch is opened. The meter will indicate (a greater, a smaller, the same) voltage at the instant the switch is closed compared to when the switch is opened, provided the switch is operated rapidly.

2. (A) In an inductance connected to an a.c. source, the current (is in phase with, leads, lags) the voltage applied.

   (B) Given a transformer with a certain number of primary and secondary turns. When the primary current increases

2. *(Continued)*

at the rate of 5 amperes per second, ten volts are induced in the secondary. What voltage is induced in the secondary when the primary current changes at the rate of 2 amperes per second? Four volts

(C) In a transformer supplied by an a.c. source and whose secondary is open-circuited, the instantaneous voltage of the secondary is (maximum, minimum, of average value) when the current in the primary is changing most rapidly, i.e. at zero degrees or 180 degrees of the electrical cycle of the current.

(D) In a transformer supplied by an a.c. source the voltage of the secondary, when open-circuited, is (in phase with, 90 degrees out of phase with, 180 degrees out of phase with) the current of the primary.

(E) The insulation of a large coil may be protected from arcing between turns or to ground by the use of (a spark gap, a low value fuse, a magnetic circuit breaker).

3. (A) When the switch is closed in a circuit which has an inductance, such as a relay, connected to a d.c. power source, for all practical purposes the current (rises to full value immediately, rises to full value over a finite length of time, will never rise to full value) owing to the action of the self-induced voltage.

(B) In the same circuit, the current change is greater at the instant the switch is (opened, closed) than when the switch is (opened, closed) provided the switching action is rapid.

(C) In (opening, closing) an inductive circuit, care must be taken in this operation to prevent burning the switch contacts. This burning is caused by (electrolysis, local action chemically, extreme local heating, nuclear fission, ionization).

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EXAMINATION, Page 3.

3. *(Continued)*

(D) The burning due to arcing mentioned in (C) is the dissipation of the energy (from the nuclear fission, from the I^2R losses, from the change in the magnetic field).

(E) In the phenomenon known as (repeater action, self-inductance, mutual inductance, secondary emission), each coil turn acts both as one turn of the primary and as one turn of the secondary.

4. (A) Inductance is that property of an electrical circuit which (resists current flow, resists a change of current, increases voltage).

(B) The inductance of a coil depends *directly* upon:
(a) core material, (b) type of metal used in the wire,
(c) diameter of the coil, (d) length of the coil,
(e) frequency used, (f) diameter of the wire used,
(g) number of turns on the coil, (h) angle of lead.

(C) A straight piece of wire may be used as an r.f. choke at high frequencies. This is possible because (the inductance increases at high frequencies, the inductive effect is greater at high frequencies, as frequency is increased less power is required).

5. (A) The unit of inductance is the henry which is defined as that inductance in which an induced EMF of 1 volt(~~s~~) is (~~are~~) produced when the current changes at the rate of 1 ampere(s) per second.

(B) A current change of 5 amperes per second produces a constant induced EMF of 5 volts. The inductance of this circuit is one henry. (Give units).

6. (A) At radio frequencies, i.e. 100 kc and up, the current (travels in the center, is somewhere between the surface and the center, travels on the surface) of the conductor for all practical purposes.

6. (Continued)

(B) A solid conductor has (a higher, the same, a lower) radio-frequency resistance than a tubular conductor owing to (hysteresis, Edison effect, voltaic action, eddy current) losses.

(C) Stranded wire has a lower r.f. resistance because of its (molecular structure, capacity between strands, increases surface area) than a solid conductor of the same area taken as a cross section.

(D) A straight piece of wire, isolated in space, (will, will not, can but probably doesn't) possess the property of inductance.

7. (A) It is impossible to saturate an air core inductance such as an r.f. coil because the permeability remains constant regardless of the current flowing in the inductance.

(B) To saturate an iron core inductance, such as a filter choke, the current must be raised until (the steepest portion, the middle portion, the flattened portion) of the B-H curve is reached.

(C) When the current of an iron core inductance such as a filter choke is increased to saturation, the inductance has (reached a maximum efficiency as, decreased in efficiency as, become practically worthless as) a ripple filter.

(D) A filter choke for use in a television regulated power-supply unit has a rating of 10 henries at 200 ma d.c. flowing through it. Its inductance will be (greater than, less than, 10 the same) if 300 ma d.c. are passed through it. Core is saturated

8. If all other factors remain the same and the number of turns on a coil is doubled:

(A) The total magnetic flux will be TWO times as great as before.

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8. *(Continued)*

(B) The voltage induced will be ___two___ times as great as before.

(C) The inductance will be ___Four___ times as great as before.

(D) Given a coil of 50 turns. If you wish to increase the inductance to 5 times its original value, what is the number of turns that must be *added*, assuming that all other values remain constant? *Show work.*

Inductance varies as N^2

$\therefore$ turns required $= 50 \times \sqrt{5} = 112$ turns.

No. of Turns added $= 112 - 50 = \underline{\underline{62}}$ turns

9. Given a receiver r.f. coil wound with 120 turns of No. 28 wire. The diameter of the coil from center to center of the wires is 0.75 inch and the length of the winding is 1.88 inches. What is the inductance in microhenries?

$$L = \frac{.03948\, A^2 N^2}{B} K \qquad \frac{D}{L} = \frac{.75''}{1.88} = .4$$

$$K = .8499$$

$$A = \frac{.75''}{2} \times 2.54 = .953 \text{ cm.}$$

$$B = 1.88 \times 2.54 = 4.78 \text{ cm.}$$

$$L = \frac{.03948 \times .953^2 \times 120^2}{4.78} \times .8499 = \underline{\underline{92.015\ \mu H.}}$$

EXAMINATION, Page 6.

10. Using Equation 1, design a coil to have an inductance of 8 henries, with a length of winding = 1.8 inches, a mean diameter of winding = 1.5 inches, μ of the core including the air gap at the field intensity to be used = 300. How many turns will be required?

$$L = \frac{1.26\, N^2 A \mu}{10^8\, l}$$

$$N = \sqrt{\frac{L\, l\, 10^8}{1.26\, A \mu}}$$

$$R = \frac{1.5}{2} = .75'' = .75 \times 2.54 = 1.9 \text{ cm.}$$

$$A = \pi R^2 = 3.14 \times 1.9^2 = 11.3 \text{ sq. cm.}$$

$$l = 1.8 \times 2.54 = 4.572 \text{ cm.}$$

$$N = \sqrt{\frac{8 \times 4.572 \times 10^8}{1.26 \times 11.3 \times 300}} = 925.6$$

$$= \underline{\underline{926}} \text{ turns}$$