Challenges of Performing Electrical Tests in EHV Substations

Dinesh Chhajer, PE

Manager, Technical Support Group

Megger North America

Dallas, TX USA

Ian Kreher

Engineer – Transmission Field Services

American Electric Power

Roanoke, VA USA

I. Abstract

With ever growing demand for power, it is not uncommon for transmission utilities to build and operate substations at High Voltage (HV) and Extra High Voltage (EHV) levels. Maintenance and testing of assets in EHV stations is critical for proper electric power grid operation and reliability. Performing electrical measurements accurately and reliably in such environments is always a challenge because of the presence of unwanted electrostatic noise and interference. Testing Bushing Current Transformers (BCT) on a transformer or circuit breaker can be especially problematic because of induced voltage on bushing terminals from their proximity to overhead energized lines. In these high noise environments, tests recommended in IEEE standard C57.13.1 such as ratio, polarity, excitation and DC insulation resistance may suffer from inconsistent and unreliable measurements.

This paper addresses how to perform IEEE recommended tests on BCTs safely and accurately in EHV stations. It discusses how different sources of undesired electrical signals can affect the measurement circuit. Techniques such as smart grounding principle are shown that can suppress electrostatic interference and makes the test setup immune to external factors. Paper concludes with a case study of testing multiple BCTs on a 765/500/13.8 kV, 750 MVA auto transformer with tertiary in an energized EHV substation in inclement weather condition, where the BCTs were tested with high accuracy and precision despite extreme interference conditions.

II. Introduction

Current Transformers (CT), DC power supplies, circuit breakers and relays are some of the key components of the protection and control systems. The reliable operation of a protection system depends to a large extent on the performance of these devices. Any mis-operation of these components may leave the power system in a vulnerable state with the possibility for irreparable damages. Periodic testing of these assets will ensure a protection circuit that would operate when it is called upon.

CTs not only provide a means to reflect the status of the primary circuit but also provide isolation between the high voltage primary and secondary measurement and control devices. BCTs on transformers and circuit breakers are electrically tested as per IEEE recommendations to verify their performance and ensure that they meet manufacturer’s specifications. Testing BCTs can become a challenge when they are under overhead energized lines such that measurements suffer by induced voltage on bushing terminals. This problem gets more pronounced when testing is performed in EHV stations. This paper attempts to address the issue by first understanding the root cause of the problem, recommending the solution, performing the test as per the recommendations and finally evaluating the results.

III. IEEE Recommended Tests for Relaying Type CTs

Due to the importance that CTs play in power system protection, the IEEE Power Engineering Society recommends certain field test measures for relaying type CTs. These tests are designed to verify proper operation, connection, and condition of the CTs. IEEE Standard C57.13.1, "*IEEE Guide for Field Testing of Relaying Current Transformers"*, Reference [1] outlines the intention for the designated tests as well as the test procedures. Following are a list of the recommended tests and measurements.

1. *Ratio Test:*

   This test verifies the ratio and connection of the CT, as well as any taps that are available. This can be accomplished with the equipment both in and out of service. The out-of-service voltage method require injecting a voltage into the secondary (V_1) and measuring the primary voltage (V_2), which will be directly related to the CT turns ratio(N_1/N_2).

$$\frac{\mathrm{N}_1}{\mathrm{N}_2} = \frac{\mathrm{V}_1}{\mathrm{V}_2} \qquad (1)$$

   The in-service current method requires placing ammeters on both the secondary and primary leads and recording the current values. These values will also be directly related to the CT turns ratio.

2. *Polarity Test:*

   This test verifies that the current flow in the secondary matches the designed flow respective to the primary current. This is especially important for CTs being used in differential or comparative relaying. This can be accomplished in a number of ways including: temporarily applying a DC voltage to either the primary or secondary and verifying analog meter deflection, applying an AC voltage to the secondary and using an oscilloscope to compare with the primary voltage, paralleling a reference CT with the secondary of the test CT and verifying current magnitudes, and measurement of phase angle. Another method commonly used by field test instruments is comparison of the phase angle between secondary voltage V_S and primary voltage V_P where phase angle close to zero would indicate correct polarity and close to 180^o would represent incorrect polarity.

3. *Insulation Resistance Test:*

   This test verifies that the CT insulation is satisfactory between both winding to winding and winding to ground. This is usually performed with an insulation resistance tester. Three tests are usually performed to check the integrity of the insulation system:

   a. Primary to ground
   b. Secondary to ground
   c. Primary to secondary

4. *Resistance Measurement:*

   This test verifies the DC resistance of the CT secondary winding as well as the connections within and on the equipment. This can be measured using a traditional low resistance ohmmeter or calculated using a DC volt-amp circuit.

5. *Excitation Test:*

   This test verifies the saturation characteristics of the CT and its taps, thereby confirming accuracy ratings, connections, and absence of internal short circuits. This is performed by applying a varying ac voltage to the secondary winding and recording the associated current. The supplied voltage is increased until the CT has fully saturated. Knee point can be calculated using the ANSI 45 criteria which finds the unique point crossing the excitation curve with a 45° tangent. The plot of this measurement is compared to previous data and any deviation should be investigated.

6. *Admittance Test:*

   This test verifies the nearly constant internal and external burden of the CT as it is installed. This is performed by injecting an acoustic signal into the CT and detecting the circuit admittance. This measurement will be compared to previous system results and any deviation will indicate an abnormal condition.

7. *Burden Test:*

   Part of the rating classification of a CT is its ability to supply a known current into a known burden and meet a stated accuracy. Burden test verifies that the CT can maintain a designated accuracy for a known burden and supplied current. A rated secondary current is applied to the burden connected to the CT secondary and voltage is measured across it to calculate the impedance and phase angle of the burden. In field, it is very important to verify that the burden of the circuit does not exceed the conditions in which the CT will maintain it specified accuracy and performance. Any significant drop in current will show that the CT's designed burden has been exceeded.

Other specialized tests that may be used include:

i. *CT in a closed delta*

   If there are no secondary terminals brought out these CTs must be tested for ratio and polarity before being assembled.

ii. *Inter-Core Coupling Test*

   Inter-core coupling occurs when an unintended conducting loop is established between isolated CTs. This is especially possible on closely mounted secondary cores with a common primary lead, such as BCTs. This coupling can produce current imbalances which will affect differential or comparative relaying schemes. This test is performed by applying a varying voltage on the secondary winding and measuring full winding voltages on adjacent CT cores one at a time while keeping remaining CT secondaries shorted.

IV. Field Challenges of Testing BCTs in EHV Environments

EHV environments can compound the difficulty of testing BCTs. This is a result of a variety of factors, but the most influential is the high level of induced voltage. Today U.S. electric utilities operate complex transmission systems at voltages up to 765 kV. These EHV power lines interact with external objects to create capacitive, inductive, and conductive coupling. Equipment under or near an energized line will become charged by capacitive coupling resulting in an induced voltage that can reach several kilovolts. This voltage can be calculated using the equation (2) listed in reference [3]:

$$V_{object} = V_{line}\left(\frac{Capacitace_{line-object}}{Capacitace_{line-object} + Capacitace_{object-earth}}\right) \quad (2)$$

When testing a BCT, the bushing terminals can be left open, effectively insulating the tested equipment from ground. When this occurs, the open-circuit voltage that is induced can be calculated using the equation (3) listed in reference [3]:

$$V_{open} = 0.25 * V_{LL} * h_o\sqrt{\frac{h_1^2}{d_{1o}^4} + \frac{h_2^2}{d_{2o}^4} + \frac{h_3^2}{d_{3o}^4} - \frac{h_1 h_2}{(d_{1o}^2)(d_{2o}^2)} - \frac{h_2 h_3}{(d_{2o}^2)(d_{3o}^2)} - \frac{h_3 h_1}{(d_{3o}^2)(d_{1o}^2)}} \quad (3)$$

Where,

V_{LL}= line voltage between phases (kV)
h_o = height of the object above ground (m)
h_j = mean height of phase conductor j (j = 1, 2, 3) (m)
d_{jo} = distance between phase conductor j and object (m)

This induced voltage makes testing BCTs extremely difficult, especially for verification of ratio and polarity in an automated test set. The addition of stray voltage on any floating bushing terminals will drastically change the voltage on the primary winding, making it impossible to accurately measure voltages on the primary. This has been verified by field measurements that result in ratio errors in excess of 15-20%. This will preclude the use of any test equipment that requires ungrounded terminals or does not take measures to guard against the induced voltage. While excitation, insulation, and inter-core coupling tests can be completed with an automated test set, ratio and polarity testing must be performed by other means or with an automated instrument that is capable of measuring with one terminal grounded that guards out the induced voltage effects. With advancements in instrumentation and measurement techniques, some of the new test instruments have means to automatically ground the bushing terminal under test internally which allows high level of noise immunity and suppress the induced voltage effects.

V. Interference and Noise:

The IEEE recommended field tests on relaying class CTs are mostly performed by the secondary voltage injection method because of the ease of connections and instrument portability. Measurements for tests such as excitation, winding resistance, inter core coupling and burden are primarily taken on the secondary side of the CT. Since the secondary circuit is electrically isolated from the primary side, interference and noise from surroundings negligibly affect these tests, and even under high interference conditions the results are within an acceptable range.

Insulation resistance tests between the CT primary to ground and primary to secondary can be affected by induced voltage on high side bushing terminals. Some instruments even warn the users of presence of any live potential due to the coupling effect and induced voltage on the bushings.

As shown in Figure 1, the ratio and polarity tests are the two tests where the test instrument's primary side leads are connected to the bushings of the BCT under test. Since the voltage induced in the CT primary when using secondary test voltage method would be only a few volts, it is challenging to measure it accurately under the influence of external electrostatic interference and in the presence of a resulting, much higher noise floor. Even a small level of interference can easily throw the ratio error off by a great amount leaving the results unacceptable and unreliable. Since the level of interference and external conditions can vary greatly from one high voltage substation to another, it becomes a big challenge to measure the ratio and polarity accurately, reliably and with repeatability.

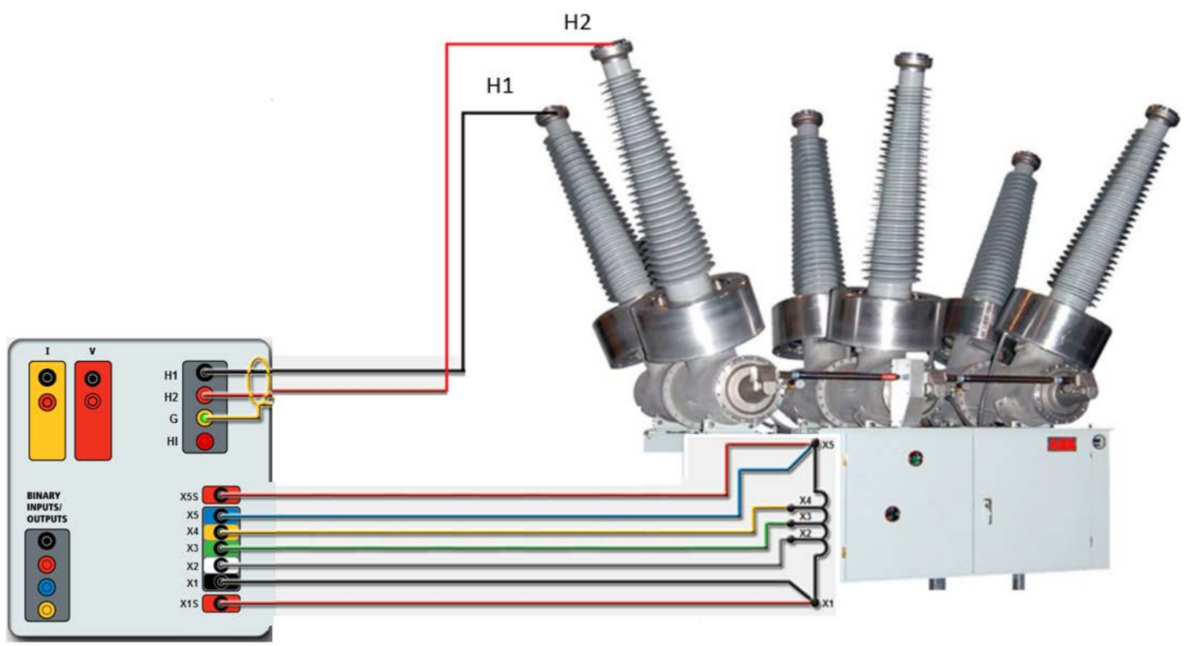

Figure 1: Connections to primary and secondary side of the CT for ratio and polarity test

Another factor that may affect the ratio and polarity results is the impedance of the measuring circuit. As shown in Figure 2, when testing BCTs mounted on a transformer bushing the voltage drop across the transformer winding can introduce an error in the measurement. The voltage V_2 measured by the test instrument can be different than the actual induced voltage V_2' across the CT primary. Any difference between V_2' and V_2 would contribute to the ratio and phase angle error. Ratio and phase angle error of CTs are discussed in detail in reference [2].

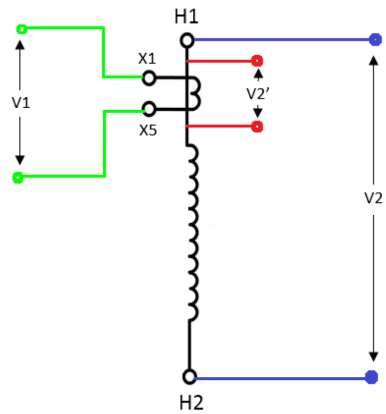

Figure 2: Measuring circuit diagram for the ratio and polarity test

VI. Interference Suppression Methods:

Methods to minimize ratio errors due to interference and transformer circuit impedance are better explained by looking at the transformer exact equivalent circuit. As per Figure 3, a transformer can be represented as an ideal transformer with a turns ratio of N_1 to N_2 by adding the following components.

Primary winding resistance R_P and primary leakage reactance X_P

Secondary winding resistance R_S and secondary leakage reactance X_S

Core loss component R_C and magnetizing reactance X_m

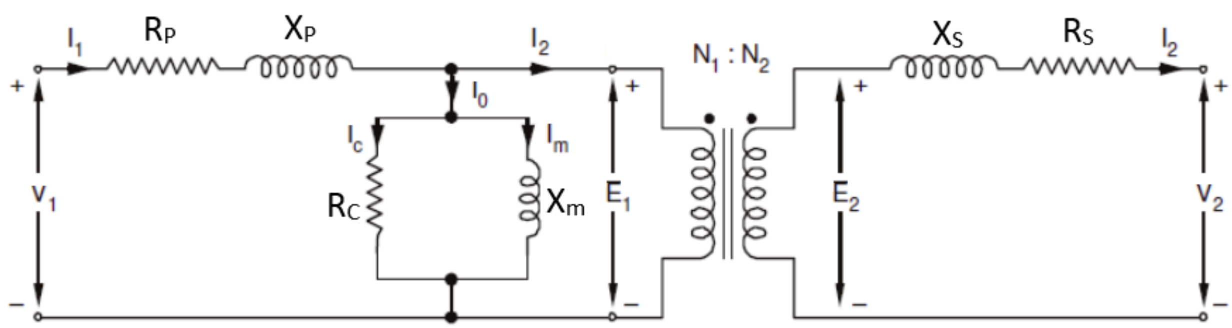

Figure 3: Transformer exact equivalent circuit

Secondary winding impedance when referred to primary side can be represented by an equivalent circuit as shown in Figure 4

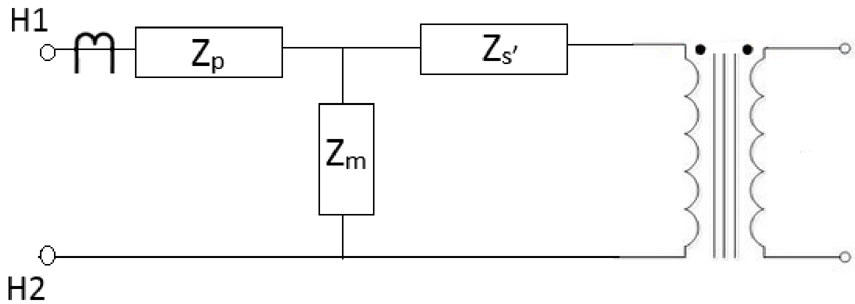

Figure 4: Transformer equivalent circuit as referred to primary

Where,

$$Z_P = R_P + j * X_P$$

$$Z_m = R_C \,||\, X_m$$

$$Zs' = \left(\frac{N_1}{N_2}\right)^2 * (Rs + j * Xs)$$

For any transformer, magnetizing impedance Z_m is much larger than primary winding impedance Z_P and secondary winding impedance Z_s'.

$$Z_m \gg Z_P \text{ } or \text{ } Z_s \qquad (4)$$

To reduce the error in the measurement, it is important to reduce the impedance or inductance of the circuit. Under an open circuit condition, the impedance seen by the measuring circuit (as viewed from H1-H2 terminals) is primarily magnetizing impedance as shown in Figure 5. Under an induced voltage condition on the bushing terminals, this can lead to an undesired voltage drop in the measuring circuit and can lead to a ratio error outside the tolerances.

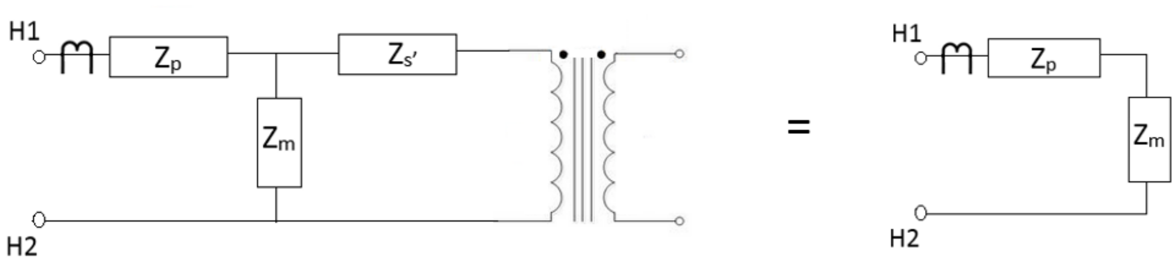

Figure 5: Transformer circuit impedance under open circuit condition

In order to reduce the impedance of the circuit, it is recommended to short the corresponding secondary winding of the transformer as shown in the diagram below.

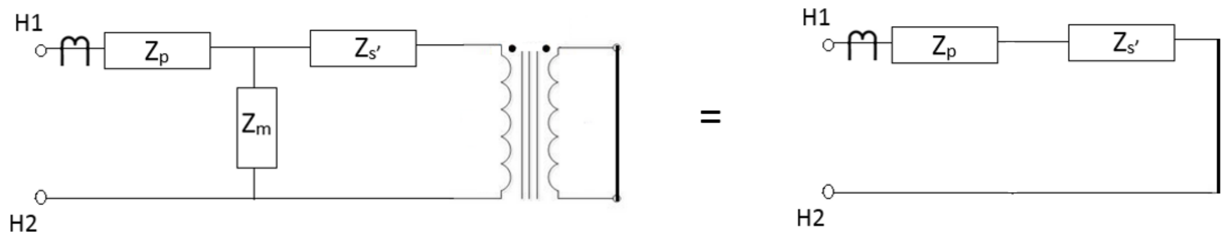

Figure 6: Transformer circuit impedance under short circuit condition

With the secondary winding short circuited, the impedance seen by the measuring circuit is reduced to the primary and secondary winding impedance. The voltage drop across winding impedance is much lower and this helps in reducing the ratio and phase angle error.

When working under high voltage energized lines, the induced voltage on the bushing terminals and high inductance of the transformer winding together can create a problem. Any induced voltage would cause leakage or stray current through the circuit and with high impedance it would create a higher voltage drop, thereby affecting the measurements. Therefore, in addition to shorting the secondary winding it is recommended to ground the bushing terminal corresponding to the BCT under test to guard against any induced voltage due to coupling effect. Technicians operating the test instrument should be careful in implementing smart grounding principle and avoid any possibility of ground loops which can create a circulating path and influence the current flow in the measurement circuit. It is important to note that only one terminal should be grounded on high voltage bushing terminals to suppress the interference from overhead energized lines. It is also recommended to connect the unused bushing terminals to the return path H2 lead. This serves two purposes; it reduces the effect of any induced stray voltage on the floating terminals and depending upon the winding configuration, it would further reduce the overall impedance of the measurement circuit.

The following diagrams depict the recommended connections for testing BCTs on different transformer configurations:

1) Testing H1 BCTs of a transformer with delta winding configuration is shown in Figures 7 and 8. Connection configurations for all the delta winding bushings are given in Table 1.

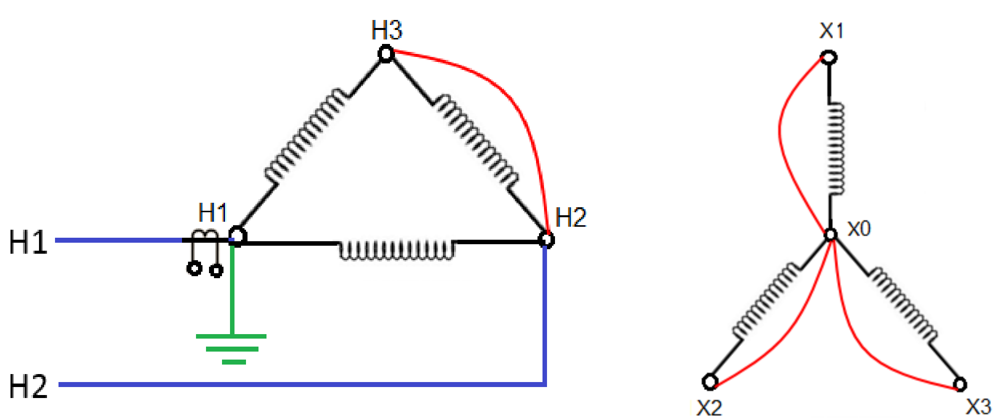

Figure 7: Connection diagram for testing primary side BCTs for a delta-wye configuration

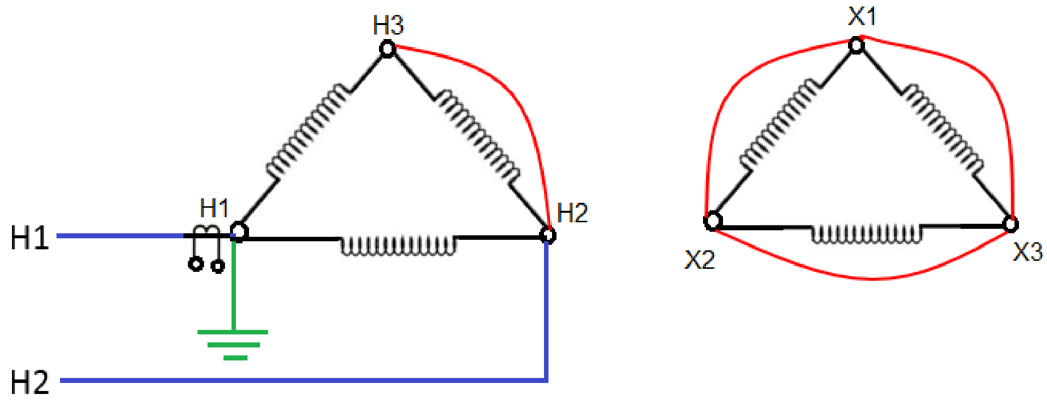

Figure 8: Connection diagram for testing primary side BCTs for a delta-delta configuration

BCT under Test	H1 lead	H2 lead	Ground	Jumpers H side	Jumpers X side
H1	H1	H2	H1	H2, H3	X1,X2,X3 and X0 (if available)
H2	H2	H3	H2	H3, H1	X1,X2,X3 and X0 (if available)
H3	H3	H1	H3	H1, H2	X1,X2,X3 and X0 (if available)

Table 1: Connections for each BCT for a delta configuration winding

2) Testing H1 BCTs of a transformer with wye winding configuration is shown in Figures 9 and 10. Connection configurations for all the wye winding bushings are given in Table 2.

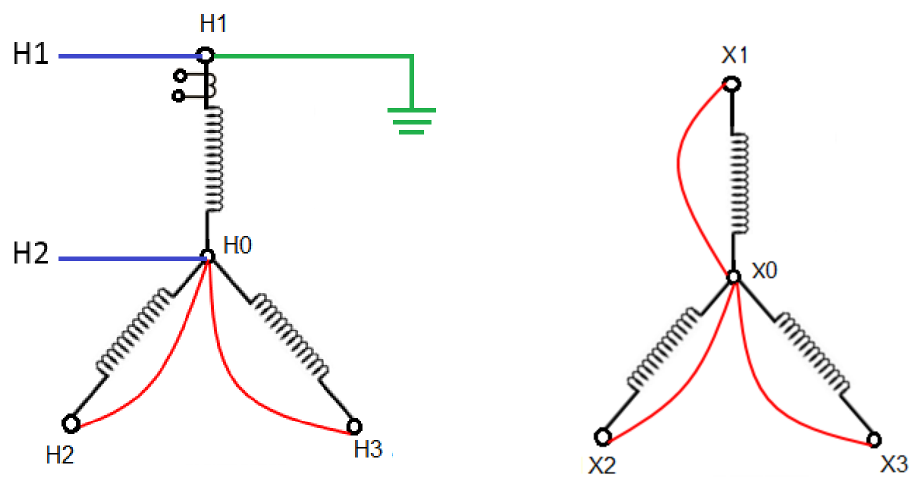

Figure 9: Connection diagram for testing primary side BCTs for a wye-wye configuration

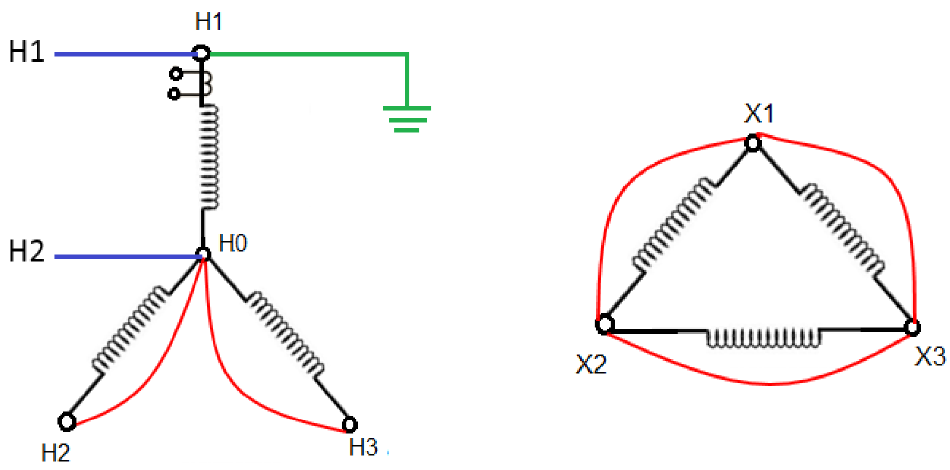

Figure 10: Connection diagram for testing primary side BCTs for a wye-delta configuration

BCT under Test	H1 lead	H2 lead	Ground	Jumpers H side	Jumpers X side
H1	H1	H0	H1	H2, H3, H0	X1,X2,X3 and X0 (if available)
H2	H2	H0	H2	H3, H1, H0	X1,X2,X3 and X0 (if available)
H3	H3	H0	H3	H1, H2, H0	X1,X2,X3 and X0 (if available)
H0	H0	H1	H0	H1, H2, H3	X1,X2,X3 and X0 (if available)

Table 2: Connections for each BCT for a wye configuration winding

3) Testing H1 BCTs of a single phase auto transformer with tertiary winding is shown in Figure 11. Connection configurations for all the bushings of an auto transformer with tertiary are given in Table 3.

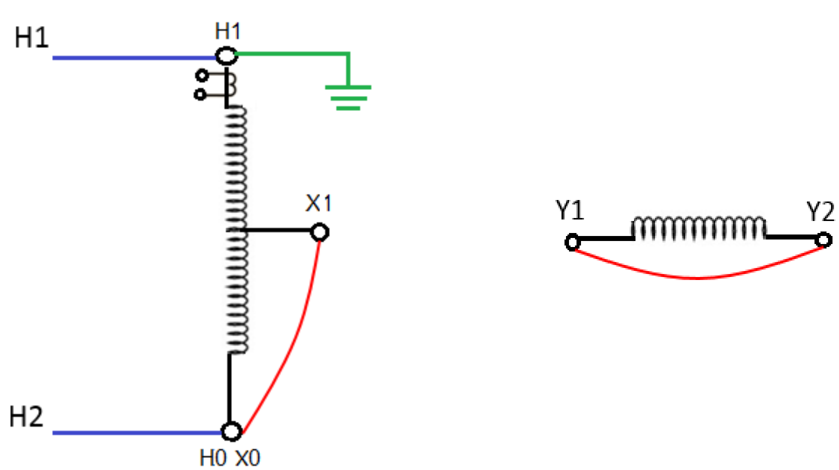

Figure 11: Connection diagram for testing high side BCTs on an auto transformer with tertiary

BCT under Test	H1 lead	H2 lead	Ground	Jumpers Primary side	Jumpers Tertiary side
H1	H1	H0	H1	X1, H0	Y1 and Y2
X1	X1	H0	X1	H1, H0	Y1 and Y2
X0	X0	H1	H0	H1, X1	Y1 and Y2
Y1	Y1	Y2	Y1	H1, X1, H0	N/A
Y2	Y2	Y1	Y2	H1, X1, H0	N/A

Table 3: Connections for each BCT of a single phase auto transformer with tertiary

VII. Case Study

Electrical testing in proximity of overhead energized lines and inductance associated with large windings of power transformers were proving to be problematic for one of the largest utilities in the USA. The company was finding it impossible to test BCTs on transformers in their 765 kV substations. The results obtained were inconsistent and unreliable because of large amounts of error in the measurements. This utility which owns North America's largest transmission network and operates numerous 500 kV and 765 kV stations, was looking to develop a complete and effective solution to this challenging problem.

A crucial part of the commissioning process for power transformers in EHV substations is the testing of BCTs. A 765/500/13.8 kV, 750 MVA single phase auto transformer with seventeen BCTs was tested in an energized EHV substation during inclement weather conditions as shown in Figure 12.

Figure 12: Picture showing the testing under energized lines and rainy condition

As shown in Table 4, a total of seventeen BCTs mounted on different bushings of a single phase auto transformer with tertiary were tested for all the IEEE recommended tests.

BCT	1	2	3	4	5	6
H1	3000:5 C800	3000:5 C800	1000:5 0.15S B1.8	3000:5 C800	3000:5 C800	1698: 5 C200
X1	3000:5 C800	3000:5 C800	3000:5 C800	3000:5 C800		
X0	3000: 5 C800	920: 5 C200				
Y1	30000: 5 C800	5000: 5 C800	4963: 5 C200			
Y2	30000: 5 C800	5000: 5 C800				

Table 4: BCT with different classes and ratios mounted on different bushings

With cloudy and rainy weather conditions along with the nearby energized lines, the outside field conditions were not very conducive to get precise and accurate measurements where even a small measurement error (in the mV range) of high side voltage could have easily thrown the ratio readings off. Insulation resistance was first performed as per the recommended connections in IEEE Standard C57.13.1. When performing the primary to ground insulation resistance test, the test instrument detected a presence of live voltage on bushing terminals and gave a "live voltage present" warning message. The presence of induced voltage and size of the transformer gave indications that test results might get influenced and would pose a challenging situation.

Figure 13: Picture showing the location of each bushing on single phase auto transformer with tertiary

As shown in Figure 13, connections to the bushings were made by bringing a wire from top of the bushing for easy access. The test was first carried out by connecting the leads in a traditional way. The H1 lead was connected to the H1 bushing and the H2 lead to the H0/X0 bushing. All tests such as excitation and winding resistance were performed on the BCT without any difficulty. While performing the ratio and polarity tests, readings would not stabilize on high side terminals and manually recording the results gave a ratio error of 20-23 %. After performing a variety of connections that involved different bushings and trying different BCTs it was evident that traditional connections would not work in this situation.

To ensure that repeatable and accurate measurements are obtained, three actions were taken:

- Reduce the effect of electrical noise and electrostatic interference from overhead energized lines by grounding the bushing of the BCT under test. This also required that the test instrument used should be capable of measuring very low voltage levels through a one terminal grounded circuit.
- Short the secondary and tertiary winding (separately) to reduce the circuit impedance
- Short all the floating unused terminals and connect to the return path (H2 lead).

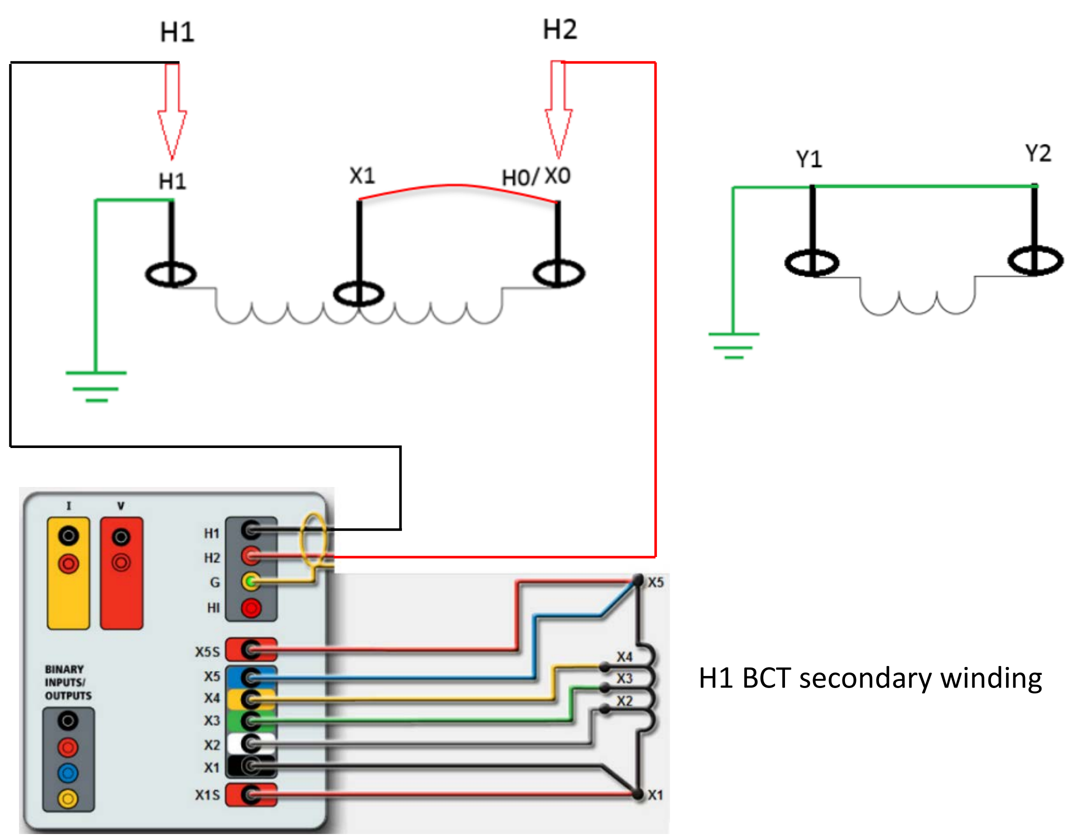

Figure 14: Connection diagram for testing BCTs on single phase auto transformer with tertiary

Using the connections shown in Figure 14, testing was repeated and consistent results were obtained for all the tests. The following results were collected on a C800 3000:5 multi tap CT mounted on the H1 bushing as shown in Figure 15.

	Tap	X1-X2	X1-X3	X1-X4	X1-X5	X2-X3	X2-X4	X2-X5	X3-X4	X3-X5	X4-X5
RATIO	Nameplate	1000:5	2200:5	2500:5	3000:5	1200:5	1500:5	2000:5	300:5	800:5	500:5
	Measured	1000.32:5	2200.83:5	2500.68:5	3000.26:5	1200.51:5	1500.37:5	1999.95:5	299.855:5	799.435:5	499.58:5
	% Error	0.032	0.038	0.027	0.009	0.043	0.024	0.003	0.048	0.071	0.084
	Test V (V)	99.530	218.98	248.81	298.52	119.45	149.28	198.99	29.835	79.543	49.708
	Test I (A)	0.1644	0.0747	0.0658	0.0548	0.1370	0.1096	0.0822	0.5485	0.2057	0.3292
	Prim V (V)	0.4975	0.4975	0.4975	0.4975	0.4975	0.4975	0.4975	0.4975	0.4975	0.4975
Phase Dev.		0°29'	0°29'	0°29'	0°29'	0°29'	0°29'	0°29'	0°29'	0°29'	0°29'
Polarity		Correct	Correct	Correct	Correct	Correct	Correct	Correct	Correct	Correct	Correct
Knee	Volt.(V)	196.05	431.26	489.45	587.71	235.22	293.38	391.63	58.422	156.44	98.259
	Cur.(A)	0.2604	0.1186	0.1042	0.0867	0.2179	0.1737	0.1300	0.8603	0.3223	0.5170

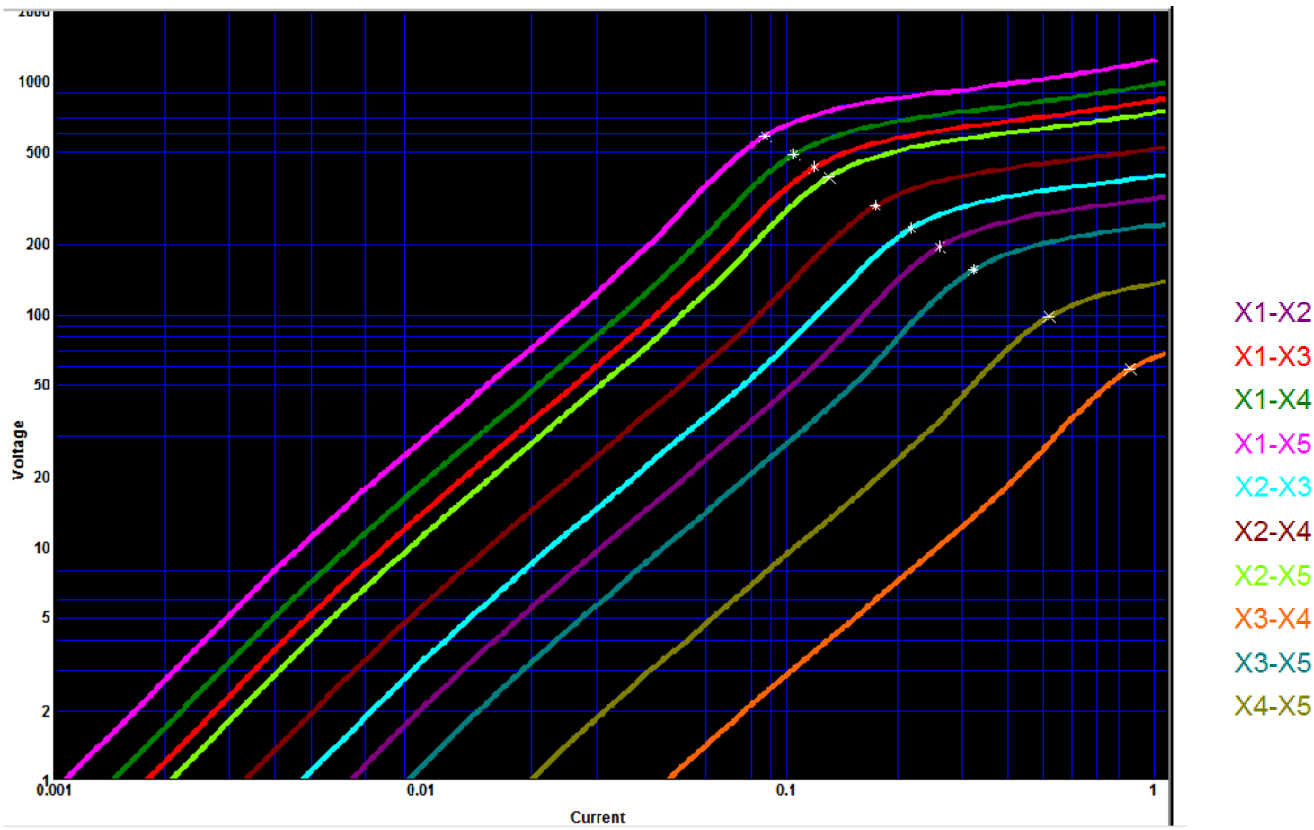

Figure 15: Ratio and Saturation results of H1 BCT

Based upon the connections successfully applied for the first BCT, the other BCTs were tested using the same procedure and highly accurate results were obtained on all of the CTs. It is noted that since the bushing terminal was grounded to eliminate the interference present, it was not possible to run insulation resistance tests with this setup. Insulation resistance tests were run separately at the completion of all the tests. The results obtained on C800 5000:5 BCT mounted on tertiary winding Y1 bushing are shown in Figure 16.

Tap		X1-X2	X1-X3	X1-X4	X1-X5	X2-X3	X2-X4	X2-X5	X3-X4	X3-X5	X4-X5
RATIO	Nameplate	1500:5	2000:5	4000:5	5000:5	500:5	2500:5	3500:5	2000:5	3000:5	1000:5
	Measured	1495.39:5	1995.21:5	3995.07:5	4995.44:5	499.822:5	2499.69:5	3500.06:5	1999.86:5	3000.24:5	1000.37:5
	% Error	0.308	0.240	0.123	0.091	0.036	0.013	0.002	0.007	0.008	0.037
	Test V (V)	89.405	119.28	238.85	298.66	29.883	149.45	209.25	119.56	179.37	59.809
	Test I (A)	0.0796	0.0597	0.0298	0.0238	0.2383	0.0476	0.0340	0.0596	0.0397	0.1191
	Prim V (V)	0.2989	0.2989	0.2989	0.2989	0.2989	0.2989	0.2989	0.2989	0.2989	0.2989
Phase Dev.		359°58'	359°58'	359°58'	359°58'	359°58'	359°58'	359°58'	359°58'	359°58'	359°58'
Polarity		Correct	Correct	Correct	Correct	Correct	Correct	Correct	Correct	Correct	Correct
Knee	Volt.(V)	123.45	164.86	329.93	412.22	41.430	206.47	288.78	165.07	247.40	82.414
	Cur.(A)	0.1016	0.0762	0.0381	0.0304	0.3053	0.0609	0.0434	0.0761	0.0506	0.1510
Resist. (Ohms)		0.448	0.587	1.187	1.549	0.139	0.739	1.101	0.600	0.962	0.362

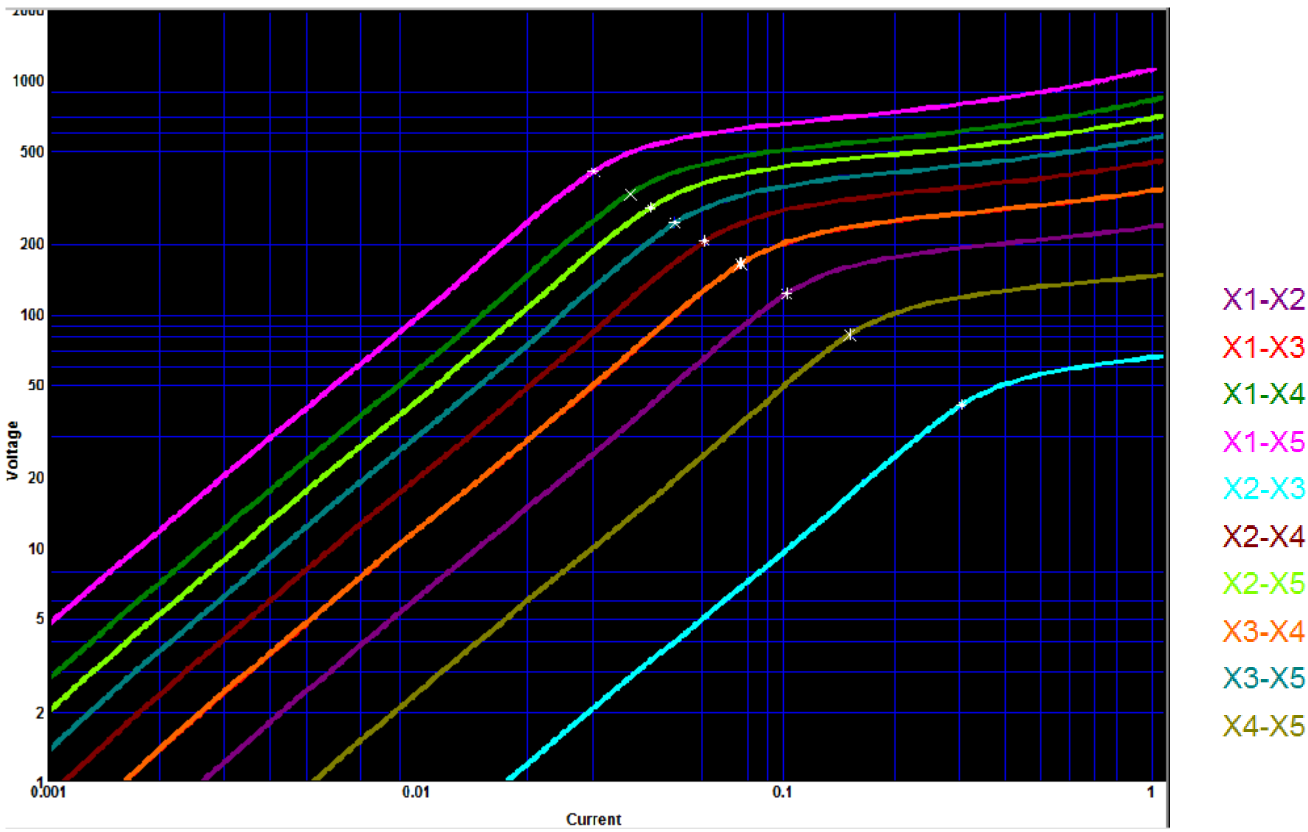

Figure 16: Ratio and Saturation results of Y1 BCT

Three other transformers in 500 kV and 765 kV substations with multiple BCTs were tested with the same concept and all the CTs ratio and polarity measurements were obtained with high accuracy and repeatability. Overall more than fifty CTs were tested with the same procedure. This proved the theory and concept used for testing BCTs in EHV substations as described in the paper.

The utility was able to identify the correct technique to counteract the challenges faced in the EHV stations to obtain consistent and reliable measurement on the BCTs. A standard procedure was developed for each of the different types of winding configurations to help the field technicians make correct connections and measure accurately. It is noted that when working with lower inductance transformer windings where there is little or no interference, some of the recommended steps above could be skipped and reliable measurements can still be obtained.

VIII. Conclusion

As was seen in the test cases with the major utility, effective grounding and isolation techniques can be used to safely obtain highly accurate measurements on BCTs even in less than ideal environments. This paper outlined these measurement techniques for various winding configurations to reduce the noise and interference seen especially in EHV substations. This interference was reduced to levels that provided near perfect accuracy. These methods improved the measurement values of secondary injection tests by minimizing winding impedance and eliminating the effects of electrostatic voltage buildup on bushing terminals. This allows for precise testing of BCTs as outlined by IEEE, thus verifying the integrity and operability of the protective systems serving the electric grid.

IX. References

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X. Authors

Dinesh Chhajer received his Master of Science in Electrical Engineering from University of Texas at Arlington. He is the Manager of Technical Support Group at Megger USA. His responsibilities include providing engineering consultation and recommendations in relation to testing of transformers, circuit breakers and other substation assets. He has presented a number of white papers related to asset maintenance and testing at various conferences within power industry. He has previously worked as an applications engineer at Megger and substation and design engineer at Power Engineers Inc. He is currently a licensed professional engineer in the state of Texas.

Ian Kreher received his Bachelor of Science in Electrical Engineering with a Power Emphasis from Missouri University of Science and Technology. He is currently an Engineer for American Electric Power in Roanoke, Virginia in their Transmission Field Services department where he provides technical oversight and assistance for substation asset commissioning and maintenance. Ian is also heavily involved with new substation construction coordination and system capital improvements, as well as mobile substation equipment usage. Outside of professional interests, Ian enjoys outdoor activities and travel.