The ART and SCIENCE of TESTING

RELAYING CURRENT TRANSFORMERS.

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THE REQUIREMENTS.

Power system relaying systems must have accurate information if they are to operate properly under normal and system fault conditions. Such information is provided by voltage and current transformers (VTs, CTs). This means that the output signals from VTs & CTs must represent primary voltage and current values, as failure to do so may result in protective relays operating when they are not supposed to operate, or alternatively – they may fail to operate when they are required to operate. The characteristics and performance of CTs is much more important than VTs because the CTs are required to operate over a very large dynamic range. We are going to concentrate on the requirements of CTs for protection applications and on test methods suitable for verifying their performance.

THE STANDARDS.

There are primarily two standards that are used to specify the performance of CTs for protection applications, namely the ANSI and the IEC. Although these two standards are describe the performance of the same product – the protection CT – their approach is somewhat different and may appear to be completely different to the inexperienced professional.

Here are some of the differences between the ANSI and the IEC standards for CTs as they relate to relaying performance:

* ANSI recognizes only one power frequency, namely 60 Hz, while IEC recognizes and is applicable all power frequencies, including: 16 2/3, 25, 50 60 Hz.

* ANSI recognizes only one Rated Secondary Current – namely 5 amperes, while IEC recognizes various values of Rated Secondary Current, including – 1, 2, 5 amperes.

* ANSI recognizes only one Accuracy Limiting Factor, namely 20, while IEC recognizes many Accuracy limiting Factors, including – 5, 10, 15 and 30.

* ANSI recognizes relaying burdens to be 0.5 power factor and having impedances of 0.5, 1, 2, 4 and 8 ohms (12.5, 25, 59, 100, 200 and 400 VA), while IEC recognizes burdens at 0.8 power factor and having a variety of ratings, with the preferred values being 5, 10, 15 and 30 VA.

* ANSI differentiates between relaying CTs that are of “low-impedance” (low leakage flux, CTs with toroidal cores & uniformly distributed windings) and those that are of “high-impedance” (high leakage flux, wound primary & wound secondary CTs).

* ANSI recognizes a 2.5% and a 10% Class of relaying CTs, while IEC recognizes a 5% and a 10% Class.

* IEC specifies “ratio error” and “phase displacement” limits for CTs at rated current and “composite current” over the specified range of Accuracy Limit Factor (5 . . . 30), while ANSI specifies the composite error only at the Accuracy Limit Factor of 20.

ANSI SPECIFICATIONS & TESTS.

Expression of Accuracy Class.

The ANSI accuracy class is expressed as: - 10C400, 2.5C800 or 10T200, where:

* The first number indicates the CT Accuracy Class – 2.5% or 10%.

* The letter “C” indicating a “low leakage”, low-impedance CT, whose performance can be readily “C”alculated from excitation measurements. The letter “T” indicating a “high leakage”, high-impedance CT, whose performance must be obtained from a full-power test.

- * The second number indication the burden rating of the CT. Here 0.5, 1, 2, 4, and 8 are represented by 50, 100, 200, 400 and 800. As the ANSI Accuracy Limit Current is always 100 amperes, this number approximately indicates the knee-point voltage of the CT.

Tests Required to Determine Accuracy Class.

As the “T” class CTs must be determined only by means of a full-power test, we shall consider here only the “C” class CTs, whose performance can be calculated from low-power tests. The calculation of “C” class relaying CTs requires a knowledge of the:

1. Excitation characteristics.
2. Winding resistance.
3. Burden.

There are other tests, like polarity and insulation resistance, but these are not used to determine the relaying accuracy of the CT.

IEC SPECIFICATIONS & TESTS.

Expression of Accuracy Class.

The IEC accuracy class is expressed as: 10VA5P20, 30VA10P30, where:

- * The first number indicates the burden rating of the CT. The burden is 0.8 power factor and expressed in “VA”.
- * The second number indicates the Accuracy Class – 5% or 10%.
- * The letter “P” indicating that it is a “Protection CT”.
- * The third number indicates the Accuracy Limit Factor – 5, 10, 15, 20 or 30.

Tests Required to Determine Accuracy Class.

The specification recognizes only CTs that are of low impedance (“low leakage”) and whose protection class can be calculated from the measurement and knowledge of:

1. Excitation characteristics.
2. Winding resistance.
3. Burden.

Similarly to ANSI, there are other tests, like polarity and insulation resistance, but these are not used to determine the relaying accuracy of the CT.

CTERP - 2000.

General.

The CTER-2000 is an instrument especially designed for testing the characteristics of CTs for relaying performance. The CTERP’s measurement technology departs from the typical “traditional” measurements of CTs as they may be described in electrical textbooks or standards. Nevertheless, the operation of the CTERP strictly adheres to all the electro-magnetic theory and principles and one will find its origins in papers and textbooks on electricity & magnetism.

Thus, for example, the CTERP is battery operated, applies no high voltage to the winding of the test CT, but produces excitation characteristics that are equal, or even superior, to those provided by “conventional test sets” that are ac-line powered. The reason the CTERP can do this is because it measures the magnetic characteristics of the core using the secondary winding, and then calculates the performance of the CT. As the measurements are conducted using dc, the results of the measurements can be calculated for any power frequency such as 50, 60, 25 or 16 2/3 Hz.

Principle of Operation.

The CTERP-2000-5A operates and relies on fundamental physical principles. Measurements of the fundamental magnetic quantities of field strength and flux density allow the instrument to calculate and provide the desired results. It applies magnetic flux density, in volt-seconds, and measures the resulting magnetic field strength, in amperes. This process allows one to draw full hysteresis loops for the test specimen. Multiple hysteresis loops allows one to calculate the excitation characteristics for the test specimen.

In addition to the above, the CTERP uses a “modified test sequence”. This modified test sequence uses “four-phases” of measurement (+; 0; —; 0) rather than the traditional two-phase measurement (+;—) and allows the separation of core loss into the “hysteresis” and “eddy-current” components.

Dealing with magnetism, we have the following basic units:

1. The Magnetomotive Force Ampere (A)
2. The Magnetic Flux Weber ($kg*m^2/A*s^2$) (V*s)
3. The Magnetic Field Strength (H)

   Ampere per meter (A/m)
4. The Magnetic Flux Density (B)

   Tesla ($kg/A*s^2$) ($V*s/m^2$)

The above indicates that the quantities that need to be measured are – current (A), voltage (V) and time (s). All the required AC characteristics can be calculated from the above three measurements.

Measurements.

The CTERP-2000 CT Analyzer primarily measures and displays the following:

1. Insulation resistance of the secondary winding.
2. Residual magnetism (remanence).
3. Ratio.
4. Polarity.
5. Winding resistance.
6. Maximum possible residual magnetism.
7. Volt-Ampere excitation characteristics – volts, amperes & watts.
8. Demagnetizes the CT.
9. Draws the excitation characteristics on a log-log graph.
10. Determines ANSI relaying CT Class or the IEC protection CT Class.

Explanation of Measurements.

The above tests are performed using the following methods:

1. Insulation resistance of the secondary winding is measured using a 500 volt insulation resistance tester.
2. Residual magnetism is measured by conducting a hysteresis loop test and calculating the "as found" residual magnetism (remanence).
3. Ratio is measured using the voltage injection method. A square wave voltage is applied to the secondary winding and the output is measured on the primary winding.
4. The polarity is measured by comparing the polarity of the square wave voltage applied to the secondary winding to the polarity of the voltage measured on the primary winding.
5. The winding resistance is measured by measuring the voltage drop across the secondary winding when a known current is flowing in the winding.
6. Maximum possible remanence is calculated from the hysteresis loop taken at the highest test current.
7. The excitation characteristics is required to be determined using a sinusoidal voltage of 60 Hz. The voltage is measured using a rms responding voltmeter and ammeter. Incase of distortion, a rms and an average (flux) responding voltmeters are required. The excitation characteristics also require the measurement of excitation power. As a suitable wattmeter are typically not available, this is usually not carried out.
8. Degaussing, or demagnetization is carried out by saturating the core and then applying a square wave voltage of gradually increasing frequency.
9. The excitation characteristics is calculated from an analysis of 40 – to – 80 hysteresis loops. The test starts at the largest loop (highest excitation current) and gradually reduces to a very small value.
10. The ANSI Accuracy Class is calculated based on the excitation voltage corresponding to a magnetizing current of 2.5 amperes rms and the winding resistance.

    The IEC Accuracy Class is calculated from the excitation characteristics, winding resistance and a knowledge of the burden.

As the CTERP traces hysteresis loops at various excitation field strengths, it can reproduce these loops on the screen and provide data about them in digital format. Similarly, the instrument measures the peak values of field strength, from which the rms values are calculated, it can display these instantaneous values in the Full Test sequence.

Measurement Sequences.

The above 9 measurements are organized to provide four distinct test, namely the ANSI Test, the IEC Test, the Full Test and the Hysteresis Test. The first two tests (ANSI & IEC) are designed for shop or field application and intended to verify the performance of relaying CTs before these are placed in service. The second two tests (Full & Hysteresis Test) are intended to be used by professionals for studying core materials and troubleshooting problems on CTs.

TYPICAL TEST RESULTS.

ANSI Test.

The results obtained after conducting an ANSI test include:

1. ANSI Accuracy Class.
2. Voltage at 2.5 A Excitation (Vfl)
3. Excitation Current (Irms=2.5 A)
4. Winding resistance (Rw)
5. Ratio
6. Remanence (%)
7. Core Loss at 45 deg point (W)
8. Core Loss Power Factor at 45 deg point
9. Insulation Resistance (Mo)
10. Eddy-current Loss (%)

IEC Test.

The results obtained after conducting the IEC Test include:

1. IEC Accuracy Class.
2. Kneepoint Voltage (Vfl)
3. Kneepoint Current (Irms)
4. Winding resistance (Rw)
5. Ratio
6. Remanence (%)
7. Core Loss (W)
8. Core Loss Power Factor
9. Insulation Resistance (Mo)
10. Eddy-current Loss (%)

Full Test.

Whereas the ANSI and the IEC Tests test the CT over its normal operating range, the Full Test allows the operator to limit the magnetizing force and study the characteristics of the core material over a selected region. In addition to providing a graphical presentation of the excitation characteristics (log-log graph), the CTERP provides numerical values for the excitation loss and power factor at the selected magnetizing force. The graphical presentation can be for ac excitation at the selected frequency, or it may be for the INSTANTANEOUS values, where peak magnetizing field is plotted against flux density (in volt-seconds). The results include:

1. Kneepoint voltage (Vfl) – (Vsm)
2. Kneepoint Current (Irms) – (Im)
3. Winding resistance (Rw)
4. Ratio
5. Remanence (%)
6. Core Loss (W)
7. Core Loss Power Factor
8. Insulation Resistsance (Mo)
9. Eddycurrent Loss (%)

Hysteresis Test.

The hysteresis test allows the operator to select the magnetizing field at which he wishes to study the core material. In addition to plotting the hysteresis loop for the selected magnetizing force, the CTERP provides numerical values of flux density, loss and power factor of the magnetizing force.

The hysteresis plot is done on an arbitrary scale, where the peak field (H) is equal to 100% and the peak induction (B) is 100%. The numerical values of field and induction are given in numerical form in a table. The table of results is as follows:

1. Peak Flux Density (Vsm in Vs)
2. Peak Magnetic Field (Im in A)
3. Winding resistance (Rw)
4. Ratio
5. Remanence (%)
6. Core Loss (W)
7. Core Loss Power Factor
8. Maximum Remanence (Vsr in %)
9. Coercive Force (Ic in A)

DISCUSSION.

ANSI offers a “Testing Guide” for commissioning CTs into service, where in addition to the tests discussed here, they specify that one needs to measure the service burden and to check for “inter-core coupling” of multi-core CTs. As the burden measurement requires a source of ac current it is not possible to do it with the CTERP.

The inter-core coupling requires that one core out of an assembly be excited with power frequency voltage and that voltages on the windings of other cores be measured. This also is a test not suited for the CTERP as it requires a large source of ac power and is best done with a current injection set and a sensitive voltmeter.

The IEC does not offer a “CT Testing Guide”, thus many of the tests and tests methods are at the discretion of the individual. This means that all of the tests can be conducted in the same fashion as suggested by ANSI.

IEC does identify a particular value – the “Knee-Point” that is of interest. The IEC “Knee-Point” is that value on the excitation characteristics where a10% increase in applied voltage causes a 50% increase in excitation current. It should be noted that this point is where a 10/50 sloping line touches the excitation characteristics on a log-log graph paper. Note that the IEC knee-point is different from the point of “Maximum Permeability”. The point of maximum permeability is the point where a 45 degree sloping line touches the excitation characteristics on a log-log graph paper.

As may be obvious from information herein that the CTERP provides more information then is needed for checking CTs into service. In particular the CTERP is most suitable for detecting and tracking problems with CTs with respect to shorted turns or damaged cores. This ability is due to the instrument being capable of differentiating “eddy-current” loss from “hysteresis” loss in a CT. It should be remembered that eddy-current loss is caused by eddy-currents within the core structure or that caused by a shorted turn. Thus, when one CT out a batch shows higher loss, and especially higher eddy-current loss, then damage to the core or shorted turns should be suspected.

It should be remembered that the traditional “excitation test” was not only designed to determine the CT relaying accuracy, but also to sense shorted turns, as such turns would increase the excitation loss. It should be also pointed out that improvements to the excitation test required one to measure not only the excitation current, but also the excitation power. The reason for this is that the increase in excitation power was much more sensitive to shorted turns then the current (say 3 to 5 times more sensitive, depending on the core loss). As shorted turns cause eddy-current loss, thus a measure of the eddy-current loss is most sensitive to shorted turns, more sensitive than a power measurement and much more sensitive than an increase in excitation current.

ITEMS THAT INFLUENCE THE PERFORMANCE OF ACT.

There are numerous factors that affect the performance of a CT. These include:

Core Material Characterisitics.

Ideally the core material should have a very high permeability, Little or no losses and a very high saturation flux density. The permeability of available core materials varies from less than 100 to 1,000,000 but the actual core materials used for CT cores varies from about 500 to 50,000. The typical saturation flux densities of core materials varies from about 0.4 Tesla for the very high permeability materials to about 1.8 Tesla for materials of lesser permeability.

Metering CTs, that operate over a range of 5 . . . 120% current range, require high permeability core material to provide good accuracy. Protection CTs, that require to operate to with a large accuracy limit factor, require core material that exhibit high saturation flux density.

Core Geometry.

Ideally, the core of a CT should be of toroidal construction. This geometry reduces flux leakage and CT impedance.

Core Quantity.

Generally speaking, the more core material is used – the higher will be the winding knee-point voltage and the better will be the performance of the CT.

Winding Arrangement.

A uniform winding arrangement reduces flux leakage and CT impedance. All other winding arrangements increase leakage flux and reduce CT performance.

Winding Resistance.

The lower the winding resistance – the lower will be the internal burden of the CT – the better will be the performance of the CT. This indicates that it is advisable to use series-parallel connections when changing ratios on CTs.

Ratio.

The CT ratio determines, in part, the Accuracy Limit Factor and thus determines the amount of "overload" the CT can handle. The higher the ratio, the lower the Accuracy Limit Factor, and the more likely the CT will operate within its accuracy class.

Burden.

The higher the burden, the larger the will be the core requirement. This also means that it will be more difficult for the CT to meet its accuracy class. The resistive component of the burden is especially troublesome as it is the resistive component that causes the CT to loose performance under transient system fault conditions.

TERMINOLOGY.

Excitation Characteristics.

A graphical representation of the voltage-current relationship of the secondary winding of a current transformer. Such characteristics are typically drawn on log-log graph paper. The characteristics depends on the frequency and the wave shape of the applied voltage. Such characteristics become wave shape independent if the voltage is measured using a "flux voltmeter" and the current is measured as "peak current".

Ratio.

Coefficient of transformation.

Toroidal current transformer.

A transformer whose core is the shape of a doughnut and the secondary winding is uniformly distributed about the circumference.

Bushing current transformer.

A transformer of toroidal shape, consisting only of a core and secondary winding and secondary insulation and designed to fit on the bushings of a power transformers or circuit breaker. The bushing provides the "one-turn" primary winding and the primary insulation.

Wound Current transformer.

A transformer consisting of a primary winding, primary insulation, a core, secondary insulation and a secondary winding.

Remanence.

Remanence or residual magnetism in the core. Closed-core CTs, such as bushing current transformers, may have large residual magnetism in the core. Such residual magnetism is caused by faults, especially by faults with transient components, and may be as large as 80% of saturation flux density. The relaying performance of a CT with large remanence may be compromised, thus it is desirable to "demagnetize" or "de-gauss" CTs after severe faults. Metering CTs are always tested in the "demagnetized" condition, as residual magnetism increases the CT errors.

Low Remanence Current Transformers.

Protective current transformers whose remanence it typically less than 10% of Saturation flux density. Such CTs typically have galled toroidal cores, larger excitation current and are used on extra high-voltage networks.

Flux Density.

"Magnetic Flux Density" or Induction, is the magnetic field within the CT core. It is measured in Gauss or Tesla. Typical Electrical steels support a flux density of about 1.7 Tesla, low-loss nickel steels support density of about 0.7 Tesla, while amorphous materials support a magnetic field in the range of 0.4 . . . 2 Tesla.

Magnetizing Force.

The current that is required to achieve a particular flux density in the CT core. The force is measured in "amperes" or "ampere turns" and represents the loss in the transformation of current from the primary to the secondary winding.

Accuracy Class.

A method of grading the accuracy of a CT. There are basically two types of accuracy classes recognized by standards – the "Metering Class" and the "Relaying Class".

The metering class applies to the performance of the CT over the normal operating current range, say 5% . . . 120% of rated, while the relaying class applies over the fault current range of the CT, say 100% . . . 2,000% of rated. The accuracy of the CT depends greatly on the loading of the CT – or the "burden" that is connected to its secondary winding.

There are primarily two systems of grading the accuracy of CTs, namely the IEC (International Electrotechnical Commission) and the ANSI (American National Standards Institute) methods.

Composite Error.

For relaying CTs, the rms value of the difference between instantaneous primary current and instantaneous secondary current multiplied by the rated transformation ratio.

For metering CTs - composite error is the square-root of the sum of the squares of the ratio error plus the phase error.

Ratio Error.

It is the in-phase component of the error exhibited by a CT.

Phase Error.

Is the quadrature component (out-of phase error) of the error exhibited by a CT.

IEC Knee Point.

It is a point on the CT excitation characteristics where a 10% increase in voltage causes a 50% increase in excitation current. It is a 10/50 (V/I, B/H) slope on the log-log graph of the CT excitation characteristics. It is typically considered that the CT has reached the limit of its performance.

Point of Maximum Permeability.

It is the point on the CT excitation characteristics that represents the highest magnetizing impedance. It is represented by a line sloped at 45-degrees on the log-log graph of the CT excitation characteristics.

Rated Instrument Limiting Primary Current (IPL).

The value of the primary current at which the composite error is equal to 10%.

Instrument Security Factor (SF).

Ratio of the IPL to rated primary current.

Secondary Limiting emf.

The product of SF rated secondary current and the vectorial sum of rated burden plus impedance of secondary winding.

Exciting Current.

The rms value of current drawn by the secondary winding of a transformer when a sinusoidal voltage of rated frequency is applied.

Rated Accuracy Limit Primary Current.

The primary current to which the CT complies with composite error.

Accuracy Limit Factor.

The ratio of Rated Accuracy Limit Primary Current to the Rated primary current.

Internal Burden.

Typically the winding resistance of a low-leakage CT. Typically the winding resistance plus the leakage inductance of a wound CT.

Toroid.

The doughnut-shaped object enclosed by a torus.

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