A Comprehensive Approach to Current Transformer Field Diagnostics

By

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A COMPREHENSIVE APPROACH TO CURRENT TRANSFORMER FIELD DIAGNOSTICS

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Abstract

Current transformers (CT) serve as a critical and essential interface in the world of electrical power. The role of a CT, at first glance, may appear to be a simple one but, CTs function as one of the most important components of the electrical system infrastructure. The performance of these devices is reflected in the correct operation of metering devices, relays and circuit breakers. CTs differ from other transformers in that their robust construction and rugged design cause them to be uniquely applicable to long-term operation with minimum maintenance. In a high voltage current transformer (HV CT) the insulation system is limited to off-line testing, and oil sampling during operation is forbidden. Therefore a comprehensive, simple approach to evaluating the condition of low voltage, medium voltage and high voltage CTs is paramount for testing service companies and utility operators.

CT saturation, incorrect polarity, ratio inaccuracies, wrong sizing of burden and insulation failure can all lead to malfunction, or failure of protection schemes. Unreliable, unpredictable CT performance could increase the risk of damage to major devices, so a complete evaluation of a CT should include electrical tests that will verify the function and performance of the CT in relation to nameplate data and industry recommendations. Standards and guidelines referenced in such an evaluation would include IEEE C57.13.1, C57.13.5, IEC 61869 and NETA ATS and MTS standards.

Moreover, assessment of the electrical insulation of a CT would involve common and modern techniques such as insulation resistance, power factor (tanδ) and dielectric frequency response (DFR) tests. These tests provide a better understanding of the condition of electrical insulation through the increasingly important interpretation of test data collected in the performance of such tests.

Throughout this paper, a simple approach to testing CT in the field is presented in the form of a logical sequence of testing best practise. The theory and purpose of functional and dielectric tests are reviewed and new measurement techniques like simultaneous multiple saturation curves and advanced frequency based insulation diagnostic techniques are analyzed.

Introduction

Besides the obvious difference between devices that transform voltage and others that transform current, one of the differences between power and distribution transformers versus a CT is that power and distribution transformers can have a number of devices monitoring their outputs. These outputs can be viewed and responded to by operators on site or remotely. However, CTs do not have the additional monitoring instrumentation to assess their condition while energized. Therefore, those involved in the operation of the electrical system seek advanced diagnostics alternatives for identifying potential risks of failure before they arise. A detailed review of the tests applied to CTs of high, medium and low voltage are described in order to better support field activities and avoid catastrophic failures.

Current Transformers - Basics

Perhaps the best approach to understanding the unique operating characteristics of this essential power system component, as well as the possible causes for their inaccuracies, would be to define the function and purpose of a current transformer. By definition, CTs are instrument transformers whose primary winding is connected in series with the conductor carrying the current to be measured or controlled. [1-2]

Ideal vs. Real Current Transformers

Under ideal conditions a CT views the secondary current as being inversely proportional to the turns' ratio relative to the primary winding current. Thus, any variation in the primary current will be reflected in changes to the secondary current as well. This is illustrated in equation (1).

$$I_2 = \frac{N_1}{N_2} \times I_1 \tag{1}$$

However, CT users must recognize the limitations of this instrument and understand that the theoretical ideal conversion described in equation (1) is not perfectly achievable in real applications. In practice, the accuracy of a current transformer or its ability to precisely represent the primary current is dependent on two factors:

a. The external load applied to the secondary of the CT (referred to as burden)
b. Magnetic losses that occur in the core of the CT

Transformation errors will always exist in varying degrees because of losses that occur within the magnetic circuit of this specialized type of instrument transformer. Errors in the accuracy of current transformation can be related to both CT construction and their specific application. CTs are a magnetic device and require a portion of the primary current in order to simply excite the core of the transformer, or to cause magnetic flux to flow within the core of the transformer. Similarly, the magnetic coupling of the flux that is flowing in the core of the CT must be transferred to the secondary winding which also results in losses which may affect the accuracy of the transformer. Therefore, it can be said that the resulting current in the secondary of a CT corresponds to the primary current (carried to the secondary winding) minus the excitation current and other magnetic losses. This leads to the expression (2), graphically represented in Fig 1.

$$I_2 = \frac{N_1}{N_2} \times I_1 - I_e \tag{2}$$

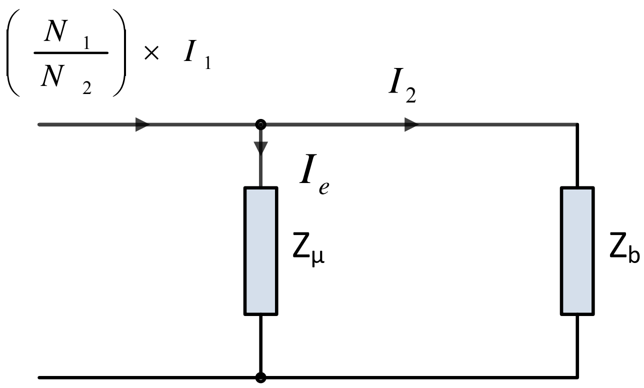

Figure 1: Real CT Equivalent Circuit

Z_μ - corresponds to the impedance of the magnetic circuit and core losses
Z_b - corresponds to the impedance of the load or "burden"

Accordingly, the vector diagram shown in Figure 2 illustrates the vector components of the primary current as it is transferred to the secondary circuit.

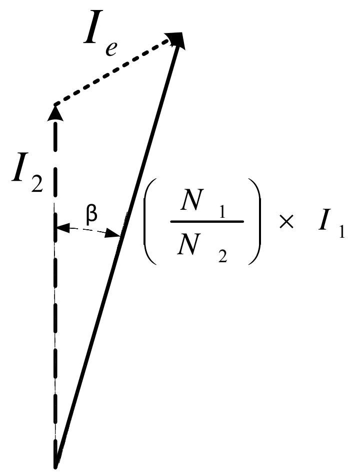

Figure 2: Vector Diagram of the Current Components of a Real CT

The illustration in Figure 2 clearly shows the two main types of CT errors:

a. Accuracy errors (related to the gain or linearity of the response)
b. Phase angle errors

The magnitude of the error is known as ratio error and phase angle error is known as phase deviation. When a CT is used for current measurements only, then the ratio would be the only consideration. However, if the CT is used in power measurement applications where the phase relationship between voltage and current is involved, then the phase angle error of the CT should be considered as well.

Accuracy of Current Transformers

CTs are used mainly for two applications: measurement and protection. These applications are clearly defined in the international standards by their performance characteristics. In the case of CTs that are to be used strictly in measurement type applications, the accuracy of the measured ratio between the primary and secondary is extremely important. In section 5.3 of [3], the standard accuracy classes for metering CTs and the corresponding limits of TCF for a power factor between 0.6 lagging to 1.0 are tabulated. Those values are shown in Tables 1. These classifications are based on the requirement that the transformer correction factor (TCF) of the CT be within the specified limits when the power factor (lagging) has a value from 0.6 to 1.0, and has a standard load of 10% and 100% of rated primary current. Notice that a CT that is burdened to 10% of the specified load, does not necessarily have the same TCF as when that same CT is burdened to 100% of the specified load. It is then necessary to define some terms used to express the errors in the magnitude of the ratio relationship in (3)

$$RCF = \frac{\text{Actual Transformer Ratio}}{\text{Nameplate Transformer Ratio}} \qquad (3)$$

Phase angle error β (as shown in Figure 2) is the angle between the vector of the secondary current and primary current vector. This angle is considered positive when the secondary current vector leads the primary current.

TCF involves both components of error; the ratio error factor (RCF) and the phase deviation error (β - in minutes). Generically speaking, the TCF for a CT that has a lagging power factor of 0.6 would be expressed as shown in the following equation (4).

$$TCF = RCF - \frac{\beta}{2600} \tag{4}$$

However, the equation used in (4) is generic and only an approximation that assumes β is a very small value close to zero. The correct and therefore more precise formula, under the same conditions where the power factor is 0.6 lagging is shown in equation (5):

$$\cos(53.13° - \beta) = 0.6 \cdot \frac{RCF}{TCF} \tag{5}$$

Table 1

ANSI/IEEE Accuracy classes measuring CTs standard and corresponding limits of TCF (PF from 0.6 to 1.0 lagging) [3]

Accuracy class for measurement	**At 100% of rated current**		**10% of rated current**	
	Minimum	**Maximum**	**Minimum**	**Maximum**
0.3	0.997	1.003	0.994	1.006
0.6	0.994	1.006	0.988	1.012
1.2	0.988	1.012	0.976	1.024

The accuracy limits established in the IEC reference standard [10] are shown in Tables 2, 3 and 4 as described in sections 5.6.201.3 and 5.6.202.2.4.

Table 2
IEC Accuracy classes - limits of ratio error and phase displacement
For measuring CTs (classes 0.1 to 1) [10]

Accuracy Class	**Ratio error % At current % of rated**				**Phase displacement**							
					± Minutes				**± Centiradians**			
	5	**20**	**100**	**120**	**5**	**20**	**100**	**120**	**5**	**20**	**100**	**120**
0.1	0.4	0.2	0.1	0.1	15	8	5	5	0.45	0.24	0.15	0.15
0.2	0.75	0.35	0.2	0.2	30	15	10	10	0.9	0.45	0.3	0.3
0.5	1.5	0.75	0.5	0.5	90	45	30	30	2.7	1.35	0.9	0.9
1.0	3.0	1.5	1.0	1.0	180	90	60	60	5.4	2.7	1.8	1.8

Table 3
IEC Accuracy classes - limits of ratio error and phase displacement
For measuring CTs (classes 0.2S and 0.5S) [10]

Accuracy Class	**Ratio error % At current % of rated**					**Phase displacement**									
						± Minutes					**± Centiradians**				
	1	5	20	100	120	1	5	20	100	120	1	5	20	100	120
0.2 S	0.75	0.35	0.2	0.2	0.2	30	15	10	10	10	0.9	0.45	0.3	0.3	0.3
0.5 S	1.5	0.75	0.5	0.5	0.5	90	45	30	30	30	2.7	1.35	0.9	0.9	0.9

Table 4
IEC error limits for protective CTs class P & PR of ratio error and phase displacement
For measuring CTs (classes 0.2S and 0.5S) [10]

Accuracy Class	**Ratio Error at rated primary Current ±%**	**Phase displacement at rated primary current**		**Composite error at rated accuracy limit primary current %**
		±Minutes	**±Centiradians**	
5P and 5PR	± 1	± 60	± 1.8	5
10P and 10PR	± 3	-	-	10

The fact that TCF and RCF limits are the same is why in [3] the accuracy class parallelogram references both RCF and β as shown in Figure 3.

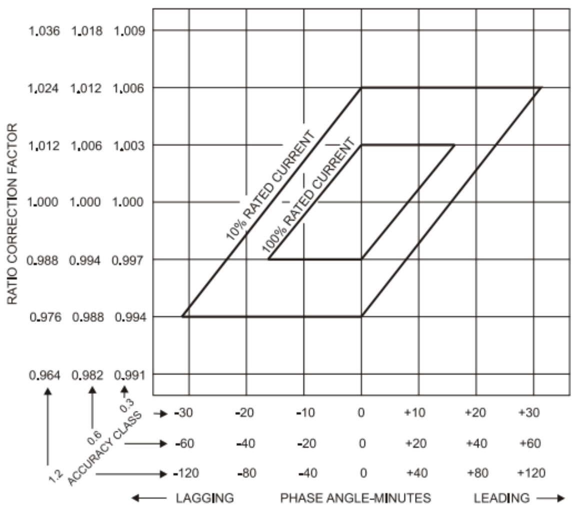

Figure 3: Limits of Accuracy Classes for Metering CTs

The accuracy characteristics of CTs in a dedicated system protection scheme must be maintained while simultaneously tolerating adverse over-current conditions. There are three kinds of protection CTs: C, T and X. For CT classifications of C and T, the accuracy class is given by the secondary voltage at which the CT is able to output up to 20 times the rated secondary current (5A) without exceeding its specified ratio error. For this reason, it is important to know the correlation between this voltage value and the standard burden specified on the nameplate of the CT as presented in Table 5 for the IEEE reference [3]

Table 5
ANSI/IEEE Accuracy class for classification C & T

Voltage in the secondary circuit	**Standard load (Ω)**
10	B-0.1
20	B-0.2
50	B-0.5
100	B-1.0
200	B-2.0
400	B-4.0
800	B-8.0

The precision required for protection CTs at rated current value is 3%. At 20 times the rated current, the limit for ratio error is 10%. The limits of accuracy for protection CTs and the relationship between current and voltage in the secondary circuit are shown in Figure 4.

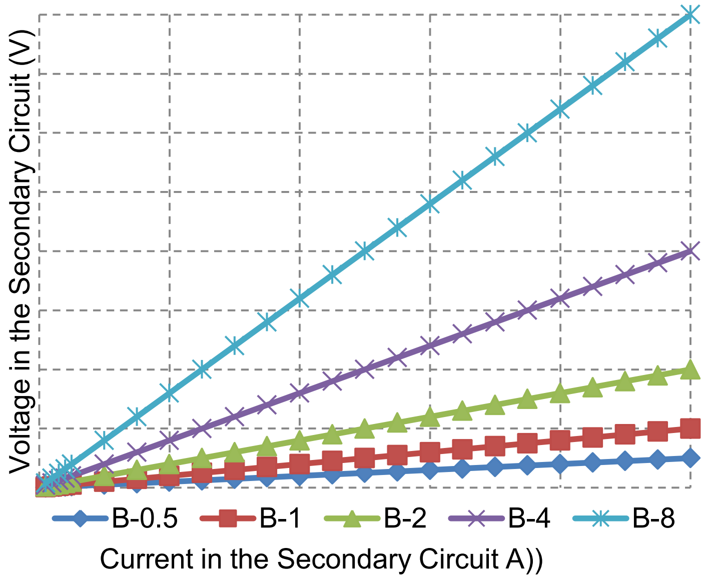

Figure 4: Standard limits for Protection CTs (5A rated secondary)

Residual Magnetism in Current Transformers

There are special applications where CTs are operated under a direct current (DC) while simultaneously superimposing an alternating current (AC). The influence of DC current tends to saturate the magnetic core material of a CT. Any residual magnetism, referred to as magnetic bias, that remains after having applied DC to the transformer can directly affect the accuracy of the ratio. These special applications should be discussed with the manufacturer so precautionary measures can be added during the design of the CT.

Also, during normal operation, the CT may be subjected to DC when there is no flow of AC. Regardless of the application, whether measuring or protection, the CT core can be magnetized either by:

a. the application of DC via one of the windings of the transformer,
b. the passage of AC when the opposite winding is opened, and;
c. under a transient condition or sudden interruption.

These conditions will result in increased excitation current values and ultimately an increase of the ratio and phase angle error *(see Figure 2).* To remove the magnetic remnants in the CT, the flux density should be raised to saturation level and then gradually reduced to zero. This process is known as demagnetization and can be done in both DC and AC. Take note that in the course of field testing, specifically when performing winding resistance test, DC is used to saturate the core of the transformer. The change in current with respect to time will vary until the core becomes saturated and will no longer accept any additional flux.

$$V = I \cdot R + L\frac{di}{dt} \tag{6}$$

At the point of saturation, the variation of current flow with respect to the change in time will ideally go to zero based on equation (6).

Field Testing of Current Transformers

Based on the information provided in the introduction and description of CTs, the need to diagnose CTs in the field with highly reliable and accurate results is imperative. For this reason, there must be a test plan that covers the operating characteristics as defined by the nameplate data. Additionally, and just as importantly, the condition of the dielectric system must also be assessed by tests performed when the equipment is out of service by neither intrusive nor destructive techniques.

Current Transformer Field Testing Sequence

A proposed basic plan for the implementation of field testing is shown in Figure 5.

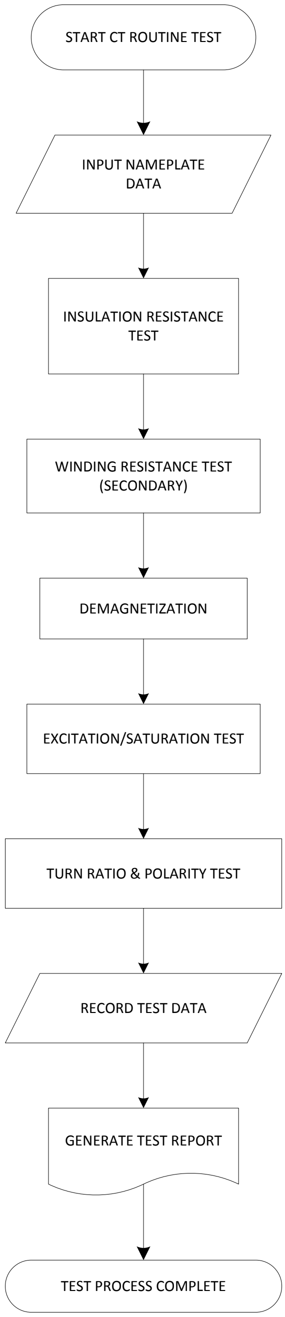

Figure 5: Process diagram for basic field testing of CTs

In routine testing with advanced equipment, it is necessary to input the CT nameplate data, identifying and differentiating its application and accuracy class. The ability to enter and track this information not only allows the electronic recording of nameplate data and test results, but also allows for the added analytical benefits of being able to compare actual measured test parameters to anticipated nameplate or industry standard values.

It is especially important in high voltage CTs to have a historical assessment of the CTs' insulation resistance. In the absence of an acceptable insulation resistance test result, there is a safety concern regarding electrical shock during testing or operation of the unit. Electrical acceptance testing of current transformers is described in Section 7.2.1 of [4]. NETA recommends that the testing of insulation resistance between windings or between a winding and the ground connection is made at 1000VDC or at a tolerance recommended by the manufacturer. Once a CT's dielectric properties have been verified to be acceptable, the next step is to verify the performance characteristics and nameplate compliance of the transformer.

The first test performed is the winding resistance test. This test is performed by injecting DC current into the secondary winding. Once the core of the CT begins to saturate, fluctuations in current will begin to stabilize, allowing the voltage drop across the winding to be measured (somewhere in the order of 100mV). Ohm's law can then be applied to accurately calculate and record the resistance of the winding.

Traditionally, this test has to be repeated on each secondary winding section of a selectable-ratio CT, one at a time. This process is very inefficient and time consuming, especially on CTs with multiple taps, due to the time it takes to swap the test leads between each test. New testing technology now allows the entire winding to be energized and measurements for each section taken simultaneously, so values of all combinations of terminals can be obtained from performing the test only once. The circuit for performing concurrent testing of CT secondary windings is illustrated in Figure 6.

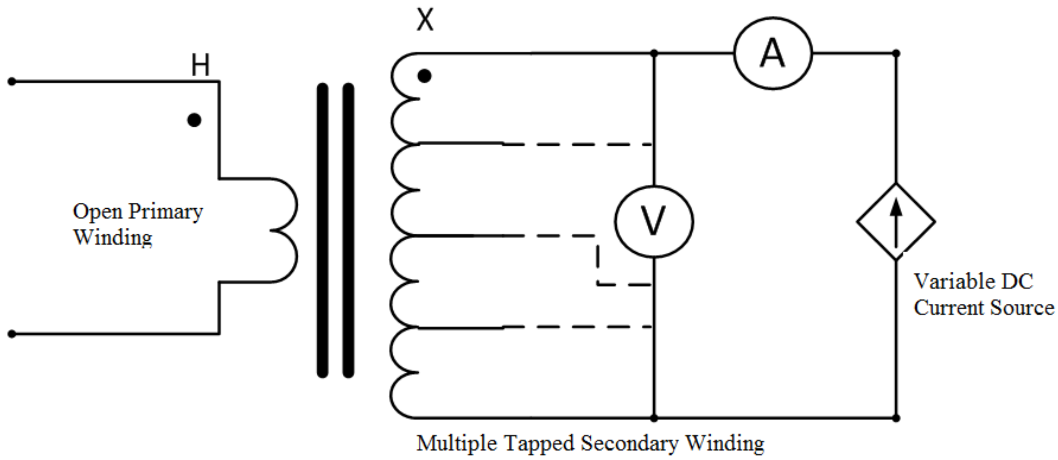

Figure 6 : Simultaneous measurement of the secondary winding resistance in a CT using multiple leads

After performing the winding resistance test, the core of the CT must be demagnetized. Demagnetizing the CT can be accomplished by applying an algorithm that can utilize either AC or DC current. It is essential that this step in the testing process be completed prior to subsequent testing to ensure that excitation and ratio test results are both accurate and reliable.

Following the proposed plan to test the CT, and having it fully demagnetized, the next step is to perform excitation and saturation testing. Both excitation current and the RMS voltage of the secondary winding should be clearly observed in the measurement process. Some may incorrectly contend that there is no difference in whether the secondary voltage measurement is the average or the RMS.

Tap	Knee Voltage (V)	Knee Current (A)
X1-X2	46.167	0.2637
X1-X3	69.049	0.1753
X1-X4	184.56	0.0659
X1-X5	278.77	0.0443
X2-X3	22.900	0.5233
X2-X4	138.40	0.0878
X2-X5	232.60	0.0532
X3-X4	115.48	0.1055
X3-X5	209.65	0.0592
X4-X5	93.732	0.1344

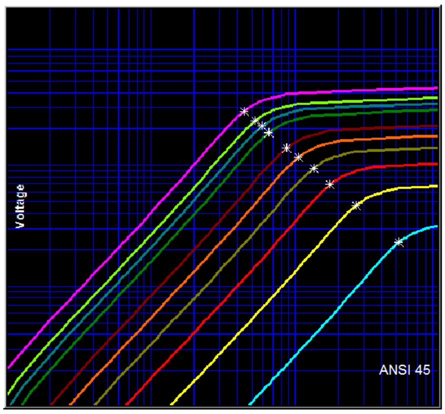

Figure 7: Saturation test results of a multi-tap / selectable-ratio CT under simultaneous mode

In [9], annex B shows two curves generated; one representing each type of measurement. The two curves essentially overlap in the linear region below the knee (saturation point). However, beyond the knee of the saturation curve, Figure 8 shows that RMS values are higher than the average voltage measurement.

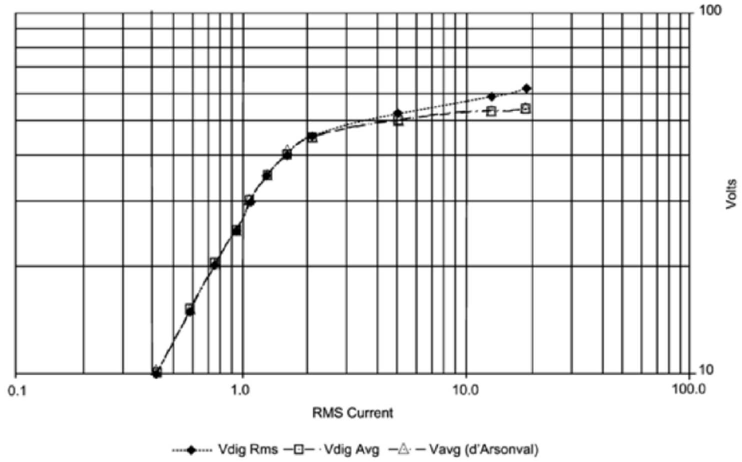

Figure 8: CT excitation curve RMS current vs. average responding voltmeter [9]

As defined in section 3.4.214 of [10], the excitation characteristic is a graphical presentation of the relationship between the rms value of the exciting current and a sinusoidal voltage applied to the secondary terminals of a CT. From here the knee point voltage is observed as the rms value of the sinusoidal voltage at rated frequency applied to the secondary terminals of the transformer, all other terminals are floating, which when increased by 10%, causes the rms value of the exciting current to increase by 50%. The excitation characteristic made at rated frequency allows comparison against the curves supplied by the CT manufacturer. This comparison provides a means by which CT accuracy class and saturation point can be verified for the appropriate application of the CT.

One additional test can prove the ratio and the polarity of the CT. Ratio measurements would need to be collected in the linear portion of the excitation curve, below the point where the CT would begin to saturate. IEEE C57.13.2008 [3] indicates two methods of obtaining this information; one requires that primary current be injected into the CT and secondary current measured, and the other that allows for the application of voltage to the secondary of the CT and the primary voltage measured. Either method is acceptable, however, the size, cost and commercial availability of primary current test equipment has caused its utilization to decrease in recent years. Test equipment conforming to the second method mentioned above, simply applies a voltage to the secondary of the CT and compares it to the measured primary voltage. A ratio of these two voltages can be calculated that is approximately equal to the turn ratio of the transformer. The polarity test, performed during the same step as the ratio test, confirms that the predicted direction of secondary current flow is correct for a given direction of primary current flow.

The performance of these final tests completes the basic field testing process as outlined in Figure 5 of this paper. However, to complement these basic tests, one should also verify the impedance of the applied load to ensure that the burden of the circuit does not exceed the conditions in which the CT will maintain its specified accuracy and performance.

Complementary Dielectric Tests

While the importance of the Insulation Resistance test as part of the basic test plan has been described, the high voltage (HV) dielectric system devices require additional dielectric tests. This is how power factor tests are typically performed on HV CTs.
For HV instrument transformers, it is important to verify if the CT has a test tap or not before performing the test. In the more complex case of a CT where the insulation system consists of paper wrapped in graded sections and immersed with a test tap, all capacitive sections as shown in Figure 9 can be tested.
In Figure 9, all possible capacitances to be tested in a CT with a test tap are described below [5]:

- HV - high voltage terminal
- LV - low voltage terminal
- D - tap test point
- C1 - represents the main insulation between HV and D
- C2 - represents the insulation between the test tap and ground. Typically the test voltage for this capacitance does not exceed $500V_{AC}$ unless there is a different recommendation provided by the manufacturer.
- C3 - represents the insulation between the test tap and the secondary winding
- C4 - represents the insulation between LV and ground
- C5 - representing the insulation between the HV-terminal directly to ground including porcelain surface.

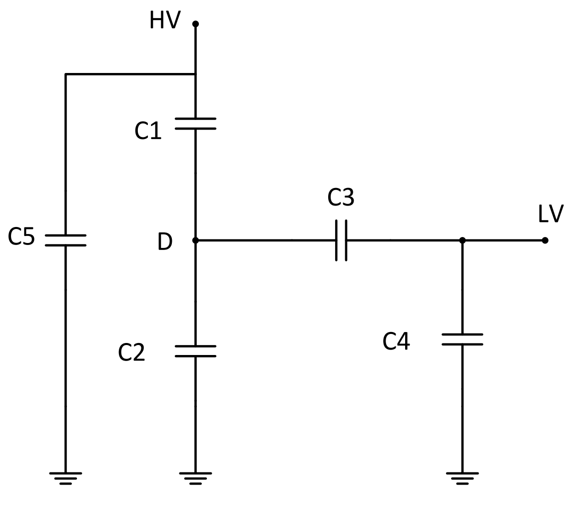

Figure 9: CT testing capacitances for diagnostics

If advanced diagnostic tests are conducted to determine moisture content in the solid insulation system, it is then necessary to apply dielectric spectroscopy techniques preferably in the frequency domain. Dielectric response in the frequency domain (DFR) involves a procedure similar to the power factor test method, but in this case, a wide band frequency sweep generates the unique the dielectric response of the insulation (capacitance) where the greatest amount of solid insulation is located. For most cases, the capacitance C1 is tested for CTs with test tap and C5 for CTs without test tap.

For accurate interpretation of results, the CT test plan should set the geometry of the insulation at X: 50-90; and, Y: 0-5. More information on DFR methodology applied to in oil immersed transformers can be found in [6-8]. One example of a field test on a CT is presented in Figure 10.

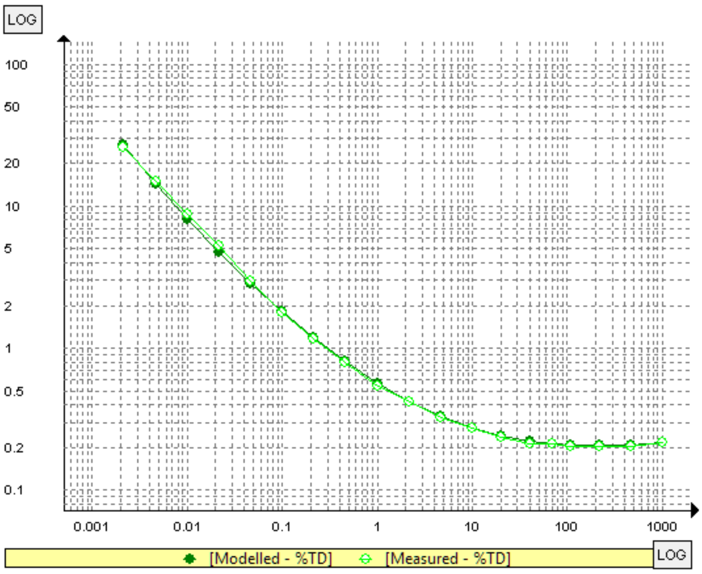

Figure 10: DFR CT, 33°C, with 1.5% moisture and 0.2% FP @ 20°C, oil conductivity 0.05 pS/m

Conclusions

This document compiles the fundamental concepts related to the operation of metering and protection CTs. It emphasizes the need for a well-documented and well performed test process to evaluate the overall condition (electrical and dielectric) of the current transformer in the field.

The most time consuming part of CT testing is going through the repetitive process of connecting and disconnecting test leads for every single combination of phase and tap configuration. Modern CT testers now feature multiple input ports so that operators can connect the instrument to selectable-ratio CTs on all the taps at once. Saturation, Ratio, Polarity, Phase Angle and Winding Resistance measurements are made on all taps at once, significantly reducing testing time.

A practical and comprehensive approach to field testing of CTs including power factor testing to different capacitive areas of the CT was covered. An advanced application of power factor is the method of dielectric response in the frequency domain and its main benefit to determine the moisture concentration in the solid insulation.

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Biography

Diego Robalino currently works for Megger, North America as a senior applications engineer, where he specializes in the diagnosis of complex electrical testing procedures. While doing research in power system optimization with a focus on ageing equipment at Tennessee Technological University, Robalino received his electrical engineering Ph.D. from that institution. With an international background spanning the distance from South America to Eastern Europe, he's garnered additional education and experience in project management and electric drives/automation. Robalino has many years of management responsibility in power systems, oil and gas and research arenas managing the design, construction and commissioning of electrical and electro-mechanical projects. He is an active member of IEEE, ASTM and PMI with multidisciplinary engineering research interests.