COUNTING TURNS OF AIR AND BOBBIN WOUND COILS

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Turn count verification of coil windings can be a helpful step in the production of electrical products. Transformers are particularly dependent on accurate turns ratios between primary and secondary windings. Although winding ratios can be easily measured after a transformer is assembled, errors found at this point can be costly to correct. Significant cost savings can be realized by testing for turns count early in the production process.

This paper will describe the means available to measure turns counts before transformer cores are installed. Traditional methods and recent technology developments will be discussed.

Key words: Inductors, Transformers, turns ratio, counting Turns, Rogowski Coil

I. INTRODUCTION

The technical problem of measuring the turns count of a coil is fairly straightforward. Because the number of turns of a coil is proportionate to the voltage induced in it by an AC magnetic field, that induced voltage can be measured and used to calculate the number of turns. The voltage measurement is a relatively simple task and does not present any real complication. The real problems arise from the need to energize the coil in a uniform and repeatable way and to avoid nonlinear electrical characteristics in the coils being measured.

II. ELECTROMAGNETIC CHARACTERISTICS

It will be helpful to discuss the electromagnetic characteristics of coils in order to better understand the problems encountered in measuring them. The primary quality of coils that makes them useful is their ability to inductively couple with magnetic fields. By energizing a coil with a magnetic field, an electrical voltage V will be induced in the coil. This relation is expressed as:

$$V = N(d\phi/dt) \qquad (1)$$

Where N is the number of turns, and
ϕ is the magnetic flux

From (1), if the flux is established by a constant-amplitude sinusoidal current, then the induced voltage will be directly proportional to the number of turns on the coil. It is a linear relationship: the more turns in the coil, the more voltage induced by the field. This electromagnetic transformation is the fundamental working property of all coil design.

Inductance L is a measure of the effectiveness with which a coil will transform magnetic flux into electrical voltage, again assuming a sinusoidal magnetic flux of constant amplitude. This relation is influenced by the number of turns in the winding and by the cross-sectional area and the mean length of the magnetic path.

$$L = N^2\mu A_c / l_c \qquad (2)$$

where μ is the effective permeability of the magnetic path,
A_c is the cross-section area of the magnetic path, and
l_c of the mean magnetic path

The relation of turns to inductance is not linear, as is the turns-to-voltage relation; as turns double, inductance increases by four. The same is true of the winding radius, in cases where a circular coil is used; this has significant consequences as coil sizes increase.

An interesting property of inductive coupling is the influence that one winding will have on adjacent windings. This effect is referred to as mutual inductance. The mutual inductance value shared by two windings will be increased by the proximity of the windings and will be theoretically maximized if all of the lines of flux in a given magnetic field are shared by both windings. Mutual inductance, M_{12} is defined in equation form as:

$$M_{12} = k(L_1L_2)^{0.5} \qquad (3)$$

where L_1 is the inductance of coil #1,
L_2 is the inductance of coil #2,
k is the coefficient of coupling

In reality, k will always be less than unity, but it is desirable to make it as closed to unity as possible.

As we discuss the electrical characteristics of coils, it is important to keep in mind that we are usually referring to an AC or alternating current field. This implies a frequency, and coils can exhibit non-linear responses in relation to frequency. The resonant angular frequency ω_{res}

of a coil is determined by its inductance and capacitance values:

$$\omega_{res}^2 = 1 / L C \qquad (4)$$

where L is the inductance of a given coil, and C is the distributed capacitance between windings of the coil.

All coils will exhibit a self-resonant characteristic. As the frequency of the energizing field approaches a coil self-resonance in a parallel L-C network, the voltage induced in the coil will exhibit a peak amplitude – again assuming a constant-amplitude sinusoidal current source. This peak results in a undesired response and will limit the accuracy of test measurements. In order to avoid this response, the test frequency must be well-above or -below the coil self-resonance. It is helpful to know the resonant frequency of a coil under test, or at least to know that the coil resonance does not interfere with the frequency of the measurement being performed. In order to avoid this problem, test frequencies are typically lower than 1KHz.

Coil capacitance is not easily measured, and is not usually considered in coil testing, but interwinding capacitance will influence coil measurements. It is important to recognize that the resonant frequency of a coil will decrease as its inductance (number of turns and area) increases. As a coil resonant frequency approaches the testing frequency, inaccurate measurements can be expected.

III. ENERGIZING COILS

Now that we have some idea of how coils work, we can discuss the means of how to energize them for testing purposes. Of course, transformers can be measured at the end of their assembly process. After the transformer core has been installed in a winding, a turns ratio test is readily performed. The primary winding is energized, and voltage levels can be measured across each of the windings. The problem with this end-of-line testing method however, becomes apparent when errors in winding ratios are discovered. It is often very expensive and time-consuming to correct errors after the transformer has been assembled.

Turns ratio testing can also be done at intermediate points in the manufacturing process, but it is still time-consuming. The windings must be installed on a core, the core closed and the primary winding energized at a high enough current to magnetize the core. A core with high permeability, as provided by a conventional transformer core, will tend to maximize and confine the magnetic field. The core must offer a uniform magnetic path; any gaps in the magnetic circuit will offer opportunity for leakage flux which will not link all turns of the coils and result in inaccuracy. The need to install and remove a magnetic core to make a test adds to the time and reduces the repeatability of the ratio test.

Effective turns count verification within the manufacturing process must be easily performed, with a minimum of time and, of course, with maximum accuracy. The coupling of the coil under test to the magnetic field that is energizing it must be uniform and repeatable. Magnetic coupling of a coil to an energizing field can be enabled by either air core or permeable core coupling.

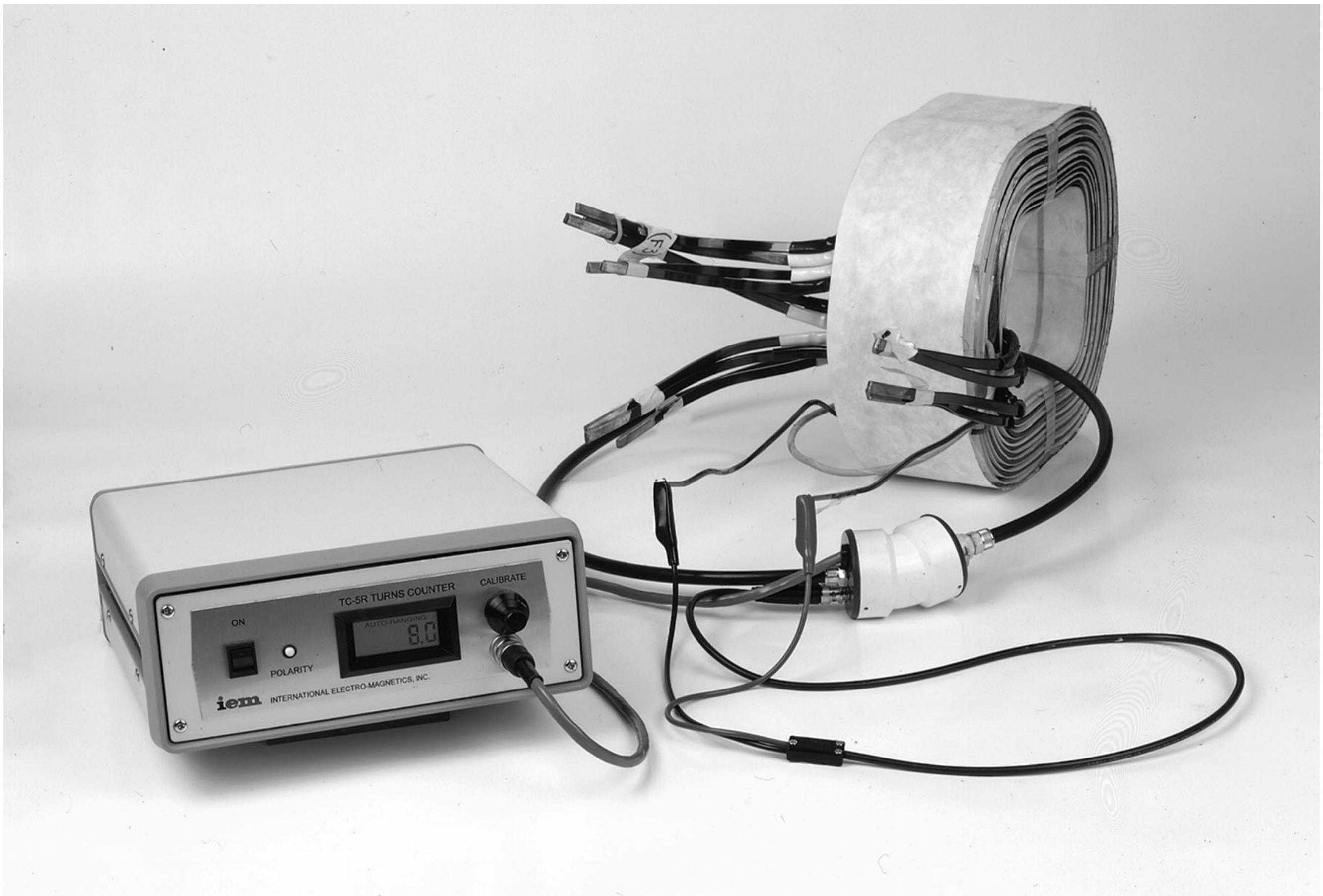
Testing coils without a core, or with an air core, offers several advantages. First, it is much quicker to place a coil over a test probe than to place the coil in a closed core. Secondly, test signal levels are of very low level, typically measured in microvolts per turn. This assures complete operator safety.

Traditionally, a solenoid coil type test probe is used to energize a coil for turns counting purposes. In order for the test to be accurate, the test probe must generate a uniform magnetic field that will energize the coil in a predictable way. The coil under test is placed at the midpoint of the test probe. In general, the probe length needs to be at least four times larger than the maximum width of the coil. This ratio assures that the flux lines of the magnetic field are parallel and maximize the coupling of the magnetic flux among all the turns of the coil with a linear and uniform field. When the volume of the coil is contained within the uniform field, and the axes of the coil and the probe are parallel, we can assume that the coil is energized in a optimal way. This will assure that test measurements will be accurate and reliable.

The primary limitation of using a solenoid coil test probe is one of size constraint. As a coil is brought to either end of the probe, non-parallel flux lines generate a complex magnetic field and complicate the measurement. We call these complex flux lines 'end effects'. As coil sizes increase beyond four or five inches (10 cm), probe lengths become unwieldy if end effects are to be avoided.

A recent development that IEM has made is to utilize a Rogowski Coil test loop in place of a solenoid coil test probe. A Rogowski Coil is essentially a flexible solenoid coil that is looped around to close on itself, very much like a torus shape is formed. The advantage to this construction is that the end effects of a solenoid coil are eliminated. As applied to coil testing, a Rogowski Coil test loop is light and portable, making it easy to test large coils that can weigh several hundred pounds. Instead of placing the coil to be tested onto a test probe, the test loop can be placed through the window of the winding. The

Rogowski Coil is also much less susceptible to measurement error due to axial misalignment. The test loop does not need to be on the same axis as the winding being measured. It is a very user-friendly configuration.



TC-5R with Rogowski Coil Test Loop

IV. COUNTING TURNS

We now have all of the parts in place to measure turns count. We know that coils will inductively couple with a magnetic field and generate an induced voltage proportionate to their turns count. We also know that coil geometry must be considered in selecting a proper test probe to assure proper coupling between the magnetic field and the coil. With these facts in mind, we can proceed to the actual measurement.

In schematic terms, a turns counter consists of: a signal generator and amplifier; a test probe to project a magnetic coupling field; and a voltage measurement circuit. The TC-5R photograph above shows all of the basic components. All of the components in the signal chain need to be as stable and precise as possible. Typically, reference coils, internal to the instrument or external, are used to maintain measurement stability.

As discussed, the voltage measurement of an energized coil will give us a measure of turns count. The accuracy of this measurement should be considered. Most transformer specifications specify a tolerance of .5% or 1 turn in 200. Of course the measuring equipment should be capable of higher accuracy than the specified tolerance.

Accuracy is a complex term, and it may be helpful to define some of the terms associated it. Resolution, repeatability, hysteresis, and linearity are all components that contribute to accuracy. Resolution refers to the ability of the measuring instrument to indicate the smallest increment of change. Repeatability is obvious enough; a measurement is repeatable to a certain resolution.

Repeatability is typically better than overall accuracy: linearity can affect accuracy over a range of turn counts, while repeatability allows comparison to a standard of one set value. Hysteresis is the phenomenon of measurement change that can occur when the polarity of the measurement is reversed. Linearity refers to the accuracy of the voltage measurement over the entire range of turn count.

Actual measurement accuracy is dependent on several factors. The simplest case is a repeatable measurement, where a single winding type is being measured. By using a production standard as an external reference to calibrate the instrument, repeatable measurements within one turn in 2,000 are possible.

Without a production standard, the accuracy of the instrument is dependent on its internal reference, the linearity of the instrument over its full measurement range, and the matching of the winding to the probe energizing field. Of course, resonant frequency can be an issue. We know that as either the coil radius or turn count increases, the coil inductance value will increase by the square of the increase, and that resonant frequency will decrease by the square of the inductance change. Also, as coils increase in size, they become more and more efficient as an antenna for ambient electromagnetic noise. As noise increases relative to the test signal level, it will disturb measurement accuracy. These factors combine to limit overall accuracy to within .5% or one turn in 200.

Another source of potential confusion is the difference of measurement that can occur due to hysteresis. This error is usually less than .2 turns, but it can be noticeable when measuring turn counts below 20 turns or so. To help identify this source of error, a relative polarity indicator is typically provided. This is a bi-stable red/green LED that will indicate the polarity of the winding connection relative to that of the energizing field. Polarity indication is also useful for verifying the proper polarity of multiple windings within a coil.

The testing procedure itself is a simple process. The coil to be tested is placed on a test probe platform (or the test loop is placed through the coil) and test leads are connected to the start and end of the winding to be measured. Once test connections are made, the instrument makes it measurement, and a turn count reading is displayed in a digital readout. This process should not take more than one or two seconds.

We have gone to some lengths to describe the operating principles involved and the complications that can arise when principles are applied to the real world. Turns count verification can be a valuable tool in the quality control and production of electrical coils. As with any measurement tool, it is important to monitor test results in a logical and systematic way. Test data can be very helpful in identifying production problems as they occur, but it is of little use if this information is not used in a timely and effective manner. This is the main advantage to in-process turns count verification. It provides valuable information with a minimum of process interruption.

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