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BEST PRACTICES FOR RATIO VERIFICATION OF **POWER** TRANSFORMER CTs

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Current transformers (CTs) are essential for reliable and safe operation of electrical power networks. They function as the link between the primary system, which includes the assets directly involved in the energy flow, and the secondary system consisting of the protection, control, and metering devices. CTs do this by transforming high primary currents into the more measurable quantities used by the secondary system and providing isolation from high primary currents and voltages. Problematic CTs could pose risks to operators, such as malfunction of protection systems, measurement errors, and losses in revenue.



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FIELD TESTING

Field testing CTs during installation/commissioning and maintenance is important for ensuring good quality and performance. Specifications for field testing CTs are defined by ANSI/NETA ATS-2021, *Standard for Acceptance Testing Specifications for Electrical Power Equipment & Systems*, and ANSI/NETA MTS-2023, *Standard for Maintenance Testing Specifications for Electrical Power Equipment & Systems*, and guided by IEEE C57.13.1-2017, *IEEE Guide for Field Testing of Relaying Current Transformers*

The most common electrical tests referenced in these documents include resistance measurement, insulation resistance, polarity, ratio verification using the voltage or current

method, excitation on CTs used for relaying, and burden tests. While these CT tests follow well-established procedures, the special techniques necessary for the ratio verification test on bushing-type current transformers (BCTs) are less widely known and understood. This article serves as a guide to demystify the ratio testing of these CTs by offering techniques, explanations, and additional considerations to get the most accurate and repeatable measurements.

UNDERSTANDING BCTs AND THE RATIO TEST

Bushing-type current transformers (BCTs) are window-type current transformers that can be found in power transformers, voltage

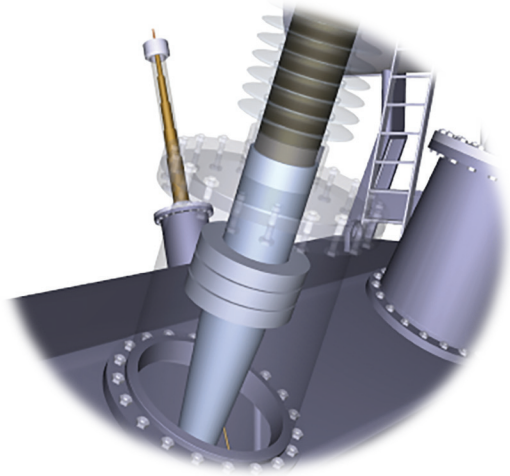


Figure 1: BCT on a Power Transformer

regulators, power circuit breakers, and other equipment. They feature a wound secondary over an annular core with uniformly distributed windings. In a BCT on a power transformer, the bushing center conductor, which connects to the winding of the power transformer, acts as the CT’s primary winding (Figure 1).

BCTs often present challenges to operators using testing equipment to perform the turns ratio test on current transformers. Several techniques unique to testing BCTs are not well-known despite being crucial to the repeatability and accuracy of the measurement. Because the type of power transformer the BCT is mounted on influences the CT turns ratio measurement, several steps must be taken to minimize the influence of the power transformer on the measurement results.

When it comes to testing, the ratio test is vital in verifying the overall function of the CT by checking the rated ratio stamped on the CT’s nameplate. For offline testing, two common methods are used to verify the CT ratio:

1. Primary current injection
2. Secondary voltage injection

It’s important to note that verifying the ratio with these two methods is different from evaluating a CT’s accuracy. The accuracy of a CT can only be assessed by subjecting it to

real operational scenarios as defined by IEEE C57.13 or by employing a model-based method that can calculate the true current ratio for these scenarios.

The primary injection current method determines a CT’s turns ratio by injecting and measuring a current on the primary side (I_{prim}) and measuring the resulting current on the secondary (I_{sec}). The two measured quantities are then divided to calculate the turns ratio (N) (Equation 1). For primary testing BCTs, the power transformer’s added impedance in the primary injection loop becomes an issue because portable test sets struggle to drive the necessary primary currents due to power limitations. The secondary injection voltage method is the preferred method for mounted BCTs on a power transformer.

$$N = \frac{I_{prim}}{I_{sec}} \tag{1}$$

Ratio Test: Secondary Voltage Injection Method

For the ratio test via the secondary voltage injection method, a voltage is applied on the secondary of the CT (V_{sec}) resulting in an induced voltage on the primary side (V_{prim}). The turns ratio N can be estimated with Equation 2.

$$N = \frac{N_s}{N_p} \cong \frac{V_{sec}}{V_{prim}} \tag{2}$$

To prevent saturating the CT, the voltage V_{sec} applied on the secondary should not exceed the knee-point of the CT. If not known, the kneepoint can be determined by performing an excitation test before the ratio test. It is recommended to set the test voltage to 50–75% of the knee-point voltage for the ratio test so that the CT operates in the linear range. Because CT ratios are often large (i.e. 2000:5; 1200:5; 100:5) the measured V_{prim} can result in significantly reduced voltage that can be considerably affected by interferences. If testing in a live environment, the frequency should be set slightly off the mains frequency of 60 Hz, to avoid 60 Hz interferences from energized lines

nearby. Typically, this frequency shift will not affect the voltage ratio.

Figure 2 depicts a secondary voltage injection turns ratio test on a BCT on a y-configured winding of a power transformer. As shown, V_{prim} is not directly measurable since the Phase A winding is now in series with the voltmeter and becomes a part of the primary voltage measurement loop. Instead, the voltmeter measures the combined voltage of $V_{prim} + V_{winding}$. The additional complex impedance, Z , added by the winding can largely impact the voltage measurement in the ratio test depending on the measurement setup, transformer design/configuration, and impedance of the voltmeter.

Mitigating the Effects of the Power Transformer on the Ratio Test

For an improved measurement, the impedance introduced by the transformer winding on the corresponding phase should be reduced as much as possible. This can be done through the test setup. In an open-circuit condition, the transformer impedance Z is mainly comprised of the transformer's magnetizing impedance, which can be quite large. By short-circuiting the opposite side of the phase on which the CT is mounted, this impedance can be reduced and the influence on the error minimized. Note, that short-circuiting the windings on all legs of the transformer on the opposite side is a more practical option for CTs outside of a delta-configured winding and on a y-configured winding. To illustrate the magnitude of the effects, two different test setups will be compared: one where the power transformer is shorted appropriately and the other where the power transformer is left open-circuited. In addition, all CTs not under test must be shorted on their secondary side or remain connected to the burden.

TESTING CTs OUTSIDE OF A Δ-CONFIGURED WINDING AND ON A Y-CONFIGURED WINDING

All functional CTs of the Dyn1 power transformer in Figure 3 were tested. CTs 1–7 are

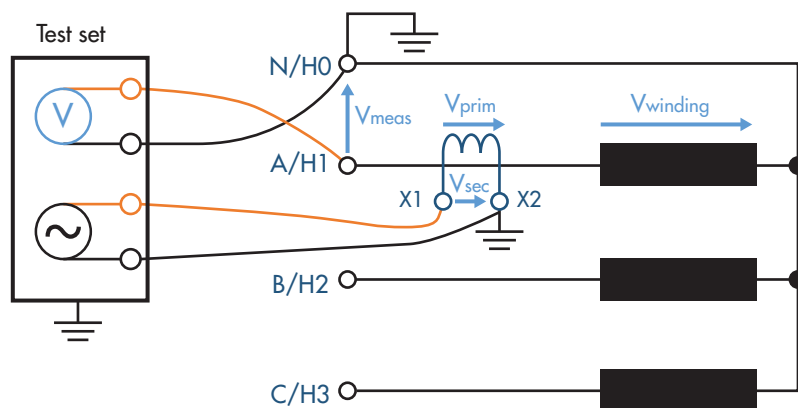


Figure 2: Measurement Setup for BCT on Y-Configured Windings of Power Transformer

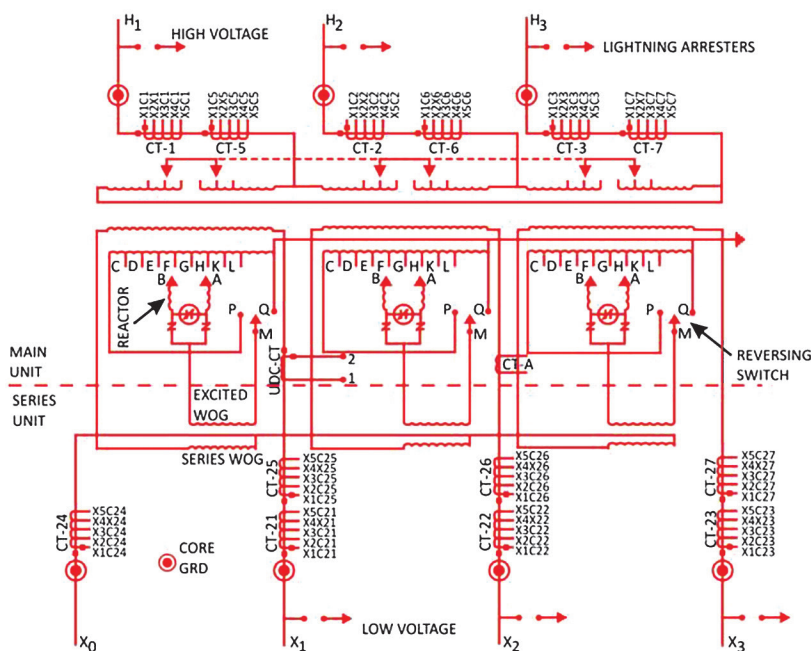


Figure 3: Power Transformer Diagram Dyn1; Voltage Rating 67000-4160Y/2400, 7500 KVA

mounted on the primary side outside of the delta, while CTs 21–27 are on the secondary Y winding.

Figure 4 depicts a typical setup for testing a CT outside of the delta on the high-side winding. In addition to shorting the LV bushings, the terminals of the adjacent phases on which the CT is not mounted are also shorted to ground. Note: To test CTs on the low side, a similar setup was used, with the high-side terminals shorted together and the terminals of the

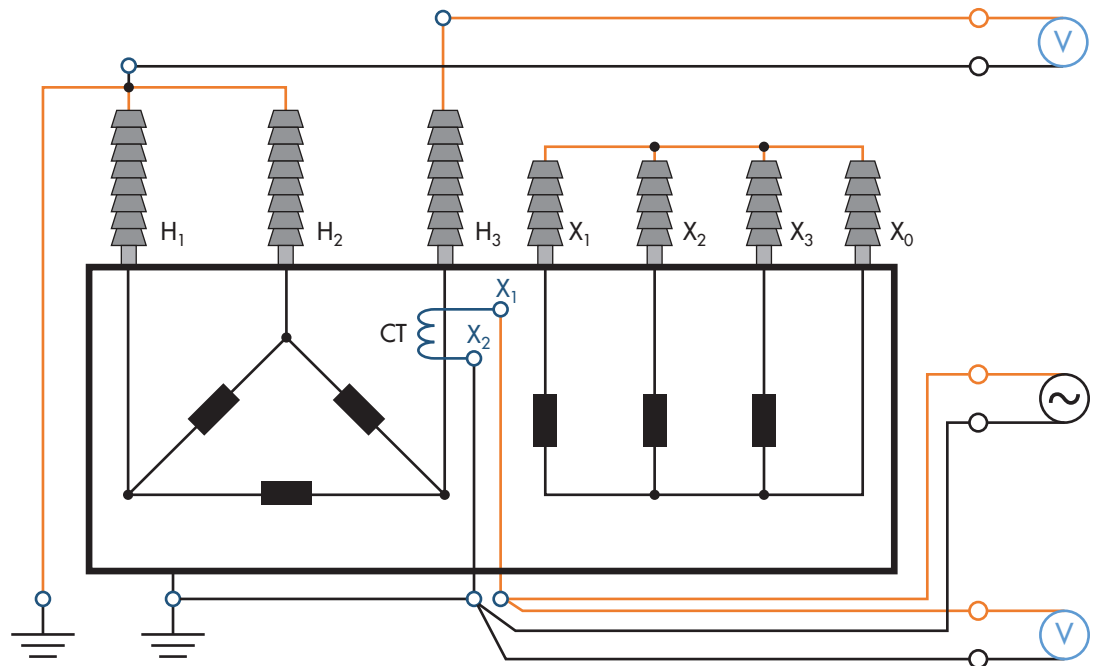


Figure 4: Example of Appropriate Shorting for CT outside of Delta Winding on Phase C

adjacent phases on which the CT was not mounted shorted to ground.

The turns ratio error in Figure 5 can be calculated for each CT by comparing the

measured turns ratio $N_{measured}$ to the rated value N_{rated} calculated from the nominal primary current I_{pn} and the nominal secondary current I_{sn} obtained from the CT nameplates as shown in Equation 3.

$$\text{Turns ratio error} \cong \frac{N_{measured} - (N_{rated})}{(N_{rated})} \cong \frac{\left(\frac{V_{sec}}{V_{prim}}\right) - \left(\frac{I_{pn}}{I_{sn}}\right)}{\left(\frac{I_{pn}}{I_{sn}}\right)} \quad (3)$$

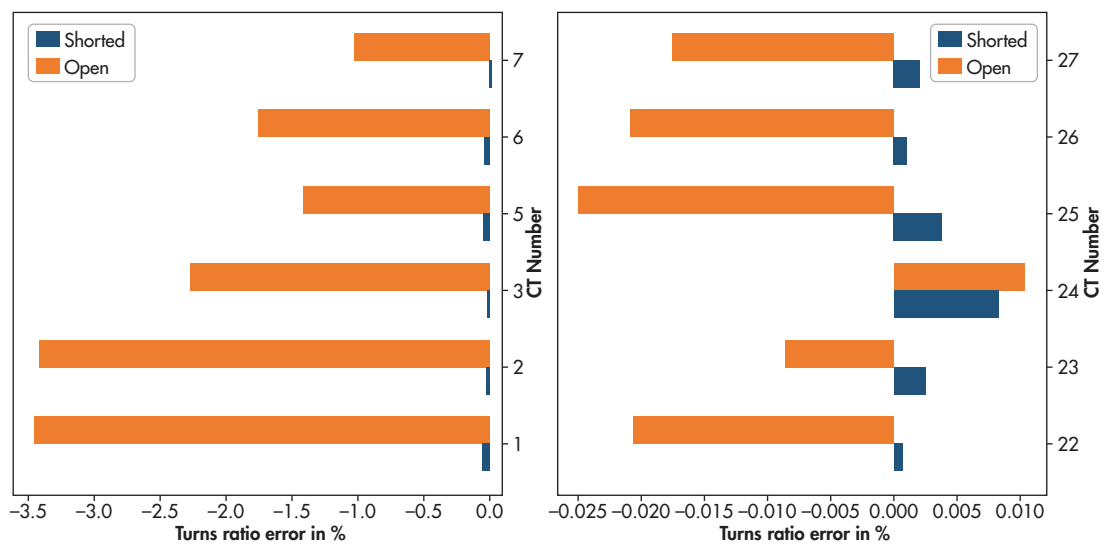


Figure 5: Turns Ratio Error for Shorted and Open-Circuit Conditions for the Power Transformer in Figure 3

The test results presented in Figure 5 highlight the importance of proper shorting. Turns ratio errors as high as -3.5% were observed when the windings were open-circuited compared to when the windings were shorted. In the case of all the high-side CTs, the measurement would fail if the recommended procedures were not followed. For the low-side CTs, the errors remain small for both setups. Although the low-side CTs would still pass in this case, the deviation between the results is still noticeable.

SPECIAL CONSIDERATIONS FOR CTs INSIDE A DELTA-CONFIGURED WINDING

Current transformers (CTs) mounted inside delta-configured windings uniquely affect turns ratio tests using the secondary injection voltage method. In these cases, the delta configuration functions as a voltage divider (Figure 6) for the induced voltage (V_{prim}). As a result, a different testing approach is needed compared to the one previously described. It is no longer recommended to short all bushings of the power transformer on the opposite side on which the CT is mounted. Implementing a ratio correction factor, also known as the delta compensation factor, may also be necessary to account for the voltage distribution.

Three configurations can be used. The first two require a compensation factor of 1/3 and 2/3, while the third test setup does not require any compensation. The voltage divider equation (Equation 4) is used to derive compensation factors and determine the appropriate test

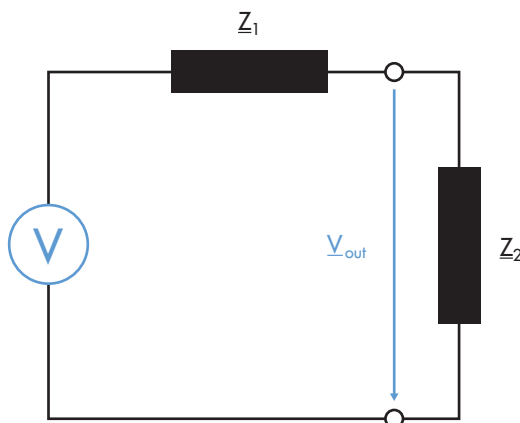


Figure 6: Basic Voltage Divider Circuit

setups. Using this equation, we can determine the voltage drop across impedances in series when subjected to an input voltage.

$$V_{out} = \frac{Z_{out}}{Z_{total}} * V = \frac{Z_2}{Z_1 + Z_2} * V \quad (4)$$

Delta Compensation

The delta compensation factor of 1/3 for Test Setup 1 (Figure 7) and 2/3 in Test Setup 2 (Figure 8) are derived from the assumption that each winding presents an equal open-circuit impedance, thus dividing the induced voltage V_{prim} in the delta into thirds. Note, this assumption cannot be made if shorting all three phases and the neutral, as this may introduce discrepancies in impedance values. Therefore, it is recommended to leave the power transformer open-circuited for test setups 1 and 2.

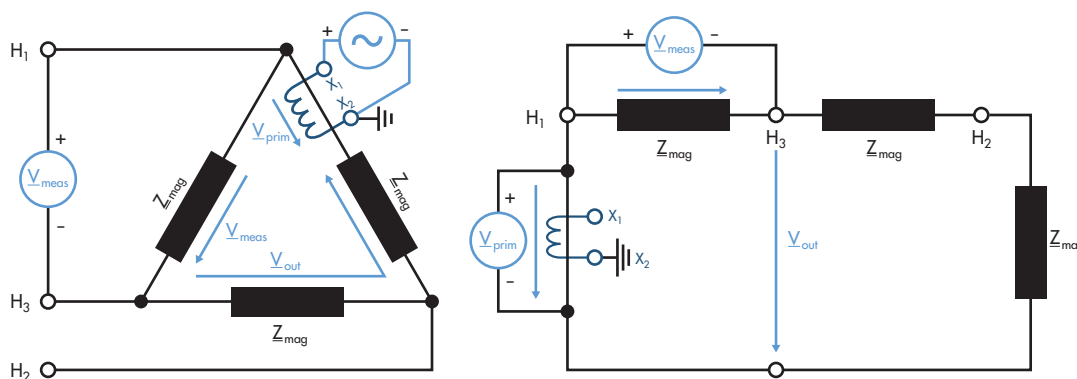


Figure 7: Delta Compensation of 1/3 When Measuring the Primary Voltage in the Adjacent Leg to the CT

Test Setup 1

The calculation of the delta compensation 1/3 is derived from Equations 5, 6, and 7.

$$V_{meas} = V_{prim} - V_{out} \tag{5}$$

$$V_{out} = \frac{Z_{mag} + Z_{mag}}{Z_{mag} + Z_{mag} + Z_{mag}} * V_{prim} = \frac{2}{3} * V_{prim} \tag{6}$$

$$V_{meas} = V_{prim} - \frac{2}{3} * V_{prim} = \frac{1}{3} * V_{prim} \tag{7}$$

Test Setup 2

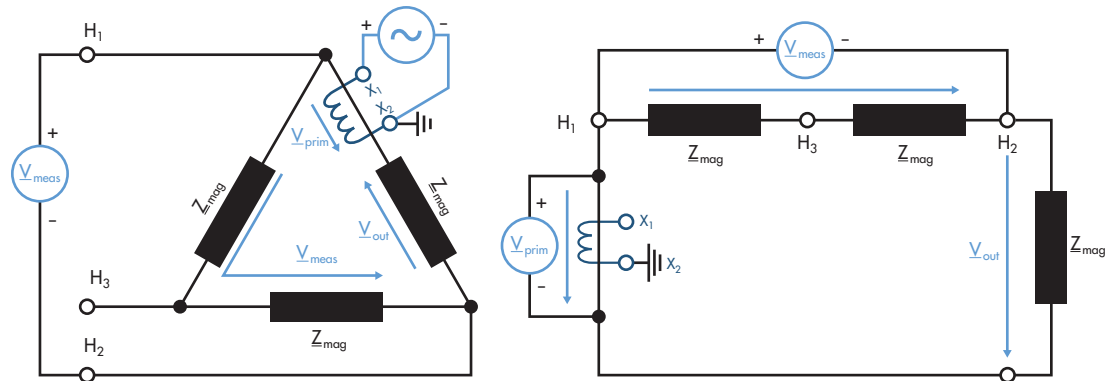


Figure 8: Delta Compensation of 2/3 When Measuring the Primary Voltage in the Same Leg as the CT

The calculation of the delta compensation 2/3 is derived from Equations 8, 9, and 10.

$$V_{meas} = V_{prim} - V_{out} \tag{8}$$

$$V_{out} = \frac{Z_{mag}}{Z_{mag} + Z_{mag} + Z_{mag}} * V_{prim} = \frac{1}{3} * V_{prim} \tag{9}$$

$$V_{meas} = V_{prim} - \frac{1}{3} * V_{prim} = \frac{2}{3} * V_{prim} \tag{10}$$

No Delta Compensation

For the alternative and recommended approach, a short-circuit is applied on the opposite side of the power transformer phase corresponding to the CT's location. Therefore, if the CT is mounted on phase B on the high

voltage side of the power transformer, only phase B on the low voltage side is shorted. The meter is then connected across the phase the CT is mounted on, as shown in Figure 9. With this test setup, no delta compensation factor is necessary.

Test Setup 3

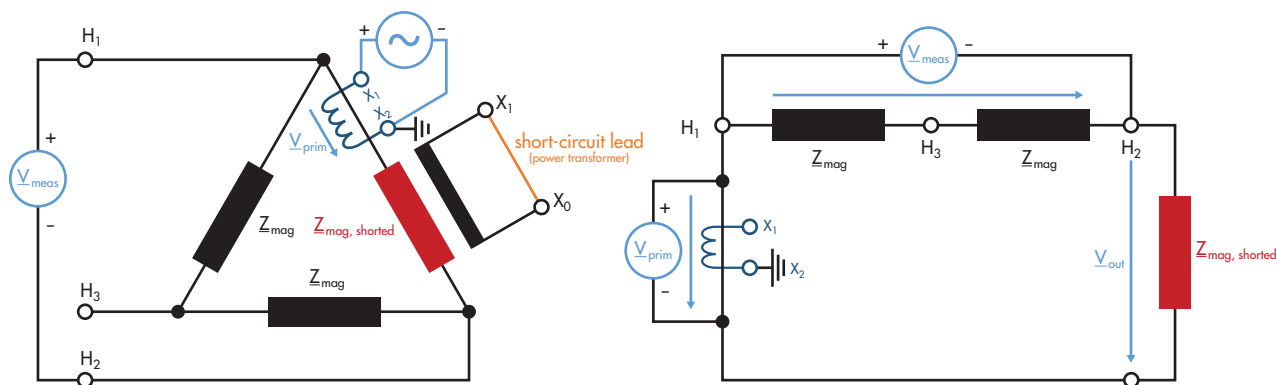


Figure 9: No Delta Compensation when Measuring the Primary Voltage in the Same Leg as the CT and the Corresponding Phase of the Power Transformer Is Shorted

The calculation of the relationship between V_{out} and V_{prim} and the compensation factor is done using Equations 11 and 12.

$$V_{meas} = V_{prim} - V_{out} \tag{11}$$

$$V_{out} = \frac{Z_{mag,shorted}}{2 * Z_{mag} + Z_{mag,shorted}} * V_{prim} \tag{12}$$

The impedance Z_{mag} is much higher than the impedance $Z_{mag,shorted}$ (Equation 13). Therefore, the voltage V_{out} becomes close to zero (Equation 14).

$$Z_{mag} \gg Z_{mag,shorted} \tag{13}$$

$$V_{out} = \frac{Z_{mag,shorted}}{2 * Z_{mag} + Z_{mag,shorted}} * V_{prim} \rightarrow V_{out} \cong 0 \tag{14}$$

$$V_{meas} = V_{prim} - 0 = 1 * V_{prim} \tag{15}$$

The result of Equation 14 is inserted into Equation 11 resulting in a delta compensation of 1 (Equation 15).

CONCLUSION

When performing turns ratio tests on CTs in power transformers, the secondary injection voltage method is preferred due to the large impedance introduced by the power transformer.

Key points:

- Avoid exceeding the CT's knee point to prevent saturation.
- Utilize a test frequency slightly offset from 60 Hz to avoid interference at line frequency.
- Perform appropriate shorting to reduce the power transformer impedance as much as possible, hence minimizing its effect on the measurement.
- For CTs inside a delta winding, alternative techniques must be applied and compensation factors that vary with the connection setup may need to be used.
- It is important that other CTs not being tested are short-circuited on the secondary.

The example case has demonstrated that failure to adhere to proper shorting practices for the power transformer results in significant discrepancies in the outcomes for the ratio test, potentially leading to measurements outside the acceptable tolerance range. An improper setup could yield even greater errors if the appropriate delta compensation factor or connection setup is not used for CTs located inside delta-configured windings.

Although not discussed in this article, it's important to note that model-based testing approaches that utilize the secondary injection method as part of its test routine for creating the CT model will also be affected, possibly leading to accuracy tests outside the acceptable range. For model-based testing the CT turns ratio is part of the test procedure, alongside testing the excitation and secondary winding resistance. Therefore, it is important to follow the best practices highlighted in this article to ensure the most accurate and repeatable measurements. [NW](#)



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