THE PRACTICAL DESIGN OF IRON-CORED TRANSFORMERS AND CHOKES CARRYING D.C.

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SEVERAL circuit elements in normal radio equipment carry steady direct currents, with alternating currents of smaller amplitude superimposed upon them. Typical instances are the filter chokes in rectifier systems, and inter-stage and output transformers. The inductance of these components is required for circuit calculations, and it is with the predetermination of this inductance that this article is concerned.

An air-gap is normally included in the magnetic circuit to prevent saturation of the iron by the direct current, so that the physical quantities that the designer has to manipulate to obtain a given inductance are:—

(*a*) Stamping size.
(*b*) Stacking depth.
(*c*) Number of turns.
(*d*) Air-gap length.

The method described herewith departs from the usual practice and results in a simpler and speedier manipulation.

Choice of Optimum Gap

The original method of Hanna,[1] and subsequent methods,[2] was based on the principle of designing the transformer or choke with an optimum length of air-gap in the magnetic circuit; that is, the gap which when either increased or decreased in length causes a reduction of the inductance. That there is such an optimum value depends upon the fact that if the number of turns and the core section are held constant, the inductance varies with the reluctance of the magnetic circuit. The reluctance may be increased by making the air-gap longer; but so doing reduces the d.c. saturation, increases the permeability of the iron, and decreases the reluctance. So that it follows that there is a point where the two effects balance.

In the present method it has been thought desirable to discard this principle, for the following reasons:—

(*a*) The optimum gap is often difficult to obtain in practice, if of small dimensions, because of the mechanical limitations of the gap material.

(*b*) If, by some chance, the iron quality is below normal, the required inductance value cannot be obtained by altering the air-gap length.

(*c*) Methods based on the optimum gap principle give little assistance in evaluating the inductance at some value of direct current other than the design current, a point of importance in the design of swinging chokes (i.e. chokes whose inductance is required to vary within prescribed limits with the direct current).

(*d*) In general, optimum gap methods make inadequate allowance for the increase of inductance due to the alternating flux density present, being based on very small alternating m.m.f's.

Basis of New Method

Normally, a choke is required to have a certain inductance, within limits, at a given direct current, and with a given alternating test voltage across its terminals. This test voltage is usually at a frequency of 50 c/s, its value being chosen so that the flux density corresponds to that which will be present under working conditions.

The first step in the design procedure is to select a core stamping size. This can only be done satisfactorily from past experience, but with even a wild guess as a start, two or three attempts should be all that is necessary.

Given a core size, the designer first fixes the wire size to be used in the winding, normally from considerations of temperature rise, or maximum permissible winding resistance. The number of turns in the winding is then obtained by finding the maximum number of turns of the selected wire which can be accommodated in the given core window space. (In the case of a transformer, allowance must be made for the space occupied by the secondary windings.)

After evaluating the d.c. magnetizing force, the designer finds the d.c. flux density from the curves of Fig. 1. The gap factor is selected so that it compromises between an excessive d.c. flux density and an excessive increase in the reluctance of the air-gap.

The effective permeability of the magnetic circuit is obtained from the curves of Fig. 2, and the inductance per inch of core depth evaluated from the given formula. Division of this figure into the required inductance gives the approximate core depth. If this depth is too great, in proportion to the stamping size, a fresh start with a larger core plate is necessary.

The designer, having fixed the core depth, and hence the cross-sectional area, can now find the a.c. volts per turn and the a.c. flux density.

Reference to the curves of Fig. 3 will give the increase in the effective permeability of the magnetic circuit, due to this superposed a.c. flux density. Substitution of this value in the inductance formula gives the actual inductance which will be obtained on test. It may be higher or lower than the required figure, depending upon what allowance, if any, was made when estimating the core depth. Slight readjustment of the latter may be required.

Once the details have been fixed, it is simple to find the inductance under any combination of direct and alternating currents, within the limits of the curves.

DERIVATION OF DESIGN DATA

Estimation of D.C. Flux Density

The curves of Fig. 1 enable the d.c. flux density to be found quickly.

Let B be the d.c. flux density (lines/cm^2),
A the cross-sectional area of the core (cm^2),
l the mean length of magnetic path (cm),
μ the static permeability of the iron,
$a/2$ the air-gap length in each limb of the core (total gap a cm),
N the number of turns in the winding,
I the direct current (amps),
and k the gap factor, or ratio of a/l.

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If a is small compared with l, as is normally the case,

$$BA = \frac{4\pi NI}{10} \div \left(\frac{l}{\mu A} + \frac{a}{A}\right)$$

$$\therefore B = \frac{4\pi NI}{10l}\left(\frac{\mu}{1 + \mu\frac{a}{l}}\right)$$

$$= \frac{4\pi NI}{10l}\left(\frac{\mu}{1 + k\mu}\right)$$

When k is zero (i.e. when there is no air-gap), the values of the magnetizing force in ampere-turns per cm, together with the values of μ, for assigned values of B, may be found from the B-H curve of the core material.

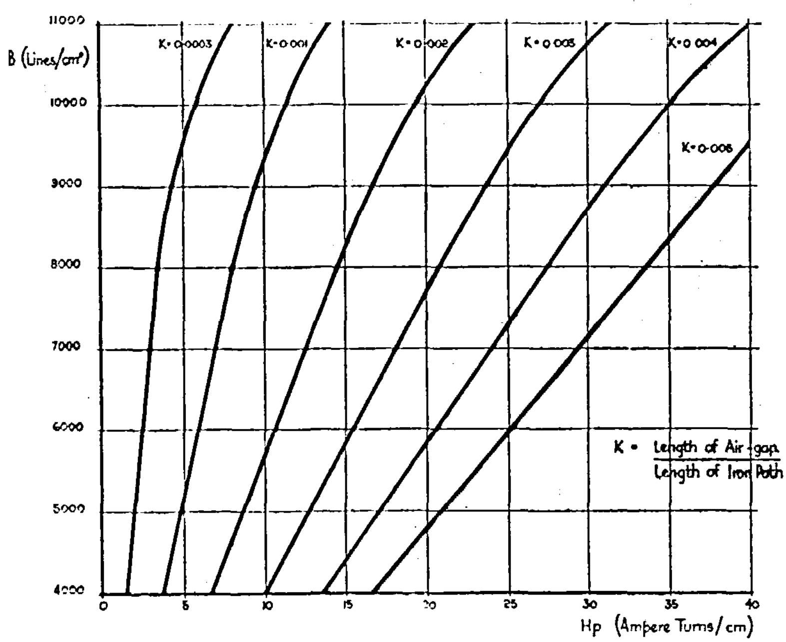


Fig. 1.— Determination of gap factor

The curves of Fig. 1 were constructed by evaluating the expression $\frac{B}{1{\cdot}26}\left(\frac{1 + k\mu}{\mu}\right)$ for various values of k, using several values of B and μ taken from the B-H curve for 0·014 in Stalloy.

Estimation of Effective Permeability

(1) *Small Alternating Flux Densities*

The manner in which the incremental permeability of the iron varies with the d.c. flux density, for very small alternating flux densities, can be obtained from makers' curves; or a test may be carried out on a sample core.[3]

The values used in this paper were obtained from tests on a 2-in depth of M.E.A. 75A stampings cut from 0·014-in insulined Stalloy, wound with a 900-turn coil and assembled without an air-gap.

The inductance was measured on an Owen type bridge with various direct currents in the coil, the alternating flux density, B_1, being approximately 10 lines/cm.[2]

The incremental permeabilities were obtained from the expression $\mu_1 = \frac{Ll10^9}{4\pi N^2 A}$, where L is the measured inductance in henrys and μ_1 is the incremental permeability.[4]

The effect of introducing an air-gap is to increase the reluctance of the magnetic circuit. The effective permeability of the whole magnetic circuit may be derived from this increased reluctance, which is $l/\mu_1 A + a/A$.

Dividing through by l/A, and inverting, will give the effective permeability, $\mu_{eff} = \mu_1/(1 + k\mu_1)$, where k is the gap factor.

The curves of Fig. 2 were constructed by evaluating this expression for various values of μ_1 and k.

(2) *Larger Alternating Flux Densities*

The variation of the incremental permeability with the a.c. flux density, for a given d.c. flux density, may be determined from a test, or from makers' curves. Since the results of the test in the previous section agreed with the latter, these were used, instead of test results, in the derivation of the curves of Fig. 3.

The effective permeabilities, $\mu_{eff} = \mu_1/(1 + k\mu_1)$, were calculated for various gap factors and d.c. flux densities over a range of values for B_1 of 10, 12·5, 100 and 500 lines/cm.[2]

When they were plotted to a base of $\log_{10}B_1$, a series of straight lines was obtained, varying in slope with both the d.c. flux density and the gap factor.

According to curves given by Terman,[4] this linearity holds for values of B_1 up to about

10,000 lines/cm², but this has not yet been confirmed by experiment on the author's part.

The slopes of the various lines were calculated, and with a value of $B_l = 10$ as a reference, the effective permeability for any d.c. flux density and gap factor becomes

$$\mu'_{eff} = \mu_{eff} + m(\log_{10} B_l - \log_{10} 10)$$
$$= \mu_{eff} + m(\log_{10} B_l - 1)$$

where μ_{eff} is the effective permeability for $B_l = 10$ (i.e. as given by Fig. 2), m is the slope of the particular line, and B_l is the particular alternating flux density.

wire, with a section of 0·00009161 in². The maximum number of turns which can be comfortably accommodated in the window space of $1\frac{1}{8}$ in × $\frac{3}{4}$ in is 2,600.

Mean magnetic length of path = 15·9 cm.

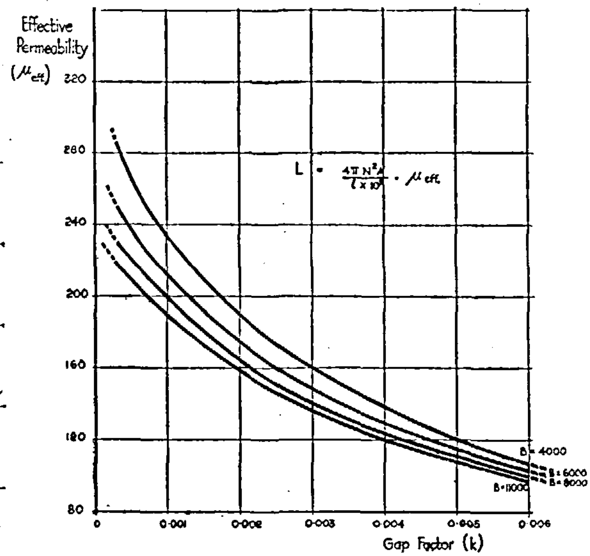
$$\text{Ampere-turns/cm} = \frac{2600 \times 0{\cdot}08}{15{\cdot}9} = 13{\cdot}1$$

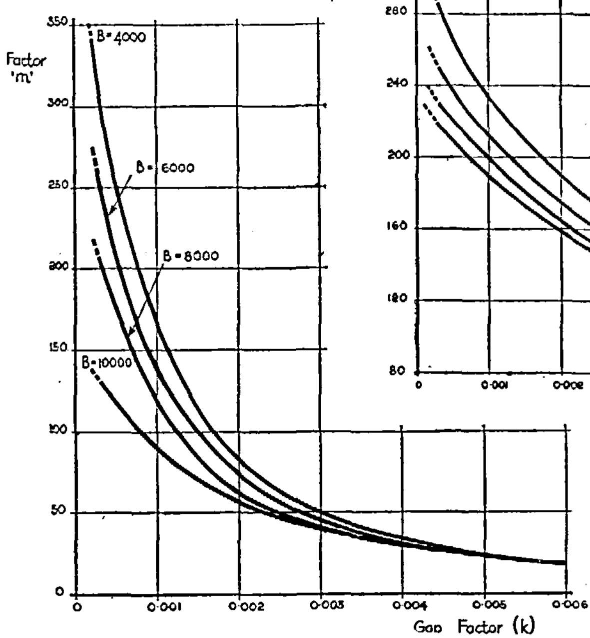
Referring to Fig. 1, a suitable value of k is 0·0015, which gives a d.c. flux density of 9,000 lines/cm.² The actual gap will be

$$\frac{0{\cdot}0015 \times 15{\cdot}9}{2{\cdot}54} = 0{\cdot}0094 \text{ in, say } 0{\cdot}005 \text{ in per leg.}$$

Referring to Fig. 2, $\mu_{eff} = 178$, so that the

Fig. 2. ⟶ Variation of effective permeability with gap





⟵ **Fig. 3.** Variation of factor m with gap factor

Values of m are plotted against values of k and B in Fig. 3.

Typical Design

The following example of a choke design will illustrate the calculation involved, and the accuracy likely to be attained.

A choke was required to have an inductance of 10 H at a direct current of 80 mA, and a test voltage of 10 V, 50 c/s.

Owing to restrictions imposed by the method of mounting the choke in service, the core plate chosen was an M.E.A. 130A, which is much longer than it is high, usually an uneconomic proportion.

A wire which will carry 80 mA at a moderate current rating is a 0·0108/0·0121 round enamel

inductance per inch depth of core, assuming a space factor of 0·9 and using the formula

$$L = \frac{4\pi N^2 A}{10^9 l}\mu_{eff} \text{ is}$$
$$\frac{12{\cdot}57 \times 2600^2 \times 6{\cdot}45 \times 0{\cdot}9 \times 0{\cdot}9375 \times 178}{10^9 \times 15{\cdot}9}$$
$$= 5{\cdot}18 \text{ H}$$

The approximate core depth is therefore $\frac{10}{5{\cdot}18} \simeq 2$ in.

Anticipating the effect of the a.c. flux density, $1\frac{1}{2}$ in is selected.

The a.c. volts/turn $= \frac{10}{2600} = 0{\cdot}00385$, and from the transformer voltage equation

$$B_1 = \frac{0\cdot00385 \times 10^8}{4\cdot44 \times 50 \times 6\cdot45 \times 0\cdot9 \times 0\cdot9375 \times 1\cdot5}$$
$$= 212 \text{ lines/cm}^2.$$

Referring to Fig. 3, the value of m for $k = 0\cdot0015$ and $B = 9{,}000$ is 58, and μ'_{eff} is

$$178 + 58 (\log_{10} 212 - 1)$$
$$= 178 + 58 (2\cdot3 - 1)$$
$$= 178 + 75$$
$$= 253$$

The inductance will thus actually be

$$\frac{5\cdot18 \times 1\cdot5 \times 253}{178} = 11 \text{ H}$$

This choke, when made, had an inductance of 10·6 henrys at 82 mA, d.c., with 10·5 V, 50 c/s a.c. superposed.

SUMMARY

With the restrictions that the data applies only to 0·014-in Stalloy, and that the ranges of gap factors and polarizing amp-turns/cm given will, in general, cover only the smaller sizes, the method given here may be used to estimate the inductance of transformers and chokes carrying both d.c. and a.c. with fair accuracy.

The method is capable of extension to any kind of core material, such as the nickel-iron alloys.

The author's thanks are due to the English lectric Co., Ltd., for permission to publish this aper.

REFERENCES

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CURRENT COMMENTS

THE numerous wartime applications of plastic materials have resulted also in several new developments in that branch of industry, a notable example being the organo-silicon polymers (which, like Polythene, is a development initiated in this country).

Silicon resins have been a commercial product in the United States for about eighteen months now—the outstanding characteristic of this material being its ability to remain flexible at extremes of temperature (from about − 40° C to 220° C for intermittent service).

As binders for glass fabric, silicones have permitted higher operating temperatures when used in the electric motor field, while oils and greases prepared from silicon resins have shown relatively small change in their viscosity/temperature characteristic, thus offering improvement in service over petroleum base oils.

In his recent Students' Lecture Mr. H. Warren showed a piece of material resembling putty but which was capable of being bounced like a golf ball on the floor, and he referred to it as "a product of research, a substance with a new combination of properties."

The raw materials for silicon resins are some of the most abundant of the earth's elements, but at present research in this country has not reached the stage of commercial production achieved by the U.S.A. This subject is, however, being actively pursued in many research laboratories in this country.

An Electronic Calculating Machine

News has recently been released of a machine known as the Electronic Numerical Integrator and Automatic Calculator, the invention of Dr. J. W. Mauchley and J. P. Aeckert of the University of Pennsylvania. It operates by the counting of electrical pulses produced at the rate of 100,000 per second. These are fed into counting circuits by electronic switching circuits, according to the operation to be carried out. A 10-figure accuracy is claimed, in addition to which the units provide a memory with a capacity of about 20 numbers, constituting the result of previous operations, and these intermediate stages can be brought out if required.

The addition of two numbers takes about 0·2 millisec, while multiplication of two numbers of 10 digits takes a few millisec. It was originally designed for the integration of equations in ballistics, but it has many other applications.

It comprises about 40 units, each about 8 ft high and 2 ft wide, embodies 18,000 valves, 3,000 indicating lamps, 5,000 switches, and takes 150 kW for its operation!

E.R.A. Jubilee

The Electrical Research Association has just completed 25 years of existence, and Mr. E. B. Wedmore, C.B.E., the original Director of Research, has handed over the reins to Dr. S. Whitehead. The Association's position is peculiar in that 90% of the research work done by industry is carried out in the specialized laboratories of the larger manufacturers. The Electricity Supply section of the industry, however, has only limited facilities for research, and much of the work of the E.R.A. has been on problems of this character.

There have been notable achievements. For example, the increased efficiency of modern steam plant, arising from the use of higher temperatures, has only come about as a result of painstaking research on steels for boiler construction and turbines, while the contributions of the Association to dielectric research are well known.

Originally the Electrical Research Committee functioned by placing its research work in the hands of such Industrial and Government Labora-