Using ferrite pot-cores

Basic inductor design for the development engineer

by D. E. O'N. Waddington, M.I.E.R.E.

When, as a schoolboy, I became interested in radio, I blamed all my failures to persuade crystal sets to work on the coils. As I lived about 50 miles from the nearest transmitter which radiated a meagre 2kW, I now feel that this was a bit unjust to the coils. Nevertheless, coil design remained a bogey for many years. One of the main reasons was that so many variables are involved that the design is always complicated. To design a single layer coil with a specified inductance value, one has to assume diameter, winding length, wire diameter and winding pitch before starting on the calculation of the number of turns. The odds are that the first try will produce a ridiculous answer and it will probably be necessary to try several times before a practical result is achieved. Even at the end of all this, there will be a nagging doubt as to whether the result is correct or not! Multi-layer coils are even worse, if possible, as the dimensions predicted by theory are seldom realizable in practice. In fact the only method appears to be to take an "educated" guess at the coil design and to check by calculation. Thus it was with a great sense of relief that I learned to use ferrite pot cores. At last here was an inductor which could be designed (most of the time!).

I will start with a short description of the core material and manufacture. It is well known that placing a magnetic core inside a coil increases its self-inductance. However, the alternating magnetic field causes eddy currents to flow within the core absorbing energy from it and reducing the effective Q of the coil. This loss occurs mainly because of the low resistivity of the core material. It also increases with frequency. In transformers it is usual to reduce this loss by laminating the core material and insulating each lamination from its neighbour. The thinner the laminations, the lower the eddy current loss, and the higher the frequency to which the core may be operated. However, a practical limit is reached very quickly so that this technique, while giving a substantial improvement, does not provide the answer for radio-frequency coils.

One method of overcoming the limitations of laminations is to use a powdered iron dust core in which finely divided particles of iron, or other ferro-magnetic material, are suspended in an insulating medium and moulded into a core. This effectively insulates the particles from each other and reduces eddy current flow but, at the same time it reduces the effective permeability of the core to ten or less. Nevertheless, these iron dust cores are very useful at radio frequencies as not only do they increase the effective inductance of coils, but, when used in cup form, they tend to confine the magnetic fields within the coil, providing a measure of screening. For high frequency work iron dust cores are superior to ferrites both in performance and cost. The design methods which I will be describing can also be applied to iron dust cores.

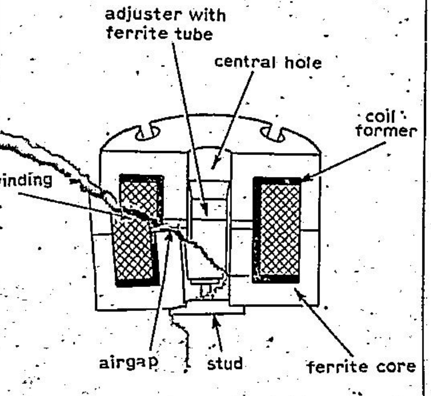

Fig. 1. Cross section of a typical pot cure.

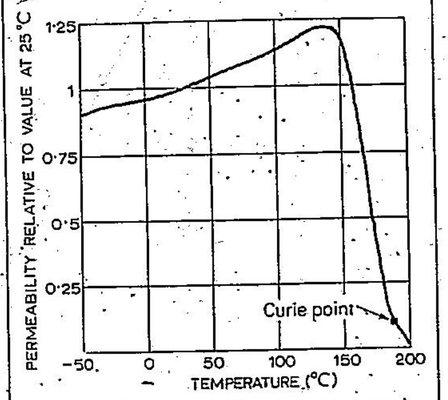

Fig. 2. Variation of permeability with temperature for a low-frequency ferrite material.

Unlike iron dust cores, ferrite cores are primarily made of non-conducting materials, which belong to the family of ferrites. The ferrites are non-metallic refractory materials composed of the oxides of iron and other metals, usually cobalt, copper, manganese, magnesium, nickel or zinc. The most important ferrites for pot cores are manganese zinc and nickel zinc-ferrite[1]. In manufacture the correct proportions of the relevant oxides are milled together so that they are thoroughly mixed. They are then moulded into the desired shape in a press and fired at a temperature in the range from 1000°C to 1300°C. During this process chemical reactions occur and when the resultant cores are cooled to room temperature, they are hard and brittle. This firing or sintering process is a very critical one as the properties of the finished core depend largely upon the precise firing temperature and the time for which it is "cooked". The cores shrink appreciably (between 20 and 25%) during the firing process and, as the ferrite is very hard to machine, it is also essential that the density of the moulded core must be correct before firing as subsequent adjustment would be very costly. The cores used for inductors are said to be "soft". In this context soft means that the core does not remain magnetized to any appreciable extent after a magnetizing field has been applied. This is analogous to "soft" iron cores recommended in text books for electric bells, etcetera.

For use in inductors, the cores are usually made in the form of cups as shown in Fig. 1. The mating surfaces are ground smooth and polished so that the air gap is reduced to a minimum. The effective permeability of the basic core material will be of the order of 2000 for low frequency ferrites, reducing to 100 for high frequencies. This basic permeability is very sensitive to temperature variations, the degree of sensitivity depending upon the composition of the ferrite. Normally the permeability increases fairly steadily with temperature until it suddenly falls off very rapidly to the Curie point (see Fig. 2). Curie point is generally defined as the temperature at which the permeability has fallen to 10% of its maximum value and lies in the range from 150 to 200°C for most ferrites although some ferrites have Curie points as high as 500°C. For inductors, the cores are usually modified by grinding the centre spigot so that there is an air gap in the magnetic path. The working permeability of the finished core depends upon the length of this gap which also confers two very desirable properties. Firstly, the temperature coefficient is greatly reduced and now depends to a greater degree upon the physical dimensions of the core. Thus it is possible to specify the temperature coefficients of various cores with fair accuracy. Secondly, by adjusting the position of a ferrite slug so that it "bridges" the air gap, it is possible to adjust the working permeability of the core and hence the inductance of a coil wound on it. As would be expected, cores with small gaps (high permeability) have less adjustment range than those with large gaps although neither has a very large range (5% to 25%). In early cores, the adjuster was not a built-in feature and it was necessary for the user to grind the core himself to adjust the inductance. This was done by rubbing the core on fine emery paper taking great care to keep the surfaces flat. I mention this method as it still has its uses when an inductor is just out of the adjuster range. However I would not recommend its use as cores are easily cracked by the overheating which can be produced by too vigorous rubbing. For repeatable and stable performance, it is essential that the two halves of the core are adequately clamped together. Most manufacturers supply excellent clamping systems although gluing, with Araldite for example, is a very effective assembly method. Cores are usually made in matched pairs so it is best to keep them in pairs. Sorting is both tedious and frustrating.

Core losses

The losses which occur in ferrite cores are of three main types; hysteresis, eddy-current and residual.

Hysteresis loss. This is usually very small compared with the other losses and, at low drive levels, it may be ignored. At high signal levels, however, it can contribute an undesirable effect in the form of non-linear distortion, mainly third order. The degree of distortion depends upon the flux density and can be predicted by calculation[1]. Normally this effect is of little significance but, in some audio applications, it may become important. The cure is

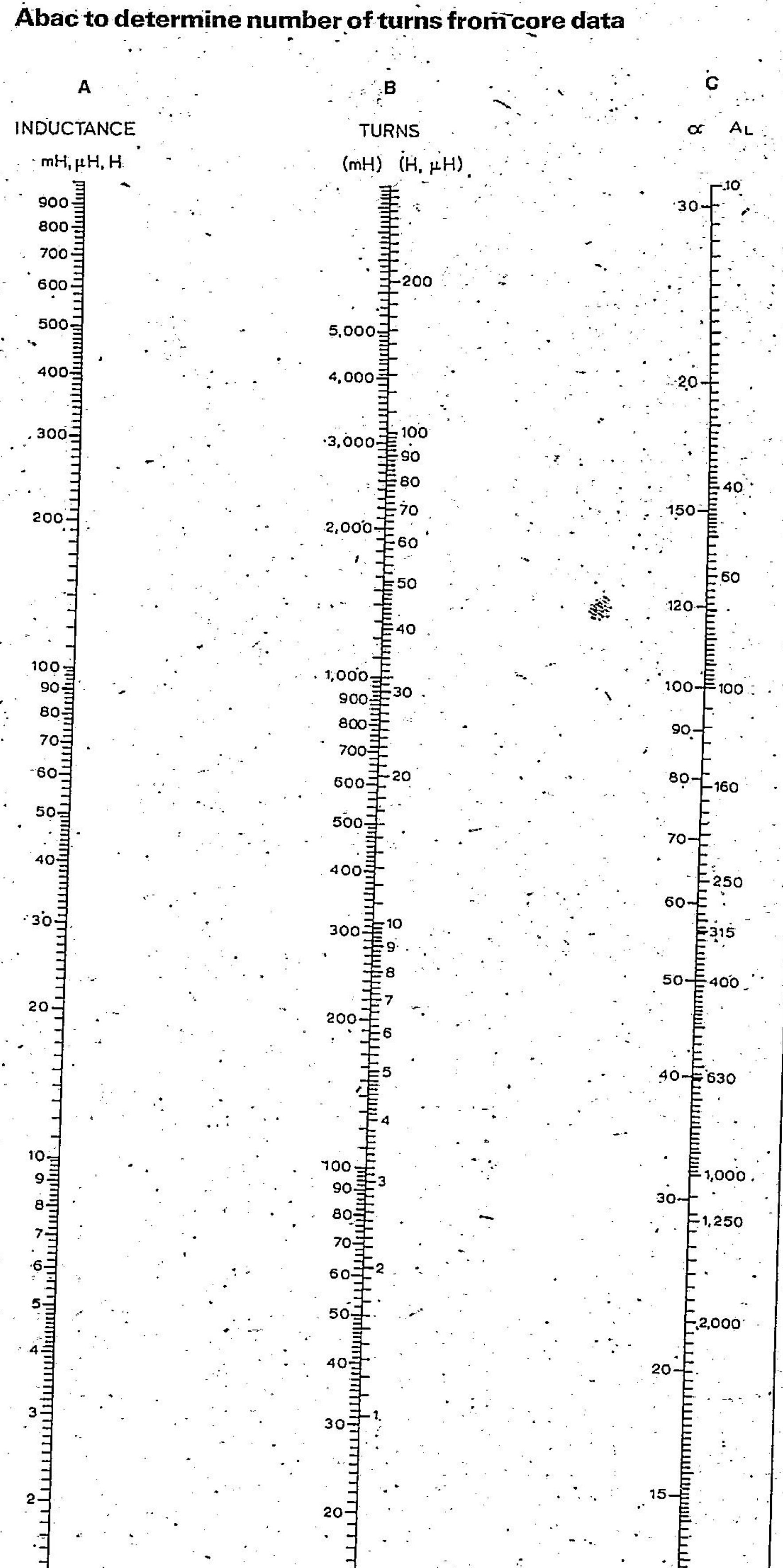
Abac to determine number of turns from core data

Fig. 3. To work out the number of turns required to give a specified inductance value, lay a ruler across the abac connecting the required inductance (on scale A) with the A_L or α (on scale C) of the core used. The number of turns is read from scale B.

Note. For micro-henries use the right-hand calibration of scales A and B. For milli-henries use the left-hand calibration of scales A and B. For henries use the same scales as for micro-henries but multiply the number of turns by 1000.

either to run the core at a lower level or to use a larger core (which amounts to the same thing!).

Eddy-current loss. This depends mainly on the resistivity of the core material. Thus, in most ferrites this loss is small so that it is normally lumped in with the residual losses. There are exceptions where the eddy-current losses "resonate" with the dimensions of the core at high frequencies[2]. The discussion of them, however, is beyond the scope of this article.

Residual losses. These depend upon the composition of the ferrite and will vary with the different grades. These losses are frequency dependent, usually increasing relatively slowly up to a "critical" frequency after which they increase drastically. Thus the grade of ferrite determines the high frequency operating limit.

Coil losses

These are far more severe than in air-cored coils because, in addition to skin effect, there are eddy-current losses in the conductors caused by proximity effects. This means that the Q of the inductor will also depend upon the type of wire used as well as the core losses. In general, solid conductors give a maximum Q at a very much lower frequency than that for maximum Q with stranded wire and the Q will also be lower. One manufacturer quotes the following:—

Solid wire $Q_{max}=200$ at 20kHz (10–100mH)
Stranded .06mm $Q_{max}=600$ at 150kHz (.2–1mH)
Stranded .04mm $Q_{max}=700$ at 200kHz (.2–1mH

This information is usually included in the manufacturers' data books in the form of typical ISO–Q curves although it is sometimes in tabular form. The word "typical" seems to have the meaning ascribed to it by a cynical engineer; namely "It has actually been achieved once!" In all fairness, however, the quoted Q can be attained under ideal conditions with all details fully under control. However, even if the final Q is less than that predicted, it should be far higher than could have been obtained using an air-cored coil and, of course, the dimensions of the coil will be considerably smaller.

Inductor design

The calculation of the number of turns necessary to achieve a particular inductance value is very easy as manufacturers quote either A_L (induction factor) or α (turns factor). These can be defined as follows:—

A_L (induction factor)—The self-inductance, in nano-henries, that a coil wound on the core should have if it consisted of a single turn.

$$A_L=\frac{L}{N^2} \text{ or } N=\sqrt{\frac{L}{A_L}}$$

L is in nano-henries
N is the number of turns.

The term α (sometimes C or K) is the turns factor or the number of turns required for a coil wound on the core to give an inductance of 1 milli-henry.

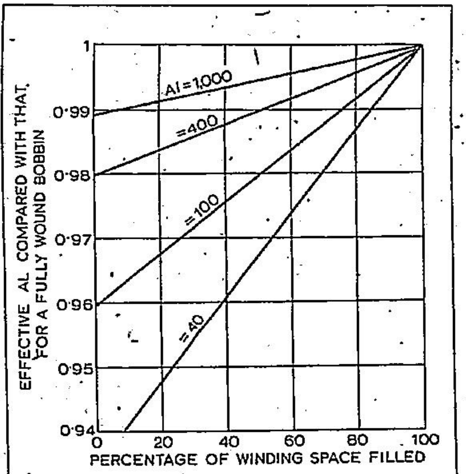

Fig. 4. This family of curves shows how the induction factor varies with the "fullness" of the available winding space for an 18mm pot core. Other core sizes will exhibit similar variations.

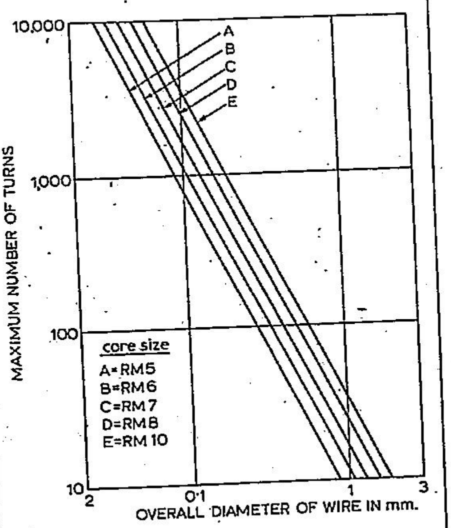

Fig. 5(a). These curves apply to round cores conforming to B.S.4061 range 2 or I.E.C. Pub.133.

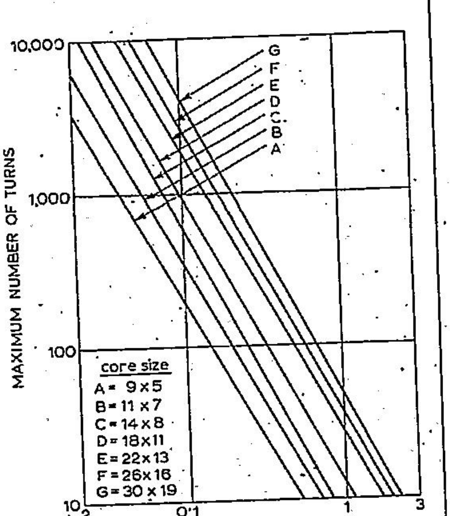

Fig. 5(b). These curves apply to R.M. (rectangular module) cores.

$$\alpha=\frac{N}{\sqrt{L}} \text{ or } N=\alpha\sqrt{L}$$

L is in milli-henries
N is the number of turns

e.g., required—a 9mH inductor. The core selected has an A_L of 400 or α of 50. $N=\sqrt{9 \times 10^6/400}=3 \times 10^3/20=150$ turns or $N=50 \times \sqrt{9}=50 \times 3=150$ turns

The abac shown in Fig. 3 provides a simple alternative method of determining the number of turns. Lay a ruler across the abac connecting the A_L or α on the right-hand scale with the required inductance value on the left-hand scale and read the number of turns from the centre scale.

Normally the winding factors given in the manufacturer's data will refer to a coil wound so that it fills a predetermined percentage of the winding space and it may be necessary to adjust the number of turns slightly depending upon whether the bobbin is fuller or emptier. Fig. 3 shows the sort of variations which can be expected with a typical core. In general it will be seen that, with high permeability (i.e., "small gap"), the degree of "fullness" of the bobbin has very little effect upon the turns factor. On the other hand, lower permeability cores (i.e., "large gap"), are more affected by the "fullness". This effect is caused by fringing of the magnetic field in the gap. It is good practice however to choose a wire gauge which fills the winding space as completely as possible. This gives the lowest d.c. resistance together with the highest Q value. Most core manufacturers give tables or charts showing the numbers of turns which will fill the various bobbins. Now that there has been a degree of standardization of core sizes (British Standard B.S.4061 range 2 and International I.E.C. Pub.133) it has been possible to prepare some winding charts which have fairly universal application. Fig. 5(a) shows winding data for the round cores and Fig. 5(b) gives data for r.m. (rectangular module) cores. The numbers of turns which should fit the cores are nominal so that it is generally safer to use a slightly thinner gauge than suggested by the chart.

I feel that a word of warning is necessary here. As George Orwell says, "All animals are equal but some are more equal than others." This comment could well be applied to ferrite pot cores. So far the standardization only goes as far as specifying the dimensions of the cores and A_L. Nothing is said of clamp-formers and A_L. Nothing is said of clamping systems, termination methods or adjusters so far as I know. At least, if it is specified, it is frequently ignored. In general British manufacturers produce reasonably compatible systems but the same cannot be said for all the imported products. This means that it is necessary to study alternative core types very carefully before accepting them as equivalents.

Earlier in this article I referred to the temperature coefficient of the permeability. Obviously this will affect the stability of the finished inductor. In practice there are one or two more points to be watched if the best stability is to be obtained. Movement of the coil in the core will change the inductance slightly so the coil should be locked in position. Similarly movement of the individual turns of the coil can also introduce instability. This makes it desirable to impregnate the coil. Actually, if moisture penetrates the coil it can degrade the Q so there is a second reason for impregnation.

If the impregnation is carried out with the coil fitted to the core care must be taken that the adjuster system is kept clear. While moisture does not affect the permeability of the basic core to any measurable extent, it can affect the adjuster system so that it is wise to check this point. Personally I have found that the adjusters which consist of a ferrite tube fitted on a plastic sleeve with a hole up their centres to screw onto a brass screw are the best. A further point to watch is a phenomenon known as "disaccommodation". This is a temporary change in permeability which occurs if the core is subjected to a thermal or mechanical shock. However, provided that final adjustment of the inductance is not carried out until 24 hours after the shock, this effect should not prove troublesome.

In conclusion I would like to thank Mullard Ltd for permission to reproduce illustrations of their cores and graphs.

References

1. Snelling, E. C. "Soft ferrites, properties and applications", Butterworths, London 1969.
2. Mullard Ferroxcube. Mullard Components Division, May 1955.