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A method of winding wire inductors to required inductance

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Abstract. A method is described for winding simple wire inductors with minimum preparative effort. A demountable variable-geometry former dispenses with bobbins. A measurement of total wire length and a simple design formula deliver inductance reliably close to required values.

1. Introduction

In the laboratory environment it is often desirable to be able to make simple prototype inductors quickly and cheaply without recourse to specialist manufacturers. Such independence, often needed in power electronics work, is usually impeded by lack of experience and particularly by the delay and inconvenience of making one-off coil formers. This paper describes a class of inductors that are simply designed to value, and do not have formers.

It is generally understood that air-cored solenoids have round wires more or less regularly wound in a rectangular envelope on a cylindrical former, as shown in figure 1(*a*). A popular alternative uses foil conductors, with the foil width defining the coil axial length as in figure 1(*b*). The inductance depends mainly on the number of turns and the shape of the envelope, and only weakly on how the conductors are arranged within. For wire-wound inductors it has long been known that the most economical design, in the sense of giving the greatest inductance with a given length of wire, has a square envelope with mean turn diameter three times the side of the square. Although this problem was studied by Gauss and Maxwell, the optimum solution, figure 1(*c*), is nowadays known as the Brooks inductor, after Brooks (1931). An important property of such inductors is that the value is relatively insensitive to departures from optimum envelope shape and proportions, provided the overall wire length is correct and the conductor packing is tight. This means, for example, that a coil made with too few turns and all too large, or a coil made with too many turns and all too small, will have inductances only slightly less that the Brooks ideal.

In a recent theoretical study Murgatroyd (1986) showed that if a given length of wire is regularly wound into a triangular section coil, as in figure 1(*d*), the maximum available inductance is only about 3% below the optimum of the Brooks geometry. The deficit occurs because wires near sharp corners are relatively less well coupled to the whole coil. Calculations also indicate that hexagonal or nearly circular sections should be slightly more efficient than the Brooks

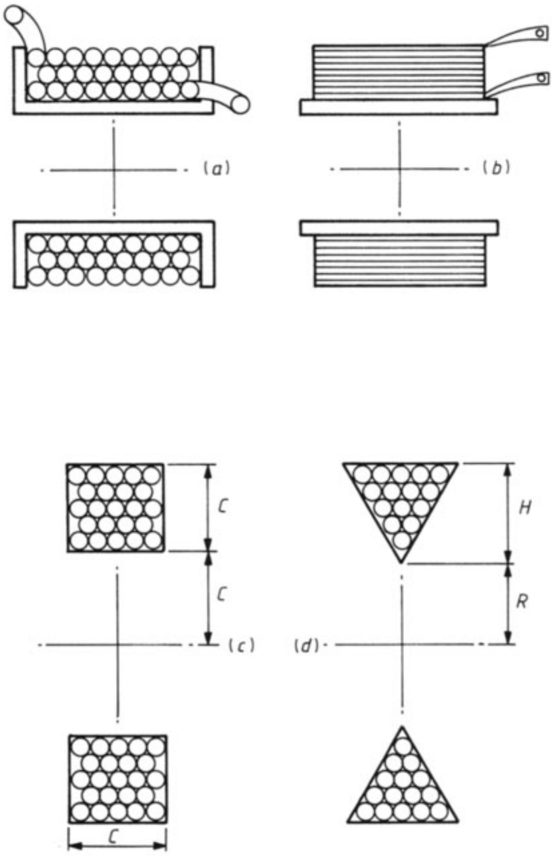

Figure 1. Solenoid inductor cross sections. (*a*) Rectangular, on pre-formed bobbin. (*b*) Full width foil winding on cylindrical former. (*c*) The most economic (Brooks) section. (*d*) Equilateral triangle section.

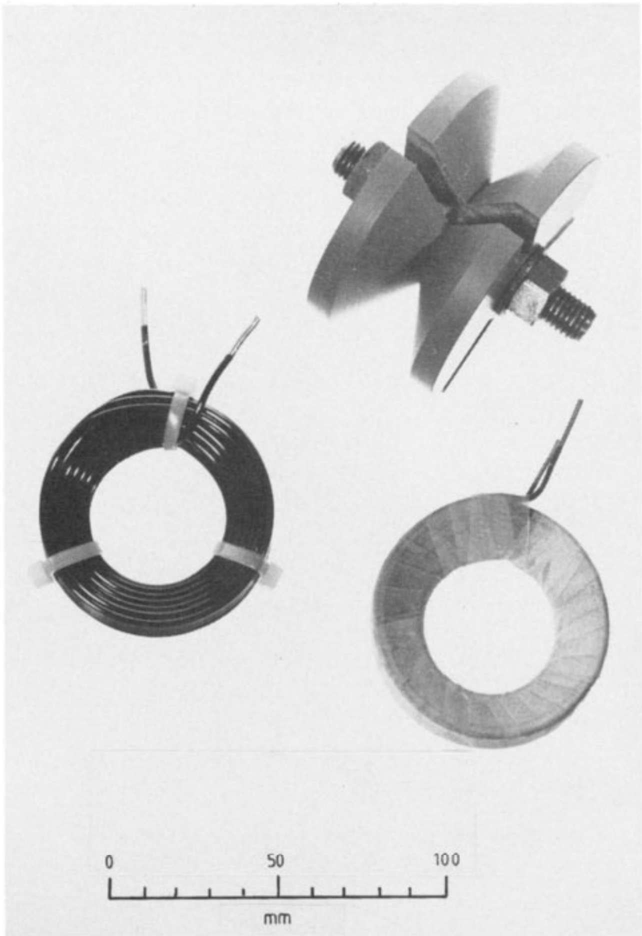

Figure 2. The single-size vee-shaped coil former, also showing coils after removal.

geometry, though the gain is unlikely to be worth the extra manufacturing effort required.

While the comparisons with conventional coils are theoretically interesting, the main motivation for studying triangular sections is practical. A variable-geometry jig has been demonstrated which not only allows manufacture of triangle-section coils in a range of sizes and inductance values, but also is immediately re-usable because the coils are tightly secured before removal. A further feature of the new construction method, desirable though not essential, is an attachment to a standard winding machine that continuously measures the wire length during winding, and will if required stop the machine automatically at a preset length. The combination of the jig with winding-to-length enables winding to required inductance, within 1% or, at worst 2%, at the first attempt.

This paper describes the construction and use of the variable-geometry jig, and the continuous wire-length measurement device. Results are presented, comparing designed and achieved inductance values, and demonstrating the scaling of inductance with the five-thirds power of wire length.

2. Method of construction

Successful winding of triangle-section coils depends on the regular packing of round wires, which lie naturally with centres on an hexagonal grid, and thus achieve the maximum possible space factor. Orthocyclic winding into a rectangular section, described by Lenders (1962), requires coil formers finely adjustable in width to accommodate an exact number of wire diameters. It appears that orthocyclic winding into a triangular section may actually be easier, because the former angle is always right even if the wire diameter changes. A possible former design is shown in figure 2, for making coils of one size only. This former is made from the hard plastic material Darvic, and is in two symmetrical parts, split at the vee, so the sloping cheeks may be separated along the coil axis, allowing removal of the coil. The cheeks each have three milled slots, which permit plastic cable ties to be tightened around the coil before disassembling the former. When the nuts on the former axle are loosened, the coil may be removed without risk of collapse. The cable ties may then be replaced (and some types may be reused) if the coil is progressively secured with plastic or fibreglass insulating tape. Impregnation or other mounting can then follow standard procedures. Coils made on this single-size former are also shown in figure 2. While this method gives a good coreless coil, and the former is reusable, the system lacks versatility. The number of layers of wire can be varied, but only one inner radius is available, unless a range of similar formers is provided.

An alternative former, which is continuously adjustable in a range of sizes, is shown in figure 3. The vee shape is created by six pairs of inclined rods, and the turn radius at the vee is varied by the setting of the locking nuts on the drive shaft. If the nuts are tightened, the alloy supporting plates move closer together, the two sets of silver-steel rods interpenetrate further, and the radius at the vee increases. Only one of the alloy plates is keyed to the threaded steel drive shaft: drive to the other plate is through the six points of contact of the inclined rods. In practice the coils finish nearly circular as the number of wire layers increases. To facilitate coil removal, the plates are each slotted to allow cable ties to be passed under the wires. Since for a given type of wire the inductance of a correctly proportioned triangle-section coil varies as the

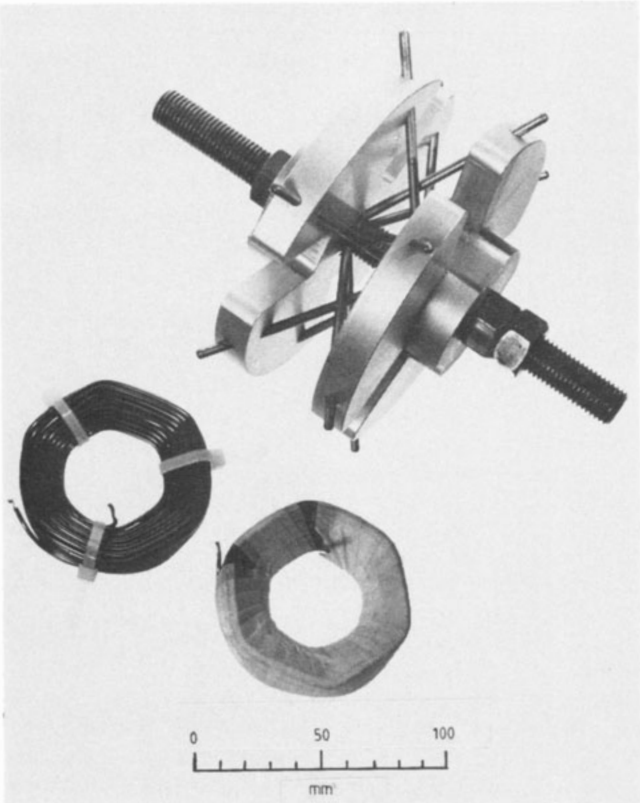

Figure 3. The variable-geometry coil former with coils secured by cable ties and by fibreglass tape.

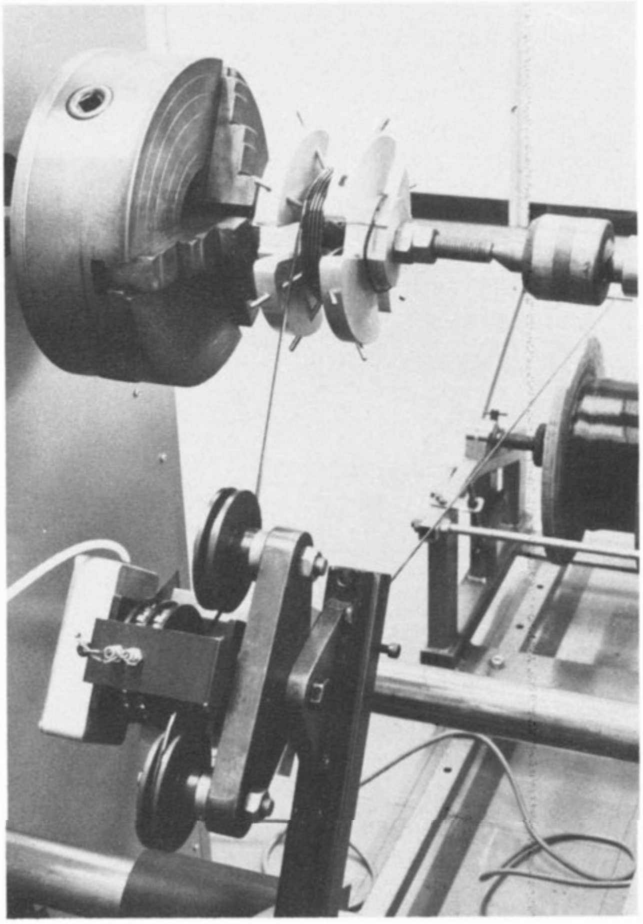

Figure 4. Installation of the wire-length measurement system on the winding machine.

fifth power of the vee radius, the range of inductance achievable with this type of variable-geometry former is potentially very wide. The only problem encountered in tests has been slight bending of the 4 mm diameter rods when attempting to wind solid copper wire of 3 mm diameter, so in practice the largest wire used so far has been 2.5 mm diameter.

3. Wire length measurement

The photograph in figure 4 shows the measuring head attached to a Whitelegg coil-winding machine. (Standard equipment on such machines would be a large face-plate, and the three-jaw machine chuck is a local modification.) The wire supply is from a stock reel with a demand-release friction brake. The standard wire-guide pulleys are retained. Between them, the wire passes over a rubber-sheathed wheel used to measure length simply by friction, and on the same shaft are two steel cogwheels, mutually offset in angle by half a cog. As this shaft is driven, as the wire is drawn onto the coil, cogs are detected using passive permanent-magnet heads (RS Components 304–166) providing pulse signals which, when amplified and squared, may be counted, scaled and displayed. The use of two heads makes the system sensitive to direction, so that if for any reason the wire must be pulled off the coil the system counts backwards.

Calibration of the length display is made by repeatedly running a measured loop of string through the system. If the winding machine is driven at its minimum rate, equivalent to below 100 mm feed per second, there is a risk of measuring short, because the pulse amplitude from the magnetic heads reduces in proportion to the cog speed. However, even at the slow rates normally used to achieve perfect layering with the wire steered by hand, the calibration is stable.

A standard feature of the winding machine, in addition to a turns counter, is an automatic stop at a preset number of turns. By interrupting this circuit with a jack-socket, a facility has been provided to stop winding at a preset wire length, which is in practice a preset pulse count determined by the calibration factor. The required count is set up on the wire-length display using thumb wheel switches. With the length measurement unit connected, three options are available: 'stop on revs', 'stop on length', or 'free run', where the latter requires intervention by the operator. If length control is not required, removal of the jack plug leaves the winding machine operating normally.

While the automatic measurement system described here is certainly convenient, it is not essential. If only small numbers of coils are needed the length of wire may be measured and marked on the wire, in advance, by temporarily dereeling in a long corridor, and using a surveying tape.

4. Inductance formula

The starting point for the inductance formula is the Brooks design, figure 1(c), which has

$$L_B = 2.029\mu_0 c N^2 \tag{1}$$

where c is the side of the square section containing N turns. The total wire length is

$$W = 3\pi c N. \tag{2}$$

In perfect hexagonal packing, the wires occupy 0.907 of the sectional area, so

$$0.907c^2 = N\pi d^2/4 \tag{3}$$

where d is the wire diameter, over the enamel. It is convenient to define a scale inductance $L_0 = \mu_0 d/2\pi$ and to express the wire length as the dimensionless number $k = W/d$.

Table 1. Comparison of designed and measured inductance values.

Wire diameter d (mm)	Wire length W (m)	k/1000	Turns N (nearest)	Inductance (μH) Target	Measured	%Error
1.6	20.65	12.9	100	700	695	−0.7
2.0	18.45	9.2	80	500	496	−0.8
2.0	12.17	6.1	61	250	249	−0.4
2.0	9.83	4.9	53	175	176	+0.6
2.0	8.60	4.3	48	140	140	0.00
2.5	7.68	3.1	39	100	98.5	−1.5
2.5	5.06	2.0	29	50	49.1	−1.8
2.0	3.74	1.9	28	35	34.6	−1.1
2.5	4.09	1.6	25	35	34.4	−1.7
2.5	2.92	1.2	20	20	19.6	−2.0

In these variables the Brooks design is given by

$$L_B/L_0 = 0.318\,k^{5/3} \qquad N = 0.235\,k^{2/3}. \tag{4}$$

It has been calculated (Murgatroyd 1986) that the best equilateral triangle section should give about 3% lower inductance than the Brooks, so the expected maximum possible inductance is given by

$$L_T/L_0 = 0.3085\,k^{5/3}. \tag{5}$$

There is some latitude in the choice of proportions of the triangle-section coil, i.e. height of triangle relative to inner radius, but from knowledge of the Brooks section the design is not expected to be sensitive to the choice. It is convenient therefore to let the inner radius equal the triangle height, $R = H$ in figure 1(d). With this assumption the total wire length is

$$W = 2\pi N(R + \tfrac{2}{3}H) \to \tfrac{10}{3}\pi\,NH. \tag{6}$$

Provided N is not too small, the section area $H^2/\sqrt{3}$ is assumed filled with wires, so

$$0.907\,H^2/\sqrt{3} = N\pi d^2/4. \tag{7}$$

Using the above relationships, the design procedure is as follows.

(i) The wire diameter d is selected, having regard to current density or other criteria, and the scale inductance is $L_0 = \mu_0 d/2\pi$.

(ii) The required inductance L_T is used to calculate the required length of wire W from

$$W/d = k = (L_T/0.3085\,L_0)^{3/5}. \tag{8}$$

(iii) The inner radius, assuming the proportions $R = H$, is given by $R/d = 0.5232\,k^{1/3}$.

(The approximate number of turns will be $0.1825\,k^{2/3}$. This number probably will not fill the last layer completely, and is not controlled in the winding procedure, which depends on the correctness of W and on neat regular layering.)

5. Inductance measurements

The variable-geometry former has been used to wind a series of coils, some of them shown in figure 3, to test the design formula. Details are given in table 1, and the scaling of inductance with $k^{5/3}$ is demonstrated on the logarithmic plot figure 5. The calculations have used the nominal wire diameters, so d and k are only correct to two figures. The diameter may in practice vary slightly from reel to reel, or even on the same reel: Lenders (1962) suggests redrawing if the spread of d is excessive, but the procedure has disadvantages and was not done in the present work. Spot checks with a micrometer are useful, and a simple way to obtain the average diameter is to wind a tight single-layer solenoid and count turns in a long axial length. Averaged over the 10 coils, the measured inductances are 1.2% below the designed values. The largest errors were all found in the coils with fewest turns, which tend to follow more closely the hexagonal shape imposed by the former: the coils with most turns become more nearly circular in their outer layers. The results suggest that with only a small amount of practice it could become routine to wind similar coils to within 1% of design value. It is interesting to note that in the mid-range of the test series, $N \sim 50$, the addition or removal of just one turn would displace the inductance by 4%. The setting-up of the former is done by adjusting the separation of the supporting plates. For the test coils described in this paper this was done by eye against a steel ruler, so although the angle is exact, the inner radius is probably only correct to the nearest one or two

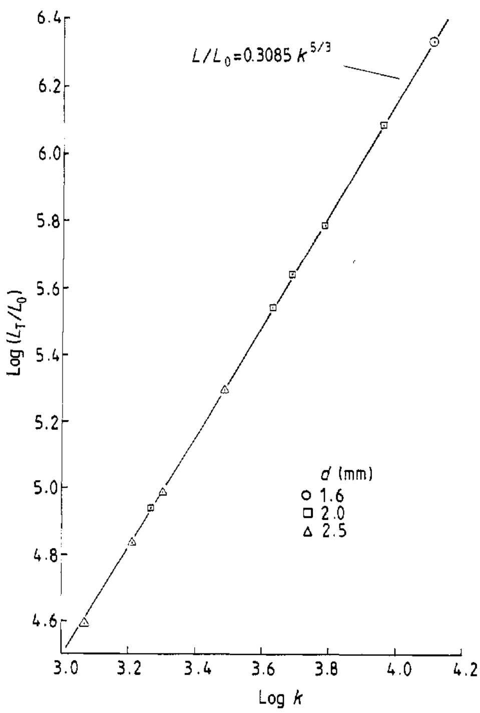

Figure 5. Logarithmic plot of normalised inductance and normalised wire length.

millimetres. Both the underlying theory and the results obtained indicate that very accurate setting of the former is not required: the most important quantity determining the inductance is the overall wire length.

6. Conclusion

This paper has demonstrated a simple and usefully accurate method of making wire inductors to required values. The most important measurement is overall wire length. The initial effort of make the vee-shaped formers, both fixed and variable geometry types, is not excessive, and they may be reused indefinitely.

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An improved and semi-automated version of the drop volume technique for interfacial tension measurement

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Abstract. Although it requires only small volumes of liquids, the drop volume technique is capable of measuring interfacial tensions with high precision. The volume of the drop which just detaches from a cylindrical support of known radius is determined, and this value is used in conjunction with known liquid densities and empirically derived tables (Harkins and Brown 1919) to calculate the interfacial tension.

A recently introduced syringe micrometer head (Mitutoyo Digimatic Series 164) allows the traditional technique to be improved in two ways. First, the new head has an increased capacity, which in certain systems means that the accessible range of interfacial tensions is widened and in others that more data are obtained from a single setting-up of the system. Second, the head is capable of outputting in BCD form. This allows the technique to be made on-line and eliminates a tedious calculation routine.

1. Introduction

The drop volume method for interfacial/surface tension measurement is capable of a precision comparable with that of the 'Wilhelmy plate' method, whilst having the advantage over this technique (and many others) of only requiring quite small amounts of the liquids concerned. The method involves the accurate measurement of the volume V of the drop which just detaches from a cylindrical support of known radius r, the tension being calculated using the empirically derived, system-dependent coefficient $\varphi(r/V^{1/3})$ due to Harkins and Brown (1919):

$$\gamma = \Delta\rho g V/2\pi r\varphi(r/V^{1/3}) \tag{1}$$

where $\Delta\rho$ is the density difference between the two liquids and g is the acceleration due to gravity. In favourable cases the precision is of the order ± 0.01 mN m^{-1}.

2. Delivery system modifications

The technique traditionally utilises the 'Agla' all-glass micrometer syringe (manufactured until recently by The Burroughs Group) or its equivalent. This is coupled to a standard micrometer head having a maximum distance of anvil travel of 25 mm (equivalent to a syringe delivery of 0.5 ml) and capable of being read to 0.001 mm. A recently introduced micrometer head, the Mitutoyo Digimatic Series 164 has, unusually, double the normal maximum anvil travel, whilst