# WOUND COMPONENTS

## Measurement needs, problems and solutions

## David Sheath – Application Engineer

Wound components appear to be simple devices - easy to design, manufacture and test. In reality they are complex components. To manufacture them well requires technical knowledge, practical experience and considerable skill. Efficient and comprehensive design analysis and testing is vital.

Parametric measurements need to be undertaken to establish the dynamic characteristics of the device. For inductors, these characteristics will almost certainly be:

| | |
|---|---|
| L | Inductance |
| Q | Quality factor |
| Rdc | DC (winding) resistance |
| Z | Impedance |
| θ | Phase angle |

and, additionally, for transformers:

| | |
|---|---|
| | Number of turns |
| | Turns ratio |
| Lm | Mutual inductance |
| | Leakage inductance |

A number of secondary parameters, often considered equally important, may also be required for inductors. These are:

Main parameter alternation with Direct Current (DC bias) flowing
Resonant frequency
Self capacitance

and for transformers:

Inter-winding capacitance (useful for checking balance)

There are several alternative methods of measuring the required parameters but the most popular method, allowing quick and reliable access to a comprehensive set of measurements, is an AC component tester, commonly called a 'bridge'. Good examples, for inductance measurement, are Wayne Kerr's 3260A and 3255 instruments. This class of instrument will allow comprehensive analysis of all the required parameters. The measurement bridge should offer:

1) a number of test frequencies covering the widest possible range so that the inductance value can be measured at its most suitable test frequency. This aspect also enables the quality factor to be established and, at suitable frequencies, such values as self-capacitance and resonant frequency to be measured or calculated. Controlled frequency conditioning will also allow such parameters as skin-effect to be assessed. This may be important as it effects the dynamic equivalent series resistance (ESR) of an inductor and its ability to work effectively at higher frequencies.

When DC flows in a conductor, the current is distributed across the whole cross-section of that conductor. As the stimulus frequency is increased, the current tends to migrate away from the centre and thus reduces the current flow. This is seen as a rise in the effective ESR. Because current flow is finally limited to a physical depth around the conductor, the proportion of 'used' area is much more marked in large conductors which will therefore be effected even at relatively low frequencies. Thus, unless special precautions are taken with the design of the inductor to alleviate the skin-effect - such as using specially plied multi-strand wiring - it would be useful to measure this parameter too.

The component tester should also offer:

2) a controlled progression of stimulus voltage steps. This is a very important feature because

inductors, particularly those using iron, ferrite or iron dust as a core material, are notoriously level sensitive. This means that they often exhibit changes of inductance relative to the stimulus voltage level but not in a linear fashion. The reason for this is that a certain amount of energy, determined by physical factors, is lost in energising the core material. This shows as a major deviation from the expected inductance value until the core is fully energised after which the value will remain relatively stable.

With too little energy, the magnetic dipoles in the core are not very active, thus restricting the flux which couples the distributed windings of the inductor. With adequate magnetising energy the dipole activity is optimised. As the energy increases, the dipoles will again suffer restricted activity and thus the inductance will once more be affected. This is more apparent at low frequencies when core saturation will have the effect of distorting the current waveform flowing in the inductor as a result of the sinusoidal voltage applied.

From this one can see that an inductor designed for a particular stimulus level should be measured at that level. Another level is likely to give an incorrect value of inductance. This becomes more noticeable when the results from two component test instruments are compared, especially when one relies on 2-terminal measurement. Any stimulus generated by the 2-terminal test set will be attenuated by its output impedance and the device under test.

A test instrument using 4-terminal measurements is better because it overcomes not only the lead drop error (removed in trimming) but also the contact variation at the Kelvin clip jaws and provides a true voltage drop reading across the unknown inductance.

The component tester should also provide:

3) a method of measuring values of inductance with direct current flowing in the coil. Many inductors are used in circumstances where direct current must flow through them. Application examples might include power supplies or powerful transmitters. The ability of the device to pass DC is as important as its ability to perform as an inductor. DC flowing in an inductor will create a unidirectional magnetic field which, if enclosed within a magnetic core, will tend to restrict the movement of magnetic dipoles within that core.

As the DC is increased, the dipole movement will become more restricted until at saturation, all movement will virtually cease. When current is reduced, activity will commence at a different level from where it stopped thus giving rise to the well known B-H or hysteresis loop. This aspect is theoretically non-existent in air-cored inductors but the physical size of an air-cored inductor compared to the same value with a magnetic core will often prohibit the use of air-cored coils. Air-cored coils also exhibit other susceptibilities which may also preclude their use. Thus the provision of DC current bias for testing magnetic cored inductors should be regarded as of prime importance for both analytical and testing purposes.

Another major requirement when analysing magnetic wound components is the DC resistance of the winding. This value represents the total length of the wire used in conjunction with its cross-sectional area. It is often important to measure this value as it determines the ability of the component to pass any DC bias which may be required. It is particularly important when dealing with components such as relays or solenoids which often rely on DC for energisation. Inexperienced designers are often confused when measuring the DC resistance of such components as seemingly inappropriate measurements are noted.

The reason for this variation between expected and measured values is that with few exceptions we will be reading the Equivalent Series Resistance (ESR) or the Equivalent Parallel Resistance (EPR) of the device under test. These readings reflect the AC losses of the device at a specific frequency and, unless the test frequency tends towards DC, then the ESR value will differ from the DC resistance. At low frequencies the AC loss component will be effectively swamped by the DC resistance and the Q will fall to such a low level as to make the associated inductance value meaningless. Thus the ability of selecting a frequency such that the inductance and loss parameters may be checked with confidence, together with a low enough alternative frequency to confirm the DC resistance - ideally DC - is of prime importance when choosing a test instrument for wound magnetic components.

Devices with multiple windings (transformers) require even more control over test conditions. The inductance of each winding is without doubt of great importance but a measure of the ratio of primary to secondaries will provide details of both the correct construction and identify problems like shorted turns within the device. Inter-winding capacitance tests can be used to check for balance between secondaries in a balanced output transformer, whilst the low-level efficiency can be ascertained by measuring the mutual inductance of sets of windings.

Other tests a designer of wound magnetic components might wish to make relate to the magnitude of the impedance (Z) or admittance (Y) together with phase angle (θ) or the value of the AC current flowing as a result of the AC voltage applied. All can be recorded as of critical importance in establishing component quality and are best measured using one piece of test equipment, the performance and accuracy of which is understood, and which may be calibrated with reference to National Standards, thus locating quality where it should be, firmly in the grasp of the Quality Department.

The major benefit of this approach is that all tests are performed under controlled and specified conditions leaving little room for operator error or personal mis-interpretation. This is the route to confidence in component quality.

# MEASUREMENT PROBLEMS

Let us now look at some of the pitfalls of inductance measurement but first we need to define the unit of inductance:

**The Henry**

This is derived from Faraday's Law as:

$$E = -L \frac{dI}{dt}$$

The unit is in two forms:

1) Self Inductance - A circuit has a self-inductance of one Henry if the e.m.f. induced in it is one volt when the current is changing at the rate of one ampere per second.

2) Mutual Inductance - Two circuits have a mutual inductance of one Henry if the e.m.f. induced in one of them is one volt when the current in the other is changing at the rate of one ampere per second.

**The simple coil**

If we wind some turns of wire linearly on a thin-walled insulating former, the inductance of the coil can easily be calculated within about 1%. The permeability of the air core is unity - permeability being the ratio of magnetic flux density to magnetising force - and unlike magnetic material cores which we will discuss later, the inductance will be the same at any frequency of measurement until the coil resonates with its own self capacitance at a high frequency:

$$L = \frac{N^2\ r^2}{9r + 10l}$$

Where $L$ is the inductance in microhenries

$r$ is the mean radius of the coil in inches

$l$ is the mean length of the coil in inches

$N$ is the number of turns

The formula should only be used if the length of the coil is greater than 0.8 of the radius.

## Measuring the simple coil

If we wind 9 turns of thin guage wire on a 3/8" diameter former, covering approximately 5/8" length of former, we can make a coil of 0.35 microhenries suitable for a resonant circuit to work at 20MHz when associated with a capacitor of 180 picofarads - all figures rounded to within 1%.

If we measure this coil, without the capacitor, at 20MHz we will measure 0.35 microhenries associated with about 250 milliohms of series resistance (according to the type and diameter of the wire used). It is customary to refer to the Q of the coil as a measure of merit. It is equal to reactance divided by resistance. The Q factor thus determines the rate of decay of stored energy. The higher the Q, the longer it takes for the energy to be released. In this particular case Q is approximately 175.

Supposing we measure the coil now on a 10kHz bridge which displays the values of inductance and Q. Our inductance reading is the same but the Q is now down to below 0.1. This illustrates a common measurement confusion - beware of Q measurements unless they are done at the correct operating frequency.

As a 'worked example', the two measurements can be summarised:

1) at 20MHz

$$Q = \frac{2\pi fL}{R}$$

$$\frac{6.28 \times (20 \times 10^{6}) \times 0.35 \times 10^{-6}}{0.25}$$

$$= \frac{43.96}{0.25} = \mathbf{175.8}$$

2) at 10kHz

$$\frac{6.28 \times (10 \times 10^{3}) \times 0.35 \times 10^{-6}}{0.25}$$

$$= \frac{0.022}{0.25} = \mathbf{0.088}$$

($L = 0.35 \times 10^{-6}$ Henries, $R = 0.25$ ohms)

## Skin effect

A phenomenon which is noticeable at high frequencies is skin effect. As frequency is increased, the current in a conductor flows nearer the surface. The effect is observable at medium frequencies. At 1MHz the maximum permissible wire diameter to avoid skin effect resistance error of greater than 1% of the d.c. value is 0.0045" (37 American Wire Gauge).

## Magnetic cores

So far we have only considered air-cored coils. In order to increase the inductance - and hence the Q factor - magnetic cores are used. We will consider the principal types in turn, but all magnetic cores produce problems. Basically they are non-linear, frequency sensitive materials with a tendency to saturate at high magnetizing force. The magnetic field causes eddy currents to flow in the core resulting in loss of energy which offsets some of the benefits to Q gained by using such cores. However, the pitfalls can be avoided by a closer understanding of the constraints.

## Laminated cores

These are familiar in low frequency transformers. The electrically insulated laminations, formed by varnishing or oxidising the metal surfaces, reduce the effect of eddy current loss as would an air gap. As the frequency is increased, however, the laminations must be made thinner in order to keep the loss as low as possible. There is , of course, a limit to how thin laminations can be made and therefore, at medium and high frequencies, other forms of core materials are employed.

## Ferrite cores

Ferrites have an intrinsically high d.c. resistivity, over 1Megohm/cm, and being homogenous magnetic materials, they contain no 'insulation gaps' as do laminated materials.

The permeability of these materials is very high, but as their structure is crystalline, they also have a high dielectric constant with a considerable loss factor. This results in greater conduction as the frequency increases and in addition, the saturation flux density - which drops the permeability to a low value - limits the use of these materials to relatively low power applications.

### Dust iron cores

These cores are used for high frequency applications. Powdered iron is bonded with a resin compound which insulates each particle from the others. Although the losses at high frequencies are reduced, the bonding acts as a distributed air gap and the effective permeability is considerably reduced.

### Turns ratio

The turns ratio of a transformer can be measured by connecting a known voltage to the primary winding and a high impedance voltmeter to the secondary. Errors can be caused by the loss of voltage in the resistance of the primary winding, and the error becomes worse as the frequency is lowered, leading to an apparant reduction in the turns ratio. This effect is related to the problem encountered with Q measurement and can be corrected by applying the formula:

$$\frac{Actual\,turns\,ratio}{Observed\,ratio} = \sqrt{1 = \left(\ \frac{R}{\omega L}\ \right)^2}$$

Where R is the d.c. resistance of the primary and $\omega L$ is the reactance of the primary inductance.

### Practical measurement problems

Here are a few more measurement hazards you may encounter:

a) Beware of the impedance in series with the coil due to connecting leads and the contact resistance of the connecting clips. Kelvin clips and 4-terminal measurement remove these effects as independent pairs of leads pass the a.c. current and measure the resulting voltage across the coil. If the impedance of the unit under test is high, an improved version of this type of lead assembly has five terminals where the fifth connection is an overall guard or screen which removes stray capacitance fields.

b) Remember the worked example of Q at two different frequencies. Measuring Q at a low frequency can be misleading - but if the frequency of measurement is increased beyond the self-resonant point of the coil with its self-capacity, the measurement can show a startling result - the inductance now measures as a capacitance.

c) Do not put more a.c. current through the coil than is necessary for the required accuracy - unless you are researching this effect. High a.c. currents and superimposed d.c. both effect the core permeability in most cases when magnetic cores are used. Very high currents can also give rise to heating of the assembly which can substantially alter the permeability. A common observation can be summarised by the comment 'The inductance is unstable - it is drifting in value'. The effect is usually thermal.

Wayne Kerr Electronics are world leaders and innovators in LCR measurement technology. In the 1980s the solution to these measurement problems was to use the Wayne Kerr 3245 Precision Inductance Analyzer. In 1996 Wayne Kerr introduced the PMA3260A Precision Magnetics Analyzer and this year the 3255 Inductance Analyzer. This is today's solution to your measurement problems on all kinds of wound magnetic devices - the definitive tool for development, production and test of coils and transformers.

# DEFINITIONS

## DEFINITION OF INDUCTANCE

| | |
|---|---|
| For ideal inductor, value | L Henries |
| if current changes at | $\delta$ amps per second |
| then voltage is | $\delta$ . L volts d.c. |
| For sinusoidal AC drive at frequency | f Hz |
| if we define $\omega$ equals | 2 . $\pi$ . f |
| and a.c. current equals | i amps r.m.s. |
| then a.c. voltage equals | I . $\omega$ . L volts r.m.s. |

*No power is consumed by an ideal inductor as voltage and current are in phase quadrature (90° phase separation).*

## DEFINITION OF LOSS

| | |
|---|---|
| Real inductors dissipate power | in the wire (resistance of copper) |
| | in the core (hysteresis and eddy current losses) |

*A single measurement cannot separate these two*

Conventions for expressing loss term:

| | |
|---|---|
| series circuit | ESR + Ls |
| parallel circuit | EPR + Lp |
| dissipation factor D equals | $\frac{ESR}{\omega Ls}$ or $\frac{\omega Lp}{EPR}$ |
| quality factor Q equals | $\frac{1}{D}$ |
| polar form | $Z\angle\theta$ |

| | |
|---|---|
| Note: D equals tan s | where s = phase error from 90° |

# INDUCTORS

## EXAMPLES

Small signal components

Telecomms filters

Power line filters

Power supply components - linear or switched mode

Relay coils and Solenoids

Motor / alternator components

Transducers (tape heads, linear distance measurement, ultrasonics, etc.)

## CHARACTERISTICS

Most real inductors are iron- or ferrite-cored

Characteristics of magnetic core:

- non linear at low flux levels
- saturates at maximum flux level
- inductance falls at high frequencies
- losses are non linear
- losses increase at high frequencies

Different materials for different applications:

- small signal applications need best linearity
- power applications need highest saturation flux
- laminated iron gives highest inductance but linearity and stability may be poor
- thinner laminations for frequencies up to 100kHz
- ferrites used at higher frequencies, linearity is better

Physical form affects characteristics:

- interleaved laminations cost effective at low frequencies
- toroidal construction yields lower external magnetic fields and has sharper saturation characteristics
- air gap may be added to improve linearity and stability (small signal application)
- air gap may be added to prevent saturation with d.c. (power filter application)
- powder cores (iron dust material) used in some filters have distributed air gap
- mechanical stresses may reduce inductance

# TRANSFORMERS

## EXAMPLES

Small signal wideband (including Telecomms): impedance matching (balanced/unbalanced)
Amplifier output : load matching
Power transformers : linear
Power transformers : switched mode
Specialist : e.g. rotating head transformer for VTR

## CHARACTERISTICS

High permeability cores always used to maximise coupling between windings.

Magnetising current small compared to load current (2% to 10%).

Magnetising current waveform may be very distorted - power transformers are often operated close to the core saturation point.

Measured Q typically quite low - values between 1 and 10 are normal for power transformers.

Stability of inductance may be poor - varies with mechanical handling, electrical or thermal shock.

Resonant frequency of primary may be well below maximum operating frequency for wideband transformers.

Voltage ratio differs slightly from actual turns ratio - measuring close to primary resonant frequency gives best correlation.

On load performance affected by winding resistance - independent of signal level, but increases with frequency due to skin effect.

On load performance affected by leakage inductance - due to imperfect magnetic coupling between windings, appears in series with the secondary winding resistance. Largely independent of signal level.

# CAPACITORS

## CHARACTERISTICS

The following applies to most types other than electrolytics, which are used mainly as energy storage and decoupling devices in power supply applications.

Linearity better than inductors - measurement level not critical

Lower losses than inductors - good phase measurement accuracy essential

C value and loss vary only slightly with frequency - decade spaced frequencies are commonly used

Ceramic types:

Wide range of dielectric types with differing characteristics

Low losses and good stability at low C values (up to 500pF)

Multilayer construction, hi-k ceramics give higher losses, poor temperature stability for values up to 1uF.

Widely used for RF work

Silver mica types:

Traditional RF type which predates ceramic

Better stability in some applications

Special construction yields very high stabilities. Used as calibration standards.

Wound types:

Used instead of ceramics for larger values (up to 10uF or more).

Range of dielectric films giving different trade offs between performance and size.

Modern construction techniques give low ESR. Low inductance required in switch-mode applications.

Power supply and filter applications.

Manufacturers require to make high frequency measurements (100kHz or 1MHz) to verify low ESR with possibly a lower frequency used to check the C value.