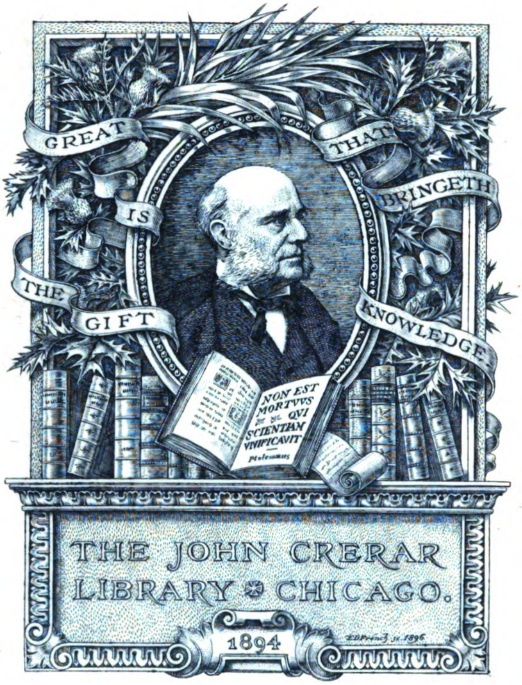
AUTO-TRANSFORMER DESIGN

A. H. AVERY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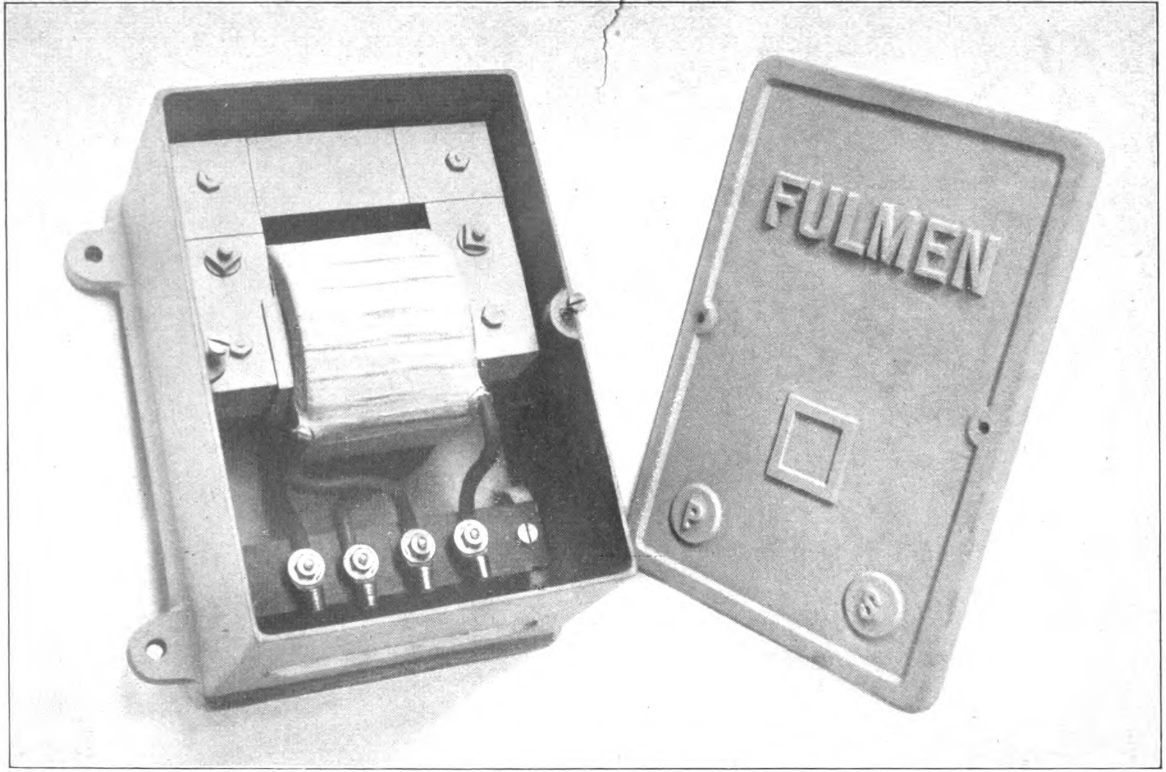
AUTO-TRANSFORMER DESIGN



FRONTISPIECE.—AUTO-TRANSFORMER IN IRON CASE WITH LID REMOVED.

AUTO-TRANSFORMER DESIGN

A PRACTICAL HANDBOOK
FOR MANUFACTURERS, CONTRACTORS,
AND WIREMEN

BY

ALFRED H. AVERY
ASSOC. INST. ELECTRICAL ENGINEERS

TWENTY-FIVE ILLUSTRATIONS

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INTRODUCTORY.

THE position of the Auto-transformer appears to be much the same as that of the small dynamo a few years ago—a little more than toys, and yet hardly worth the serious consideration of our electrical designers. What I attempted to do in the "A B C of Dynamo Design" by indicating certain systematic lines on which the design of *small* machines could be successfully conducted, will I hope bear the same method of application to the present kindred subject, with some measure of success.

The design of large transformers has been reduced to a fine art by many of our leading authorities; auto-transformers, however, are in a class by themselves, and are, in the main, too small for the methods that are in vogue with their larger brethren to be strictly applicable.

To fill this palpable gap, to eliminate rule-of-thumb, and to do common justice to what is really an important commercial instrument at the present juncture, has been my object; and I wish to take this opportunity of tendering my grateful acknowledgments to the various technical friends who have lent their kindly aid in the preparation of this little work.

ALFRED H. AVERY.

TUNBRIDGE WELLS:
August, 1909.

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AUTO-TRANSFORMER DESIGN.

CHAPTER I.

CLASSIFICATION OF TRANSFORMERS.

Comparison of different types—Ordinary, auto, and balancing transformers—Points of economy—Diagrams of connections.

ONE hears a good deal about "Auto-transformers" since the advent of the metallic-filament lamp; in fact they have come so much into prominence as to justify some little attempt to investigate the practical side of their design, to an extent befitting an instrument which plays such an important part in the commercial electrical world of to-day, where electric light is no longer merely a luxury, but a necessity. Moreover, apart from the scientific interest attached to this subject, there is a pecuniary side which will appeal strongly to those of us who have the privilege of paying quarterly electric light bills.

Economy.

To give an instance of the extent to which auto-transformers touch the pocket, let us take for an illustration the comparative cases of two private house installations, one with ordinary carbon filament lamps, and the other with metallic filament lamps; each house wired for fifty 16 c.p. and twenty-four 8 c.p. lamps.

The initial outlay in each of these two cases will be :—

	£	*s.*	*d.*
(1) Carbon lamps: 74 lamps at 1*s*.	3	14	0
(2) Metallic filament lamps: 74 lamps at 3*s*. . . .	11	2	0
1 k.w. auto-transformer	2	19	6
	14	1	6

But the running expenses, assuming that the consumption of current will be equivalent to the whole of the lamps being in use one hour per diem throughout the year, will be as follows :—

	£	s.	d.
Carbon lamps : annual cost of current at 4½*d.* per unit	27	0	0

	£	s.	d.
Metallic filament lamps : with current at 4½*d.* per unit	7	0	0
To which must be added "open circuit" transformer losses amounting to about	2	0	0
	9	0	0

At the end of the first year's working, then, the accounts will stand :—

	£	s.	d.	£.	s.	d.
Carbon lamps :						
Initial outlay	3	14	0			
Running expenses	27	0	0			
				30	14	0
Metallic filament lamps :						
Initial outlay	14	1	6			
Running expenses . . .	9	0	0			
				23	1	6
Saving effected by using metallic filament lamps				7	12	6

Clearly then, the extra capital outlay entailed in changing over from carbon to metallic filaments, is justified on the very first year's outlay. In the second and subsequent years, owing to the life of metallic filaments being double that of carbon lamps, and no further outlay required on the transformer, a clear saving of over £15 for current per annum would be realised. The saving is nearly proportionate whether the installation be large or small.

Let it be understood, the auto-transformer is by no means a new invention ; it has been known and used experimentally for a number of years ; it has merely leapt into popularity by its particular adaptability to the needs of the present day low-voltage metallic filament lamps, which have done so much for the electrical industry lately.

Classification.

"Transformer" is a word rather loosely used :—there are (1) ordinary transformers ; (2) auto-transformers ; (3) Tesla transformers ; (4) rotatory transformers ; and (5) the whole class of induction coils (including ignition coils) which are really only extreme cases of "step-up" ordinary transformers. All these are called promiscuously "transformers" by the man in the street, and it may not be out of place to define a little more clearly what is the difference between this large variety of instruments all grouped under this generic description. Transformers may be classified into either "static" or "rotatory" types, and as the words indicate, the former is a stationary piece of apparatus without any moving parts, while the latter has one or more rotating elements. Static transformers are only of use on alternating or oscillatory currents, while rotatory transformers are needed for dealing with continuous current. The rotatory appliances can be altogether disregarded here, as they belong to the sphere of dynamo-design, and we are only concerned now with static apparatus as used on public alternating supply circuits for lighting and power. Neither is it proposed to deal with induction coil design here, nor with the well-known Tesla high-frequency transformer, which although a static instrument does not concern us at present, as its utility is confined to the region of the scientist and medical man.

There are still two kinds of static transformers left, the "ordinary" and the "auto-" transformer. The exact difference between the two is not generally understood very clearly.

Ordinary transformers.

The distinction is briefly thus:—the ordinary transformer, Fig. 1, has two separate and entirely distinct windings, P the primary and S the secondary, both wound over the same iron core C, each with its own terminals, and the primary side insulated and distinct from the secondary side; E is the external secondary circuit consisting of lamps. The figure is only to be regarded as diagrammatic, as in actual practice the coils would be wound one over the other, or sandwiched in between each other as alternate sections of primary and secondary.

Auto-Transformers.

Compare this with the diagram in Fig. 2. showing the connections of an auto-transformer, the same lettering being employed as before to indicate primary and secondary coils, core, etc.

According to the time-honoured Law of Lenz, which declares that in all cases of electromagnetic induction "the direction of the induced currents is such as to tend to oppose the current producing them," it is necessary to imagine the directions of the individual primary and secondary currents in the transformer coils respectively as being in a contrary sense to one another. This is indicated by the direction arrows in the figures, which are also marked with one or two heads, according to the relative amount of current flowing in that particular part of the circuit. The fact of the current being alternating in direction makes no difference as to the instantaneous conditions of the primary and secondary circuits relatively to one another.

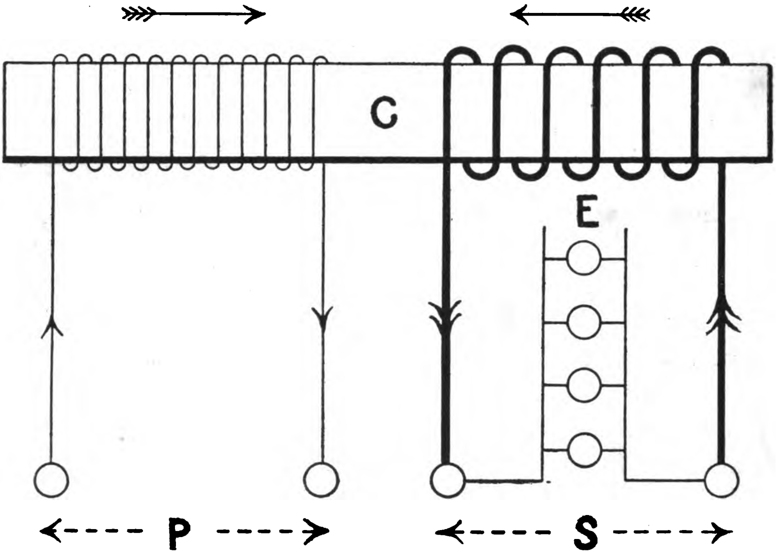

FIG. 1.—ORDINARY TRANSFORMER DIAGRAM.

Assuming, now, when comparing the two diagrams, that both transformers are of the same output and designed to work under the same conditions, it is clear that in Fig. 1 the primary coil P must consist of a sufficient number of turns to give the required reactive electromotive force, and of sufficiently large gauge of wire to carry the requisite current. And since the primary input of electrical energy and the secondary output of energy are approximately equal except for a slight loss in transformation, it follows that there must be an equal weight of wire on the secondary coils to that on the primary, although the actual number of turns of wire and gauge will not necessarily be the same, but will depend on the "ratio of transformation." In fact, this rule always holds good either for ordinary or auto-transformers, and if there are 5 lb. of wire on the primary

Relative advantages.

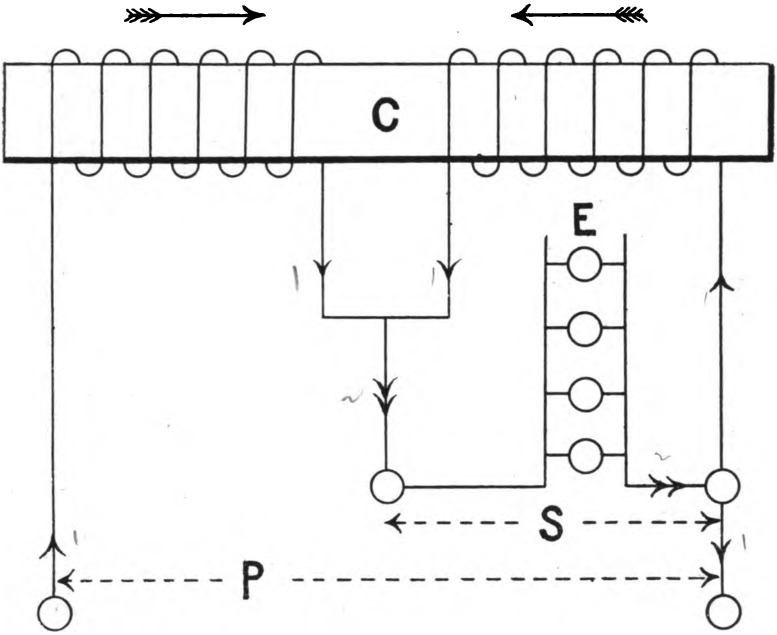

FIG. 2.—AUTO-TRANSFORMER DIAGRAM.

coil, there will always be about 5 lb. on the secondary, making 10 lb. in all.

Let us suppose the ratio of reduction to be 2 : 1, i.e. the primary voltage is say 200 volts, and the secondary voltage 100 volts. As the energy in watts is approximately the same in both windings, we will also imagine the primary coil to be carrying two amperes of current at 200 volts pressure, and the secondary coil four amperes at 100 volts pressure. This state of things is represented in Fig. 1 Now let us further imagine that the *same primary winding* P is distributed over the whole length of the same core, and tapped at a central point as shown in Fig. 2. On applying the same primary voltage at the ends of the coil it will be now working under just the same conditions as before, and when fully loaded will carry the same current. But by "tapping" the coil at a point about midway, and making this and one end of the primary the secondary terminals, we shall find, bearing Lenz's Law in mind still, that the directions of the induced currents are such that *two* parallel circuits through the winding are now opened up, branching at the secondary terminals S and re-uniting at the end of the primary P, as shown by the direction arrows again.

Reactive effect.

Since each individual turn of wire on the primary coil contributes a proportionate amount of reactive electromotive force, a connection taken off from any point situated between the extreme ends of the primary will give a proportional pressure if treated as a secondary. If a point exactly mid-way in the coil be chosen, the potential value between that point and either of the ends will be exactly half that of the whole coil—in this case 100 volts. But now the two currents—inducing and induced—will unite in parallel circuit at this point, and merge together; and the secondary circuit, while giving only 100 volts, will contribute four amperes instead of two, without increasing the current density in any part of the circuit.

Copper economy with auto-transformers.

Although, therefore, we have entirely eliminated our independent secondary winding by the above means (and also 5 lb. of wire), we have still the same capacity of transformation with but one-half the weight of copper, and also the additional advantage of a great saving in cost. The above is of course an extreme case, and applies to examples of 2 : 1 transformation ratios only. But even when dealing with 4 : 1 or 8 : 1 conversion ratios there is still a considerable saving of weight in material when designed as Fig. 2, and for this reason auto-transformers are always cheaper to construct than ordinary independent circuit transformers, at any rate in the smaller sizes such as dealt with here, besides possessing an equally high efficiency.

Balancing transformers.

There is another rather curious advantage possessed by the simple 2 : 1 auto-transformer. It is apparent in looking again at the diagram in Fig. 2 that the secondary circuit S might equally well have been taken from the centre point to the left-hand terminal on the figure, instead of between centre and right-hand as drawn; the transformer would work equally well thus. To go one step further:—why not use *both* such secondary circuits, and put a load on both circuits, getting double the output from the transformer? As a matter of fact this is done in a good many instances, and the instrument is then called a "balancing" transformer, having a capacity double that of its previous single secondary circuit conditions, and, *mirabile dictu,* has a minimum energy loss at full load, for when both secondary circuits are equally loaded, practically none of this secondary current passes through the transformer coils at all, but goes direct through the two secondary circuits in series from main to main as shown by the direction arrows in Fig. 3, representing a case where both secondary circuits are equally loaded with lamps. Only a very small amount of energy is shunted off round the transformer coils as "magnetising current," representing quite an insignificant number of watts. How

Unbalanced secondaries.

the behaviour of such balancing transformers is affected when the two secondary loads are out of balance is shown by the further diagram Fig. 4. The left-hand circuit is supposed to be fully loaded, causing a circulation of current round the left half of the transformer windings sufficient to supply one of the two lamps on that side, while the other remaining lamp on the left-hand circuit is balanced by the single lamp on the right-hand side, therefore the right-hand side of the transformer winding is not called upon to supply any energy at all, two of the lamps being in series direct across the mains. This effect may be likened to an ordinary 3-wire system working under the same conditions of balanced or out-of-balance loads. In a 3-wire system (Fig. 5), two 100-volt dynamos may be coupled up together in series, giving a potential difference of 200 volts between the outer conductors, and 100 volts between the inner conductor

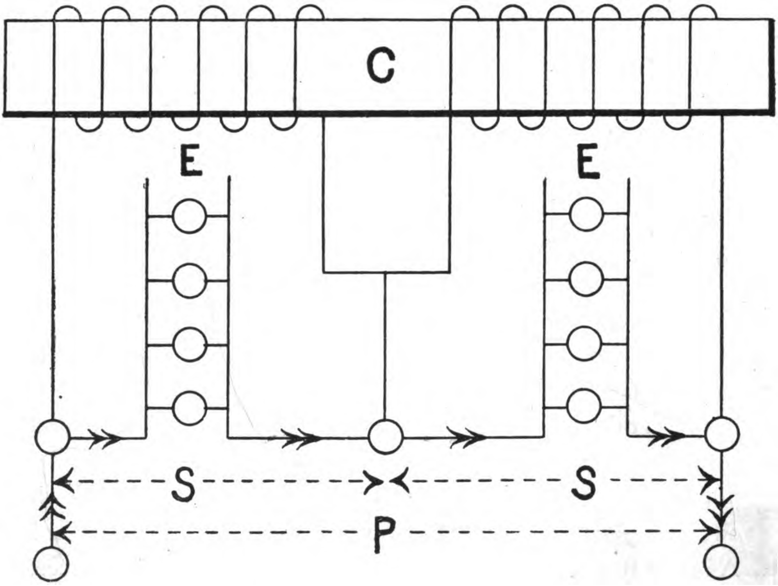

FIG. 3.—BALANCING-TRANSFORMER DIAGRAM.

and either of the outers. If now the same number of lamps (each requiring the same amount of energy) are distributed evenly on both sides of this system as drawn, the central conductor will be idle as there is no balancing to do, and the 100 volt lamps are simply wired up as series pairs across the outer 200 volt mains. Should all the lamps be switched off one side of the system, either A or B, current will flow at 100 volts pressure along that circuit only from outer to

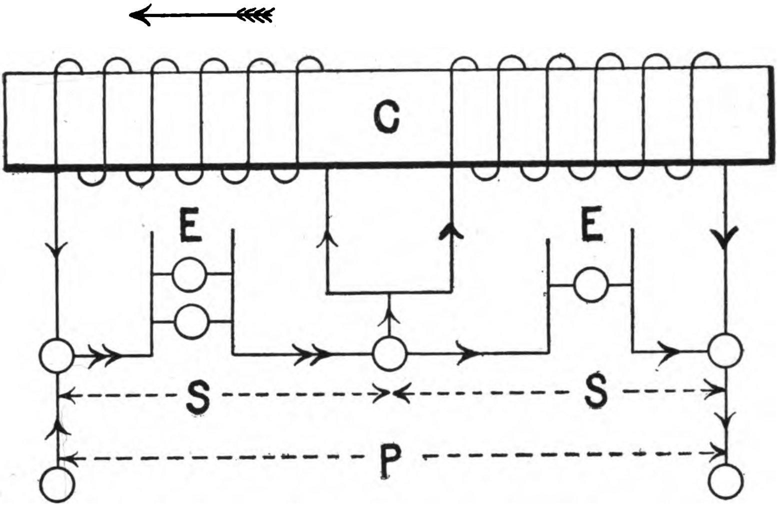

FIG. 4.—BALANCING TRANSFORMER UNEQUALLY LOADED.

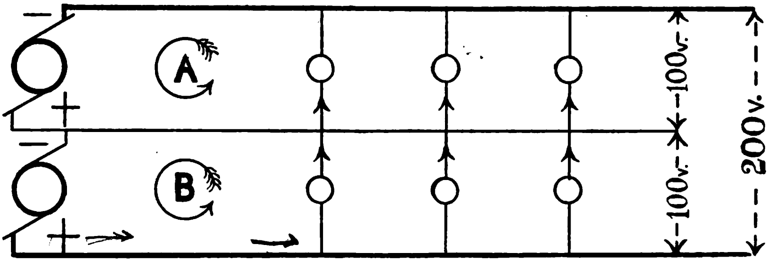

FIG. 5.—THREE WIRE SYSTEM OF DISTRIBUTION.

Multiple secondaries.

inner, as shown by the curved arrows, the others remaining idle. The case is perhaps not quite a parallel one, but may assist somewhat in realising that when the two circuits of a balancing transformer are equally loaded, it is doing practically nothing at all, so far as internal work is concerned. This feature is not confined to two balancing circuits merely, but any number of similar secondary circuits can be so balanced. Transformers so constructed are generally spoken of as having "multiple circuit secondaries."

CHAPTER II.

MODERN METHODS OF ILLUMINATION.

Transition stages from carbon to metallic filaments—Voltage restrictions—Public supply pressures—Advantages of transforming to low pressure.

SO much for theory, and now for practical details. But first of all let us be clear why we are using "auto-transformers" at all—and this involves a few words of explanation as to the various modes of illumination in vogue at the present time.

Methods of illumination.

The ordinary carbon filament lamp is too well known by everyone to need any description, and it has held its own for many years, having no serious rivals until comparatively recently. Then began a series of epoch-making discoveries first by Nernst, then by Dr. Auer, Cooper, Hewett, and others, resulting in a gradual evolution of the present metallic filament lamps under various fancy names, none of which appear greatly to increase their illuminating power, it is true, but serve as convenient handles for descriptive purposes. Some of these new types had but a brief existence, others seem to have come to stay: finality has not been reached by the best of them; they can none of them be regarded as in any but the transition stage.

The best success has been obtained up to the present by the use of highly infusible and rare metals such as tantalum, tungsten, etc., the former giving its name to lamps descriptive of that class, and the latter being formerly known as "osmi," "osmium," and "osram" lamps.

The great advantage possessed by all the metallic-filament class of lamps is that they can be raised to a satisfactory degree of incandescence with a far smaller expenditure of electrical energy than was the case with the older forms of carbon-filament lamps. In other words, the same light is obtained at a lower cost, and anything that has the remotest tendency to reduce the expenses of living in any degree is certain to be hailed with acclamation in these strenuous times!

Relative energy consumption.

The amount of energy consumed by carbon-filament lamps was a variable quantity, depending in some degree on the method of producing the filaments—never less than 2½ watts for every standard candle-power of illuminating power, and often rising to 5 or 6 watts per candle, when that lamp had lost its youthful freshness. Three-and-a-half watts per candle-power was reckoned in bygone days a most reasonable and satisfactory efficiency for a carbon lamp, especially if it could be depended on to last its allotted span of 1000 hours. At this stage it was supposed to have reached its "smashing point," and, if it survived so long, the interests of its owner demanded that it should be smashed forthwith, unless he was sufficiently easy-going to pay for his illumination at the rate of five or six watts per candle-power.

The carbon lamp, however, must not be under-rated; it possessed many virtues, and for the lack of anything better filled a great need admirably for the time being, But the cry is always for higher efficiency, and yet higher; and when next the Nernst and then the tantalum lamps came into being they were regarded as a wonderful advance, owing to the much smaller energy consumption they required per candle-power.

Mechanical difficulties.

The mechanical drawbacks possessed by the Nernst, however, precluded its becoming a very popular type of lamp, in spite of its remarkably high efficiency of slightly less than 1 watt per candle-power; and the tantalum lamp although a still highly efficient lamp (about 1·7 watt per c.p.) has a very fragile filament, and being expensive in first cost, does not always give a satisfactory impression owing to the heavy renewal and maintenance charges. The tungsten filament, although certainly fragile as compared with carbon, has proved itself not only highly efficient (1 to 1·3 watt per c.p.) but capable of standing a fair amount of handling. "Osram" lamps, therefore, are eminently suited for such purposes as house lighting and situations where they are not subjected to much vibration. With an average efficiency of 1·2 watt per c.p. (which means using just one-third of the energy demanded by carbon lamps of equal illuminating power) and a lifetime, barring accidents, of 2000 hours as against the 1000 hours of a carbon lamp, a little thought will show that the higher prime cost of the osram lamp is an insignificant item altogether, compared with the number of units of electrical energy it is going to save during its 2000 hours of useful service. A 16 c.p. osram lamp, costing 3*s*., consumes approximately 20 watts, and would therefore burn for 50 hours with a consumption of one unit of energy. As its lifetime is 2000 hours it will have consumed 40 units during this period, which at 3*d*. per unit cost 10*s*.; or a total outlay of 13*s*. for 32,000 candle-power-hours. Compare this with a 16 c.p. carbon lamp costing 1*s*. and consuming 60 watts. This lamp will take 16 hours 40 minutes to consume 1 unit, and during its life of 1000 hours consumes 60 units. But the osram lamp lasts twice as long, therefore we must buy another carbon lamp and run it for another 1000 hours to bring the two cases to a parallel. The consumer has now spent 2*s*. on carbon lamps, and used 120 units of electrical energy at 3*d*. i.e. 30*s*. for current; or a total outlay of 32*s*. for the same 32,000 candle-power-hours. So for the sake of being conservative and not fully alive to his own interests, the consumer in happy ignorance goes on paying 19*s*. per light more than he need do, until some enterprising contractor takes him in hand and convinces him of the error of his ways.

Running expenses.

But what has all this got to do with auto-transformers? Just this: even osram lamps have not reached their ultimate state of perfection, and one of the chief drawbacks they have to contend against is that all metallic filaments naturally possess a much lower specific resistance than carbon, and must therefore either be made much longer, or of much smaller sectional area (or both), in order to present suitable resistance to a high-voltage circuit. A long thin filament is excessively fragile and unsuitable for commercial purposes, although, by ingenious methods of internally supporting the filaments, lamps have been constructed to burn direct on 100 and 200 volt circuits; but their efficiency and lifetime are both relatively unsatisfactory.

Voltage restrictions.

This led at one time to grouping the lamps two in series across the high-voltage mains, but unless the lamps are carefully selected to "pair" well, one or the other was always sure to burn out pretty soon, and the practice is being gradually discontinued. The best solution of the difficulty at the present time of writing seems to be to manufacture only lamps of comparatively low voltage, 25 volts or 50 volts, which have shorter and more substantial filaments, and a better life and efficiency than their high-voltage brethren.

Series grouping.

Advantages of low voltage.

This is just where the utility of the auto-transformer comes in. No public supply companies deliver current at the consumer's terminals at such low pressures as 25 volts or 50 volts, in fact it was not so long ago that they all changed over from the 100 volts or 110 volts to the now almost universal 200 volts or 220 volts in order to minimise transmission losses. But in the auto-transformer the consumer has a valuable ally, for it renders him quite independent of the company's supply pressure, and he can juggle with it as he pleases by installing one of these useful little appliances, of which there are already many thousands in use.

CHAPTER III.

ELEMENTARY THEORY. FUNDAMENTAL FORMULÆ.

Magnetic behaviour of iron with alternative current—Hysteresis—Energy losses in iron and copper circuits—Temperature rise as affecting the rating.

Theory of design.

THE theory of the instrument has been touched upon briefly: let us now see what are the methods of designing and constructing. Those who are acquainted in any degree with the theory of the dynamo, will know that electromotive force is set up in any circuit by oscillating it rapidly in a strong magnetic field, at right angles to the direction of the lines of force or "flux." Supposing now that instead of moving our conducting circuit itself, we oscillate the magnetic field in which it is placed instead. The effects will be just the same in either case: in the dynamo we have a fixed field and moving circuit (armature winding), while in the static transformer we have a fixed circuit (the transformer coils) and a moving flux of magnetic lines, set up by the alternating current flowing through the primary coil causing the polarity of the core to change rapidly, at the same rate as the alternating magnetising effect.

Inductive effects.

In either of the two preceding cases an induced electromotive force is set up in the coils, and, other conditions being equal, this reactive voltage is proportional to the number of turns of wire, or conductors. But there are other things besides to take into consideration:—the three factors which are necessary for the production of an electromotive force in a circuit are (1) the circuit itself; (2) the flux of magnetic lines; and (3) relative motion between the two: any two of these conditions without the third are useless. In transformers we find all three conditions: (1) the coils of wire wound round the transformer core, already mentioned; (2) is provided for by the presence of the iron core; and (3) is obtained by the alternating polarity or change of direction of the flux, which follows the "frequency" (or number of waves per second) of the alternating supply. The reactive electromotive force E, therefore, set up in the coils of a transformer—which it may be remarked becomes merely a "choking coil" when unloaded on the secondary—is expressed by the equation:—

Fundamental formula.

$$E = \frac{T \times N \times 4{\cdot}44f}{10^8}$$

Symbols are very convenient for the sake of abbreviation, and the above represent respectively: E, electromotive force; T, turns of wire; N, total lines of magnetic force, or total "flux"; while f is the "frequency" or "periodicity" of the circuit in "cycles," or complete alternations of current per second—all these terms meaning the same thing. These values being in absolute C.G.S. units it is necessary to divide by 100,000,000, or 10^8, to reduce to practical units, or volts E. The factor 4·44 times the frequency f represents the "root-mean-square" value of the alternating wave form, or the quadratic mean value of the alternating flux, varying four times per cycle. For instance, to trace the course of a complete "wave," it first grows to a positive maximum, then diminishes to zero, reverses in direction and grows to a negative maximum, and lastly diminishes to zero again, to re-start the process for the next wave. The total effect value of such an alternating sinusoidal wave is 1·1 times as great for every change in condition as that which would be due to the simple starting, stopping, reversing, and repeating process in the case of an ordinary continuous current.

Sine functions.

This fundamental formula is practically the only one that need concern the designer of small transformers, as its various inversions will give him all he requires to know in the way of turns of wire T, and requisite flux N; thus to get reactive electromotive force we use the first equation

$$E \text{ (volts)} = \frac{T \times N \times 4{\cdot}44 f}{10^8} \quad . \quad . \quad \text{(I)}$$

To get the necessary number of turns of wire on the transformer this becomes

$$T \text{ (turns)} = \frac{E \times 10^8}{N \times 4{\cdot}44 f} \quad . \quad . \quad \text{(II)}$$

Inversions.

And finally, the other factors being known, the flux can be calculated by yet another inversion of the original formula

$$N \text{ (total flux)} = \frac{E \times 10^8}{T \times 4{\cdot}44 f} \quad . \quad . \quad \text{(III)}$$

Order of design.

As with dynamo design, transformer calculations can be divided up into two principal sections: (1) those dealing with the magnetic circuit, and (2) those relating to the electrical or copper circuit. Briefly, they may be called *iron* and *copper* calculations. We must first consider very carefully the behaviour of a piece of iron when subjected to rapidly alternating cycles of magnetisation. It is not sufficient to be merely acquainted with the fact that the iron exhibits alternating polarity with every reversal of the alternating magnetising current. We shall also need to know if we are losing any energy in the process that might be saved by selecting a more suitable kind of iron or working it under different conditions, if we have any regard to the efficiency of our completed transformer.

Iron losses.

Iron losses take the form of either eddy currents or of hysteresis. The former can be easily minimised by laminating, or splitting up the core into sufficiently thin sheets, in a line with the direction of the flux; but hysteresis is not so easily overcome, and it requires great care in selecting a suitable brand of iron.

Hysteresis is best described as "magnetic friction," and

Hysteresis. appears to be an internal mechanical resistance to the molecular changes which accompany magnetisation. To understand this better, reference should be made to the diagram in Fig. 6. Here a piece of iron is supposed to be taken through one complete cycle of magnetisation, such as would be produced by a complete wave of alternating current. It is supposed that the iron under test starts in a perfectly normal and unmagnetised condition, as at the origin of the curve *o* in the diagram. The horizontal line +H and −H represents the magnetising force applied in the two different directions, while B+ and B− shows the resulting induction in the iron. An application of + magnetising force causes this induction curve to rise to the

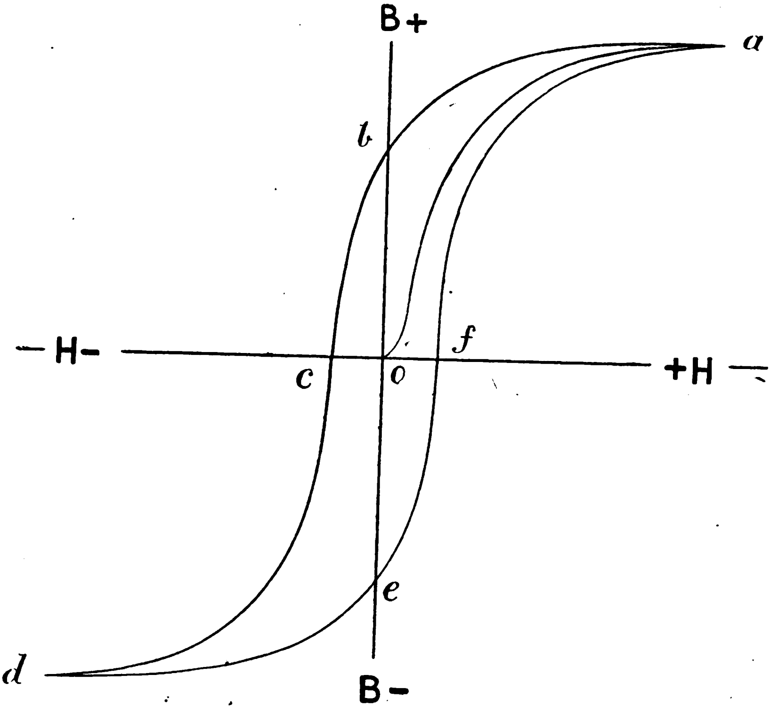

FIG. 6.—HYSTERESIS CURVE.

Cycle of Magnetisation. point *a*, in the well-known shape of the "B-curve" for iron. H then ceases, and the iron sample loses some of its magnetism (but not all), and drops to a point *b* on the diagram. A small − application of H brings the curve down to zero at *c*, and a further increase produces a complete reversal or negative induction *d*. On ceasing to apply −H the curve drops to *e*, and is brought to zero again at *f* by a small application of +H once more, ready for another cycle.

Coercive force. The position of points *b* and *e* represent what is known as the "remanance" or "retentivity" of the iron, and the distance between points *c* and *f* is proportional to the "coercive force" of the sample. All that area inclosed by the *f*-shaped figure represents lost energy in overcoming molecular resistance to magnetisation, and shows itself in practice in the form of useless heat. The closer together points *c f* and *b e* can be got the less will be the hysteresis losses, and the better the iron for transformer construction.

Transformer iron. Few persons will have the necessary instruments or experience to make these tests for themselves; one usually has to go to the makers for test-curves of their material, and as they are generally conducted in a specially equipped laboratory, perfect reliance can, as a rule, be placed on the figures they will supply. By the courtesy of Messrs. J. Sankey and Sons, of Bilston, who supply special sheets for all kinds of magnetic purposes, we are able to reproduce here the behaviour of two special kinds of material particularly well adapted for use in transformer building. These mild steel sheets known as "Lohys" and "Stalloy" have an extraordinarily high magnetic permeability, and at the same time a high electrical resistance which opposes the flow of internal eddy currents.

The curves here given will save a lot of labour, since they show at a glance such information as energy losses, permissible flux-densities, etc., at various frequencies, which it would otherwise be a difficult and laborious matter to compute. Fig. 7, for instance, shows the relative magnetic qualities of Lohys and Stalloy sheets under similar conditions of magnetisation. From this it is evident that Stalloy is preferable where the highest possible efficiency is required; and as the best is none too good for transformer work we shall decide on its use in all the following calculations.

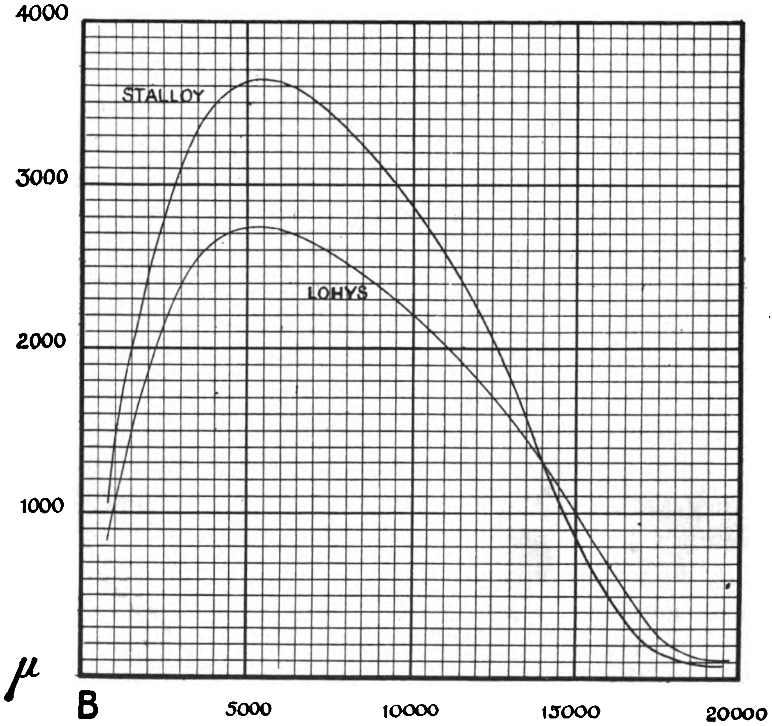

FIG. 7.—PERMEABILITY CURVES OF LOHYS AND STALLOY SHEETS.

Thickness of stampings.

Another most useful set of curves, to which the designer will need constant reference, is that illustrated in Fig. 8. This gives energy losses in the iron, such losses being compounded of hysteresis and eddy-currents. The latter may be counted negligible if the iron sheets are not allowed to exceed 0·02″ in thickness (i.e. 50 to the inch). The exact effect of using thicker sheets is not a very serious matter provided it is not carried beyond about 0·025″ in thickness; and on the other hand there is practically nothing gained by using thinner stampings, which naturally entail more work in assembling. The standard practice is now to use 0·02″ thickness for high grade transformer sheets. Returning to Fig. 8 again, which consists of a number of "straight-line-curves," it is noticeable that for a given weight of iron in a transformer core the energy loss in watts will vary directly as the frequency. Also the watts lost per lb. of iron core will bear a close relation to the value of the induction in lines per sq. inch or centimetre. For the convenience of those who prefer to work on the English system of units the induction values in lines per sq. inch have been worked out and placed by the side of the curves in Fig. 8, the lower values representing C.G.S. system, or lines per sq. centimetre, and the higher values English system of lines per sq. inch.

It is purely a matter of experience that fixes the actual flux-density value or the sectional area of iron in a transformer core, as what would be perfectly correct practice for a large transformer would be found decidedly wasteful for small work.

Flux density.

The author's own experience, based on the commercial production of auto-transformers under severe conditions of competition, go to show that the flux-density should lie between 50,000 and 60,000 lines per sq. inch for Stalloy brand sheets, and that cores designed for this flux-density will work perfectly cool for any length of time, with a minimum waste through iron losses, and "age-ing" properties.

As regards the actual dimensions to give to the core in sectional area, length, winding space, etc., an extended series of "trial and error" calculations is the only way to arrive at the best *practical* figures.* The determination of

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* The proportions between iron and copper may be widely varied without affecting the output of a transformer—only its efficiency will suffer.

N in our fundamental formula (I) is therefore not quite so simple a matter as it would appear, and to save the reader again any unnecessary repetition of a rather laborious and

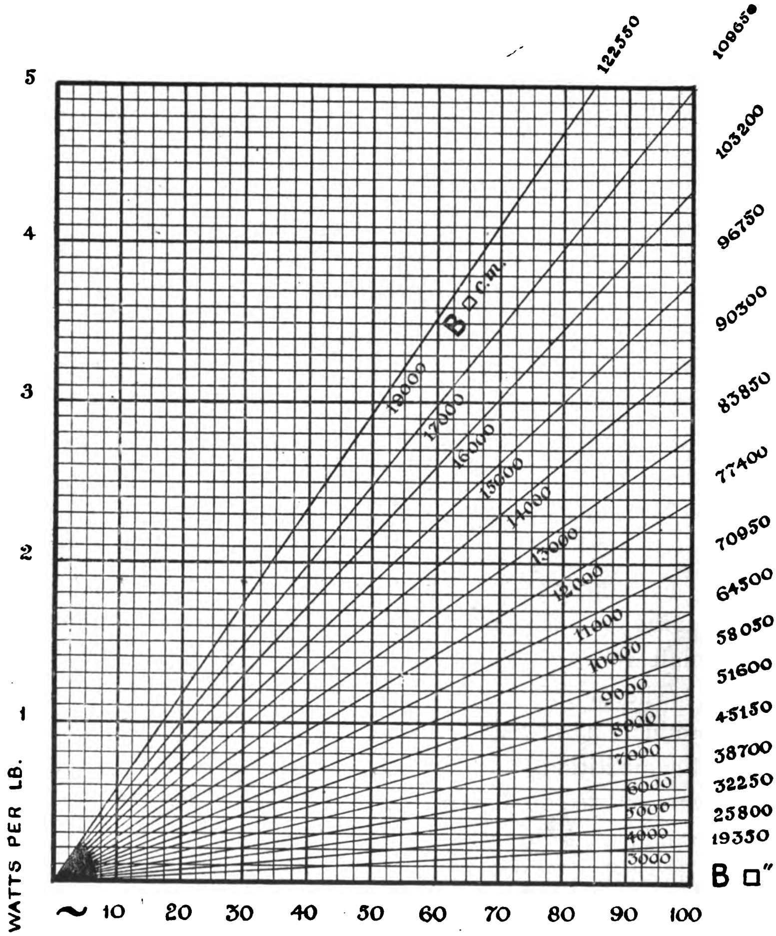


FIG. 8.—ENERGY LOSS CURVES FOR STALLOY, WORKING AT DIFFERENT FREQUENCIES AND FLUX-DENSITIES.

expensive process, it is proposed to give him the best results of a large number of practical experiments originally conducted for actual manufacturing purposes. These results are summed up in a future table of reference, Fig. 10, and need not be dealt with just yet. We have to consider the electrical part of our transformer design next, for having once decided upon N and the flux-density, the only other point of importance in our magnetic circuit is the calculation of iron losses. Fig. 8 gives us this information, so we can now pass on to consider the design of our copper circuit.

Copper calculations.

The "copper calculations" are really a very simple matter. We have only to settle the number of turns of wire T to put on the transformer to give us the required reactive voltage, and then to look out a size of wire having sufficient sectional area to carry the full-load current without undue heating. The number of turns is ascertained first by the formula

$$T = \frac{E \times 10^8}{N\,4{\cdot}44 \times f}$$

and is merely a matter of arithmetic. Then comes the question of gauge of wire to employ. There is a conventional idea that all copper conductors are designed to carry current only in the proportion of 1000 amperes for every square inch of sectional area. As a matter of fact there are very few practical instances when this particular density is the most appropriate one, and a much better rule for current-density, and the only really satisfactory one in practice, is to be guided entirely by the *final temperature-rise* of the coil, which must be kept within certain limits having regard to efficiency and Fire Office Rules.

Current density.

The temperature-rise is of a complex origin and contributed to not only by the passage of current round the wires themselves, but outside considerations as well, such as ventilation of the coil, depth of winding, radiating surface, etc. Even the colour with which the coils are varnished plays a noticeable part in radiating effects: if two similar coils are carrying an identical current, one being painted white and the other black, the black one will be found appreciably cooler after the same interval of time. The best modern practice with small auto-transformer work, is to provide good ventilation on the inside as well as the outside of all coils, and to keep the depth of winding down to one inch or less.

This question of current-density is a somewhat important one, for the "rating" of a transformer (i.e. its load capacity)

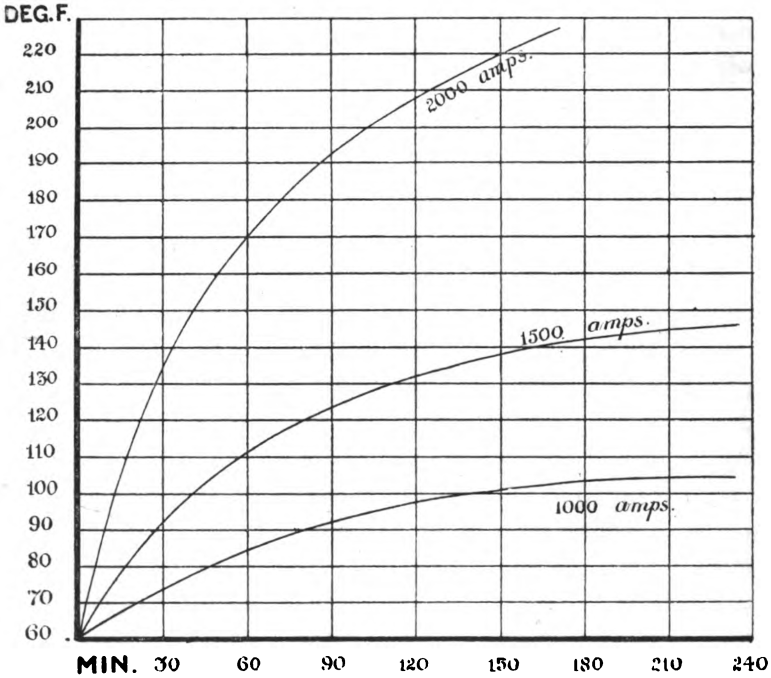


FIG. 9.—TEMPERATURE-RISE OF TRANSFORMER COILS WORKED AT DIFFERENT CURRENT DENSITIES.

Temperature rise. is entirely a matter of the permissible temperature-rise. The curves shown in Fig. 9 are reproductions from a series of actual tests of temperature-rise taken over a period of several hours on three different sized transformers working at current densities of 1000, 1500 and 2000 amperes per square inch. These curves establish the fact that at 1000 amperes the final temperature-rise is in the neighbourhood of 35° F. above the temperature of the surrounding air. At 1500 amperes a temperature-rise of 70° F. may be expected, and at 2000 amperes current-density about 150° F. rise. The first rating at 1000 amperes is unnecessarily low, and leads to large and expensive instruments for a given output. The 150° rating is rather too high for ordinary work and might constitute an objection under Fire Office regulations in some instances. Conductors should therefore be proportioned as nearly as possible to work at a 1500 ampere current-density, as by this means maximum safe output, and normal heating, are both satisfactorily obtained.

Copper losses.

We have spoken above of iron losses in terms of energy wasted in hysteresis and eddy currents, expressed as watts per pound of iron in the transformer core; there are also copper losses to be considered. Whenever current flows through a circuit possessing resistance, energy is frittered away in the form of heat, and as all heat developed in a transformer is useless for practical purposes, it is so much waste of energy, and can also be expressed in watts. If the resistance R of the transformer coil is measured, and also the amount of current C passing through it, the lost energy in watts is expressed as $C^2 \times R$. For watts = E × C, and E = C × R, therefore the formula can be written alternatively watts $= (C \times R) \times C = C^2 R$. This method of expressing watts is useful to us in the present case, since it tells us that the energy loss is proportionate, not only to the resistance, but to the *square* of the current, and our copper losses will increase or diminish rapidly according to the load on the transformer. At half-load, for instance, the copper losses will be one-fourth of their full-load value; at a quarter-load, one-sixteenth, at one-eighth load, one sixty-fourth, etc.

Losses vary with load.

The is one more loss to deal with, also a copper loss, which like the C^2R losses depends on the load on the secondary. This is the pressure drop, or lost volts, sometimes termed the "regulation" of the transformer. Lost volts are expressed in terms of resistance and current, since by Ohm's law $E = C \times R$. The resistance of a transformer coil is practically of a constant value, therefore the lost volts E will vary in direct proportion to any change in the current value C, flowing through its secondary coils. This shows the necessity for keeping the copper resistance low in order to insure good regulation, and a minimum drop of volts on the secondary terminals between no-load and full-load.

Regulation

CHAPTER IV.

PRACTICAL DESIGN.

Public supply variations—Procedure in design—Tables and constants—Balancing theoretical and practical requirements—Details of design.

SUFFICIENT data and explanation of the principles of auto-transformer design has now been given to enable a trial calculation to be worked out, and having once become conversant with the method, little further difficulty will be experienced in preparing dimensions and winding data for similar instruments of any other capacity between one-tenth and 10 k.w.

Supply variations.

As a general thing, the public supply of alternating current is delivered to the consumers' terminals at a pressure of 200 to 220 volts and a frequency ranging between 50 and 100 cycles per second. Unfortunately we have not yet reached that degree of standardisation when all public electric supply companies shall generate at the same potential and frequency throughout all the country. Thus, although 200 volts is the most general pressure adopted for lighting purposes and 50 the usual frequency, the latter is subject to considerable variations from standard practice in various power stations, and frequencies of 40, 50, 60, 67½, 83, 90, or 100 cycles may all be met with in this country.

It is important before starting on any design to ascertain carefully what the *frequency* is on that particular circuit in which the transformer is proposed to be put to work, since this will greatly affect the size and winding of the instrument.

Procedure in design.

Let us assume that an auto-transformer is being designed for a circuit of 200 volts 50 cycles, and that we require it to supply current to 50 volt 16 c.-p. Osram lamps. We will then proceed to take each calculation step by step as typical of the processes to be applied to all cases of auto-transformer design.

Core dimensions.

First we ascertain the full load on the secondary of the instrument; to do this we must find the current consumed by each lamp, and the maximum number of lamps that will be in use at any one time.

Suppose the lamps to require ½ ampere each, and twenty lamps may be alight at one time, then 20 × ½ = 10 amperes at 50 volts pressure, as the secondary load on our transformer. It is found to considerably facilitate manufacture if a regular series of standard dimensions is adopted for the transformer cores; this avoids a needless multiplicity of different patterns and sizes of core, enabling expenses to be reduced. The cores should be furthermore made of square section, for reasons that will become evident later on.

Fig. 10, with the accompanying table of dimensions, will save the uninitiated a large amount of trouble in making experiments personally, as they represent the final best results of much practical experience.

Transformer constants.

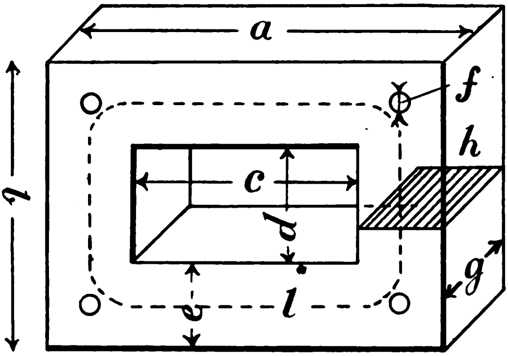
Attention must next be given to the fact that there exists a certain "constant" (k) in auto-transformer design, between the number of turns of wire, and the area of the iron core, provided the same flux-density is always adhered to, and also for any fixed frequency. That is, N the flux which is the same thing as area in this case (since flux alters directly with area), multiplied by the number of turns of wire on the coil, is always a constant quantity. In symbols

$$N \times T = k.$$

This is evident on analysing the formula

$$E = \frac{T \times N \times 4{\cdot}44f}{10^8}$$

for 4·44 times the frequency f, and 10^8 are both themselves constants, and therefore if either of the terms N or T is varied in one direction the other one must vary equally but in the *opposite* direction to preserve the equality.



No.	a	b	c	d	e	f	g	area h	length l	volume cub. inches	weight in pounds
1	5	3¼	3	1¼	1	3/16	1	1	11½	12½	3½
2	5½	3⅞	3	1⅜	1¼	¼	1¼	1½	12½	21½	6
3	6	4½	3	1½	1½	¼	1½	2¼	13½	33¾	9¼
4	7½	5⅝	4	1⅝	1¾	5/16	1¾	3	16½	54¾	15½
5	8	5¾	4	1¾	2	⅜	2	4	17½	78	22
6	9½	5¾	5½	1¾	2	⅜	2	4	20½	90	25¼
7	10½	6⅞	5½	1⅞	2½	7/16	2½	6¼	22¼	154¾	43½
8	10	8	4	2	3	7/16	3	9	21	216	60½

FIG. 10.—TABULATED DATA OF TRANSFORMER CORES.

Proportioning iron and copper.

When working at a fixed flux-density, area and flux may be regarded as the same thing. It is therefore quite possible to use several different sizes of cores for a transformer of the same capacity, varying the number of turns of wire to retain the fixed value of the constant *k*. By using a large core a lot of turns of wire can be saved, and the cost of copper diminished, but the iron losses will be increased. And, *vice versa*, by using a small iron core and many turns of wire in the coil, the same value of the constant *k* may be preserved, but at the expense of copper losses and regulation.

It needs practice in design to hit upon a nice adjustment between these two. Fig. 11 gives a curve of constants in number of turns of wire per sq. inch sectional area of core, for any sized auto-transformer from one-tenth to 10 k.w. at any ordinary frequency. Turns of wire are plotted as abcissæ, and frequency as ordinates. On selecting the frequency it is intended to design for, it is only necessary to follow the diagonal until it cuts required frequency, and then drop a vertical line on to the base, when the point of intersection will indicate the number of turns of wire needed, divided by the area of the core. At a point, *a* for instance, corresponding to a frequency of 50 periods, if projected on

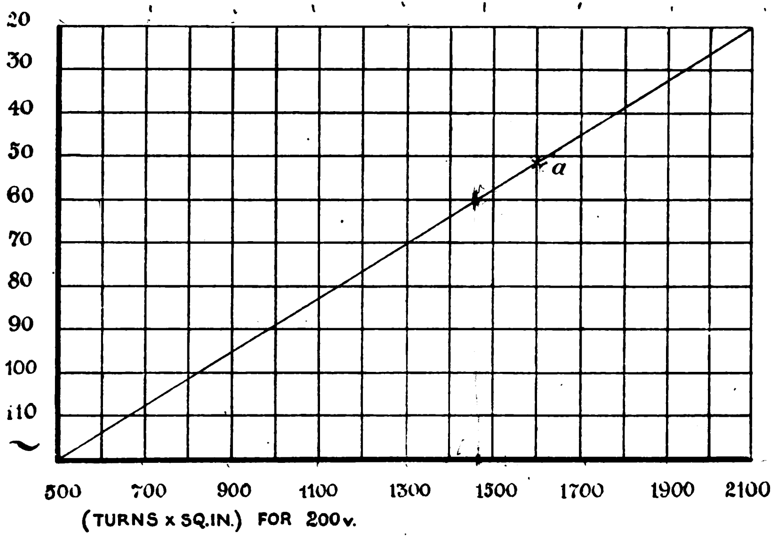


FIG. 11.—CURVE OF TRANSFORMER CONSTANTS.

the base, it will cut the value of 1600. If therefore we use a transformer of 1 sq. in. sectional area of core, we must use 1600 turns of wire for the coils. In fact the constant 1600 can be divided by the sectional area of core to give any other proportions between iron and copper; e.g. if we use a core of 2 sq. in. section we shall require 1600/2 = 800 turns of wire; if 3 in. square section, 1600/3 = 533 turns, etc. This curve is prepared for a reactive voltage of 200, and if any other voltage is required it suffices simply to make the result in turns proportionate. Thus transformers designed for 100 volt circuits and 50 cycles would have a constant of 800 = *k*, and the sectional area of core divided into 800 will then give the necessary turns.

Use of constants.

This possibility of varying proportions between iron and copper on any size of transformer makes it necessary to carefully balance up the relative advantages, both of cost of manufacture, and of efficiency, when using different combinations: needless to say the former consideration is the one which usually settles the matter in practice. Each individual size of transformer can be tried on its own merits by the conscientious and painstaking designer in order to satisfy himself, the process being to take out as close an estimate as possible of cost of material and labour in constructing, varying the proportions between iron core and copper coil until he is convinced he has obtained the least expensive result, with a good all-round efficiency, both at light load and full load.

Practical considerations.

Returning again to our design for a 200 to 50 volt ½ k.w. 50 frequency auto-transformer, we proceed next to select a core from the table in Fig. 10, and it must be one also which will accommodate in its winding space the right number of turns of wire demanded by the "constant" in Fig. 11. A few trial calculations will suffice to show that neither of cores Nos. 1, 2, or 3, will be large enough to take the requisite quantity of wire, as core No. 1 would require 1600

Determination of core size.

turns; core No. 2, 1025 turns; and core No. 3, 711 turns. Recourse must be had then to core No. 4, which has a sectional area of 1¾ in. × 1¾ in., and an area approximately equal to 3 square inches. Our flux-density, as we have seen, should lie somewhere between 50,000 and 60,000 lines per square inch; 56,500 will be a convenient number to adopt in our series of designs,* so that this at once settles the value of the total flux N by simply multiplying the number of square inches in the iron core by our flux-density. As only one factor is now left unsettled we make this the x quantity in our equation, and state it in the form:

$$x(\mathrm{T}) = \frac{\mathrm{E} \times 10^8}{\mathrm{N} \times 4{\cdot}44 f}$$

Calculating total turns of wire.

Substituting figures for the second half of this expression, we then get:

$$\mathrm{T} = \frac{200 \times 100{,}000{,}000}{(3 \times 56{,}500) \times 4{\cdot}44 \times 50}$$

which on cancelling out results in 533 turns approximately as the value of T. The exact number of total turns to 1 or 2 per cent. is of no great importance, since it merely results in a slight change of the flux-density, and does not affect the re-active E.M.F. But whatever the actual number of turns may be, it is of great importance to have the *ratio* between the primary and the secondary coils properly adjusted, and due allowance made for regulation.

Ratio adjustment.

So far we have ascertained that 533 turns of wire are necessary for the whole coil from end to end (see Fig. 2). What proportion are we now to set aside of this to form the secondary winding, and what gauge of wire shall we employ? The first point is decided by simple arithmetic, for if we assume a reactive E.M.F. over the whole coil of 533 turns equivalent to 200 volts, any intermediate connection taken off the coil at some point between the two ends will of course give a reactance proportionate to the number of turns

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* Principally for arithmetical reasons.

included. We want 50 volts on our secondary, i.e. 50/200 of the whole coil of 533 turns:

$$\frac{50 \times 533}{200} = 133\tfrac{1}{4} \text{ turns}$$

Calculation of secondary turns.

which is the right number to include in the secondary circuit, plus a small addition for regulation, in order that the secondary volts should not drop below the proper point at full-load. The exact allowance to make is obtained by calculating the C R drop, i.e. the resistance of the secondary coil multiplied by the full-load current. It generally varies between 2 and 4 per cent. To find this allowance accurately it is first necessary to find the gauge and resistance of the wire, which is the next step.

On referring back to Fig. 2 again, and tracing out the circulation of current in an auto-transformer at work, it is seen that only a part of the current in the secondary circuit is contributed by the secondary coils, and the rest by the primary. The efficiency of a well-designed auto-transformer is approximately 93 per cent. to 98 per cent., according to size, so that we may reckon on getting nearly the same amount of energy in watts out of the secondary, as the number of watts that are put into the primary. If our secondary output in this case is to be 50 volts 10 amperes there will be a primary input of a little more than 200 volts 2½ amperes.

Relation of input to output.

Gauge of primary wire.

The maximum load on the primary coils being 2½ amperes, they can accordingly be proportioned to suit that current at a 1500 ampere current-density.

Gauge of secondary wire.

The maximum load on the secondary is 10 amperes, but Fig. 2 shows us that 2½ amperes of this will be already contributed by the primary current, since the currents of both primary and secondary are in parallel circuit in an auto-transformer. The secondary turns therefore will only need to be proportioned to carry 7½ amperes.

To put the matter in another way, the ratio between primary and secondary turns is inversely proportional to the amount of current they are respectively called upon to contribute. A glance at Fig. 12 will assist in making this clear; that part of the whole coil contributing three-fourths of the total volts only furnishes one-fourth of the total current, while the coil that furnished one-fourth of the volts for the secondary circuit has to contribute three-fourths of the total current.

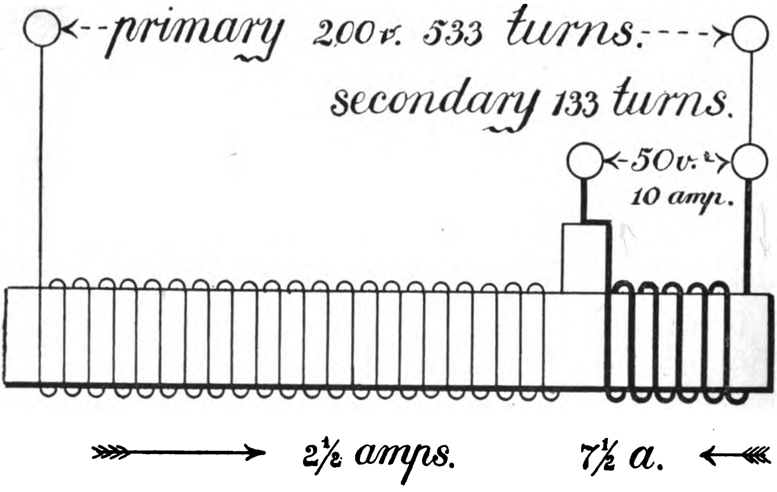


FIG. 12.—DIAGRAM ILLUSTRATING DISTRIBUTION OF LOAD BETWEEN THE TRANSFORMER COILS.

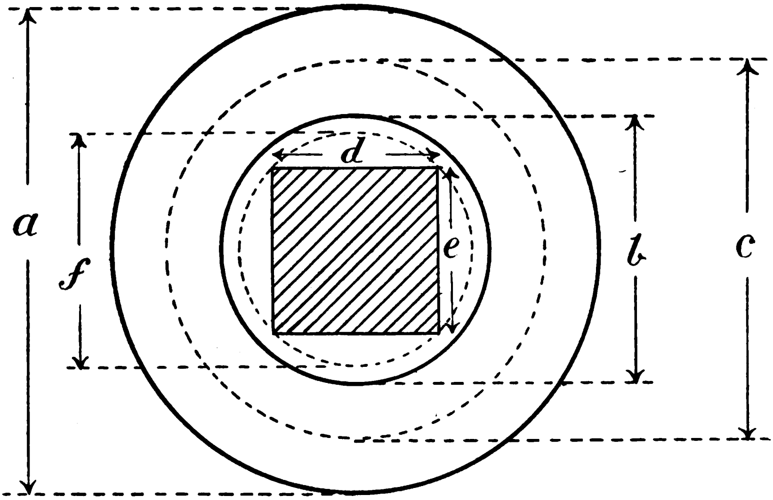
As it is somewhat difficult to obtain reliable particulars of gauges and weights, turns per lineal inch, etc., relating to copper conductors, the author has drawn up the table in Fig. 13, which will be found very handy for reference in transformer design and other work.

Volt-drop. We left our present design waiting for calculations as to the allowance required for voltage drop in the secondary, which as stated above is a CR drop, and necessitates a knowledge of the secondary resistance before it can be computed.

S.W.G.	Diameter in inches	Area in square inches	Working current at Various Densities per square inch			Resistance in ohms per yard at 60° F.	Approximate ohms. per lb.	Number of yards per lb.	Number of Turns per Linear in. for various coverings	
			1000	1500	2000				Single Cotton	Double Cotton
8	0·160	0·02011	20·11	30·16	40·22	0·00119	0·0051	4·3	5·8	5·5
9	·144	·01629	16·30	24·40	32·60	·00147	·0078	5·3	6·4	6·1
10	·128	·01287	12·87	19·30	25·74	·001868	·012	6·36	7·3	7·0
11	·116	·01057	10·57	15·85	21·14	·002275	·020	8·18	8·0	7·7
12	·104	·008495	8·495	12·742	16·99	·002831	·028	9·82	8·9	8·4
13	·092	·006648	6·648	9·972	13·296	·003617	·055	13·00	10·0	9·4
14	·080	·005027	5·027	7·540	10·054	·004784	·082	16·70	11·3	10·6
15	·072	·004072	4·072	6·108	8·144	·005904	·140	21·23	12·6	11·9
16	·064	·003217	3·217	4·825	6·434	·007478	·202	24·8	14·0	13·1
17	·056	·002463	2·463	3·694	4·926	·009762	·420	35·1	15·8	14·7
18	·048	·001810	1·810	2·715	3·620	·01328	·639	45·0	18·5	17·2
19	·040	·001257	1·257	1·885	2·514	·01913	1·32	68·8	21·7	20·0
20	·036	·001018	1·018	1·527	2·036	·02362	2·01	80·0	23·8	21·7
21	·032	·000804	0·804	1·206	1·608	·02990	3·23	107·4	26·3	23·8
22	·028	·000616	·616	0·924	1·232	·03905	5·52	129·4	29·4	26·3
23	·024	·000452	·452	·678	0·904	·05313	10·22	191·0	33·3	29·4
24	·022	·000380	·380	·570	·760	·06324	14·48	215·3	35·4	31·2
25	·020	·000314	·314	·471	·628	·07653	21·19	275·2	38·5	33·3
26	·018	·000254	·254	·381	·508	·09448	32·3	316·7	41·6	35·7
28	·0148	·000172	·1720	·258	·344	·1398	70·68	467·2	48·0	40·3
30	·0124	·000121	·1207	·1810	·2414	·1991	143·5	670·1	54·3	44·6
32	·0108	·0000916	·0916	·1374	·1832	·2625	249·3	870·2	63·2	50·5
34	·0092	·0000665	·0665	·0997	·1330	·3617	473·4	1163·0	70·4	55·0
36	·0076	·0000454	·0454	·0681	·0908	·530	1016·0	1613·0	86·2	64·1

FIG. 13.—TABLE GIVING PROPERTIES OF COPPER CONDUCTORS.

Having found the average length of one turn of the secondary, multiply this by the number of turns, and calculate the



Size of Core	Mean circumf. of Coil
1 × 1	8¼ inches
1¼ × 1¼	9½ "
1½ × 1½	11 "
1¾ × 1¾	12½ "
2 × 2	13½ "
2½ × 2½	15¾ "
3 × 3	18 "

FIG. 14.—DIAGRAM ILLUSTRATING COPPER CALCULATIONS.

resistance from the table in Fig. 13. Throughout this series of designs it is advised to make the copper coils of circular section, partly for increased ventilation, and partly for facilitating winding. The mean length of a circular turn placed round a square core is arrived at as in Fig. 14, the table in the lower part of which gives mean-turn lengths on various sized cores ready worked out to lighten the reader's labours. In the upper part of this figure, *a* represents the maximum diameter, *b* the minimum diameter, and *c* the mean diameter, the shaded centre square being the section of the iron core, necessary space for insulation having been allowed.

"Regulation" allowance.

Our 1¾ inch by 1¾ inch core selected for the present purpose gives a mean-length per turn of 12½ inches. The 133¼ turns of secondary wire will therefore give a total length of about 47 yards, the gauge of which will be No. 14 S.W.G., and the resistance 0·225 ohm. The pressure drop may be estimated therefore, at full load, as 7·5 amperes by 0·225 ohm = 1·68 volt. Extra turns of wire on the secondary will have to be provided then to compensate to the extent of

$$\frac{1 \cdot 68}{200} \times 533 = 4 \cdot 4 \text{ turns.}$$

This brings the previous number of 133¼ turns up to 138 turns, in round numbers.

CHAPTER V.

EFFICIENCY CALCULATIONS.

Calculation of no-load losses—Full-load efficiency—Power Factor.

THUS far, we have settled (1) size of iron core, (2) primary turns, and (3) secondary turns, and have only one other calculation to make before we can proceed to constructional details. The no-load loss and full-load efficiency require to be known.

No-load losses.

By "no-load losses" is meant the watts expended in magnetising the core when the primary terminals are connected across the mains, but no current is being taken from the secondary. This is got at by taking the weight of iron in the core and then looking up in the table of iron losses in Fig. 8 the watts lost per pound at that particular frequency and flux-density. It will be as well to draw up another table of iron dimensions, which will be found in the lower part of Fig. 10, and from this the lengths, areas, volumes, and weights, of our standard-sized cores may be found at a glance.

Watt-loss per lb. of core.

The 1¾ inch by 1¾ inch core has a sectional area of 3 square inches, and a mean length of 16½ inches; it contains also 54¾ cubic inches of iron. One cubic inch of iron weighs 0·28 lb., and the total weight of this core can be estimated therefore at about 15½ lb.

Fig. 8 tells us that at an induction of 56,500 lines per square inch, and a frequency of 50 periods, we shall be losing about 0·65 watt per lb. of iron, and as the core weighs 15½ lb. the total energy loss on this account, which is the no-load loss, will be just 10 watts.

The copper losses are a negligible quantity until the

Calculating copper losses.

secondary is loaded, but as soon as any appreciable amount of current begins to pass through either of the coils, energy begins to be expended in heat. To find the total copper loss at full-load we must treat the two coils primary and secondary separately, as the current values and resistances of each are different. We already know the secondary resistance, as we needed this to determine what allowance to make for regulation. This secondary resistance it will be remembered was 0·225 ohm, and the current carried by this coil at full-load = 7·5 amperes. Since watts = C^2R, the energy loss in this coil is therefore $(7 \cdot 5)^2 \times 0 \cdot 225 =$ 12·65 watts.

That part of the primary coil carrying 2½ amperes consists of 400 turns of No. 18 S.W.G. (i.e. total 533 − 133 for secondary) each 12½ inches in length, the resistance of which our wire table gives as 1·845 ohm. The watts lost in this part of the circuit will therefore be $(2 \cdot 5)^2 \times 1 \cdot 845 = 11 \cdot 53$, and the total watts for the whole coil lost at full-load $= 12 \cdot 65 + 11 \cdot 53 = 24 \cdot 18$ watts.

Total energy losses.

Had we been calculating the losses at any other load such as half-load, we should have squared *half* the previous values of current in both parts of the windings, and multiplied by their respective resistances as before.

To sum up, the total lost watts are:—

Iron losses	10 watts
Copper losses . . .	24 „
Total full-load loss .	34 „

Efficiency.

Put in its simplest aspect this means that out of every 534 watts we put into the transformer, only 500 are got out of it again. We can reduce this to efficiency terms per cent. as follows:—

$$\frac{500}{534} \times 100 = 93 \cdot 6 \text{ per cent. efficiency.}$$

Power factor.

Considerations of efficiency of any transformer would not be complete without some reference to what is known as its "power factor." This is rather a difficult matter to explain in a popular manner without treating it mathematically, but the following notes may be of assistance.

Effect of leading or lagging current.

When dealing with alternating currents on inductive circuits, the alternating waves of current which flow as a consequence of the impressed volts, are not of necessity "in step" with the volts, i.e. they may lag considerably behind the electromotive force waves. Fig. 15 is an instance of an alternating current lagging in phase behind its impressed electromotive force wave to the extent of 90° of a complete period (360°). Now unless the volts and amperes are contributing their effects absolutely together and in synchronism, it can be readily conceived that the resulting power conveyed in watts cannot ever reach its maximum possible value. And, further, should the amperes lag behind the volts by so great an extent as a quarter-phase, as drawn in the diagram, the current curve reaches its maximum value just at the instant the volts have fallen to zero. The volts too reach *their* maximum just as the current has fallen to zero.

Wattless currents.

This gives rise to a curious effect, for although energy is still taken from the mains and could be measured by two independent measuring instruments as volts and amperes, representing when multiplied together watts of electrical power, yet the current as above is rendered entirely useless for any practical purpose, because it is delivered at zero pressure. It is evident that if either of the two factors, volts and amperes (which go to make watts), are at zero value no real power can be conveyed along the circuit, for neither "voltless amperes," nor "ampereless volts" are of any use for power purposes, since they possess no power in watts.

Thus, when the self-induction of a circuit is so great as to cause the amperes to lag behind the supply volts by 90°,

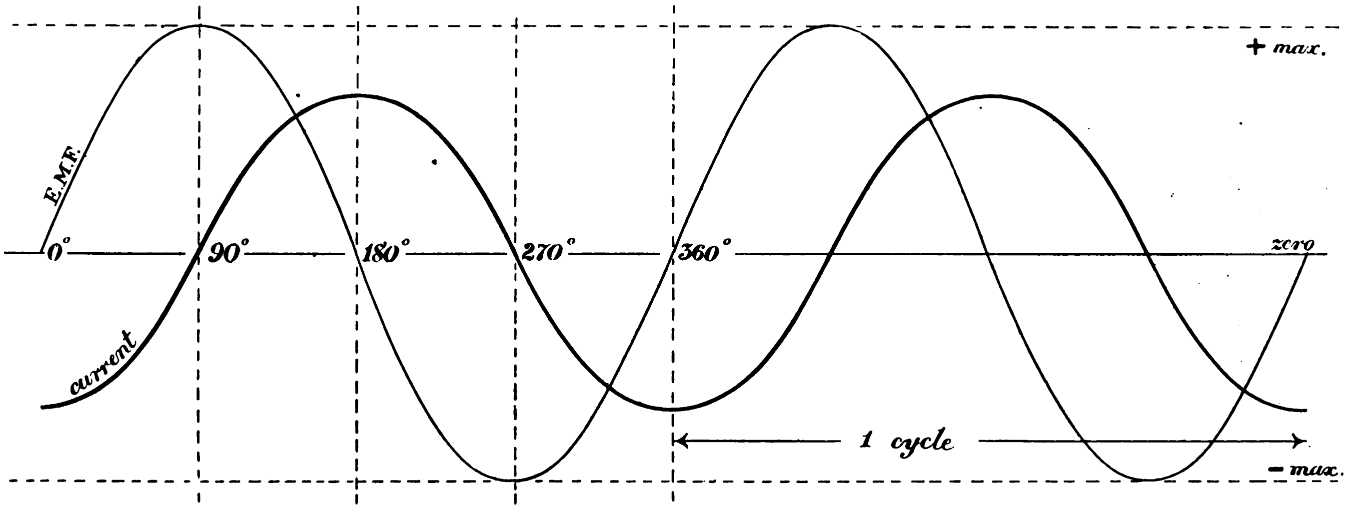


FIG. 15.—PHASE-DIFFERENCE BETWEEN ALTERNATING VOLTS AND AMPERES.

the result is merely "wattless" current. It can be proved mathematically that if there is a phase-difference between

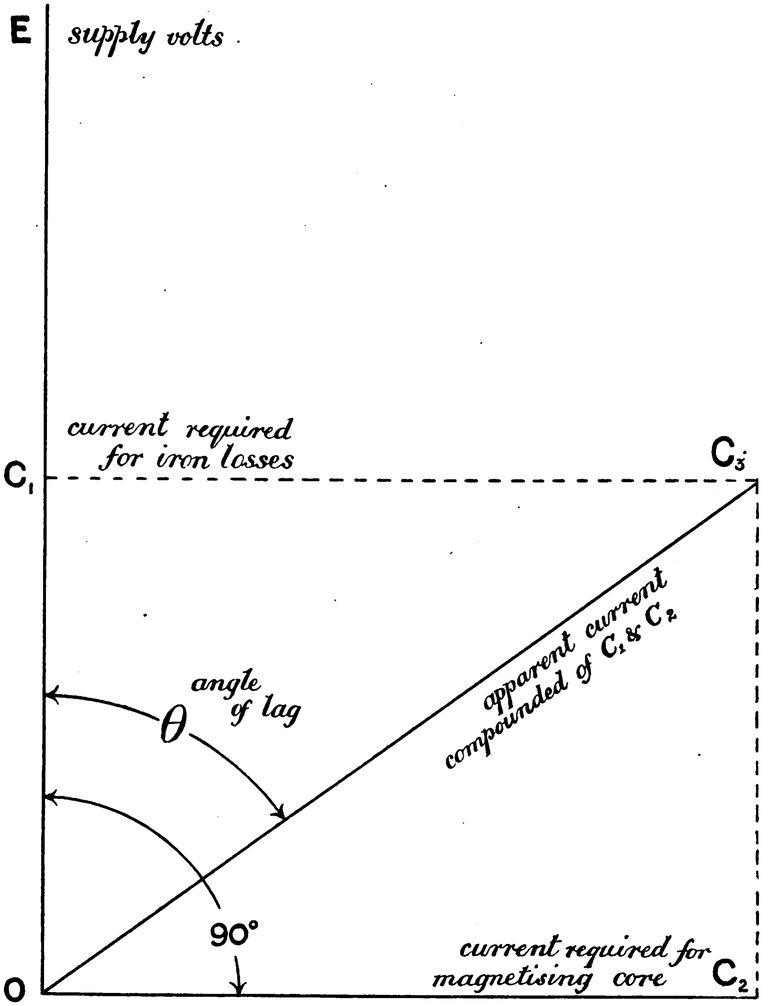


FIG. 16.—POWER-FACTOR DIAGRAM.

the electromotive-force and amperes in any circuit, the power factor is the cosine of the angle θ by which the current lags behind the supply volts. In a transformer with unloaded secondary the small current taken by the primary is resolved into two parts, one C_1 (Fig. 16) required to balance the energy losses in the iron, in step with the supply volts E, and another part C_2 utilised in magnetising the core sufficiently to produce the required reactive electromotive force, this being in quadrature (or lagging 90°) with the supply volts.

Analysis of primary currents.

These two components are plotted out to scale in Fig. 16, and the parallelogram of forces completed. The current C_3 represents the actual reading that would be given on an ammeter placed in series with the coils. The ratio between the *apparent* power supplied to the transformer $E\,C_3$, and the *true* power as represented by $E\,C_1$ (both acting in phase), gives the "power factor" of the transformer. Since the more widespread use of auto-transformers, the question of power-factors becomes an important consideration with the central station engineer. Low power-factors mean wattless currents from the station generators, and losses in the mains. As small auto-transformers are very often left in circuit continuously day and night, it may easily occur in large towns where a great number of these instruments are installed, that a considerable portion of the station plant has to be kept running merely to supply their no-load and magnetising currents, energy which is entirely unremunerative.

Importance of high power-factors.

Most service meters will not indicate the small number of watts called for by a single auto-transformer; these losses naturally form rather a tender subject to the station engineer because they cannot be charged up to the consumer!

CHAPTER VI.

CONSTRUCTIONAL DETAILS.

Core assembling—Coil winding—Insulating—Mounting--Enclosing.

WE are now quite ready to consider our designs from their practical side, and to settle upon a method of construction which shall not only conform to theoretical requirements, but shall involve the least labour in building.

As will be gathered from the following notes and illustrations, all the work is of quite a simple character, and requires no special tools, training or experience, but merely care and due attention to details.

Preparing the core.

The starting point will naturally be the iron core, and for this "Stalloy" brand sheets, or ready cut stampings must be procured. Do not use sheets thicker than No. 25 B.W.G., which will run about 50 to the inch thickness, when pressed up. The process of cutting out the strips by hand, drilling, filing up exact to template, etc., is a somewhat tedious one, and it is advisable wherever possible to procure these ready stamped or cut to size, as they are not only more accurate as to dimensions thus, but the metal itself is less likely to have suffered from an excess of filing, bending, etc., which all tend to upset its magnetic properties. If, however, the strips are cut from the sheet by hand, observe that they are all cut the *long way of the grain* or fibre, to insure getting the best results.

Alternative methods.

The form of core advised here takes the shape of a square framework, having one central aperture to admit the wire coil. It is obviously impossible to get this coil into place unless one end or side of the iron core is made removable; so that this circumstance must be met either by making the body of the core solid on three sides of the square, with a fourth one removable, or by making each side an independent member. The former saves work in assembling, but presents magnetic disadvantages since the path of the flux must cross the grain of the metal at some points. The separate side construction requires more time to build up, but is better magnetically and cheaper as regards cost of stampings. The great consideration is to obtain as perfect and as short a magnetic circuit as possible, and special attention must accordingly be paid to the avoidance of unnecessary reluctance at the joints.

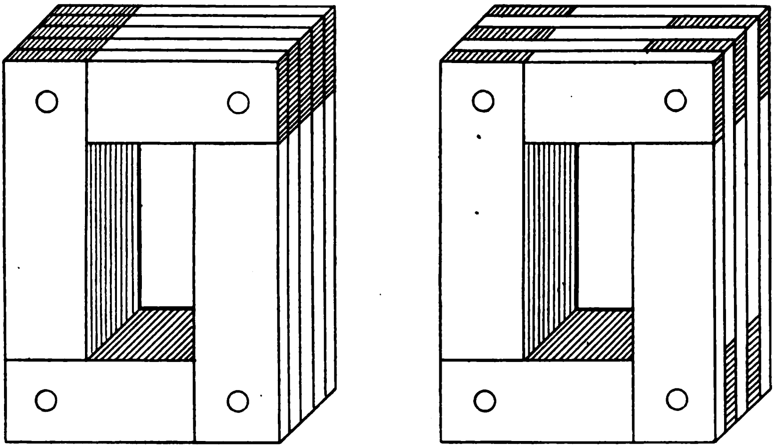


FIG. 17.—MAGNETIC JOINTS IN CORES.

Magnetic joints.

By a peculiar method of assembling the stampings resulting in what is termed "imbricated" joints at the corners this end is secured. The core stampings are of two different lengths, to form the two long and the two short sides respectively, but it will not do to assemble them all in four sets, all of the same length, simply placed together with "butt" joints at the corners as shown in the left-hand diagram Fig. 17. The long and short stampings must be interleaved and assembled alternately right and left as at *a* and *b* Fig. 18, and then placed one over the other as at *c* in proper sequence until the whole depth of core is piled up. They will then break joint at the corners as shown on the right hand side of Fig. 17, which of course shows greatly exaggerated thicknesses of stampings to render the method of assembling clear.

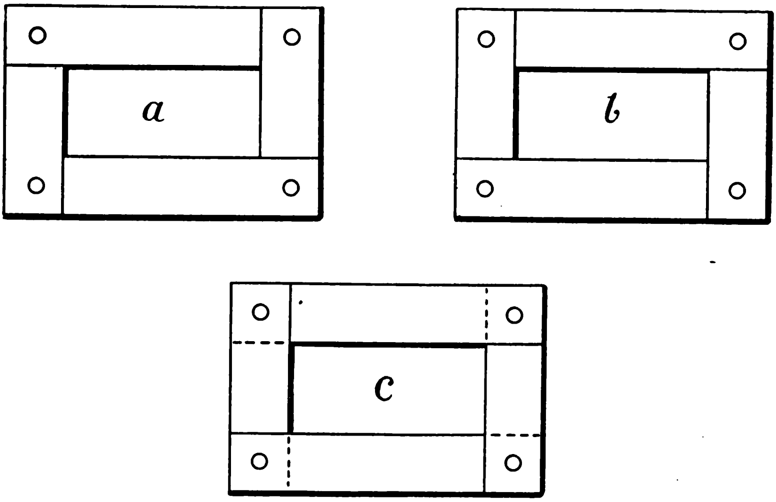


FIG. 18.—METHOD OF ASSEMBLING STAMPINGS.

Insulation of all bolts.

Three sides of the core are built up thus, and the fourth or bridge-piece left out until the copper coil is finished and put into place. Iron bolts are used to clamp the corners together firmly, but the holes provided for this in the stampings must be a little larger than necessary for the bolts, to allow of the latter being lightly insulated from the core by thin fibre or presspahn sheet. This is a very necessary precaution, since if the bolts made metallic contact with the stampings the benefit derived from lamination of the core would disappear, as heavy eddy-currents would be set up through the bolting-up pins, short-circuiting the stampings together.

The bolts are left long, to afford a means of fixing the core to a case or bracket, if desired, later on.

Preparing the copper coil will be the next item. This, as stated before, takes a circular form, being easier to wind than a square bobbin, taking less time, and providing much better ventilation than a close-fitting square coil would do.

A "former" will be wanted on which to wind this coil, fashioned after the style of Fig. 19, and made of hard wood or metal with one fixed and one removable flange. The inside diameter of the coil *a* must be such as to allow it to easily clear the corners of the square iron core, leaving room for insulation between coil and core.

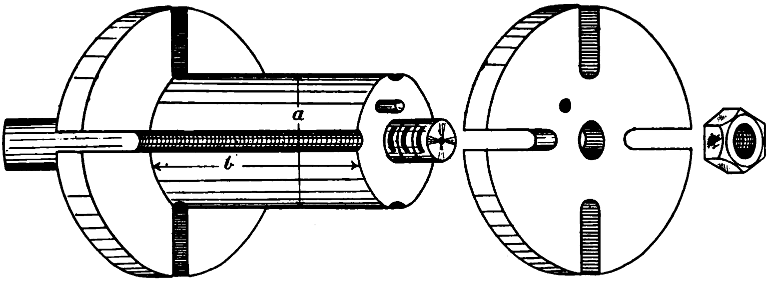


FIG. 19.—FORMER, FOR WINDING COILS.

Calling the length of the two sides of the square core Fig. 14, *d* and *e*, the diameter *f* which will have to be given to a circle that will just touch its corners is:

$$f^2 = d^2 + e^2,$$

from which

$$f = \sqrt{d^2 + a^2}.$$

"Formers" for coil winding.

An allowance of $\frac{1}{8}$ inch for insulation must be made on this diameter, therefore *a* in Fig. 19 will be $f + \frac{1}{8}$ inch for all sizes. A slight taper should be given towards the loose flange end, so that the copper coil can slip off easily after being wound. The length of this bobbin, i.e. between the insides of the flanges *b*, must for the same requirements of insulation be $\frac{1}{8}$ inch less than the length of the opening in the iron core, for all sizes. The four radial slots seen in the end flanges of the "former," and extending a little way into the body, are to enable twine to be threaded through from end to end under the coil after it has been wound, and tied securely to keep the wire in shape when taken off the former.

Winding precautions.

When starting the winding do not wind directly on to the former itself, but cut a strip of presspahn of the same width as the distance between the flanges, and wrap once completely round the body. This, with a little French chalk dusted over it before starting the winding, will insure the coil slipping off easily, without damaging it in the process.

Winding the primary.

Leave a foot or so of wire out for one end of the primary connection, and, passing this through one of the radial slots, wind on evenly and tightly the whole of the primary wire first, taking care to get the exact number of turns. The winding is best done in the lathe, but a hand turning device can be easily fitted up with a little ingenuity, if a lathe is not available. Sufficient tension must be put on the wire to keep the coil quite close and hard, because under the flow of alternating current there will be a rapid and continual series of alternating stresses, tending to rack any loose wires to and fro, damaging insulation, and causing humming when at work. Too much force will stretch the finer gauges of wire, however, so that it is necessary to use some judgment, and not overdo the matter in this regard.

Having completed the first coil, cut the wire, leaving a foot or so out as before, and carry this end also out through one of the radial slots coming nearest to the finishing point, providing only that it is not the same slot as the one in which the coil started.

It seldom happens that the primary coil fills an exactly even number of layers, but more generally ends up rather awkwardly somewhere near the middle of a layer ; in which case this layer should be wound more open, so that the last turn finishes at one end of the coil. This naturally leaves an uneven surface for the secondary winding to bed on, and to start fair again, it is best to cut another sheet of presspahn, about 1 mm. thick, and fit a layer of this snugly between the flanges to make an even surface for the next winding.

Winding the secondary.

Since the finishing end of the primary coil also forms the starting end of the secondary, commence the secondary winding by passing its starting end through the same slot as the primary has just finished in, and twist the two ends loosely together to prevent mistakes in subsequently connecting up. Then go ahead with the requisite number of secondary turns, endeavouring to bring the end of this coil out on the opposite side to the start of the primary, and also in the same slot. The end of the primary is also the end of the secondary, and must be left long enough to continue to the other primary terminal, as will be seen on looking at Fig. 2 again. The disposition of these coil ends ought to be somewhat as shown in Fig. 20.

Finishing off.

Direction of winding.

Observe carefully that the secondary is wound in the *same* direction as the primary, and after cutting the wires to the required length, push pieces of strong twine through the end flanges along the bottom of the grooves under the coil, bring the ends up over the top, and tie securely. The loose end flange is then taken away, and the coil will drop off with a tap of the hammer on the end of the "former."

Drying.

Next place this coil in an oven at a temperature of 120° to 150° F. and leave it there for half an hour to thoroughly expel all moisture from the cotton covering on the wires. It is very necessary to do this always before impregnating the coil with insulating varnish, as the varnish will not penetrate so well if the covering is not perfectly dry.

Varnishing.

While the coil is still warm, immerse it bodily in a tin of good insulating varnish such as "Ohmmaline," "Armacell," or "Voltalac," etc., and note that neither shellac varnish nor paraffin wax are suitable insulators for this purpose; leave it to soak for at least an hour, covering up the top of the tin to prevent undue evaporation. At the end of an hour examine the varnish, and note whether bubbles are still forming on the surface, showing that all the air has not been expelled yet: if so, leave it in a little longer. Then hang the coil over the tin to drain for another hour, and place in an oven to bake thoroughly.

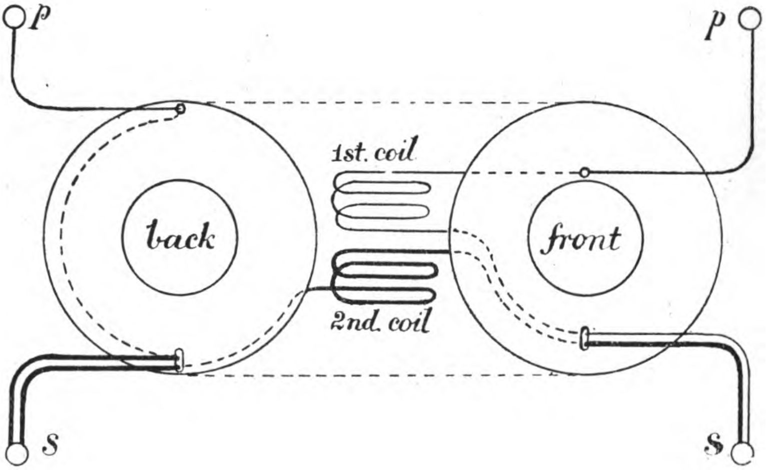


FIG. 20.—CONNECTIONS OF TRANSFORMER COILS.

Stoving. The most suitable temperature for stoving depends a little on the nature of the varnish employed, but it should not be allowed to exceed 180° F. and is better if kept a little lower than this. Two hours is the minimum time for stoving at the higher temperature, but four to six hours at the lower temperature will be better for the coil. Great care should be exercised during the stoving process not to expose the coil to the near presence of any naked lights, as the vapour given off is highly inflammable. When these directions have been well carried out, and the coil is cold

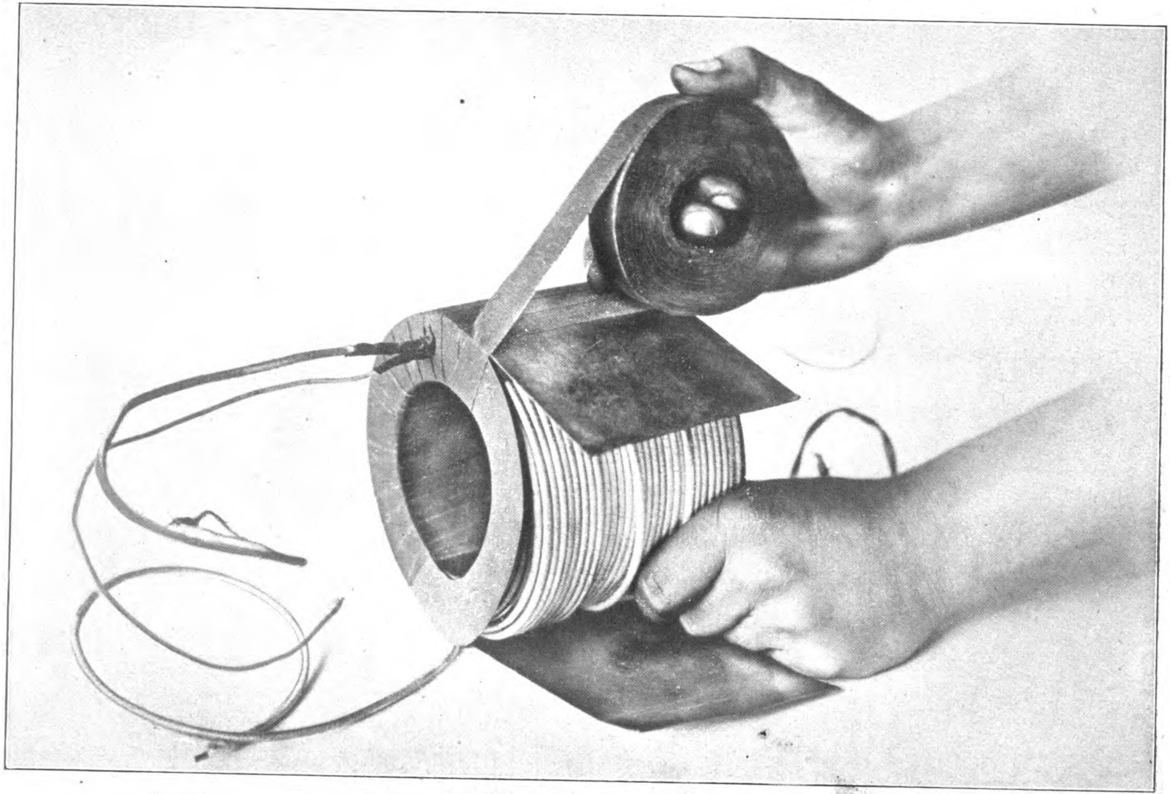


FIG. 21.—TAPING THE COILS.

again, it should feel quite hard and solid to the touch, with no stickiness or sponginess.

Extra insulation.

It is then to be dressed up with thick presspahn sheet as a further protection from mechanical injury, and lastly taped all over with black adhesive tape to bind the whole firmly together and make a waterproof covering.

Presspahn sheets, as recommended here for insulating purposes, consist of a brown fibrous material, flexible, with a glazed surface, not unlike ordinary vulcanised fibre, but less hygroscopic, and also cheaper. It forms a very useful insulation for this kind of work, being flexible, tough, and inexpensive.

Presspahn.

A strip ½ mm. thick is cut long enough to span round the coil and slightly overlap, also two end washers of the same material to match the outside and inside dimensions of the copper coil ends. Holes are made in these where required for any ends of the wires to pass through.

The presspahn coat can be tied on temporarily while being taped, this process being illustrated in Fig. 21, showing a transformer coil undergoing the final taping and insulating processes.

Hints on taping.

Taping will be more conveniently accomplished if a length of 3 or 4 yards is cut off from a large roll and made into a smaller one that can easily be passed in and out of the copper coil; it is then threaded through the centre and over the outside, as though winding a ring armature, lapping each turn of tape on the outside half over the previous one regularly and neatly, until the whole circumference has been covered. Pull the tape as tight as it will bear without breaking, and rub it down with the fingers so as to cause it to adhere firmly together. A coat of black insulating varnish over the whole improves the appearance.

Insulation everywhere must be of the best, and great care taken to carry out the above details as fully as possible, since with alternating currents there is more liability to break down the insulation than with continuous currents.

Insulating the iron core. Although the copper coil has been well and completely insulated, to prevent it suffering any damage in passing over the sharp edges of the iron core, it is advisable to cut another piece of 1 mm. presspahn sheet a little longer than the copper coil, bending it sharply and squarely to fit round one limb of the iron core where the coil is to come.

Assembling. According to previous instructions the iron core will already have been built up, so far as three of its sides or limbs are concerned. The copper coil is now carefully pushed over one of the long limbs just previously insulated as above, and the remaining stampings which bridge across the open side can then be fitted in place and the remaining two bolting-up pins inserted, not forgetting to insulate them from the stampings as before. Screw up all nuts firmly, loose tongues of stampings being secured by square sheet-iron washers under the nuts, cut long enough to just overlap the loose ends. Give the core a coat of black insulating varnish, and it is then ready to mount on a bracket or in an iron case as required.

Mounting. In the majority of instances it will be quite sufficient for all practical purposes to mount the transformer on a plain cast-iron backplate or bracket, having lugs to which the core is attached by the extended bolting-up pins, as in Fig. 24. The ends of the conductors are in this case better joined on to flexible cables, before the taping of the copper coil is done, as this makes a more workmanlike job, and they are more suitable for sweating to the primary and secondary mains than solid wires.

Where " dry joints " are permissible, i.e. clamping devices of any form, or terminals, it is convenient to have a bracket with side wings or extensions cast on, such as in Fig. 22, these extensions carrying the primary on one side, and the secondary terminals on the other, the holes of course being well bushed with ebonite or porcelain insulating collars.

Either screw-down terminals, or brass sweating sockets, with long screws and double nuts, can be employed for connecting to the main supply and to the house service mains respectively.

Local requirements.

In some towns no doubt it will be found that local electric lighting rules make it obligatory that every auto-transformer shall be completely inclosed in an iron or other metallic case, fire-proof and damp-proof.

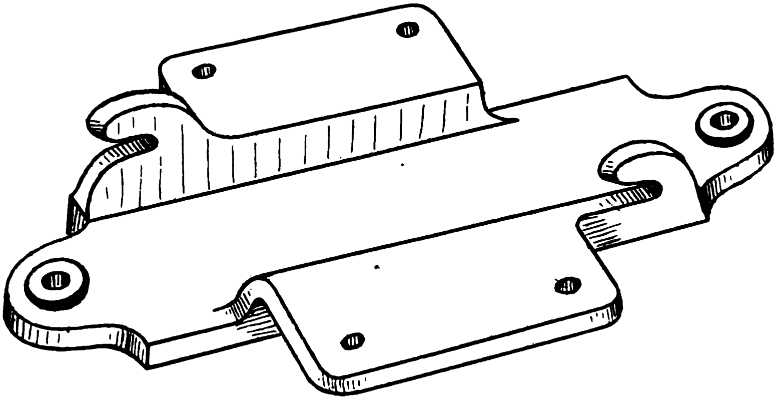


FIG. 22.—BRACKET FOR MOUNTING TRANSFORMER.

Although the open-type transformer is perfectly safe, being incombustible, damp-proof, and well ventilated if built according to the lines indicated above, it is of little use criticising compulsory conditions, however irrational, so that it will be as well before bringing this chapter to a close to consider a suitable design for a cast-iron case to comply with all and any such requirements.

Fig. 23 is a scale drawing of a case, shown in plan and section, suitable for any size of auto-transformer up to ½ k.w. capacity. It consists of a rectangular box casting *a*, with four lugs for fixing to the wall, slightly set off at the

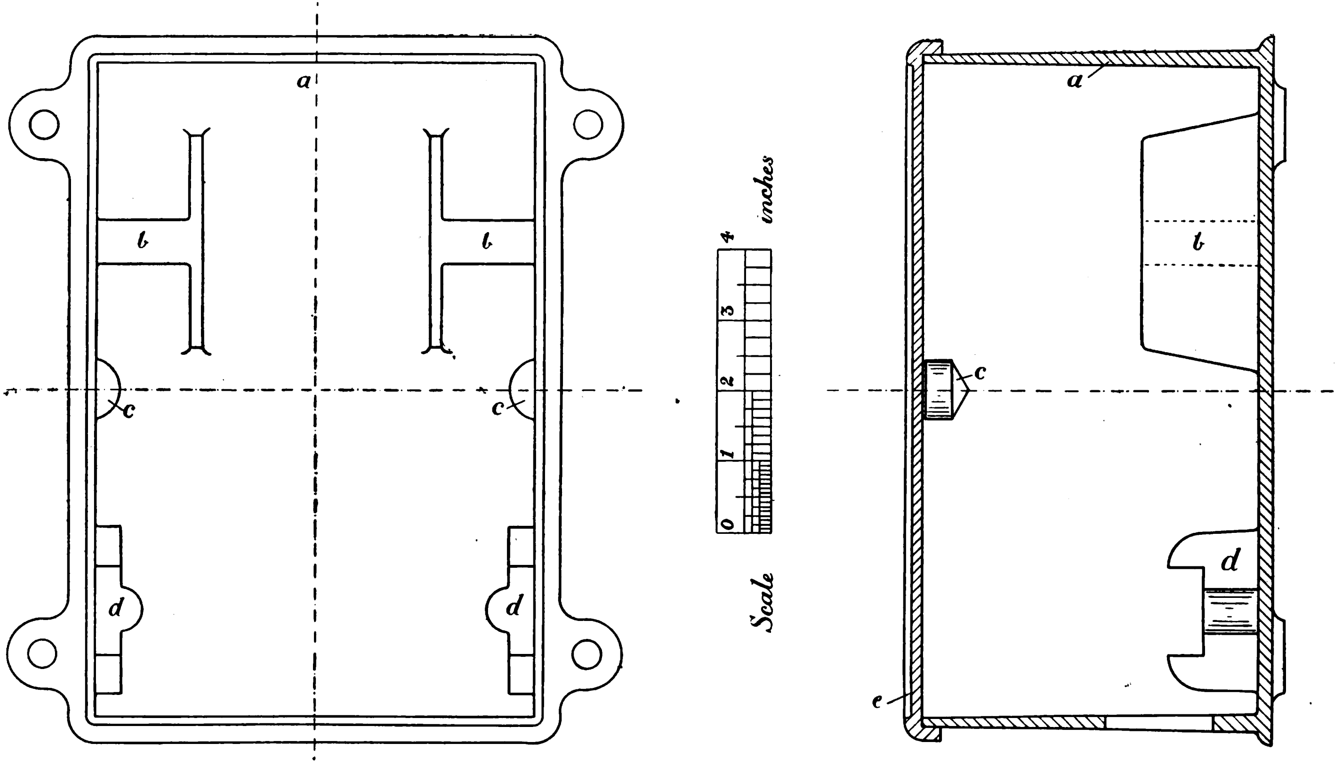


FIG. 23.—WORKINGS DRAWINGS OF IRON CASE FOR COMPLETELY INCLOSING THE AUTO-TRANSFORMER.

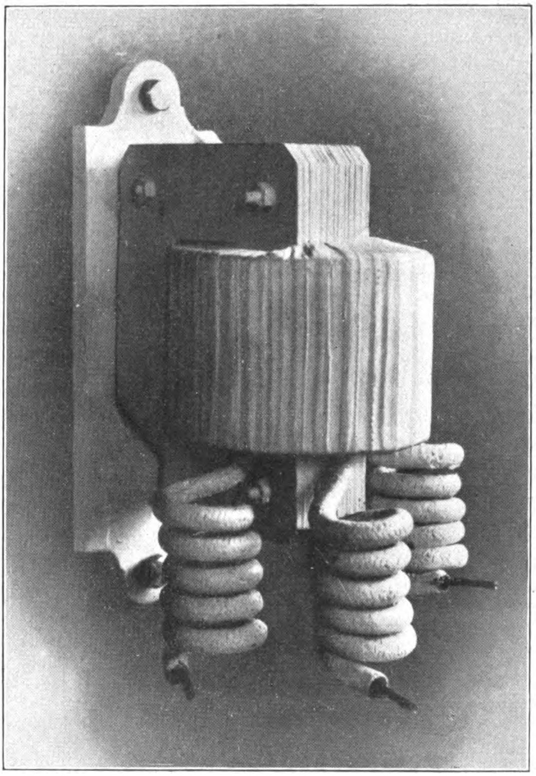


FIG. 24.—PHOTOGRAPH OF THE FINISHED INSTRUMENT MOUNTED ON IRON BACKPLATE.

back to keep it clear from any moisture that may accumulate on the walls. There is a separate cover with overlapping edges *e* secured to the lower case by two brass screws.

Iron cases.

Inside the box are two T-shaped supports *b*, *b* at the upper end on which the transformer core rests, and to which it is bolted. At the lower end of the case two recesses *d*, *d* are cast to take an ebonite terminal board, on which all connections to external circuits are made, so that all "live" metal parts are completely inclosed. The mains and service cables are led in and out of the box through an aperture left in the lower side, large enough to insure that they do not touch the iron anywhere.

A photographic illustration of the complete transformer mounted in such a case as just described will be found in the frontispiece of this book, and in this guise it will satisfy the most exacting requirements, whether of customer, contractor, or central station engineer.

The object throughout this little work, which now draws to a conclusion, has been to avoid any unnecessary mathematical treatment of the subject, but merely to indicate the lines on which a highly efficient type of auto-transformer can be produced with as little trouble and expense as possible to the builder thereof, an instrument that not only provides a somewhat novel kind of work for the amateur or professional mechanic, but, differing from the great majority of home-made productions in the electrical line, has a real and practical use when finished. Auto-transformers are interesting instruments to design and build, and their cost-saving properties constitute a pleasing reward to the successful accomplishment of one's labours.

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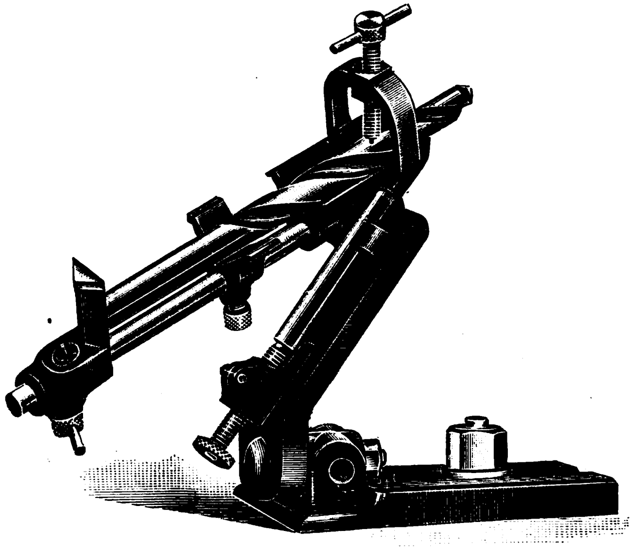

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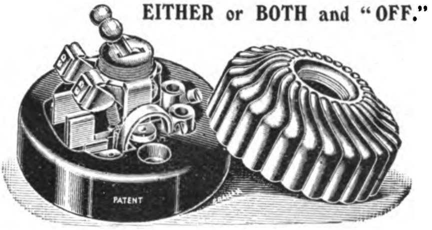
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