INDUCTORS IN PRACTICE

In spite of their apparent simplicity, inductors none the less often pose problems, because invariably they cannot be obtained ready-made, i.e. they have to be designed and wound by the constructor. This article aims at removing some of the obscurities surrounding this subject and showing that making an inductor is not such a daunting task as some think.

An inductor is an electronic component that possesses appreciable inductance. Self-inductance is the property of a circuit to oppose any changes in current flowing through the circuit: this manifests itself by the production of a voltage that tends to oppose the change of current. This voltage is called the back-e.m.f. Mutual inductance is the phenomenon whereby voltage is induced in one circuit by changing the current in another. The unit of both self- and mutual inductance is the same: the henry, but their respective symbols are L and M (or L_{12}). An inductor has an inductance of 1 henry if the back-e.m.f. in it is 1 volt, when the current through it is changing at the rate of 1 ampere per second.

Inductors invariably consist of many turns of wire wound adjacent to one another on the same support, called the former, but in high-frequency applications they are often self-supporting (i.e., air-cored). The former may also be of ferromagnetic material to increase the inductance many hundreds of times. Unfortunately, so-called eddy currents are induced in the ferromagnetic material, and these increase the DC resistance in a practical inductor. Powdered-iron cores are, therefore, used at high frequencies because their high resistivity makes eddy-current losses negligible. Such ferrite materials are not as useful as iron at low frequencies, however, because magnetic saturation restrict the maximum power level of the inductor.

Inductors have a frequency -dependent resistance (called reactance) to AC currents, and an ohmic resistance, which is primarily due to the wire from which the inductors has been wound. The reactance, X_L, is equal to ωL, where $\omega=2\pi f$, in which f is the frequency of operation, and L is the inductance in heries. The ratio of the reactance to the ohmic resistance, i.e. $\omega L/R$ is called the *Q*(uality) factor of the inductor. The combination of reactance and resistance is called the impedance, Z.

An inductor is generally called a choke if its main purpose is to present a high reactance to AC currents. At high frequencies it is often sufficient to run the supply or bias lines in a circuit through small ferrite beads to effectively prevent these lines picking up (and radiating) RF signals.

Where spurious coupling with other circuit elements is to be avoided, the diameter of the choke should be kept small as a practical way of narrowing the magnetic field around it. Pot cores are another means of obviating radiation and spurious coupling.

Nowadays, designers have a wide choice of cores and formers for all types of application.

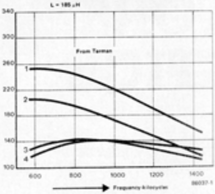
It should be noted that a wide range of standard RF chokes is available from most good electronics suppliers. These components are usually wound on a ferrite core and are encapsulated to prevent stray fields around them. The Q-factor of these chokes is often good enough to allow their use in tuned circuits. However, if they are to be used in filters, they should have a resistance of not more than 0.8 ohm per millihenry, and they must be ferrite-encapsulated. Non-encapsulated types must be separated by at least one diameter, or an earthed screen placed between them.

Inductors in tuned circuits

Inductors for use in tuned circuits, such as oscillators and filters, should normally be specially wound for the purpose to ensure correct inductance, resistance, *Q*-factor, and dimensions.

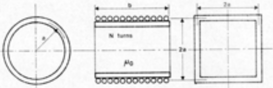
Losses in inductors are mainly due to the resistance of the wire used for winding the inductor, and the so-called *skin-effect*. Since RF currents travel mainly along the surface of a wire, this is often silvered to keep I^2R losses low. Where large wire diameters are necessary to achieve a certain inductance, it is possible to

1



Coil No.	Length/Diam.	Diam.	SWG	No of turns
1	0.96	4.25"	No. 20	51
2	0.417	4.50"	No. 24	38
3	0.96	1.875"	No. 28	75
4	2.58	1.5"	No. 28	123

2

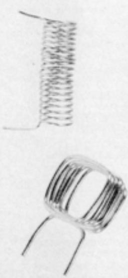


use hollowcopper tube to wind the inductor, since this may considerably lower its total costs and weight; from an RF point of view, it makes no difference whether the wire if hollow or solid, because of the skin-effect. However, it should also be noted that a solid wire has considerably lower resistance than a hollow wire of identical diameter. Since an increase in resistance inevitably causes a lower Q factor (see formula (10), the hollow tube is generally only used for relatively low frequency applications, where considerable currents flow, e.g. in the case of short-wave power amplifier tank coils, or antenna tuning units. As already discussed, designing for a known Q factor is accomplished by careful consideration of a number of factors that relate to practical inductor winding data. To illus trate the relative importance of these factors, Fig. 1 shows a number of Q factor curves obtained with different winding data to obtain a given inductance. From these and

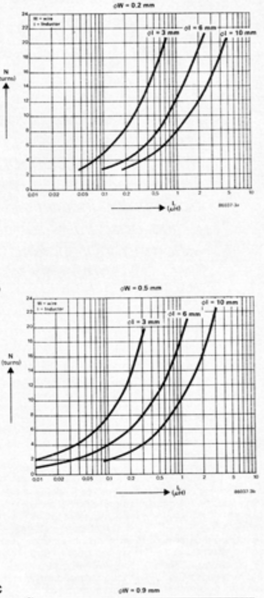
Fig. 1. These curves show that the Q factor of an inductor strongly depends on its winding data.

Fig. 2. These coil data provide the necessary information for the inductance calculations.

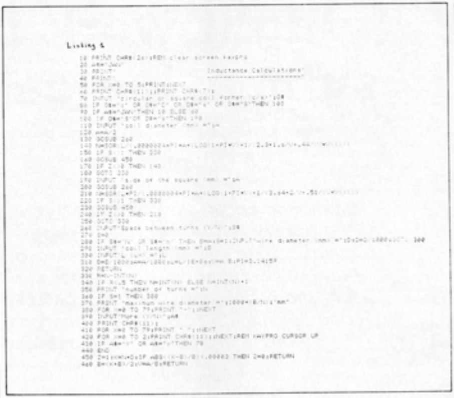
Fig. 3. Correlation between number of turns and inductance for a number of wire and former diameters.



3a



Listing 1. This program, written in MBASIC, will come up with the number of turns for a circular or square inductor, given the target inductance, wire and coil diameter.



Listing 1

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10 PRINT CHR$(26):REM clear screen kaypro
20 A$="JWV"
30 PRINT"                    Inductance Calculations"
40 PRINT"                    ========================"
50 FOR X=0 TO 5:PRINT:NEXT
60 PRINT CHR$(11);:PRINT CHR$(7);
70 INPUT "circular or square coil former (c/s)";Q$
80 IF Q$="c" OR Q$="C" OR Q$="s" OR Q$="S"THEN 100
90 IF A$="JWV"THEN 10 ELSE 60
100 IF Q$="S"OR Q$="s"THEN 190
110 INPUT "coil diameter (mm) =";A
120 A=A/2
130 GOSUB 260
140 N=SQR(L/(.0000004*PI*A*(LOG(1+PI*V)+1/(2.3+1.6/V+.44/(V*V)))))
150 IF S<>1 THEN 330
160 GOSUB 450
170 IF Z<>0 THEN 140
180 GOTO 330
190 INPUT "side of the square (mm) =";A
200 GOSUB 260
210 N=SQR(L*PI/(.0000004*PI*A*(LOG(1+PI*V)+1/(3.64+2/V+.51/(V*V)))))
220 IF S<>1 THEN 330
230 GOSUB 450
240 IF Z<>0 THEN 210
250 GOTO 330
260 INPUT"Space between turns (Y/N)";S$
270 S=0
280 IF S$="N" OR S$="n" THEN B=A:S=1:INPUT"wire diameter (mm) =";D:D=D/1000:GOTO 300
290 INPUT "coil length (mm) =";B
300 INPUT"L (uH) =";L
310 D=D/1000:A=A/1000:L=L/1E+6:V=A/B:PI=3.14159
320 RETURN
330 R=N-INT(N)
340 IF R<.5 THEN N=INT(N) ELSE N=INT(N)+1
350 PRINT "number of turns =";N
360 IF S=1 THEN 380
370 PRINT "maximum wire diameter =";1000*(B/N);"mm"
380 FOR X=0 TO 79:PRINT "-";:NEXT
390 INPUT"More (Y/N)";A$
400 PRINT CHR$(11);
410 FOR X=0 TO 79:PRINT " ";:NEXT
420 FOR X=0 TO 2:PRINT CHR$(11);:NEXT:REM KAYPRO CURSOR UP
430 IF A$="Y" OR A$="y"THEN 70
440 END
450 Z=1:K=N*D:IF ABS((K-B)/B)<.00003 THEN Z=0:RETURN
460 B=(K+B)/2:V=A/B:RETURN
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other experimental data, the following rules of thumb have emerged to obtain a high Q factor:

1. The ratio of the inductor length to diameter should be between 0.5 and 2.
2. The ratio of inductor to wire diameter must be greater than about 5.
3. For long coils, the spacing between turns should be 0.7 times the wire diameter. Short coils are best close-wound, or, where this is less desirable, with a turn-spacing not wider than 0.3 times the wire diamter may be used. (Literature reference 1).
4. Silvered wire is preferable for winding inductors for operation at frequencies above 300 MHz. (strip lines, lecher lines, UHF filters).

Inductance calculation

There are a number of formulas for the calculation of inductance, and these usually start from the the physical characteristics shown in Fig. 2. Note, however, that any inductance calculation is only a mathematical approximation, which gets closer to the actual inductance when it becomes more complex. To obtain very close approximations, the following formulas may be used (refer to Fig. 2):

$$L=\mu_0 n^2 a(\log_e[1+\pi a/b])+ + 1/[2.3+1.6b/a+ 0.44(b/a)^2) \ <H> \qquad (2)$$

for circular coils, and

$$L=\mu_0 n^2 a(4/\pi\log_e(1+\pi\ a/b])+ + 1/[3.64+2b/a+ 0.51(b/a)^2) \ <H> \qquad (3)$$

for square coils, where *a* and *b* are the inductor sizes in metres as indicated in Fig. 2, *L* is in henries, and μ_0 is the absolute permeability standard, defined as $4\pi 10^{-7}$ <H/m>.

The three charts shown in Fig. 3 give inductor winding data for a number of popular wire and former diameters, but the computer program of listing 1 allows a great many more possibilities for fast calculation of inductor winding data, both for circular and square inductors. The latter are perhaps less known among designers, but square inductors may be used as window mounted, multi-turn rhombic aerials for directive reception of medium- and long-wave signals.

The computer program listed has been written in MBASIC, and may require a patch here and there to suit the specific screen and cursor commands of some computers. For spaced inductors, the program uses an iterative approximation routine, which supplies a start value (guess) to the main calculations and adapts the variables to step towards maximum accuracy. Obviously, the better the guess, the faster the program will come up with the result, since in that case less calculation time is required. It stands to reason that n-step iteration is practically not feasible with only a pencil and a cheap calculator, since far too much time would be wasted before a useful result is obtained. Therefore, the number crunching facilities offered by the computer are welcomed by many designers of air-cored inductors.

JB;BL

Literature references:
1) Proceedings of the IEEE, Vol. 70 no 12; December 1982: Wheeler, H A: 'Inductance formulas for circular and square coils.'
2) Radio Engineers Handbook, by F E Terman; McGraw-Hill.