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INFORMATION FOR THE AMATEUR DESIGNER OF TRANSFORMERS FOR 25- TO 60-CYCLE CIRCUITS

By
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By Herbert B. Brooks

ABSTRACT

Information is given to assist the amateur designer of transformers for use on rdinary power frequencies. Most of the usual computation is avoided by the se of graphs which give the cross section of the core, the number of turns of ire per volt, the sizes of wire, the regulation, the iron loss and the copper loss, the eight of iron and of copper, and the full-load efficiency. Information is given n various kinds of magnet wire. Methods of constructing the coils and of ssembling the core are given, with special directions for three cases, namely rge currents at a low voltage, windings with low-voltage taps, and transformers have good regulation with inductive loads at low power factor. The method of esign is intended primarily for the usual frequency of 60 cycles, but may be adily adapted to 50 cycles and to 25 cycles. The range of output is from 1 volt-mpere to 10 kilovolt-amperes, that is, from 1 watt to 10 kilowatts at unity power ctor. A list of firms from whom the amateur may purchase magnet wire and ansformer steel sheets is given.

CONTENTS

I. OBJECT OF THIS CIRCULAR

The elementary information in this circular is intended to assist he amateur in the design of small and medium-size single-phase ransformers for operation on the usual power frequencies. It is ssumed that one transformer, or at most only a few transformers re to be built, and that successful operation with good efficiency nd reasonable cost is the goal, rather than high efficiency with the minimum weight and cost, which are so important when transformers are to be designed for quantity production and a competitive market. It is assumed that the reader has a general idea of the construction of a transformer, but that he does not have the engineering training necessary in the use of the more technical and elaborate design procedures given in textbooks and engineering handbooks. The design procedure here given reduces computation to a minimum, largely by the use of straight-line graphs to logarithmic and semilogarithmic scales.

II. DEFINITIONS

A transformer consists, in principle, of an iron core having a winding adapted to be connected to a source of alternating currents and one or several other windings in which alternating voltages are induced and from which alternating currents may flow through suitable circuits or "loads".

The primary winding is the one which in operation receives electrical energy from a source, and the secondary windings are those which supply currents to the loads. Since the action of a transformer is reversible, the terms "primary" and "secondary" are sometimes indefinite, and in such cases it is better to use terms such as "high-voltage winding" and "low-voltage winding". Power transformers designed by amateurs, however, will nearly always operate from ordinary house circuits of about 110 volts, consequently the terms "primary" and "secondary" are not ambiguous.

III. MATHEMATICAL BASIS FOR THE DESIGN PROCEDURE

The general relations on which the graphs in this circular are based are given by Fortescue (Standard Handbook for Electrical Engineers, 6th ed., p. 661) in the following form:

Area of core varies as	$P^{\frac{1}{2}}$
Area of winding space varies as	$P^{\frac{1}{2}}$
Turns per volt varies as	$P^{-\frac{1}{2}}$
Weight varies as	$P^{\frac{3}{4}}$
Cost of materials varies as	$P^{\frac{3}{4}}$
Percentage loss varies as	$P^{-\frac{1}{4}}$

In the above expressions P denotes the rated power output of the transformer in watts, with a load of unity power factor. For the purposes of this circular, the core-type transformer is chosen and the section of the core which is surrounded by the windings is assumed to be square. It is frequently necessary to refer to the length of the side of this square cross section. If this quantity be denoted by S it follows from the first relation just given that S varies as $P^{\frac{1}{4}}$, and from first and third that the value of turns per volt varies as S^{-2}.

IV. GENERAL BASIS FOR THE DESIGN

There is a great deal of flexibility in the design of a transformer; one can use a relatively small core and a relatively large number of turns of wire per volt, or vice versa. In the first case the transformer wil be unnecessarily expensive because of the relatively small amount of cheap iron and the relatively large amount of expensive insulated copper wire. Such a transformer may be preferable to a normal design if it is to be connected to the line 24 hours a day and it is desired to reduce the iron losses which must be supplied continually. It will, however, have larger copper losses during the load period than a transformer of balanced design. The graphs and data in this circular have been prepared with the intention of furnishing designs in which the cost of steel and that of copper are reasonably balanced. The efficiency at full load is relatively high, and the cross section of copper in the windings is sufficiently liberal to permit continuous operation with a secondary current 25 to 50 percent greater than the rated value. The design procedure may, however, be used to lay out transformers of smaller size which should not be operated above the normal rating. The procedure is laid out primarily for designing transformers to be operated on 60-cycle current. Instructions for modifying the procedure to make it apply to other power frequencies are given in a later section of this circular.

V. RATING OF A TRANSFORMER

The rated output of a small transformer is often expressed in watts at a given voltage (unity power factor being understood) but is preferably stated in volt-amperes because it is this quantity which sets the limit, regardless of the power factor. If the transformer has only one secondary winding, the rated output in volt-amperes is equal to the product of the rated secondary voltage by the rated secondary current. If there are two or more secondary windings, the sum of all such products is the rated output.

VI. THE TRANSFORMER CORE

The core should be made of sheet steel of the type usually known as transformer steel, which contains from 3.5 to 4 percent of silicon. The preferable thickness is no. 29 U. S. standard sheet gage, that is, 0.014 inch. Ordinary sheet iron is not suitable for the construction of transformers in accordance with the design procedure of this circular. The core-type transformer assumed in this design can be readily constructed from simple rectangular strips.

The general proportions of the core are indicted in figure 1, which is intended merely as a guide. The dimension *S* is the side of the square cross section previously referred to, and the open space (the "window") of dimensions 1.5*S* by 2.4*S* provides space for the windings. In the interest of economy of material and efficiency of operation this window is made only large enough to provide room for suitable windings. In relatively small transformers one or both of these dimensions may need to be increased because of the relatively greater amount of space required for insulation. In relatively large transformers it may be found possible to reduce one or both of these dimensions. Fixing the dimensions of the window also fixes the core dimensions marked 3.5*S* and 4.4*S* in figure 1. The standard proportions given in this figure may be expected to hold for transformers with rated output of about 500 volt-amperes, for voltages of about 300 volts and less. Voltages of several thousand volts, in small transformers, will require more space for insulation and will need a window relatively larger than that of figure 1.

The value of S may be found without calculation by the use of th graphs of figure 2. Before choosing a value, however, the designe should decide on the overload characteristics required of the transformer. Because apparatus for general experimental purposes i often overloaded, the basis of the designs covered by this circular is liberal one, and transformers of 1,000 volt-amperes rating and less made according to this basis, may be expected to carry for an indefinite time, 50 percent more than rated current, transformers of ove 1,000 volt-amperes, 25 percent more than rated current. If the conditions are definitely known in advance to be such that the transformer will never be used for currents greater than rated current, and if somewhat greater temperature rise and slightly lower efficiency than would be had with the standard design are not objectionable, the core may be designed for a rating in volt-amperes of two-thirds the actual maximum output desired, for 1,000 volt-amperes and below, or four-fifths the actual desired output for ratings higher than 1,000 volt-amperes. Having chosen the nominal rating, the value of S may be found from the lower graph of figure 2, for ratings between 1 volt-ampere and 100 volt-amperes, and from the upper graph for ratings between 100 and 10,000 volt-amperes.

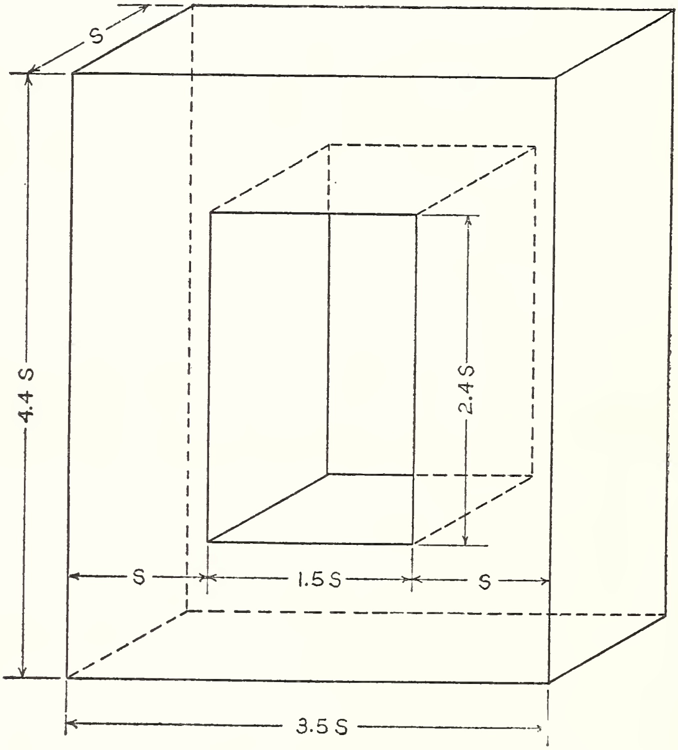

FIGURE 1.—*Diagrammatic sketch of transformer core, showing suggested general proportions in terms of S, the side of the square cross section.*

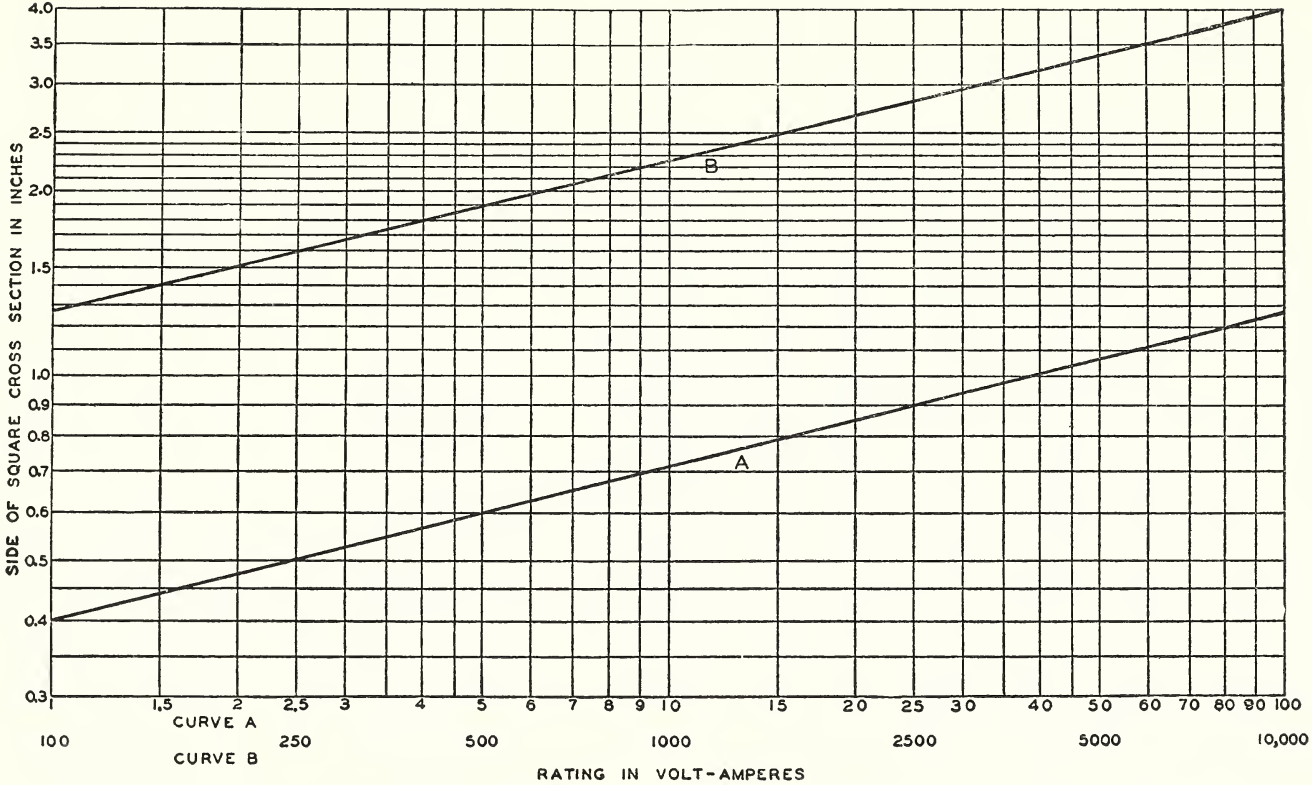

FIGURE 2.—*Graphs showing the side of the square cross section of the core, in inches, for 60-cycle core-type transformers.*

Assume, for example, that a 60-cycle transformer is to be designed for a *nominal* rating of 200 volt-amperes, and that it is desired to have the full amount of overload capacity provided in the design procedure here given; that is, that the transformer must be able to carry a secondary load of 300 volt-amperes without damage from overheating. Using the upper graph of figure 2, the length S of the side of the square cross section of the core is found to be 1.5 inches. If it is not convenient to make the core of square cross section, one of oblong cross section may be used with a reduction in efficiency, which is not serious unless the cross section differs widely from a square. For example, suppose that in the case just mentioned, where a cross section of 1.5 by 1.5 inches is called for, one has on hand a supply of transformer-steel strips 1.25 inches wide. By dividing the square of 1.5 (=2.25) by 1.25 the value 1.8 is found. A core 1.25 by 1.8 inches can be used instead of one 1.5 by 1.5 inches.

The present discussion is limited to the core-type transformer, as illustrated in figure 1. It may happen that the amateur can obtain some sheet-steel punchings of the shell type, as illustrated in figure 3.

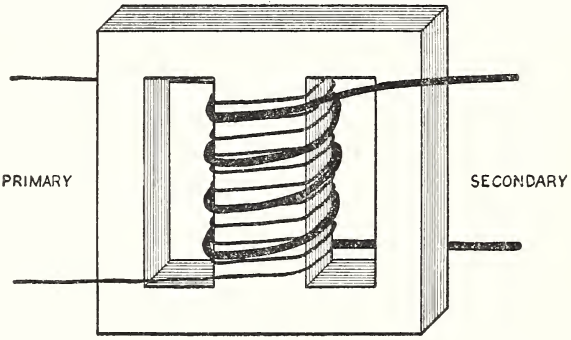

FIGURE 3.—*Diagrammatic sketch of shell-type transformer.*

The methods of this article can be followed in this case, but it is to be remembered that when the cross section of the core is mentioned it refers to the central core which is surrounded by the coils. Since the magnetic flux in this core divides between the outer cores, each of these latter may have one-half the cross section of the central core.

VII. MAGNETIC FLUX DENSITY IN THE CORE

For any cross section of the core there is an appropriate value of the number of turns of wire per volt which will cause the peak value of the magnetic flux density in the core to have a suitable value. In the design procedure here given this value is taken as 10,000 maxwells ("lines of force") in each square centimeter of the actual net iron in the core, or 64,500 maxwells per square inch of net iron. The cross-sectional area of the net iron in the core is taken as 90 percent of the gross cross-sectional area; or in other words, the "stacking factor" is taken as 0.9.

VIII. NUMBER OF TURNS OF WIRE PER VOLT

Using the graph of figure 4, the number of turns of wire per volt may be found for any value of S between 0.4 and 4 inches. In the case of the 200-watt transformer, the value of $S=1.5$ inches calls for between 2.8 and 2.9 turns per volt. While either of these values is accurate enough, one can check the value taken from the graph by dividing 6.47 by the area of the gross square cross section of the core.[1] Thus, $1.5\times1.5=2.25$, and 6.47 divided by $2.25=2.88$. This number may need to be revised to a more convenient figure if one or more of the windings are to be of very low voltage. For example, if the 200-volt-ampere transformer is to have a 4-volt winding, with no taps, it would be desirable to revise the value of S to one which requires 3 turns per volt. This increase from 2.88 to 3 turns per volt, leaving the core 1.5 inches square, would lower the maximum flux density only slightly, namely, to 96 percent of the value assumed for this design procedure. This small departure from the assumed value would be entirely permissible, as it would not materially affect the efficiency or other characteristics of the transformer. In general, the number of turns in each winding should be even, in order to be able to wind half of them on each of the two legs of the core. Special difficulties arise in the design of transformers having coils which are tapped at say 0.5-volt intervals. This question is discussed in a later section.

No difficulty arises in the use of such values as 2.88 turns per volt when the voltages of the windings are not too small. For example, for 50 volts the number of turns would be $50\times2.88=144$. Even if the value 2.89 turns per volt had been chosen, the computed number of turns (144.5) would be rounded to 144 as the nearest even number.

IX. NUMBER OF TURNS IN EACH WINDING

Before using the value of turns per volt to compute the number of turns in each winding, the "regulation" of the transformer must be considered, and a decision must be made as to how it will be allowed to affect the secondary voltage. To illustrate this matter, take the preceding case of a 200-volt-ampere transformer and let the primary voltage be 110 volts and the secondary voltage 50 volts. With 2.88 turns per volt the 50-volt winding would have 144 turns. If the primary winding is on the same basis it will have 317 turns. Such a transformer, when connected to a 110-volt supply line, will have a secondary voltage which is very close to 50 volts when no load is on the secondary. If the full load, requiring 4 amperes, unity power factor, is connected to the secondary, a part of the induced secondary voltage will be required to overcome the resistance of the secondary winding. Calculation shows that this part amounts to approximately 2 volts in this case, consequently the voltage at the secondary terminals will be only 48 volts while the load is connected. This full-load drop of 2 volts, divided by the rated secondary voltage (50 volts) is technically called the "regulation" and is 4 percent in this case.

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[1] This number, 6.47, is obtained by using the fundamental equation for the voltage induced in the windings of a transformer. It is the number of turns of wire per volt when the frequency is 60 cycles per second, the gross cross section of the core 1 square inch, the net cross section 0.9 square inch, and the maximum flux density 64,500 lines of force per square inch of net cross section.

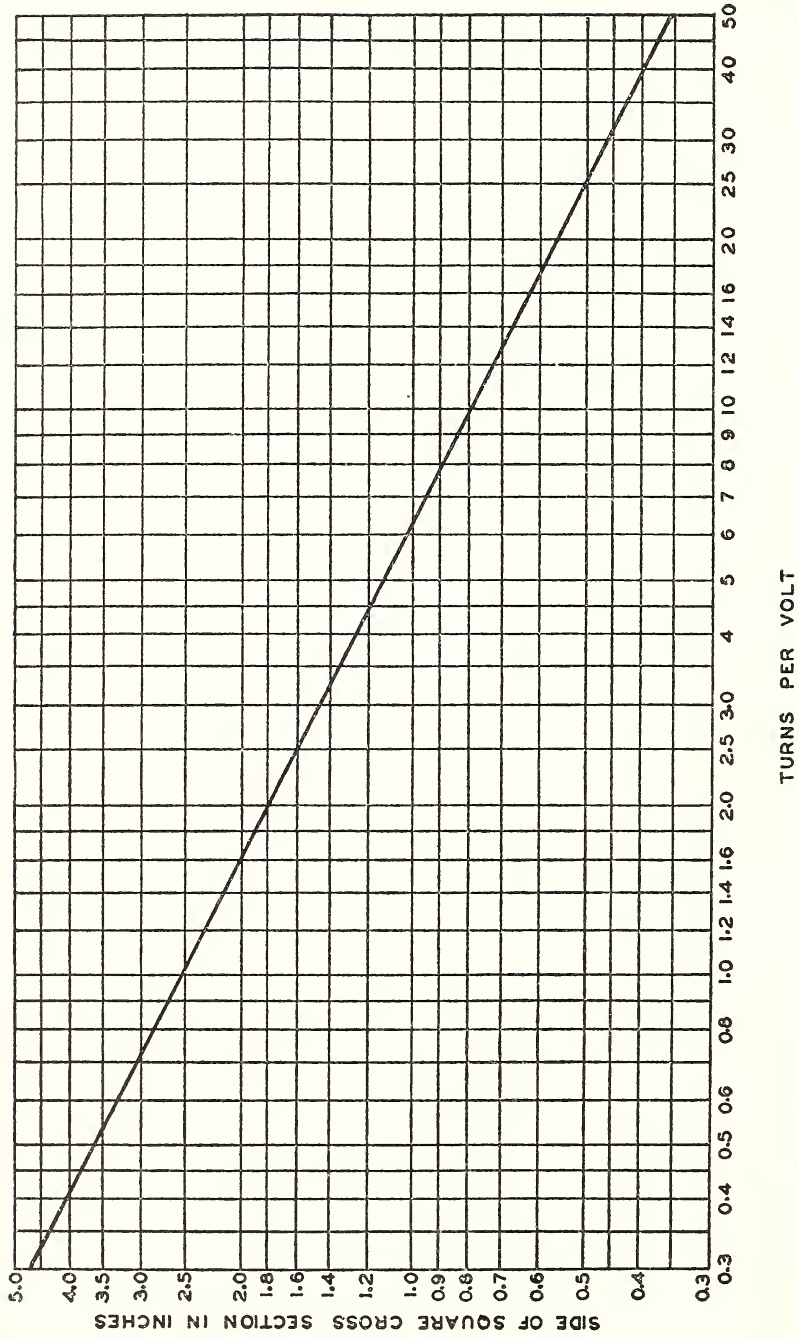

FIGURE 4.—*Graph showing the number of turns per volt, as dependent on the side of the square cross section of the core, for 60-cycle transformers.*

The upper curve of figure 5, labeled "copper loss", may be used in connection with the percentage scale at the left to obtain the regulation [2] for a transformer of any output within the range covered in this circular.

In taking the regulation into account, the designer must decide whether the transformer is to give its rated voltage at no load and a lower voltage at full load, or rated voltage at full load and a higher voltage at no load. For rated voltage at no load, the number of primary turns and of secondary turns are found simply by multiplying the primary voltage and the secondary voltage by the appropriate number of turns per volt taken from the graph of figure 4.

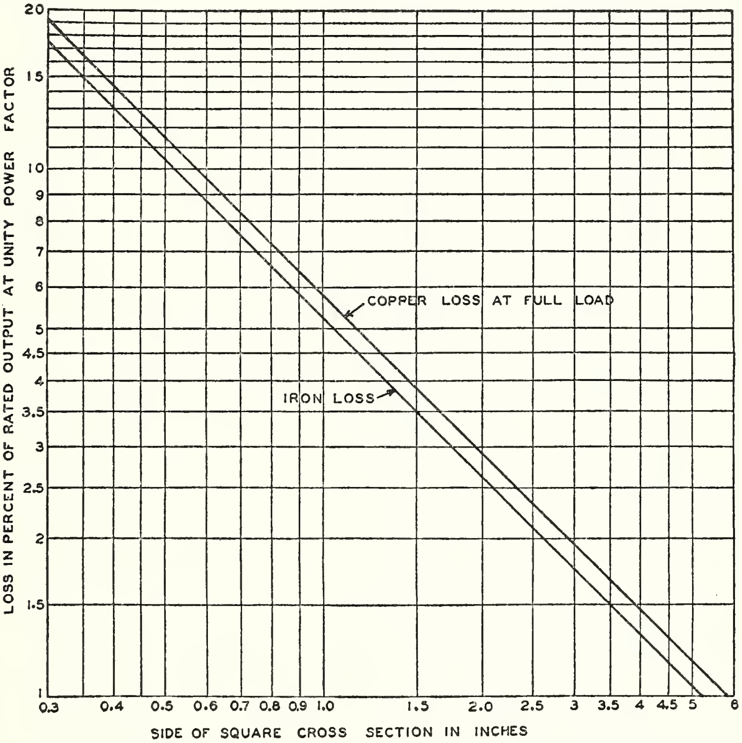

FIGURE 5.—*Graphs showing the full-load copper loss and the iron loss, in percent, for 60-cycle core-type transformers.*

It is often desirable, however, to have full rated secondary voltage with full load. For example, if the transformer just mentioned were wound to give a secondary voltage of 50 volts with rated load, unity power factor, the secondary voltage at no load would be 52 volts. To obtain this condition, either of two procedures may be followed; (1) the secondary winding (or windings) may be given the number of turns per volt (2.88) required by the graph of figure 4 and the primary winding 4 percent *less* than 2.88 turns per volt; (2) the primary winding

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[2] For any transformer operating on a noninductive load the figure for percent regulation is the same as that for the percent copper loss. In figure 5 it is convenient to label the upper curve "copper loss" in order that it may be used later (in section XV) with the curve of iron loss below it, to obtain the efficiency of the transformer at loads other than full load.

may have 2.88 turns per volt according to figure 4 and the secondary winding (or windings) 4 percent *more* than 2.88 turns per volt.

The graph of percentage copper loss given in figure 5 is computed on the assumption that the relative spaces occupied by the copper and the insulation in the windings are the same for all sizes of transformer. In general, to fulfill this condition on very small transformers requires the use of enamel-insulated wire. If silk-covered or cotton-covered wire is used for such transformers, the percentage copper loss will be greater than that shown by the graph. The upper curve of figure 5 may be used only for a load of unity power factor. If the load is inductive, there will be a greater voltage drop because of what is termed the internal reactance of the transformer. Means for reducing this internal reactance are described in section XVIII of this circular.

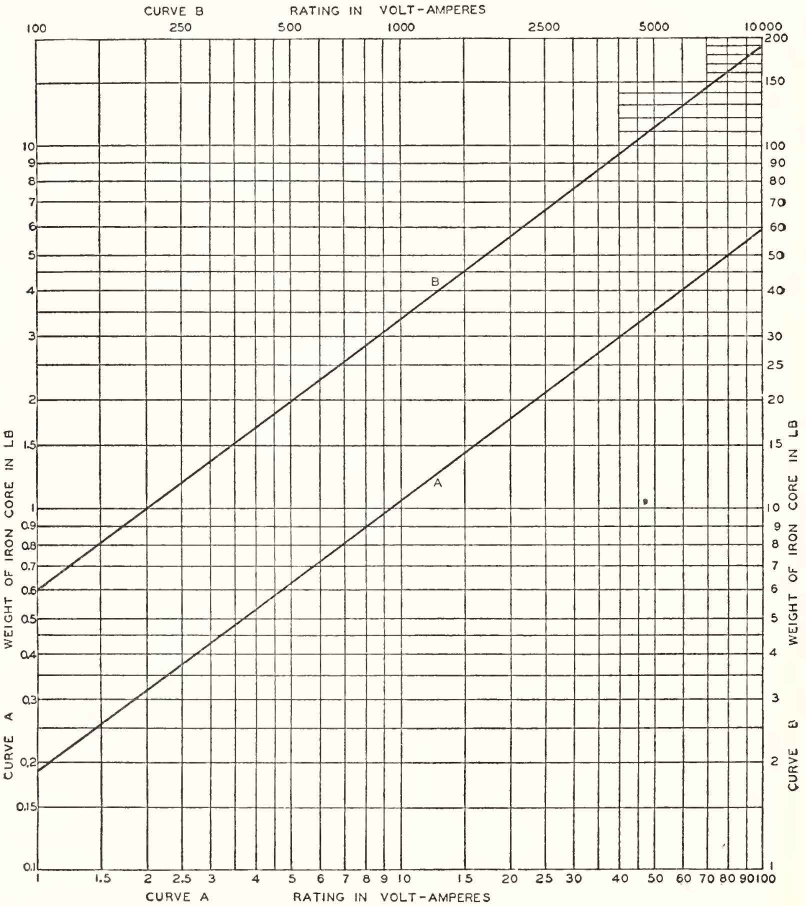

Figure 6.—*Graphs showing the weight of the iron core of 60-cycle core-type transformers, as dependent on the rating in volt-amperes.*

Before proceeding with the design of a transformer of given output, it is sometimes important to know how much iron and copper will be required in its construction. Figure 6 shows how these quantities vary with the side of the square cross section of the core. For example, using the upper graph and the corresponding scales, the weight of iron for the 200-volt-ampere transformer is 10 pounds. The weight of copper for any transformer designed by the methods here given will be approximately one-half the weight of the iron.

X. DETERMINING SIZES OF WIRES

Insulated copper wire is made in this country in sizes according to the American Wire Gage (abbreviated AWG) which is also known by its older name of Brown and Sharpe (B&S) Gage. Tables giving the diameter, cross section, resistance and weight per unit length, etc., of the various sizes may be found in the catalogs of wire manufacturers, dealers in electrical supplies, etc. For the present purpose, however, the need for such tables is obviated by the graphs (fig. 7), which are calculated on the liberal basis of a cross-sectional area of 1,600 circular mils per ampere. The use of figure 7 may be illustrated by an

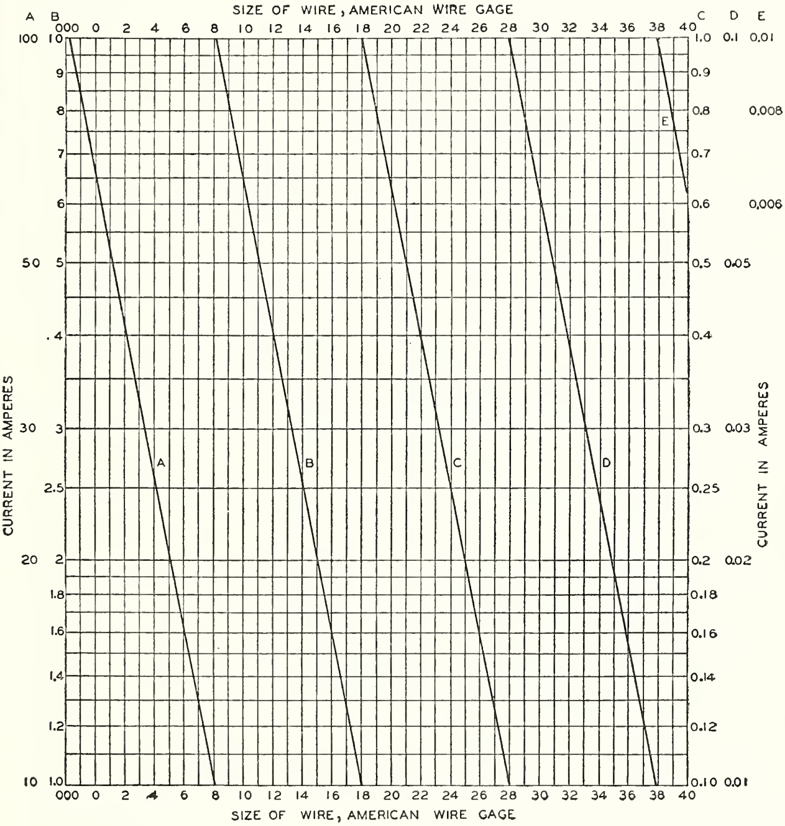

FIGURE 7.—*Graphs showing the rated current in amperes of round copper wires from no. 000* AWG *to no. 40* AWG, *on the liberal basis of 1,600 circular mils per ampere.*

If the size of the transformer or the operating conditions permit a smaller cross section per ampere, use the graph and add 1 to the AWG number, for a cross section of 1,270 circular mils per ampere; or add 2 to the number, for a cross section of about 1,000 circular mils per ampere.

example. Suppose the 200-volt-ampere transformer is to have a single 8-volt secondary winding. The rated secondary current will be 200 divided by 8 equals 25 amperes. From the graph A of figure 7 it is seen that no. 4 wire has a little over this carrying capacity. However, such a large wire would be difficult to wind. If instead of a single no. 4 wire three smaller wires in parallel are used, they wil be much easier to wind. Each will carry one-third of 25 amperes or about 8.3 amperes. From graph B of figure 7 it appears that no. 9 wire is to be used.

For the sake of completeness, the graphs of figure 7 are carried to sizes of wire much finer and much coarser than would ordinarily be used in the construction of transformers by the amateur. These graphs may be used also when it is desirable to allow a cross section of copper per ampere smaller than 1,600 circular mils. If the conditions of operation make it unnecessary to provide for other than moderate overloads, the graphs may first be used to find the nominal size of wire for a given current, after which, if 1 be added to the gage number so found, the smaller size of wire thus obtained will have a cross section on the basis of 1,270 circular mils per ampere, which permits sustained overloads up to about 25 percent. Similarly, if 2 be added to the gage number taken from the graph for a particular current, this still smaller size of wire will have a cross section on the basis of about 1,000 circular mils per ampere, which is a safe basis if the transformer will not be required to operate with sustained overloads.

In general, when the graphs of figure 7 are used the size of wire indicated will lie between two adjacent gage numbers, and one or the other must be chosen, taking the requirements as to overloads into consideration.

XI. KINDS OF INSULATION ON MAGNET WIRES

The kinds of insulation ordinarily used on wires suitable for the construction of transformers and similar apparatus are designated as follows: Single-cotton-covered, single-silk-covered, enamel, enamel-and-cotton, enamel-and-silk. Double-cotton-covered and double-silk-covered wires were formerly much used, but for some purposes, in the finer sizes, have given way to wires insulated with enamel and cotton and enamel and silk because the double-cotton and double-silk coverings take up an undesirable amount of space. Single-silk insulation takes up less room than single-cotton, and enamel occupies less space than single-silk. For no. 12 wire and smaller, enamel and cotton insulation is generally used. Double-cotton covering is equally good as to performance but takes more room. For wires larger than no. 12, double-cotton-covered wire is preferable because of the tendency of a single cotton wrapping to separate, leaving bare places. Below about no. 26, the reduced space occupied by enamel-and-silk insulation becomes of some importance, which increases rapidly below about no. 32. The use of plain enamel wire by the amateur in the construction of transformers is not to be recommended because an accidental contact, which shorts a single turn of wire in a transformer, will produce intense local heating and eventually make the transformer useless.

In choosing between enamel-and-silk insulation and enamel-and-cotton insulation, if only one transformer is to be made and if the highest efficiency is not required, it will probably be advisable to use enamel-and-cotton covering and to increase the dimensions marked 1.5S and 2.4S in figure 1 to provide the needed extra winding space. The price per pound of the very small sizes of magnet wire goes up very rapidly as the size decreases, and it is frequently economical to use wire of larger diameter than is necessary to carry the current. This requires the use of more iron. In short, the constructor may sometimes save money on a small transformer, or on one of relatively high voltage for its size, by making it somewhat larger and of greater rating than is necessary.

XII. LAYING OUT THE WINDINGS

The next step in the design is to lay out on paper a cross section of the proposed windings in order to determine the dimensions of the "window" of figure 1. One must first decide whether to put all the windings on one leg of the core, leaving the other core to serve with the upper yoke and lower yoke as the return path for the magnetic flux, or to divide each of the windings into halves, one on each leg of the core. The former construction has the advantage of being easier to wind, and the disadvantages of requiring somewhat more wire and having consequently greater copper loss; it is preferably for transformers of about 100 volt-amperes and less. For larger transformers the windings may advantageously be divided between the two legs.

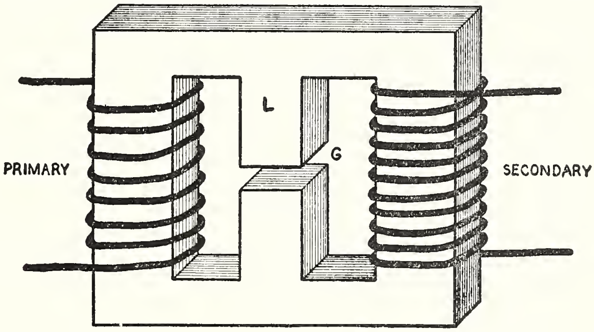

FIGURE 8.—*Diagrammatic sketch of a transformer in which the internal reactance is intentionally made large by locating the primary winding and the secondary winding on separate cores and by providing a magnetic leakage path between them.*

As the air gap G is reduced, the internal reactance becomes greater; also, as this gap is made smaller, the internal reactance depends more and more on the currents in the windings. It is necessary to use some such plan as is shown in this figure in transformers for operating neon signs, for example.

It should be emphasized that for most purposes for which transformers are used it is very undesirable to place all of the primary coil on one leg and all of the secondary coil on the other, because such a transformer will operate like a normal transformer with a reactor ("choke") in series with one of its windings. Sometimes this effect is desired, and the placing of the secondary winding and the primary winding on different legs of the core may make it unnecessary to use an external reactor. The "internal reactance" of the transformer may be further increased as much as desired by shortening the legs of the core which carry the windings, by lengthening the unwound yokes, by providing a leakage path as shown in figure 8, or by a combination of these procedures.

The manner of laying out the windings may be illustrated by an example. Taking the rating of 200 volt-amperes previously discussed, let it be desired to lay out a primary winding for 110 volts and a single secondary winding for 750 volts at rated load, unity power factor. The heavier 110-volt winding may be given the normal number of turns per volt, namely, 110 × 2.88=316 turns approximately. The upper graph of figure 5 shows that the copper loss for a transformer with a core of the given size will be 3.85 percent, and the secondary must therefore be wound for an open-circuit (no-load) voltage of 750 volts, plus 3.85 percent of 750 (=29) or 779 volts. The number of secondary turns is therefore 779 × 2.88=2,244.

The rated secondary current will be 200 divided by 750, or 0.267 ampere. Neglecting the exciting current, the corresponding primary current will be 200 divided by 110, or 1.82 ampere. If the windings are to be on the liberal basis for which the graphs of figure 7 are calculated, it may be seen that no. 24 wire is the nearest size for the secondary winding and no. 15 for the primary.

To determine the approximate space required for the windings it is convenient to use tables of data concerning magnet wires. Two of the more necessary tables are given here. The data for them have been taken by permission from the catalogs of the Belden Mfg. Co. Table 1 gives the diameters, in decimals of an inch, of bare wires from no. 8 to no. 40 AWG, inclusive, and also the diameters, over the insulation, of three kinds of magnet wire appropriate for use by the amateur constructor. Table 2 gives the number of turns per square inch of cross section of windings made of these three kinds of magnet wire, the cross section being taken at right angles to the direction of the wires. These values of turns per square inch are based on exact layer winding, and additional space must be allowed because of the unavoidable irregularities of actual windings. It has been recom-

TABLE 1.—*Average diameters (in decimals of an inch) of bare wire and magnet wires*

AWG no.	Bare wire	Double cotton	Enamel and single cotton	Enamel and single silk
8	0.128	0.1425	0.1400	-------
9	.114	.1264	.1249	-------
10	.102	.1129	.1113	-------
11	.091	.1002	.0988	-------
12	.081	.0903	.0888	-------
13	.072	.0815	.0799	-------
14	.064	.0736	.0719	-------
15	.057	.0666	.0648	-------
16	.051	.0603	.0585	0.0555
17	.045	.0548	.0527	.0497
18	.040	.0498	.0477	.0447
19	.036	.0454	.0432	.0403
20	.032	.0415	.0393	.0363
21	.0285	.0380	.0354	.0326
22	.0253	.0338	.0319	.0296
23	.0226	.0311	.0290	.0265
24	.0201	.0286	.0264	.0239
25	.0179	.0264	.0240	.0216
26	0.0159	0.0244	0.0220	0.0195
27	.0142	.0227	.0201	.0176
28	.0126	.0211	.0185	.0160
29	.0113	.0198	.0170	.0145
30	.0100	.0185	.0156	.0131
31	.0089	.0174	.0144	.0119
32	.0080	.0165	.0134	.0109
33	.0071	.0156	.0124	.0099
34	.0063	.0148	.0116	.0091
35	.0056	.0141	.0109	.0084
36	.0050	.0130	.0096	.0076
37	.0045	.0125	.0091	.0071
38	.0040	.0120	.0085	.0065
39	.0035	.0115	.0080	.0060
40	.0031	.0111	.0076	.0056

Table 2.—*Turns per square inch of magnet wire*

AGW no.	Double cotton	Enamel and single cotton	Enamel and single silk	AWG no.	Double silk	Enamel and single cotton	Enamel and single silk
8	48	52		26	2, 510	2, 155	2, 680
9	59	64		27	3, 010	2, 590	3, 275
				28	3, 620	3, 100	4, 030
10	76	80		29	4, 270	3, 660	4, 865
11	93	100		30	5, 100	4, 320	5, 890
12	114	124					
13	140	151		31	6, 010	5, 120	7, 170
14	171	187		32	6, 990	5, 960	8, 560
15	208	230		33	8, 160	7, 020	10, 400
				34	9, 480	8, 060	12, 200
16	260	289	326	35	10, 870	9, 200	14, 500
17	316	358	408				
18	378	438	505	36	12, 430	10, 550	17, 300
19	455	532	622	37	14, 100	12, 000	20, 400
20	545	644	769	38	15, 960	13, 400	23, 600
				39	17, 850	15, 150	27, 850
21	650	780	946	40	19, 900	16, 750	32, 000
22	865	1, 008	1, 175				
23	1, 030	1, 220	1, 440				
24	1, 215	1, 475	1, 775				
25	1, 420	1, 790	2, 180				

mended by one authority that a margin of 5 percent be allowed in the turns direction and 10 percent in the layers direction, and furthermore that the last layer should not be entirely filled by the calculated number of turns. The amateur would do well to increase these allowances somewhat, and to allow a further increase when the voltage of one or more of the coils is high enough to require the use of paper or cloth between layers. This point is discussed later.

Using table 2, it may be seen that for exact layer winding the 316 turns of no. 15 wire would theoretically require 316 divided by 208, or 1.52 square inches if of double-cotton covered wire, or 316 divided by 230, that is, 1.38 square inches if of enamel-and-cotton insulation. Taking the former, and adding 20 percent to the theoretical space for margin gives 1.8 square inches for the cross section of the primary winding. Similarly, the 2,244 turns of no. 24 wire will theoretically require 2,244 divided by 1,215, or by 1,475, or by 1,775; that is, 1.85, or 1.52, or 1.27 square inches, for double-cotton, enamel-and-cotton, and enamel-and-silk insulation, respectively. Double-cotton is seen to be somewhat undesirable, and enamel-and-cotton suitable. A greater addition should be made to this theoretical area for this winding because the relatively high voltage calls for the use of thin paper between layers. The cross section of the secondary winding may be assumed to be 2 square inches.

The next step is to lay out the windings in the window, as shown in figure 9, in which the dimensions of the window opening are proportioned to the side of the square cross section of the core (1.5 inches) as indicated in figure 1. A bobbin is shown in cross section, and its winding space is shown as divided by an insulating layer K into an inner space ABCD and an outer space EFGH. The outer winding should not completely fill the bobbin. The dimension AB (length of a layer of the winding) may be found by allowing three-sixteenths inch for each head of the bobbin and one-sixteenth inch clearance between head and core; AB is thus 3.6−0.5=3.1 inches. The thickness of the wall of the square tube of the bobbin, plus clearance from the core, may be taken as 0.10 inch. The winding depths BC and

FG are 0.36 inch each. The area of each is 3.1 times 0.36 equals 1.12 square inches, which is somewhat more than necessary to accommodate one-half of the turns of each of the two windings. This margin, however, is very desirable in constructing a transformer of new and untried design. It is much better to have a small margin of space than to find, as the winding nears completion, that the last few layers will not go in the space.

XIII. METHODS OF CONSTRUCTING THE WINDINGS

There are several possible methods of constructing the windings. The choice of the method and many of the details of the work must be left to the constructor.

The bobbin shown in figure 10 can be constructed from ordinary vulcanized fiber. The square tube may be made of one-sixteenth-inch sheet, soaked in boiling water until sufficiently soft, then bent around a square wooden mandrel about three-thirty-seconds inch larger on a side than the iron core to be assembled within it. It is then tied or clamped in position and left until thoroughly dry, after which it will hold its shape. The joint in the wall of the tube is most easily made by overlapping the two ends of the sheet; if a neater job is wanted, requiring more labor, the ends may be beveled off to make a scarf joint as shown. In either case, the joint may be cemented, and the fiber heads, which may be three-thirty-seconds inch thick, may be cemented to the tube. A liquid cement in collapsible tubes, made by a large paint and chemical concern for household purposes, has been found useful for this purpose. Holes should be drilled in the fiber heads through which the ends of the windings and any taps may be brought out.

The advantage of the fiber bobbin is the protection which it gives to the windings, before and after the complete assembly of the transformer. The disadvantage of the bobbin is the time required to construct it. The use of a bobbin may be avoided by winding the coils on a paper tube built up on a wooden core or form with or without wooden heads to limit the length of the windings. The tube should be made by winding on the form a strip of paper (kraft paper is very suitable) as wide as the winding space, the turns being cemented together with thin glue. When the tube wall has been built up to a thickness of one-sixteenth inch or more, the tube should be baked slowly until the glue is thoroughly dry and the tube wall is hard and strong. A washer of binder's board,[3] about 0.1 inch thick, should be held in place at each end of the tube. This washer should fit loosely over the tube and its radial width should be equal to or slightly less than that of the finished coil. To provide for holding the washers in place, a strip of cloth is placed along each side of the form, extending out between the tube and the washers. When the winding is completed within one or two layers, the ends of these cloth strips are brought around the outside of the washers and held by the finishing layer or layers of the winding. The coil leads are brought out through holes in the washers. It is advisable to reinforce the insulation of these leads with a layer of cotton tape overlapped one-fourth to one-half inch and extending 1½ to 2 inches into the winding. Means must be provided for getting the wooden form out of the finished coil with-

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[3] Binder's board can be obtained from bookbinders.

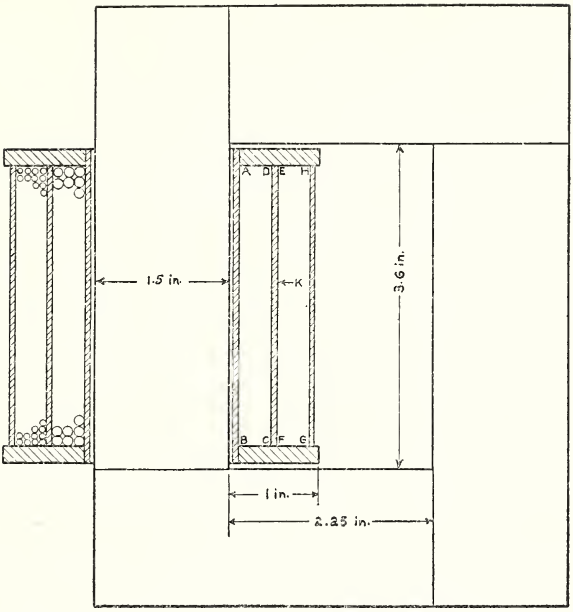

Figure 9.—*Layout of the windings of a transformer in relation to the "window" opening.*

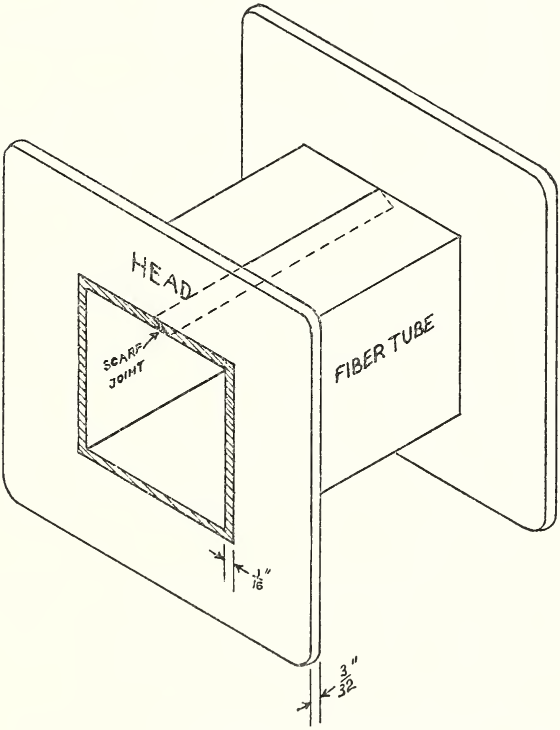

Figure 10.—*Fiber bobbin for transformer windings.*

out distorting the coil. The following expedients have been suggested for this purpose: (1) the form is first wound with a single layer of twine, over which the paper tube is built up to serve as a foundation for the windings. After the windings are completed, the twine may be pulled out and the wooden form may be readily removed. (2) The wooden form may be built up of several pieces in such a way that it may be collapsed and removed. (3) Strips of pasteboard may be laid on the wooden form, to serve the same purpose as the twine in (1). (4) The form may be coated with beeswax or paraffin to facilitate its removal from the finished coil.

The most convenient means for rotating the wooden form (either with or without the use of a bobbin) is a lathe, but if this is not available, substitutes can be devised. It is very desirable to have a revolution counter of some sort connected to the shaft by which the wooden core is rotated, in order to know how many turns have been wound on. Counting turns in the ordinary way slows down the work and leads to errors.

If the value of volts per layer in a transformer winding is 50 or less, so that the maximum stress between wires in adjacent layers is 100 volts or less, no insulation other than the covering on the wires is needed between layers. When the value of volts per layer is greater than 50, additional insulation should be placed between layers. This insulation may be a sheet of paper or thin cloth folded into a U-shaped sleeve and slipped over the wire which is to form the first turn of a layer. This sleeve is long enough (in the direction of the wire) to reach a little more than once around the layer it is to cover, and its two sides are wide enough to cover this layer. The remaining turns are then wound over these sides, which thus form the insulation between two layers.

Between two coils, one of which is wound over the other, an extra layer of insulation is required. It may be made by tightly winding on a strip of strong paper (such as kraft paper) to form a layer about one-sixteenth inch thick. If the voltage of neither coil exceeds 250 volts, the outer coil may be started directly on top of this insulating layer. If the voltage of either coil lies between 250 and 1,000 volts, it is advisable to put a band or collar of insulating material one-fourth inch wide at each edge of the last two or three layers of wire below the insulating layer which separates the coils and at each edge of each of the first two or three layers of wire above this insulating layer. This increases the "creepage distance" around the insulation and strengthens the transformer against breakdown. The finish lead of the inner coil and the start lead of the outer coil should have extra insulation in this case, and the last two or three layers of the high-voltage coil (if this coil is the outside one) should have one-fourth-inch collars as described above. Between the coils on the two legs of the assembled transformer a barrier of one or two thicknesses of 0.1-inch binder's board should be placed.

The windings of commercial transformers are insulated and sealed against moisture by the vacuum impregnation process, in which they are first heated in a closed vessel from which the air and the expelled moisture are pumped. When the windings are dry, hot melted insulating compound is admitted and pressure is applied to force it into all the crevices. This process, however, requires equipment which is out of the question for the amateur constructor.

One method of treating the windings which has given good results and requires no special equipment consists in brushing on each layer as wound a thin coat of rather thick shellac varnish. To avoid inferior adulterated varnishes, this should be made by dissolving orange shellac in alcohol, grain (ethyl) alcohol being much preferable to wood (methyl) alcohol. This varnish dries very quickly and cements the turns and layers of wire together. After the coils are entirely wound a good baking insulating varnish is applied very freely to all accessible surfaces of the coil. Such a varnish can be obtained from any well-equipped shop for the repair of electric motors. The film of shellac, applied as described, offers very little obstruction to the penetration of the varnish. When the coil appears to be saturated with the varnish, it is hung up to drain, allowed to dry in air for several hours, after which it is baked in an oven at about 212° F for several hours. This treatment binds the whole set of windings into a solid mass which is not liable to damage in the subsequent handling. Another procedure is to boil the windings slowly in a hard wax, for example, beeswax to which a small amount of rosin has been added. Paraffin wax, hardened by the addition of either rosin or carnauba wax, is also used.

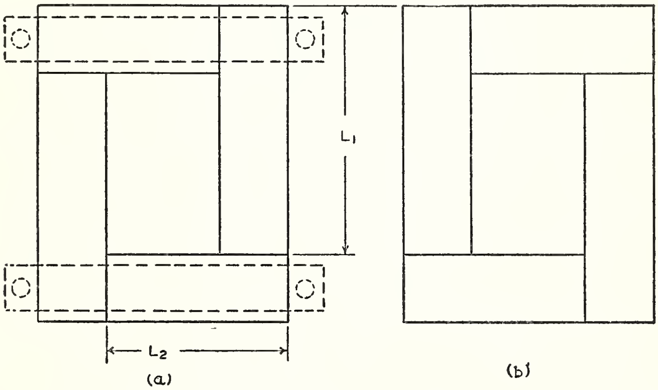

Figure 11.—*Sketch showing the manner of laying up the core laminations in order to "break joints"; also, indicating method of clamping core together*

XIV. CUTTING OUT AND ASSEMBLING THE CORE

The strips of transformer steel for the core should be cut to size with a foot-power shear such as is used by sheet-metal workers. The knife should be sharp and well adjusted. Hand shears should be avoided because they tend to bend the strips. The strips should not be cut out until after the coils have been wound because, since the windings will bulge somewhat, one cannot tell in advance how much "window" opening (see fig. 1) will be required. The strips should be of two lengths, as indicated by L_1 and L_2 in figure 11. Two methods of assembling the core and coils are available. In the first, three sides of the core are built up, including the two which are to carry the coils. The butt joints between the strips in one layer should be covered in the next layer, as suggested by figure 11; that is, one layer of strips should be laid down as in (a), the next one as in (b), and so on. When the three sides have been completed, the coils are slipped on and the fourth side of the core is built in, with the joints overlapped as just described. In the second method the coils are held in a suitable position, with temporary supports for the sides of the core which do not carry coils, and the entire core is built up, with overlapping joints.

After the core has been assembled by either of these methods a thin wooden "coil wedge" should be driven between the bobbin and the laminations to solidify the core and also to hold the coils firmly in place. The exposed parts of the core should then be tightly clamped together to minimize vibration and noise. One way of doing this is to use two pairs of pieces of bar iron, channel or angle iron, each pair drawn together by bolts, as suggested by the dotted lines in figure 11 (a). The bolts which hold the pieces of iron together may also hold the transformer to a suitable base of wood, slate, bakelite, or any material which suits the designer's taste. As the bolts are drawn up, the core should be tapped with a wooden or rawhide mallet, or a brass or lead hammer, in order to close the butt joints firmly. Many other ways of clamping the strips ("laminations") will occur to the amateur constructor. In the small transformer illustrated in figure 12 the four pieces of strap iron which clamp the core also act as supporting legs.

XV. EFFICIENCY OF TRANSFORMERS OF THIS GENERAL DESIGN

The transformer is inherently an extremely efficient device. Small transformers of a given rating are very much more efficient than motors of the same rating. The full-load efficiency of 60-cycle transformers of various volt-ampere ratings, constructed in accordance with the data of this circular, may be found by first using figure 2 to get the length of one side of the square cross section of the core and then using this length in figure 13 to get the efficiency. Thus for transformers rated at 1, 10, 100, 1,000, and 10,000 volt-amperes, respectively, the lengths of the side of the square cross section are 0.4, 0.71, 1.26, 2.25, and 4 inches, and the computed values of full-load efficiency (for loads of unity power factor) are 77.5, 86, 91.7, 95.1, and 97.2 percent, respectively.

For determining the efficiency at other than full load the graphs of figure 5 may be used. The efficiency is the ratio of the output to the sum of the output and the losses. The lower graph of figure 5 gives the iron loss, which may be assumed not to vary with the load, and the upper graph gives the copper loss, which varies as the square of the load. Thus for one-half load the copper loss is one-fourth of the full-load copper loss. For any given fraction of full load, the efficiency is equal to the output in watts divided by the sum of the watts output, the iron loss, and the copper loss for that load.

XVI. WINDINGS FOR LARGE CURRENTS AT A LOW VOLTAGE

Large wires are difficult to wind on small cores. The size of wire required for a given current may be reduced by one or more of the following expedients: (1) two or more smaller wires may be wound side by side and connected in parallel to act as a single conductor; (2) each of the two transformer cores may be wound for the full secondary voltage and one-half of the rated secondary current, the

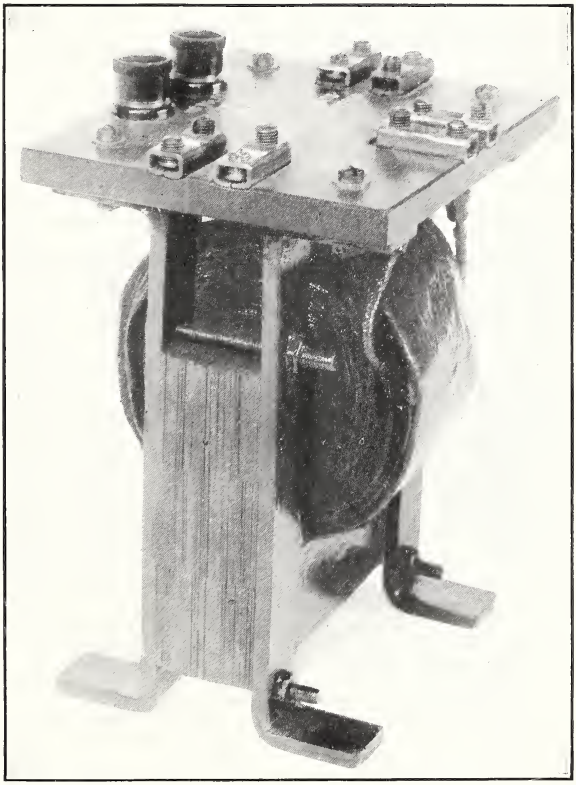

FIGURE 12.—*Transformer of 75 volt-amperes rating for operation from a 110-volt 60-cycle circuit, with three secondary windings for 2.5 volts, 8 amperes; 5 volts, 5 amperes; and 7.5 volts, 4 amperes.*

This transformer is conservatively rated, and can actually be operated at 120 volt-amperes output indefinitely.

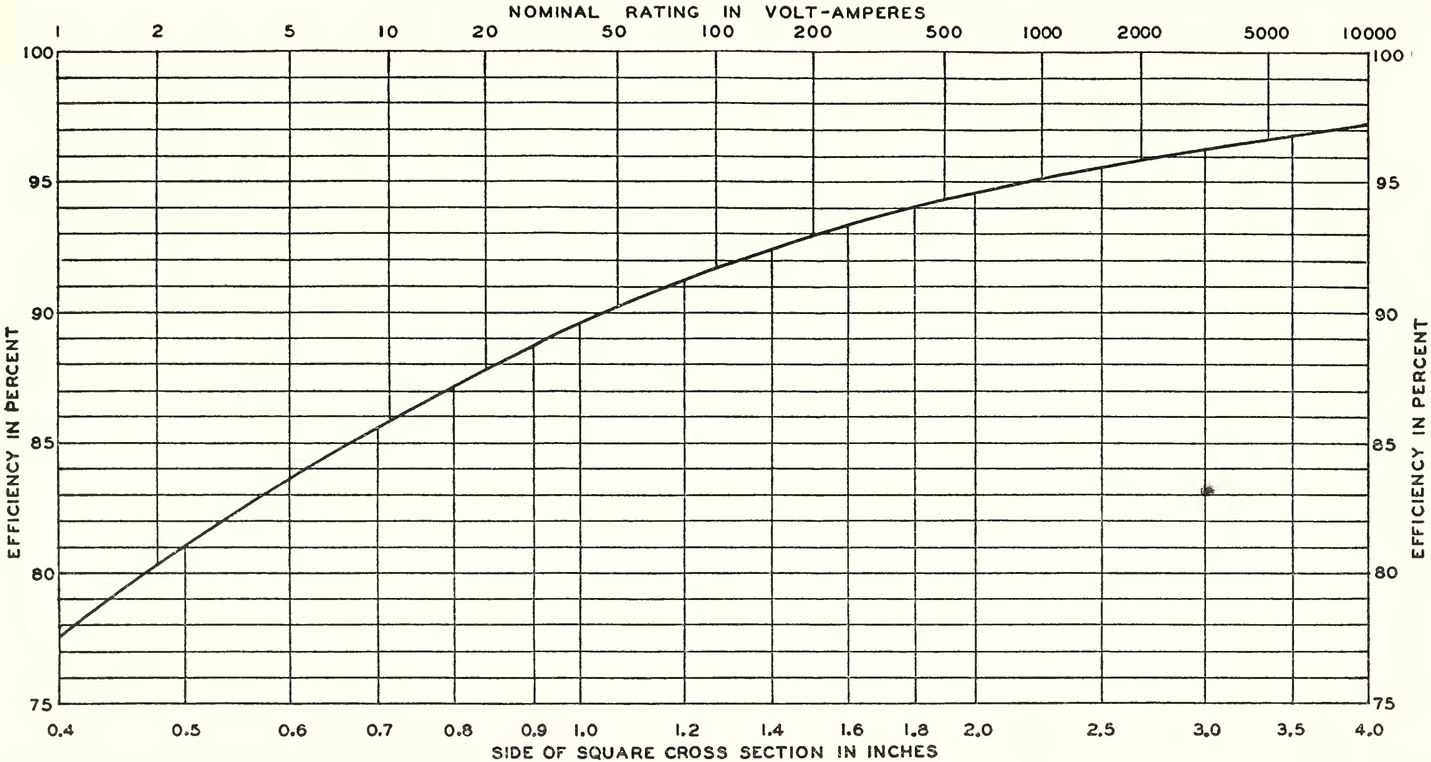

FIGURE 13.—*Graph showing the efficiency of 60-cycle transformers constructed in accordance with the methods of this circular, at rated load, unity power factor.*

two windings being connected in parallel; (3) a combination of these two expedients may be used. Paralleling of windings, either on separate cores as in (2) or on the same core, requires that the number of turns shall be exactly the same in each winding because otherwise there will be idle or circulating currents in the two windings at all times, regardless of the load, which will cause heating and lower the efficiency of the transformer.

The windings of commercial transformers for large currents are frequently made of square or rectangular magnet wire. Square magnet wire, with single-, double-, or triple-cotton covering is carried in stock by at least one maker in nominal sizes 0 to 14 AWG. It should be noted that the width or thickness of a square wire of a given AWG number is equal to the diameter of a round wire of the same gage number. Hence the square wire of a given gage number has a larger cross section than the round wire, approximately in the ratio of 1 to 0.7854. From this it follows that if the use of the curves of figure 7 indicates a given size of round wire for a particular coil, a square wire of the nominally next smaller size (that is, of the next larger gage number) can be used instead. It will have very nearly equal carrying capacity, and will make a smaller and more compact coil.

XVII. WINDINGS WITH LOW-VOLTAGE TAPS

It is sometimes desired to bring out closely-spaced taps from a transformer winding; for example, it may be required to have a secondary winding for a maximum of 8 volts with taps brought out at 6, 6.5, 7, and 7.5 volts. For a transformer of normal design there is a definite value of turns per volt corresponding to a given value of the side of the square cross section of the core, and each such value of the side of the square cross section corresponds to a definite output in volt-amperes. The use of taps one-half volt apart, with all of the transformer windings on one leg of the core, requires that the number of turns per volt be divisible by 2. If each winding (and each section of each winding) is to be divided equally between two legs of the core, the number of turns per volt must be divisible by 4 if the halves of each section are to be connected in series. However, by connecting the two halves (one on each leg) of each section in parallel, it is necessary only that the number of turns per volt shall be divisible by 2. In this case, since the current divides equally between the two coils in parallel, the wire needs to be of one-half the cross section which would be necessary if the two halves of each section were connected in series. In some cases, one must modify the shape of the core. Thus for a transformer with rated output of 150 volt-amperes, which by figures 2 and 4 would normally have 3.3 turns per volt around a core 1.4 inches square, one can theoretically use either a core 1.27 inches square with 4 turns per volt and with the dimension $2.4S$ in figure 1 increased to about $3.1S$, or a core 1.8 inches square with 2 turns per volt and the dimension $2.4S$ reduced to about $1.25S$. The former plan is to be preferred.

To obtain fractional-volt taps in the windings of relatively large transformers, one or more turns of wire may be wound around a suitable fraction of the laminations which form the core. Because these turns surround only a part of the magnetic flux in the core, the induced voltage in each of them is correspondingly lower than that in the remaining turns which are wound around all of the laminations. This procedure, however, complicates the construction.

If possible, any necessary taps should be brought out from the end turns of layers, in order to avoid running the tap across one or more turns. If this condition cannot be avoided, the tap should be very carefully insulated from the layers between which it lies. For such inter-layer taps, copper strips of appropriate cross section, soldered to the wire, are very convenient and give a neater and more compact coil than is possible if round wire is used for the taps. At each point on the wire where a strip is to be attached a flat spot may be made with a file, if a very compact joint is desired. If many low-voltage taps are required, it is better to wind the low-voltage winding over the winding (or windings) of higher voltage.

XVIII. BEHAVIOR OF TRANSFORMER WITH LOAD OF LOW POWER FACTOR

In section IX of this circular the drop in secondary voltage with load was considered, and the use of the graph of percentage copper loss in figure 5 to determine the amount of this drop was explained. As stated there, this procedure applies only when the secondary load is of unity power factor. With a load having relatively large inductance and consequent low power factor, the drop of voltage will be greater because of what is known as the internal reactance of the transformer, which exists because the primary windings and the secondary windings are separated enough to permit each winding to be linked with some flux which does not link with the other winding. This reactance will be greatest when all the primary winding is on one leg of the core and all the secondary winding is on the opposite leg. The internal reactance would be practically zero in a transformer in which the primary winding and the secondary winding consist of two wires wound on side by side, but such close proximity is usually impracticable. If the drop of voltage with a lagging secondary current is to be kept from materially exceeding the drop with the same value of current and a load of unity power factor, the primary winding and the secondary winding on each of the two legs of the core may consist of a number of flat ("pancake") coils, the assembly of coils on each leg consisting of alternately primary and secondary coils. This construction involves more labor, and care must be taken to connect all the coils of a given winding so that the current flows around the core in the same direction in all of them.

XIX. DESIGN OF TRANSFORMERS FOR FREQUENCIES OTHER THAN 60 CYCLES

Although the graphs of this circular apply primarily to transformers for operation on 60-cycle current, they may be used in the design of transformers for other frequencies. Sixty-cycle systems predominate in the United States, but there are still a considerable number of communities receiving electrical energy at 50 cycles, as well as a few at 25 cycles.

For a 25-cycle transformer, use the graphs of figures 2 and 4 to get the values of side of square cross section and of turns-per-volt as if for a 60-cycle transformer having the desired output in volt-amperes. Multiply each of these values by 1.3 to get the corresponding values for the 25-cycle transformer. The rest of the procedure is the same as for a 60-cycle transformer. For a 50-cycle transformer, use the same procedure, with a multiplier of 1.06 instead of 1.3. The sizes of wire for given currents do not depend on the frequency.

The transformer for 25 cycles will require 2.2 times as much iron and 1.7 times as much copper as the 60-cycle transformer of the same rated output. The first cost of the 25-cycle transformer will thus be about double that of a 60-cycle transformer of the same output. The 25-cycle transformer will have about 10 percent more core loss and 70 percent more copper loss, and consequently a lower efficiency than the 60-cycle transformer. These facts explain in part the tendency for the 25-cycle system of distribution of electrical energy to give way to the 60-cycle system.

The 50-cycle transformer will have about 1.2 times as much iron and 1.1 times as much copper as a 60-cycle transformer of the same output. The efficiency of the 50-cycle transformer will be intermediate between those of the corresponding 25- and 60-cycle transformers.

XX. SOURCES OF SUPPLY OF MATERIALS

The following firms have indicated their willingness to sell small quantities of silicon-steel transformer sheets to the amateur constructor. It is probable that other makers also will do this.

Allegheny Steel Co., Brackenridge, Pa.
American Rolling Mill Co., Middletown, Ohio.
Empire Sheet and Tin Plate Co., Mansfield, Ohio.
Follansbee Bros. Co., Pittsburgh, Pa.
Edgar T. Ward's Sons Co., 400 Frelinghuysen Avenue, Newark, N. J., handle small orders for products of American Sheet & Tin Plate Co.

Instead of purchasing new silicon-steel sheets, the amateur may be able to utilize the cores of discarded or burnt-out transformers or choke coils, either as they are or as material from which suitable strips may be cut.

Magnet wire may be bought of almost any motor repair shop. Small lots of wire are frequently accumulated as fag-ends which the management is glad to sell. If such a source of supply is not available, most manufacturers of magnet wire will sell small quantities with the provision that no order will be filled for less than a certain amount. The following firms have indicated their willingness to sell round magnet wire in small quantities. Most of them very properly set a minimum charge for an order, as indicated below in parentheses after the address. It should be noted that square magnet wire is carried in stock to only a limited extent, and when not in stock cannot be economically produced in small quantities. Rectangular magnet wire is usually made up only on order and in quantities much greater than the amateur would usually require, say 200 pounds and over.

Acme Wire Co., New Haven, Conn. ($5).
American Electrical Works, Phillipsdale, R. I. ($5).
Anaconda Wire & Cable Co., 20 North Wacker Drive, Chicago.
Ansonia Electrical Co., Ansonia, Conn. ($1).
Belden Manufacturing Co., 2320 South Western Avenue, Chicago ($5.)
Bradford Kyle & Co., Plymouth, Mass. ($1).
Crescent Insulated Wire & Cable Co. Inc., Trenton, N. J.
General Cable Corporation, Rome, N. Y. ($5).

Knickerbocker Annunciator Co., 116 West Street, New York City (distributors for American Steel and Wire Co.). Minimum charge $1, for which the company will furnish the amount of wire which $1, less parcel post charges, will purchase.

New England Electrical Works, Inc., Lisbon, N. H. (will furnish any amount required).

Philadelphia Insulated Wire Co., 200 North Third Street, Philadelphia, Pa. ($3).

John A. Roeblings Sons Co., Insulated Wire Division, Trenton, N. J. (price determined by quantity ordered).

The Wheeler Insulated Wire Co., 378 Washington Avenue, Bridgeport, Conn. ($5).

XXI. SELECTED REFERENCES

Information on the design and construction of transformers by the amateur is given in the Radio Amateur's Handbook (published by the American Radio Relay League, West Hartford, Conn.) and in the following papers:

C. W. Palmer, *The design of power transformers.* Radio-Craft, vol. **3**, p. 166–169 (September 1931).

Lester H. Carr, *How to make your own transformers and chokes*, part I, Radio-Craft, vol. **5**, p. 280–281, 306 (November 1933); part II, same journal, vol. **5**, p. 409, 428–429 (January 1934).

The following papers, although written for electrical engineers, are very clear and informative, with only simple mathematics:

E. G. Reed, *The essentials of transformer practice*, X, *General problems of design*, and XI, *General design relations*, Electric Journal, vol. **15**, p. 163–165 and 237–239 (1918).

WASHINGTON, March 4, 1935.

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