By H. W. SCHENDEL

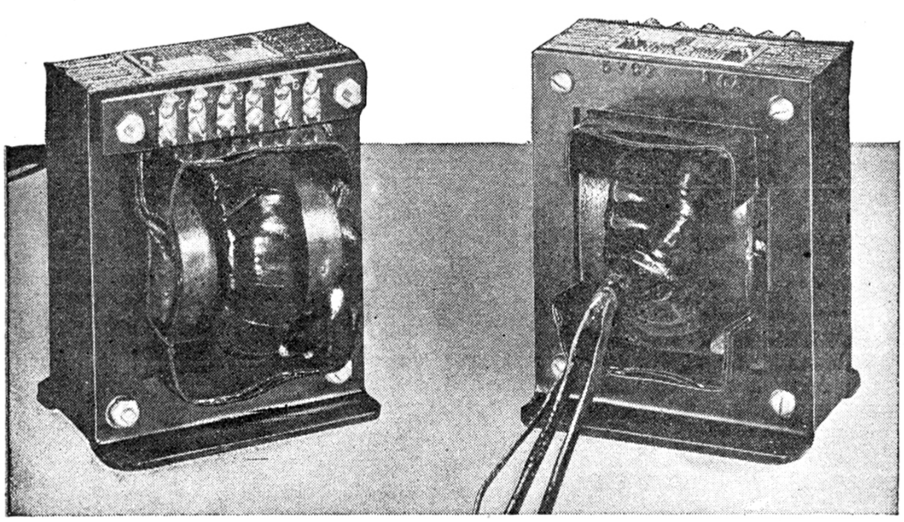
COILS, CORES AND MAGNETS

Part I—Magnetic Design Factors of Modern Radio Components

PROBABLY at some time or another most experimenters and amateurs as well as some servicemen have wished they could use the cores of some of those old electromagnets, filter chokes, or audio transformers in the junk box and rewind them to suit different conditions.

In rewinding power transformers to obtain new voltages it is possible to determine the essential final characteristics with a fairly small percentage of error even when all data on the core material are not available. Characteristics of other devices, especially those of reactors, filter chokes, audio chokes, and audio transformers, are more difficult to change. If due allowances are made for the many variables, it is possible to rewind the units for new operating conditions and obtain reasonably satisfactory results. This is true only when exact values of inductance are not critical.

In order to better understand the principles of magnetic devices let us get acquainted first with magnetic terms and symbols, magnetic effects and circuits, and the production of magnetic lines of force by electricity. Many beginners have much difficulty in remembering magnetic terms and the magnetic effects which the terms describe. These will be explained as clearly as possible as we go along.



Knowing design fundamentals, the radio man often may re-adapt commercial components.

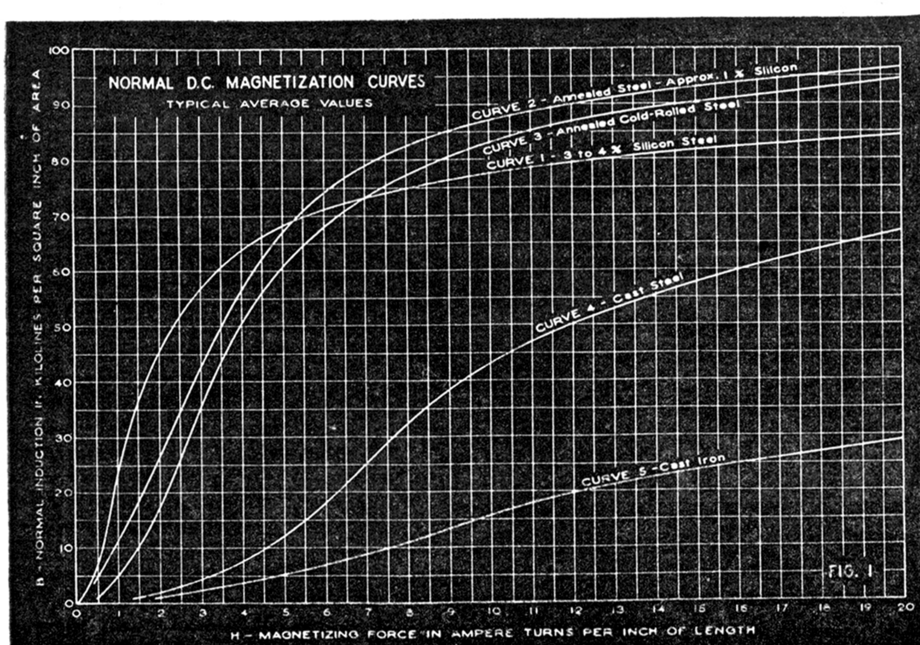


Fig. 1—The curves of the magnetic properties of steel are a prime design requisite.

Some confusion also arises from the fact that various systems use the same symbols but in each system the symbols have a different value. In this article all symbols and measurements will be in the English system with the inch as standard. Iron best exhibits the magnetic properties but a few other alloys and substances also do. There is no effective *insulator* for magnetism, but magnetism does travel more easily through some materials than others. Those materials may be used to *keep the magnetic effects confined to certain areas.* For such reasons we see heavy iron or alloy shields on transformers, chokes, and similar devices.

The attractive and repulsive effect of magnets is due to "magnetic lines of force" commonly called *magnetic flux* or just flux (Φ). A single line of force is called a *maxwell.*

Maxwells are measured by their effects. One method is to attach the ends of a single wire to a voltmeter. Then move the wire through a field of flux (as across the pole of a magnetic or electromagnet). If one volt is induced in the wire during a movement time of one second it would indicate the wire has just gone through, or cut, 100,000,000 (10^8) maxwells. More practical methods are usually used to obtain greater accuracy though the principles are the same.

An important point is that one maxwell is one unit magnetic line of force or flux and that *moving the field of flux* or changing its density (the number of lines of force per unit area) around a wire *has the same effect as moving the wire.*

To produce a strong field of magnetic flux, one having many lines of force or maxwells, with a single wire would require too much current and would not be practical for most applications. Therefore the wire is formed into a loop concentrating the flux within it. Then if we connect many loops in series, forming the turns of a coil, the magnetic flux of one turn will add to that of the next. This is the basic principle of the electromagnet.

The current flowing through a coil is the force which sets up the magnetic flux. This is *magnetomotive force* (m.m.f.) and may be compared to electromotive force in electricity. It is measured by the number of *ampere turns* (NI). This number is obtained by multiplying the number of turns (N) in the coil by the amperes (I) flowing through the turns. For example, one ampere flowing through one hundred turns will produce one hundred ampere turns. Many other combinations will give the same product or whatever product is required.

Just as electrical resistance hinders the flow of electricity, magnetic resistance, or *reluctance* (R), hinders the flow of flux in a magnetic circuit. Therefore a formula similar to that for Ohm's Law is applicable to magnetic circuits. It is:

$$NI = R\Phi \text{ or, } \frac{NI}{\Phi} = R \text{ or } \Phi = \frac{NI}{R}$$

where symbols have the meanings explained above.

Permeance (P) is a term describing the ease with which flux may travel through a substance. It is the reciprocal (opposite effect) of reluctance ($P = 1/R$). In a magnetic circuit having different reluctances in series, the ampere turns—like voltage drops across series resistors—must be figured individually for each reluctance and then all added together for the total m.m.f.

Closely related to permeance is *permeability* (μ). Permeability is a value used to express the flux multiplying power of a material. If a certain m.m.f. produces one maxwell in an air core but will produce 5000 maxwells in an equal size core of some other material, the permeability of this other material is 5000. To simplify comparisons air is considered to have a permeability of one ($\mu = 1$) and all other materials are commonly rated to this base.

Magnetic induction (B), or flux density, is the number of lines of force, or maxwells, induced in each square inch of cross-sectional area (A) of the magnetic circuit. Thus $B = \frac{\Phi}{A}$ where Φ is the total flux of the entire area under consideration. Note closely that B refers to *a specific value of area*. This distinction must be remembered. Similar ones will appear in other terms to follow.

Previously we learned that ampere turns is a measure of magnetomotive force for an entire magnetic circuit. If we divide the ampere turns (NI) by the length (l) in inches of magnetic circuit we obtain a value of *magnetizing force* (H) for each inch length of the magnetic circuit. Therefore,

$$H = \frac{NI}{l}$$

THE MAGNETIC CIRCUIT

We now have definite magnetic terms covering units of volume, area, and length.

It has been proven by experiment that one ampere flowing through one turn of wire (one NI) enclosing exactly one square inch of area will force 3.19 maxwells through an air path one inch in length. With that as a base we have a magnetizing force, $H = 1$, a magnetic induction or flux density, $B = 3.19$. With $\mu = 1$ we can form a basic formula, $\mu = \frac{B}{3.19H}$, suitable for any material. Rearrangement of previous formulas will show the reluctance, R, of air to be .313 per cu. in.

The permeability, $\mu = 1$, for air has a constant value for all strengths of magnetic induction. As the ampere turns per inch is varied the lines of force per square inch, or magnetic induction, will vary in direct proportion. In iron the permeability is a variable and may go from one to over 10,000 depending on both the type of iron and the normal induction (the name for magnetic induction in a ferromagnetic material.) As the normal induction is increased from zero until the iron is saturated with flux the permeability will vary from a low value through a maximum to a final low approaching the μ of air.

Occasionally no information is available on the original coils. In those cases and in new designs it is desirable to have electrical and magnetic data on the steel or other material to be used. This information is obtained either by measuring the qualities of the material or from average curves furnished by most manufacturers of electrical steel. Most useful are *normal d.c. magnetization* curves, typical ones being shown in Fig. 1.

Curves vary not only with each different steel and alloy but also with the way the material is handled. Punching, shearing, machining, heat-treating, core shape, and other factors contribute to variations. Therefore it would be practically impossible to show curves for all steels under all conditions. Fig. 1 is intended to show only *average* magnetization curves.

In rewinding magnetic devices the induction will have an important effect on satisfactory results. The ampere turn product NI, once it has been carefully determined in the original design, is the main consideration in rewinding relays, speaker fields and similar devices for different d.c. voltages or currents.

The amperes and the turns may be varied through wide limits as long as the product of the two is kept the same. If we have .010 ampere flowing through 1000 turns our NI product equals 10 ampere turns. Our magnetic effect would be exactly the same if we had one ampere flowing through 10 turns.

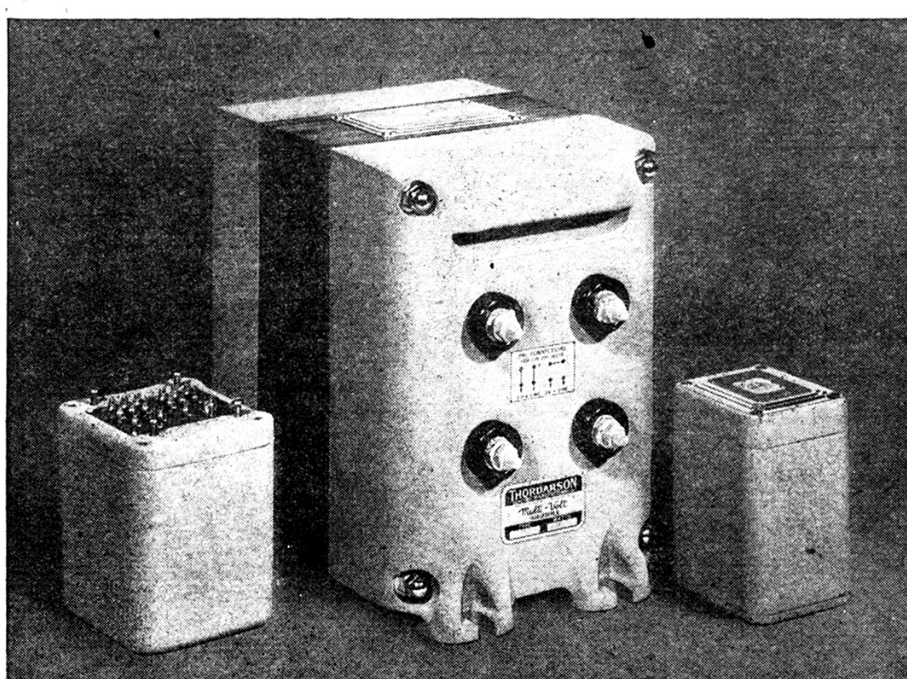
DESIGNING RELAY COILS

When the turns in the old winding are known or can be counted and the amperes for correct operation are known the rewinding problem is simplified. Otherwise it is necessary to know the original voltage or voltage drop, count the turns, obtain the size and length of wire to estimate the total resistance, then apply Ohm's Law to obtain the current, and finally determine the ampere turns. A reversal of the procedure with proper juggling of the values will enable you to rewind the coil for some specific current or voltage.

To find the wire length, add length of an inside turn to the length of an outside turn; divide by two; then multiply the answer by the number of turns in the coil.

A wire table may be consulted to estimate resistance, space required and other data for coil rewinding. In most cases relay, solenoid, speaker, and similar coils may be jumble wound with enamel wire unless extremely high voltage is used. Fine wires should have flexible leads attached. An article in the September 1942 RADIO-CRAFT gave many pointers on handling windings.

(Continued on page 42)



Some typical pieces of electromagnetic apparatus commonly employed in radio equipment.

COILS, CORES AND MAGNETS

(*Continued from page* 31)

Let us suppose we are to find the ampere turns for a coil to excite the magnetic circuit of a relay or electromagnet constructed along the lines shown in Fig. 2. The coil is to be operated from a d.c. circuit. The steel usually used for this type of application has magnetic properties similar to that of Curve 2, Fig. 1.

Assume the core is laminated, .75-inch wide, and is stacked to a height of .89 inch. Because scale, varnish, and other variations cause minute spaces between laminations the stacked height should be multiplied by a *stacking factor*, usually about 0.9, to obtain the effective value of solid metal. Thus, 0.9 x .89 = .80 inch effective stack, and .80 x .75 inch = 6 square inches, the effective cross-sectional area of metal in the core. The average or effective length l_s of the core is nine inches while the effective length of series air gap l_a is assumed to be .005 inch. This is the sum of l_{a1} plus l_{a2} (Fig. 2). The effective cross-sectional area of the air gap will be equal to the gross area of the core or, .75x.89" = .67 square inch.

The ampere turns will have to be computed separately for the steel and for the air gap. The results are added because the reluctances are in series.

Lines of force in magnetic circuits always travel through the complete circuit just as electricity does. This means we have the same number of lines of force or flux across our air gap as through the steel.

Magnetic induction for any specified area determines the total flux to be used throughout the magnetic circuit. Usually a normal induction of 45,000 to 100,000 lines per square inch is common for steel, depending on the type of steel, overall efficiency, and the necessary magnetic pull, if any. Magnetic efficiency is best at the highest permeability $\left(\frac{B}{3.19H}\right)$. The steel of Curve 2, Fig. 1 has highest permeability at a normal induction B between 50,000 and 55,000 lines per square inch. For Fig. 2 we will use a B of 55,000 for the steel. As the core area is only 0.6 square inch, the total flux will be 0.6 times 55,000 or 33,000 maxwells.

The same number of maxwells will have to be forced across the air gap where the magnetic induction B will be 33,000/.67 or 49,250 lines per square inch.

Again referring to Curve 2, Fig. 1, we find at a B point of 55,000 that H will be 3.9, the ampere turns necessary to force the flux through each inch length of the steel. As the steel core has an average length of 9 inches we will need a total of 9 x 3.9 = 35.1 ampere turns for the steel.

In the air gap, Fig. 2, the magnetic induction is 49,250 as explained previously. Applying the formula, $\mu = \frac{B}{3.19H}$ ($\mu = 1$, for air) we find the magnetizing force H to be 15,440, the ampere turns per inch. As the air gap has a length of only .005 inch we will need a total of .005 x 15, 440 = 77.2 ampere turns for it.

You will notice that a small change in the effective length of air gap will produce a great change in ampere turns needed. For an air gap length of .2 inches we would need .2 x 15, 440 = 3,088 ampere turns to force 33,000 maxwells across the gap. The ampere turns for the steel would be small compared to this.

Summing up the ampere turns for the steel, 35.1, and air gap, 77.2, shows we would need a coil having about 112 ampere turns, the total MMF. It is well to allow some extra ampere turns for flux leakage.

The following formula, a combination of previous formulas, which may be applied to any material and cross-section, may simplify calculation of ampere turns. Thus $NI = \frac{H\Phi l}{BA}$ where NI equals ampere turns for a specified material of uniform cross-sectional area and length, H is magnetizing force per inch length, Φ is the total flux in the magnetic circuit, l is length of uniform cross-section in inches, A is area of cross-section in square inches, and B is the induction per square inch. For air the formula would become $NI = \frac{\Phi l_a}{3.19A}$ where l_a would be length of air gap in inches.

In new or rebuilt designs consideration must be given to the maximum watts (W_{max}) which a coil can safely dissipate. These may be determined

(*Continued on page* 47)

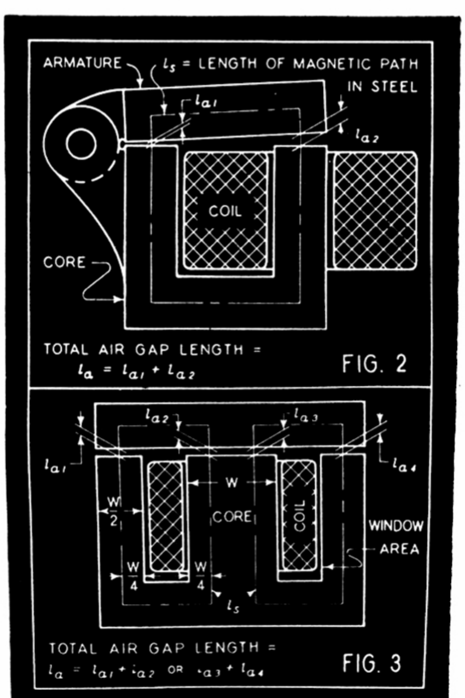


Fig. 2 (above)—The air gap shown here, and in Fig. 3 (below), are functions of the induction.

COILS, CORES AND MAGNETS

(*Continued from page* 43)

from the formula (W_{max}) = m.d. x l_c x 5.6, where m.d. is the mean or average diameter of the coil and l_c is its length.

The watts (W) actually used by any d.c. coil can be found from W = EI where E is the voltage across the coil and I is the current flowing through it. For safe design W_{max} will be larger than W. Preferred size of coil is one whose length is about 1½ times its outside diameter. This may be varied.

Thus far d.c. coils have been discussed but many relays and electromagnets must operate on a.c. The pull of the a.c. type also depends on the maximum flux in the air gap and is determined the same as for d.c. types. If a.c. and d.c. ampere turns are the same, results would be about the same except that on a.c. types the pull stroke is more uniform. This is due to the varying inductance and varying current consumption throughout a pull stroke.

When used on a.c. it is imperative that the core be laminated. Usually No. 26 to No. 29 gauge steel is used. This is done to lower the eddy current losses and reduce the core heating to a minimum. Hysteresis losses (energy expended to reverse the magnetism) depend on and vary with the a.c. frequency.

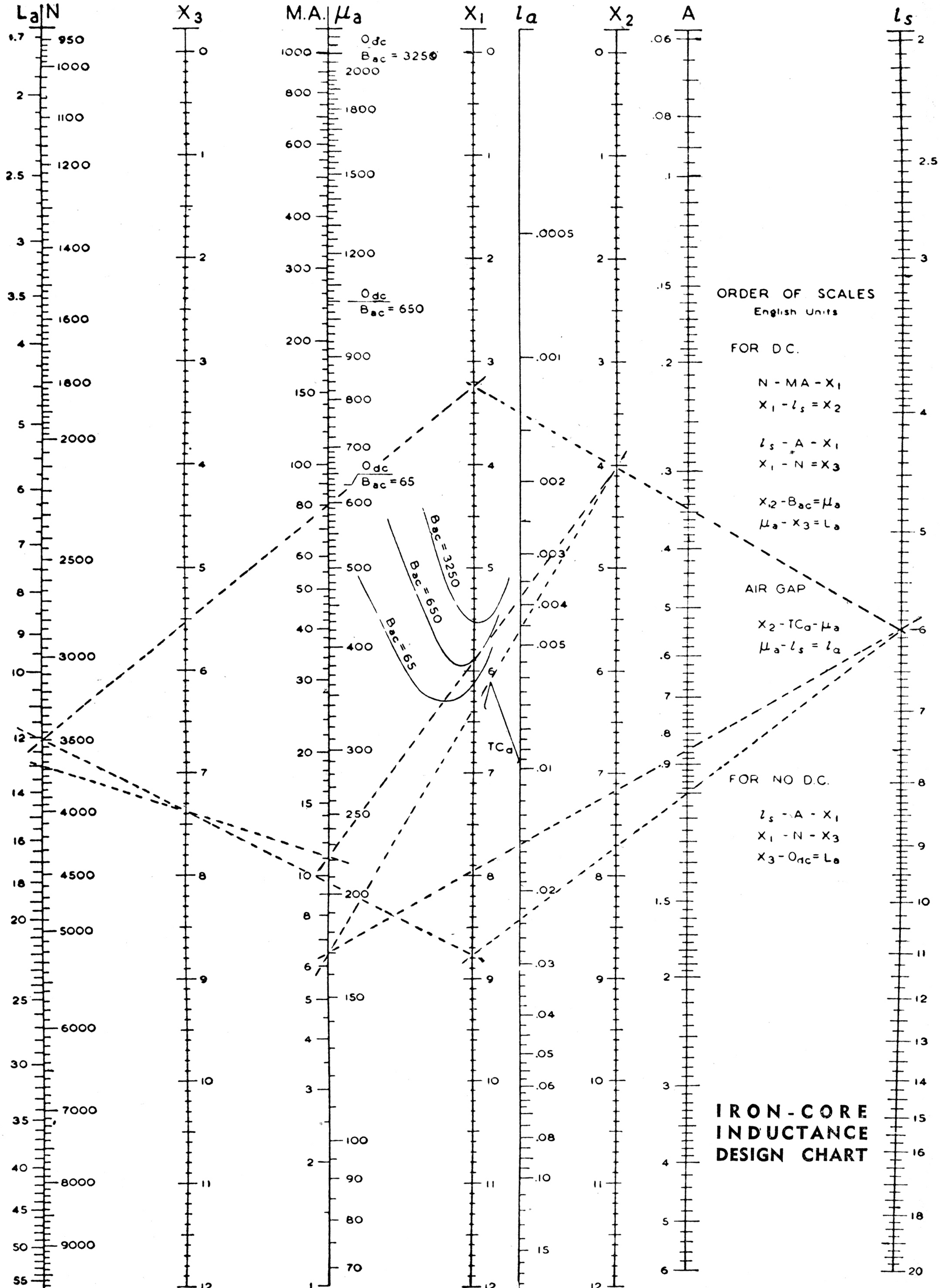
The number of turns in an a.c. coil is determined by the voltage, frequency, and maximum flux, so $N = \frac{10^8E}{4.44f\Phi_{max}} = \frac{10^8E}{4.44fAB_{max}}$ or $E = \frac{4.44fN\Phi_{max}}{10^8}$ where N = turns in a.c. coil, E = a.c. volts across coil, Φ_{max} = maximum flux, f = frequency in cycles per second, B = induction, and A = cross-sectional area of core in square inches.

Wire size is not very important because resistance is not considered in a.c. applications. It is well, though, to use a wire size as large as can be conveniently wound in the space allotted. If the pull is known the wire size may be, c.m. = $10\sqrt{F}$, where c.m. = circular mils area of wire, and F = pull in pounds.

Any appreciable load applied to the armature of a single-phase a.c. electromagnet will result in a chattering sound. To overcome this a device called a *pole shader* is used. This device produces a flux of its own somewhat out of phase with the main flux, the result being similar to two-phase action.

A pole shader is a short-circuited loop or turn, usually of brass or copper, sized to give the resistance needed, imbedded in the pole or armature face, and covering about ½ to 2/3 of its cross-sectional area. The pole faces must make good mechanical contact in the pole shader area. Exact pole shader design is too involved to explain here in detail.

Part II of this article—to be published in an early issue—will tell how to calculate and design filter chokes and audio reactors and describe apparatus for measuring characteristics of magnetic circuits.



© 1946 H W SCHENDEL

Fig. 6

By H. W. SCHENDEL

COILS, CORES AND MAGNETS

Part II—Reactor and Transformer Measurement and Design

FILTER chokes or reactors, audio frequency chokes, and audio transformers come under the classification of iron-core inductances. The unit of inductance is the *henry*. A coil has an inductance of one henry if a current changing at the rate of one ampere in one second induces one volt in it.

Basically inductances are the same as electromagnets and use cores like the relays described in the first part of this article. The essential difference is that inductance is the main consideration. This in turn depends on the permeability of the steel or alloy.

Considerable care is required in rewinding good grade audio devices but it is a comparatively simple matter to rewind filter chokes and obtain approximate original characteristics. If a unit is rewound with original size wire, with about the same number of turns, and close attention given the size of air gap, if any, no trouble should be encountered. *When an air gap has been used its size is extremely important.* In some cases a change of .001 inch in air gap total length will cause a 50 percent change in final inductance. Generally speaking it is better to err slightly oversize rather than undersize.

Much valuable information on rewinding, including a copper wire table, appeared in articles in the Aug.-Sept., October, and December 1942, and the September 1943 issues of RADIO-CRAFT.

To rewind an iron-core inductance for other than original conditions or to design one for some specific purpose involves several factors.

Windings of iron-core coils carrying only a.c. have an inductance which varies in relation to the induced flux in a manner similar to the variation of the d.c. permeability obtained from Fig. 1, which appeared last month. Push-pull output transformers in which the d.c. effects cancel and interstage transformers which have the d.c. blocked from their windings are examples of the simple a.c. class.

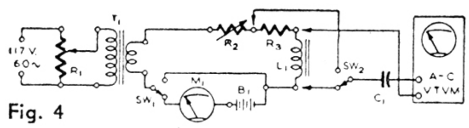


Fig. 4

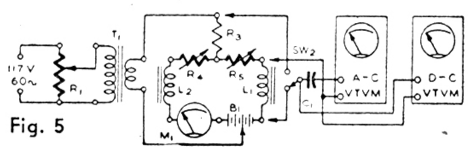


Fig. 5

R1—500-ohm, 100-w rheostat
R2—D.c. rheostat
R3—Non-inductive shunt resistor
R4,5—Two similar rheostats
C1—1-uf (or more) paper condenser
Sw1, 2—S.p.d.t. switches
L1—Iron-core inductance (under test)
L2—Iron-core inductance (like L1)
T1—Power transformer (heavy duty)
M1—D.c. milliammeter for range needed
B1—Battery, adjustable-voltage with center tap

Most iron-core inductance windings carry both a.c. and d.c. simultaneously—a.c. superimposed on d.c. As either of these may be varied in magnitude it is easy to see there would be an almost endless number of conditions, each resulting in a different inductance. The inductance rating of any device is accurate *only when the test conditions are the same as the normal load conditions.*

Curves may be prepared showing the a.c. flux density ($B_{max\text{-}ac}$) versus a.c. permeability (μ_{ac}) for various values of d.c. in the winding. Such curves prepared from test data on a special test core are called *incremental permeability* curves.

Due to the factors explained in connection with d.c. magnetization curves as well as other factors—eddy-current insulation, stacking factors, core shapes and sizes, and other characteristics of laminations — separate permeability curves are needed for each core design. The curves, when prepared from data obtained directly from a definite working design, using a specified steel or alloy, are called *apparent permeability* curves (μ_a). They indicate the actual permeability (not theoretical) which the design appears to have under selected working conditions.

An air gap is seldom used when the inductance is used only on a.c. except in such devices as fluorescent lamp and sunlamp ballasts. Lamp ballast design

(Continued on page 72)

SYMBOLS	ENGLISH UNITS	C.G.S. UNITS
M.M.F. (MAGNETO MOTIVE FORCE)	= NI = RØ (IN AMPERE TURNS)	= 0.4πNI = RØ (IN GILBERTS)
R (RELUCTANCE)	$= \frac{MMF}{Ø} = \frac{NI}{Ø} = \frac{l}{3.19\mu A} = \frac{1}{P}$ 0.313 FOR 1 CU. IN. OF AIR	$= \frac{MMF}{Ø} = \frac{0.4\pi NI}{Ø} = \frac{l}{\mu A} = \frac{1}{P}$ 1. FOR 1. CU. CM. OF AIR
Ø (MAXWELLS, FLUX, OR LINES OF FORCE IN ANY MATERIAL)	$= \frac{NI}{R} = \frac{3.19\mu NIA}{l} = \frac{MMF}{\frac{l_s}{3.19\mu A_s}\ \frac{l_a}{3.19A_a}}$	$= \frac{0.4\pi NI}{R} = \frac{0.4\mu\pi NIA}{l} = \frac{MMF}{\frac{l_s}{\mu A_s} + \frac{l_a}{A_a}}$
Ø (SAME AS ABOVE BUT FOR AIR)	$= \frac{3.19NIA}{l} = \frac{NIA}{.313l}$	$= \frac{0.4\pi NIA}{l}$
P (PERMEANCE)	$= \frac{Ø}{MMF} = \frac{Ø}{NI} = \frac{3.19\mu A}{l} = \frac{1}{R}$	$= \frac{Ø}{MMF} = \frac{Ø}{0.4\pi NI} = \frac{\mu A}{l} = \frac{1}{R}$
NI (AMPERE TURNS FOR ANY MATERIAL)	$= \frac{HØl}{BA} = \frac{Øl}{3.19\mu A}$ = AMPERES X TURNS	$= \frac{HØl}{0.4\pi BA} = \frac{Øl}{0.4\pi\mu A}$ = AMPERES X TURNS
NI (AMPERE TURNS FOR AIR)	$= \frac{Øl_a}{3.19A}$	$= \frac{Øl_a}{0.4\pi A}$
l (LENGTH–l_s = STEEL–l_a = AIR	= INCHES = CM X .3937 = 2.54 CM	= CM = INCHES X 2.54 = 39 INCHES
A (AREA)	= SQ.IN. = SQ.CM. X .155 = 6.45 SQ. CM.	= SQ. CM. = SQ. IN. X 6.45 = .155 SQ. IN
B (NORMAL INDUCTION IN ANY MATERIAL)	$= 3.19\mu H = \frac{Ø}{A} = \frac{M.M.F.}{\frac{l_a}{3.19} + \frac{l_s}{3.19\mu}}$ = MAXWELLS/SQ.IN = GAUSSES X 6.45	$= \mu H = \frac{Ø}{A} = \frac{MMF}{l_a + \frac{l_s}{\mu}}$ = GAUSSES = MAXW./SQ.CM. = MAXW./SQ.IN X 0.155
B (MAGNETIC INDUCTION IN AIR)	$= 3.19H = \frac{Ø}{A}$ = MAXWELLS PER SQ.IN	$= H = \frac{Ø}{A}$ = GAUSSES
H (MAGNETIZING FORCE)	$= \frac{NI}{l} = \frac{B}{3.19\mu}$ = NI PER INCH LENGTH = OERSTEDS X 2.02	$= \frac{0.4\pi NI}{l} = \frac{B}{\mu}$ = OERSTEDS = GILBERTS/CM LENGTH = NI PER IN. LGTH X 0.495
μ (PERMEABILITY FOR ANY MAT'L)	$= \frac{B}{3.19H}$	$= \frac{B}{H}$
μ (FOR AIR)	= 1	= 1
μa (APPARENT AC PERMEABILITY)	$= \frac{10^8 l L_a}{3.19N^2AK_1}$	$= \frac{10^8 l L_a}{0.4\pi N^2AK_1}$
La (APPARENT INDUCT. IN HENRIES	$\frac{3.19N^2\mu_a AK_1}{10^8 l} = \frac{N^2}{10^8\left(\frac{l_s}{3.19\mu_a A_s} + \frac{l_a}{3.19A_a}\right)}$	$= \frac{0.4\pi N^2\mu_a AK_1}{10^8 l} = \frac{0.4\pi N^2}{10^8\left(\frac{l_s}{\mu_a A} + \frac{l_a}{A_a}\right)}$

MISC. FORMULAE

$$L_a = \sqrt{\frac{Z^2 - R_a^2}{4\pi^2 f^2}} = \frac{0.159\sqrt{Z^2 - R_a^2}}{f} = \frac{X_L}{2\pi f} \quad \text{OR, IF } R_a \text{ IS SMALL} = \frac{0.159Z}{f}$$

$$B_{ac} = \frac{10^8 E_{rms}}{4.44fANK_1} \quad E_{rms} = \frac{4.44NØ_{max}}{10^8} \quad Ø_{max} = \frac{10^8 E_{rms}}{4.44fN} \quad N = \frac{10^8 E_{rms}}{4.44fØ_{max}} = \frac{10^8 E_{rms}}{4.44fAB_{ac}K_1}$$

$Z = \sqrt{X_L^2 + R_a^2}$ $X_L = 2\pi f L_a$ Z = IMPEDANCE IN OHMS f = CYCLES/SEC. π = 3.1416 Ra = APPARENT RESTANCE IN OHMS X_L = INDUCTIVE REACTANCE IN OHMS · K_1 = STACKING FACTOR

Symbols and equivalent English and C.G.S. units of common magnetic terms and formulas.

COILS, CORES AND MAGNETS

(Continued from page 27)

must permit sufficient current to flow through the ballast for normal operation, make available enough starting voltage, yet limit the current to a safe value at all times.

Most inductances having d.c. in the windings have an air gap in the magnetic circuit. This is to increase the apparent permeability over that available without an air gap. The length of air gap which results in highest permeability and likewise highest inductance for the particular current conditions in the windings is called the *optimum air gap.*

Optimum air gap may be computed by proper application of the normal d.c. magnetization curve and the incremental permeability curve for a given steel and core. The procedure is rather lengthy and will not be presented here. The average experimenter would probably find it faster to use a test circuit and obtain apparent inductance, apparent permeability, and optimum air gap simultaneously.

Circuits suitable for measuring inductance, determining apparent permeability and optimum air gap, are shown in Figs. 4 and 5. The Fig. 4 circuit is suitable for low and zero direct current. D.c. saturation of the transformer core is eliminated with the Fig. 5 circuit but the circuit has the disadvantage of requiring two similar chokes.

In either circuit the d.c. is first adjusted to the normal working condition. R4 and R5, Fig. 5, must be so adjusted that no d.c. flows through R3. This can be determined by a d.c. v.t. voltmeter across R3. Sufficient a.c. voltage is applied to give the working values across L1, as measured by an a.c. v.t. voltmeter. Connecting it across R3 will give the voltage drop due to the a.c. flowing through L1.

The optimum air gap may now be found by varying the gap length until the a.c. voltage across R3 reaches a minimum with the a.c. voltage and direct current across L1 held to the working values. For Fig. 5 the air gaps must be the same for L1 and L2 and both varied simultaneously.

INDUCTANCE FORMULAS

The *apparent inductance* of L1 in henries will be $L_a = .159 \times$

$$\frac{\sqrt{\dfrac{(R_3 E_L)^2}{E_R^2} - R_a^2}}{f}$$

where R3 = d.c. resistance of voltmeter shunt in ohms, E_L= a.c. volts across L1, E_R=a.c. volts across R3, f=a.c. test frequency, and R_a=apparent resistance of L1. (R_a consists of the d.c. resistance plus resistance effects due to core losses. The latter are very low in good-grade laminated cores.) Usually R_a is small compared to the inductive reactance of the coil and could be omitted, simplifying the formula to

$$L_a = \frac{.159\ R_3\ E_L}{f E_R}$$

Because L1 and L2, Fig. 5, are in parallel, L_a must be multiplied by 2 to obtain the value for L1.

Knowing L_a, the apparent permeability can be found to be

$$\mu_a = \frac{10^8\ l\ L_a}{3.19\ N^2 A\ K_1}$$

where l = length of core in inches, A = area of core in square inches, N = number of turns in coil, and K_1 = stacking factor (usually about .9).

The a.c. flux density in lines per square inch will be

$$B_{ac} = \frac{10^8\ E_{rms}}{4.44 f N A K_1}$$

where E_{rms} = a.c. voltage across L1 and other symbols as before.

To simplify calculations for average cores an Iron-Core Inductance Design Chart has been constructed in Fig. 6. The symbols at the scale headings may be identified from the previous text. The multiplying scales X_1, X_2, X_3 are used to obtain readings.

The Inductance Design Chart is constructed to automatically allow a .9 lamination stacking factor. O_{dc} points, and the B_{ac} and TC_a turning curves were prepared from data on 29 gauge (.014-inch) steel laminations having properties similar to those on Curve 1, Fig. 1, which appeared last month. These properties were taken as an average. Some steels will give more inductance, others less. Now points and turning curves may be constructed for steels and cores with other characteristics. The balance of the chart would remain unchanged.

The previous B_{ac} formula may be used to assist in selecting one of the B_{ac} turning curves or O_{dc} points on the chart. Values of B_{ac} may be less than 65 for some interstage a.f. transformers and smoothing chokes while for some output transformers and swinging or input chokes it may go well beyond 3500. Turning curve TC_a is used to obtain air gap length for all values of B_{ac}.

USE OF THE CHART

Assume we have a core like Fig. 3 (last month's issue) to be used for a smoothing choke. The core is 1 inch wide and stacked 1 inch high using 29 gauge (.014-inch) steel laminations, making the area (A) = 1.0 square inch. The entire core has uniform cross-sectional area (each of the two outer legs have one-half the area of the center leg). The core length (average length around each window as indicated in Fig. 3) l_s = 6.0 inches. Window is ½ x 1½ inch. B_{ac} = 650 will be satisfactory and there will be 80 ma d.c. in the windings. The problem is to find the maximum inductance, L_a, in henries, and the optimum air gap, l_a, in inches.

The more turns the greater the inductance but wire size, allowable re-

COILS, CORES AND MAGNETS

(Continued from page 73)

sistance and window area will limit the number. Wire size and coil dissipation watts may be computed as outlined for electromagnets. If the coil resistance is too great larger wire may be used.

A fairly reliable method is to select a wire, allowing 750 to 1250 circular mils per ampere. A wire table and a few computations will show that 3500 turns, No. 32 enamel wire, would go in the window and have a resistance of about 250 ohms.

This information may now be applied to the Inductance Design Chart, Fig. 6. The column headed "Order of Scales" indicates the function of certain groups of scales and under each function is given the order in which the scales are read at each setting of a straightedge. Mistakes will be prevented by writing down the reading for each scale.

Using the group of scales "FOR D.C." set a straightedge from 3500 (no. of turns) on N to 80 (no. of milliamperes) on M.A. and read 3.23 on X_1; From 3.23 on X_1, to 6 (lgth. of core, inches) on l_s and read 4.02 on X_2; Next from 6 (core lgth.) on l_s to 1 (core area, sq. in.) on A and read 8.78 on X_1; From the 8.78 on X_1 to 3500 (no. of turns) on N and read 7.38 on X_3; From 4.02 previously obtained on X_2 over the B_{ac} = 650 curve and read 222 on μ_a; From 222 on μ_a to 7.38 previously obtained on X_3 and read 13 on L_a, the apparent inductance in henries.

The optimum air gap may be found by using the "AIR GAP" group of scales. From 4.02 found above for X_2 over the point of the TC_a curve read 170 on μ_a; From 170 on μ_a to 6 (core lgth.) on l_s and read .0153 on l_a, the total length of the air gap, in inches. (See Fig. 3.)

Although not a part of the problem let us suppose there is no d.c. in the windings. What will be the inductance? For this we use the "NO D.C." group of scales. To proceed set a straightedge from 6 (lgth. of core) on l_s to 1 (area of core) on A and read 8.78 on X_1; From 8.78 on X_1 to 3500 (no. of turns) on N read 7.38 on X_3; From 7.38 on X_3 to $\dfrac{O_{dc}}{B_{ac}=65}$ point on μ_a and read 37 on L_a, the apparent inductance in henries. If B_{ac} is nearer 650 than 65, the L_a would be over 60 henries. No air gap would be used. Instead, the laminations would be interleaved as on any transformer.

TRANSFORMERS, SWINGING CHOKES

Audio frequency and output transformers are designed mainly on the basis of inductance of the primary winding, making the design problems similar to chokes except that secondary windings follow regular transformer procedure for impedance and turns ratios needed. Inductance values range from 2 to 50 henries and more, the higher inductance values giving better low frequency response, especially when used with tubes having high plate resistance.

Swinging chokes are often desirable when the load varies widely. The main difference between a swinging and smoothing choke is that the former, though designed for high d.c., has a shorter than optimum air gap. This shortened air gap lowers the inductance considerably at high d.c. loads and increases it at low d.c. loads when compared to a choke designed for high d.c. only.

The Fig. 6 chart is useful only for rough design of a swinging choke. Select the wire for the maximum d.c. ma and assume some value for turns to fit on the core. From the chart determine L_a at maximum d.c. and multiply the value found by 0.58 for the actual minimum swinging choke inductance. If this figure proves to be unsuitable try again using new values for turns or core.

After suitable values have been found for the maximum d.c. use all of them except that in place of the maximum d.c. ma substitute a value only 10 percent of the maximum d.c. ma and find the length of optimum air gap from the chart. Multiply the length as found by 2.6 to find the total air gap length to use for the swinging choke. Inductance ratio between maximum and 10 percent of maximum d.c. will be about 4 to 1. A shorter air gap would increase the ratio but would decrease the inductance at maximum d.c.

A handy reference chart of conversion factors and formulas (see page 27) shows some unusual variations. Unidentified symbols are explained in the text.

Acknowledgement is given Allegheny Ludlum Steel Corporation, United States Steel Corporation, and American Rolling Mill Company for information on electrical steels.

RADIO-CRAFT for NOVEMBER