Coil Testing in a Manufacturing Environment

by Anthony Pretto,
International Electro-Magnetics, Inc.

Quality control is an integral part of any manufacturing process. As a part of that process, it is important to establish proper testing procedures in order to maintain efficient production. A good testing program should allow for efficient product flow and help to reduce production costs due to the unnecessary assembly of defective parts. Typically, the sooner that product defects are identified, the less time and production effort is wasted. Of course the ideal condition is to avoid manufacturing defects altogether, but experience tells us that defects will and do occur. The focus of this paper is to discuss methods and means of effective coil testing within the manufacturing environment.

Because of the large number of test standards throughout the world, we will avoid discussions of particular specifications. By considering the fundamental properties of coils and the basic tests available in their manufacture, we will hope to establish a fundamental awareness of the tools available and their effectiveness. This paper is an introduction to, but is not complete as, a survey of coil testing.

In order to properly implement a testing program within the manufacturing process, there needs to be an understanding of the product application, that is, how is the coil used and what are it’s critical parameters. There are many different product applications for electrical coils and many approaches to manufacturing coils, but all coils have certain common elements that should be considered in the design of a quality control program. To understand a coil's function within a product, it will be helpful to first discuss the electro-magnetic properties of coils and how they are measured. There are a number of properties and materials that are unique to coil manufacturing, and a basic understanding of these properties can contribute to an effective testing program.

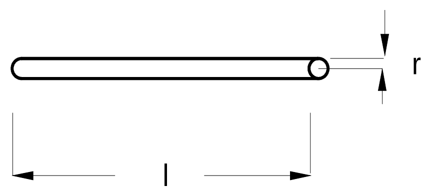
An electrical coil is a relatively simple construction. It's most basic component is magnet wire. It may also include a winding form (such as a bobbin or a toroid) and electrical termination to a connector of some type. One of the interesting features of electrical coils is that their electro-magnetic properties are influenced by their physical dimensions. Coils have both mechanical and electrical characteristics, and these elements are interrelated. This interrelation

Copyright © 2009 International Electro-Magnetics, Inc. All Rights Reserved.

is integral to the design process and needs to be understood. It will be useful to discuss these characteristics briefly and to define the basic electrical measurements that can be made.

Resistance (R)

Resistance is one of the most basic electrical properties. The resistance value of a winding is determined by the length of wire used and its diameter or circular area. By using an ohmmeter to measure the electrical resistance of a coil, gross errors in wire size or turns count can be detected. Although this method is of limited accuracy, it is an easy and quick test. Because typical manufacturing tolerances of magnet wire diameters can be several percent, resistance variations can easily approach 10% for a given wire length. Typically, variations within a given wire spool will be minimized, but lot to lot variations need to be monitered.



$$R \cong \text{length} / \pi r^2 \ \text{(area)}$$

Although magnet wire is typically made of copper, other materials are also available and will have different resistance values for a given size and length. Each material offers its own resistance values and thermal coefficients. For example, copper's resistance will increase .4% for each degree Centigrade in temperature increase. To compensate for this, temperature must be considered when making resistance measurements. As temperature rises, resistance also rises, increasing electrical losses and causing further heat build up. This phenomenon is a primary cause of coil failure. For this reason, heat dissipation should always be considered in good product design.

Copyright © 2009 International Electro-Magnetics, Inc. All Rights Reserved.

Inductance (L)

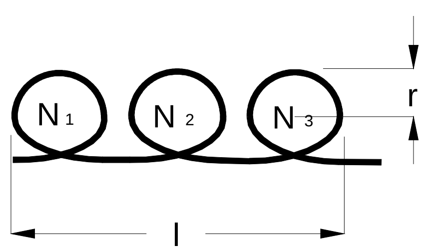
Inductance is a basic measure of the electro-magnetic properties of a coil. A magnetic field is generated when a current flows through a conductor at a changing rate. Because a DC voltage will induce a magnetic field only as the field is charging, most measurements use AC signals. Alternating current provides a constantly changing current flow. Where resistance is constant in regard to time, inductance is defined by its time component. It may be helpful to consider Ohm's Law to illustrate this point. Ohm's Law states that:

$\Omega \cong V / A$, where Ω is resistance, V is Voltage and A is current in Amperes.

Using the same terms of V and A, inductance is defined as:

$H \cong Vs / A$, where H is Henries of inductance and s is time (in seconds).

A coil of 1 Henry value will generate a back emf (electro-motive force) of 1 Volt when a current of 1 Ampere/ second is passed through it.



$$L \cong N^2 \ r^2 \ / \ \text{length}$$

A straight wire has minimal inductance. When it is wound into a solenoid coil, the proximity of one turn to the next allows the field generated by the first turn to inductively couple with its adjacent turns and to multiply its effect. In this way, the coil becomes a very efficient electro-magnetic device. The inductance of a coil winding will increase by the square of the turns and by the square of the winding radius. (It is generally proportionate to the coil area.) Because the inductive coupling that occurs is dependent on the proximity of one turn to the next, the inductance will decrease as the coil is stretched along its axial length. Dimensional variations can thus be related to inductance values.

Copyright © 2009 International Electro-Magnetics, Inc. All Rights Reserved.

Capacitance (C)

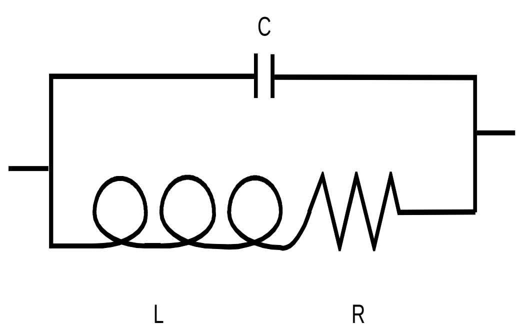
The capacitance of a coil can not be measured directly, but it can influence the testing and performance of a coil. A coil's distributed capacitance is a function of its dielectric and of voltage potential differences within the winding. A larger diameter winding will have a higher distributed capacitance due to adjacent layers having higher voltage differentials. The dielectric is a function of the physical spacing and insulation between the turns of a coil. In general, the capacitance value for a given number of turns is:

$$C \cong 2 \pi r \times \text{Length}$$

As a coil's inter-turn spacing is increased or the length of the winding layer is reduced, the inter-winding voltage differential (and its distributed capacitance) will decrease. Variations in winding tension and insulation thickness of the magnet wire will both contribute to capacitive differences. For smaller coil diameters, distributed capacitance will typically become a factor only in windings of 10,000 turns or more

Impedance (Z)

The three basic properties that we have introduced: resistance, inductance and capacitance, allow us to accurately model a coil in schematic form:



A schematic representation of a simple coil

Copyright © 2009 International Electro-Magnetics, Inc. All Rights Reserved.

Together L and C are termed Reactance in an AC circuit, X_L being Inductive Reactance and X_C being Capactive Reactance. Because the distributed capacitance of a coil can not be measured directly, X_C is not typically considered. Resistance and inductance values of a coil can be measured, and when considered with frequency, combine to form coil impedance. The equivalent electrical circuit for describing a coil is:

$$Z \cong \sqrt{R^2 + X_L^2} \text{ @ Frequency,}$$

where Z is impedance and X_L is Inductive Reactance.

Z, or impedance, is a useful term in that it defines the electrical load that a coil will present within an AC circuit. Although it is not a common test parameter, impedance is utilized by circuit designers to determine the power required to drive a particular coil design. It can be a critical parameter in resonant circuit and filter applications.

Q is for Quality

Q is defined as the ratio between a coil's inductance and its resistance and distributed capacitance values:

$$Q \cong L \; / \; R \; C_{distributed} \cong 1 / D$$

In general, the lower the resistance for a given inductance, the higher the Q factor. The inverse of this relation is called D or dissipation factor. When L is held constant, D is equivalent to the resistance and dielectric losses of a coil. These terms, Q and D, are used to define the relative efficiency of a coil.

Magnetic Properties

Permeability, refered to as μ, is a measure of a material's efficiency in carrying a magnetic flux. Air is a poor conductor of magnetic flux. When a magnetically permeable core is placed within a winding, the flux path becomes much more efficient. The inductance value of a coil with a permeable core will increase in proportion to the core's permeability value.

Copyright © 2009 International Electro-Magnetics, Inc. All Rights Reserved.

$$\mu = B / H$$, where B is flux density and H is magnetizing force or Ampere Turns.

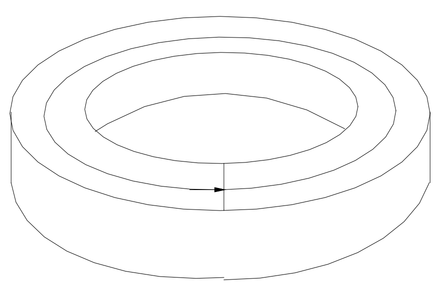
The permeability of core materials will vary with flux density and frequency. Reluctance, the inverse of μ, indicates how easily a material will magnetize at low energy levels. As field strengths increase a material will begin to lose permeability. Saturation Flux Density is a measure of how much field strength can be carried by a material before it loses its permeability.

There is a large variety of magnetic materials to be used as cores, and their selection should be based on the intended application. It is beyond the scope of our present discussion to describe them in detail, but it is important to select both test frequency and signal levels according to the materials in use.

It should be noted that manufactured core permeabilities can vary by 20% or more from the nominal value of a material. These variations can be equivalent to errors in turns count of as much as 5%. If inductance measurements are made with a core in place, permeability variations must be considered when establishing testing parameters.

Toroidal Cores

Although we have been considering the most basic coil type, the solenoid coil, these same principles also apply to toroidal coil construction. In the toroid, the length dimension of a solenoid coil becomes the mean diameter of the toroidal core. By closing the magnetic path of the coil upon itself, its efficiency is again increased.



Length $\cong \pi$ x Diameter

Copyright © 2009 International Electro-Magnetics, Inc. All Rights Reserved.

Because core permeabilities are typically measured in 1,000's of μ as compared to a value of 1 for air, the magnetic efficiency of a coil is dramatically increased when it is coupled to a core. This holds true for both solenoid and toroidal types of construction, but toroids offer a particularly efficient geometry. By providing a closed magnetic circuit, the flux path is optimized.

Dielectric Tests

The end use of a coil should be considered when designing a production testing program. There is little point in testing for qualities that are not relevant to the end product. For the simplest coil assemblies, it is possible that a functional test of the finished product is the most effective way to monitor quality. Perhaps only resistance or continuity need be checked. It is typically easier to make this test after a coil winding has been terminated to electrical contacts. In more complex assemblies, such as transformers or motors, more extensive testing must be done. Much time and effort can be saved by detecting winding faults before additional assembly is done.

There are a number of failures that can arise in the application of a coil to actual work. Virtually all of them are related to the coil dielectric breakdown. The shorted turns condition is probably the most common cause of coil failure. It occurs when the insulation resistance, or dielectric, fails within a winding, allowing a secondary, or parasitic, current path. Although a single shorted turn may not have an immediate effect on a coil's performance, the point of dielectric failure will become a source of heat build up. This localized heat buildup will cause further insulation breakdown. There are several ways of detecting this condition.

IEM produces a Shorted Turns Tester that will detect shorted turns without making electrical contact with the coil. It is a non-stress test. By generating a magnetic field that will inductively couple with a coil under test, the STT-4 uses a high Q circuit to detect shorted turns within a coil. When there is a shorted turns condition, current will flow within the shorted turn, loading the drive circuit. Although this is a non-contact test, there are some limitations. The coil must be an air core, solenoid type, and the short must be of low resistance. The advantage of this test is that it can be performed quickly since it does not require the stripping of wire or electrical contact. It is often performed after encapsulation or molding processes when internal thermal stresses can cause insulation failure.

Copyright © 2009 International Electro-Magnetics, Inc. All Rights Reserved.

The Hipot Test

The High Potential or Dielectric Voltage-Withstand Test is designed to verify insulation integrity between a winding and its adjacent conductors. These conductors may include other windings, a transformer core or motor armature, or some other gound path. The Hipot voltage level is commonly specified at 2 times the working voltage plus 1,000 volts; it is typically an AC signal, but can be DC. In either case a time duration is typically specified. The Hipot test is intended to stress the insulation beyond its normal working range in order to assure reliability at normal levels. The AC test applies a constant amplitude signal of line frequency (50 or 60Hz), to a winding and leakage current is then measured at adjacent conductors or at ground. In order to avoid a turn to turn voltage differential that could breakdown the dielectric, the signal should be applied to both ends of a conductor and the leakage current measured at both ends of the adjacent conductors or directly to ground. The DC signal is typically ramped up to maximum voltage in order to avoid damage caused by an extreme inrush current.

There are a number of current components that will effect the hipot measurement. I_A is the absorption current that is required to charge the dielectric of the winding itself. It is a function of the distributed capacitance of the winding, and it increases with turn count and with decreased dielectric spacing between turns. I_C is the charging current required to charge actual capacitors that may be in the circuit, particularly motor windings. I_L is the leakage current that continues to flow after the winding dielectric and other capacitors have been charged.

In a DC measurement, the leakage current will stabilize as the dielectric absorption and capacitive charging is completed. By timing this stabilization period for a given voltage level, decay in a winding's dielectric can be measured over time. This procedure allows for predictive maintenance of motors or transformers in service.

In an AC test the alternating polarity of the signal is likely to have changed before the capacitive charging has been completed. This charging current, termed a reactive leakage component, will mask the real, or resistive, leakage. Since typical test specifications require that a pure resistive load is used to establish the leakage current limit, the capacitive component must be isolated. Fortunately, because the reactive, capacitive, component lags the real, resistive, component by 90° of phase angle, it is possible calculate the real leakage current. This process requires sophisticated circuitry, but it is available in contemporary test equipment.

There is a potential for insulation breakdown being caused by the hipot test itself. When the dielectric begins to breakdown, high frequency arcing will typically occur. It is possible to detect this sporadic arcing before complete insulation breakdown. It is true that some organic

Copyright © 2009 International Electro-Magnetics, Inc. All Rights Reserved.

insulators can be degraded by overvoltage, and it is recommended that testing be done at the minimum allowable voltage levels and durations. Retesting should also be kept to a minimum.

When used with power transformers the hipot test may be referred to as an Applied Potential Test. As described, it will identify insulation failures between conductors. Another transformer test, Induced Potential, will identify shorted turns in any winding of a transformer, although only one is energized. A typical test calls for twice the rated voltage to be applied for a duration of 7200 cycles (120 seconds at 60 Hz). The test works by monitoring the current draw of the driven winding. Current loops in any of the windings, as presented by shorted turns, will increase current draw dramatically.

The Surge Test

The Surge or Impulse Test will also detect shorted turns. This test is particularly effective with motor windings, and it can detect a number of fault conditions in one operation. Surge testers generate an electrical pulse, typically of high voltage and low current, that will stress a coil's insulation by producing a high turn-to-turn voltage differential. The signal pulse will travel through the wire in a surge, providing a momentary stress to the dielectric. The coil resonates when it is energized in this manner, and it will exhibit a characteristic wave form.

Specific faults are indicated by variations in this characteristic waveform. Internal shorts, which provide secondary current paths, will produce a damped wave form with a reduced signal amplitude. Errors in turns count, or inductance, and variations in winding insulation ,or distributed capacitance, will be indicated by a change in resonant frequency. As in a hipot terst, high frequency arcing, or corona discharge will show up as discharge spikes on the waveform. A basic surge tester will use an oscilloscope display to visually compare the coil under test to a standard wave form. Computer driven systems can now do sophisticated waveform analysis that makes automated testing very effective.

Ratios and Turns Count

In transformer manufacturing, winding ratios are important to proper performance. For this reason, accurate turn counts are important. Transformers are often constructed with multiple taps, and it can be difficult to keep these various windings in proper phase and order. It

Copyright © 2009 International Electro-Magnetics, Inc. All Rights Reserved.

can be very helpful, particularly in low volume production where manual equipment is being used, to verify turns count before further assembly work is done. Automated line setups also need to be verified before and during production runs. One method is to measure transformer ratios. In E and I type bobbin transformers this requires that a core be installed in order to properly couple the windings to each other. By putting a known current into one winding, corresponding voltages induced in secondary windings can be measured and verified to be of the proper ratio and polarity. Of course, this procedure requires that the primary winding being energized is also of the proper turns count.

It is also possible to verify the turns count without adding a test core. By placing the windings over a test probe, a voltage can be induced in it that is proportionate to its number of turns. In order to maintain an accurate coupling, it is important that the energizing field be of uniform density and orientation throughout the coil volume. For this reason there needs to be some correlation between coil size and test probe dimensions. Accuracies within of .05%, or 1 turn in 2,000, are possible with this method. As with the ratio test, winding polarity can be verified at the same time.

Toroidal coils of multiple taps can also be measured by the ratio method. As mentioned earlier, this method assumes that the primary, or energized, winding is of the correct number of turns. A variation on this approach is available in the Toroidal Turns Analyzer. By utilizing a single test loop that is part of the drive circuit feedback, the analyzer will count turns of one or more windings on a toroid. Typical accuracy is .2%, or 1 turn in 500, however repeatabilities of .05% can be achieved. In order to maintain accuracy, it is necessary for the tester to compensate for variations in core permeabilities. The test frequency and drive levels used also need to be matched to the core materials being tested. Ferrite cores, as used in filter and choke applications, have higher permeabilities (and couple more linearly to their windings) at higher test frequencies. Silicon Steel cores, as used in power applications, require more drive current and lower frequencies.

Summary

There is a trend in the electrical manufacturing industry, and elsewhere, to use automated test systems that incorporate a series of tests in one test fixture. One advantage of this approach is that it allows comprehensive product testing at one handling. It also provides

Copyright © 2009 International Electro-Magnetics, Inc. All Rights Reserved.

ready access to test data for use in Statistical Process Control. In general, the higher the production volume, the more effective an automated system will be.

A significant portion of magnetics production is not automated high volume, however, but custom work that relies on manual assembly and short run set ups. SPC and other quality control procedures must adjust to these conditions. Testing procedures must be integrated into the production flow in a logical manner. Each product needs to be considered within its own requirements.

The development of micro-processor controls has allowed us to make our test equipment more useful and less dependent on skilled technicians to operate. It is now possible for assembly personnel to make critical measurements within their work cells, without interrupting the production flow. By placing quality controls in critical areas, a manufacturing process can be optimized. Whether high or low volume, there will always be a need for intelligent analysis of what is to be tested and when.

Copyright © 2009 International Electro-Magnetics, Inc. All Rights Reserved.

Bibliography

A Basic Guide to Electrical Product Testing , Associated Research, Inc.
Radio Engineers Handbook , Frederick Emmons Terman, 1943
Theory and Design of Inductive Coils , J.G. Wesley, John Wiley & Sons

Anthony Pretto is President of International Electro-Magnetics, Inc. IEM has built coil testing equipment since 1977. It offers a series of benchtop testers and PC based systems for the electrical manufacturing industry. IEM specializes in the custom design and production of electro-magnetic transducers.

Copyright © 2009 International Electro-Magnetics, Inc. All Rights Reserved.