

# Verifying Transformer Differential Compensation Settings

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# Verifying Transformer Differential Compensation Settings

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**Abstract**—Traditional transformer differential relay testing practices were developed for electromechanical relays. In electromechanical relaying schemes, transformer winding compensation is performed using current transformers (CTs) and is not verified during the testing of individual single-phase relays. Many differential relay tests typically involve the use of only two currents and verify only the slope and minimum pickup of percentage differential relays.

Microprocessor-based digital relays use internal calculations instead of CT connections to compensate for winding connections. Traditional two-source testing methods applied to three-phase digital transformer differential relays typically verify only the slope and pickup settings of the differential elements. Winding compensation settings are either modified to simplify the testing or accommodated using current multipliers and careful monitoring of individual differential elements. Settings errors, such as applying DACY compensation for a transformer connected DABY, yield no differences in test results when traditional two-source testing is used, but they can quickly result in an undesirable operation of a transformer differential relay under no fault and external fault conditions.

Currents associated with balanced and unbalanced faults through three-phase transformers with various combinations of delta and wye windings are reviewed in this paper and used to develop alternative transformer differential relay testing methods using existing relay test sets with two or three current outputs. These methods can also be applied to relay test sets with six or more current outputs. These alternative testing methods verify a greater number of settings compared with traditional testing methods and reduce the possibility of inadvertent tripping of transformer differential relays.

## I. INTRODUCTION

Differential relaying is perhaps one of the simplest relay concepts. The differential relay is connected so that its operation is based on Kirchhoff's current law—the sum of the currents entering a node is equal to the sum of the currents leaving that node. In other words, its operation is based on the difference of the currents flowing into and out of the zone of protection.

This zone of protection is defined by the location of the current transformers (CTs) connected to the differential relay in question. Although this sounds like a straightforward application, in practice, factors like voltage transformations, phase shift through delta-connected transformers, unequal CT ratios, different CT connections, and CT saturation all introduce complexity to the overall scheme.

This added complexity introduces the potential for settings and connection errors. Testing and commissioning by knowledgeable and experienced engineers and technicians are the last line of defense against improper settings and wiring.

The goal of this paper is to arm these individuals with a testing method to aid in verifying that the differential relay is wired and set correctly, without the need for advanced test equipment.

## II. REVIEW OF CURRENTS THROUGH A DELTA-WYE TRANSFORMER

Any commissioning effort should begin with a thorough review of the transformer nameplate, transformer primary and secondary phase-to-bushing connections, CT connections, relay connections, and settings. From this information, we should be able to determine if the proper transformer compensation settings have been applied and if the relay is properly connected.

The transformer connections described in this paper are limited to the American National Standards Institute (ANSI) standard connection, where the high-side phase currents lead the low-side phase currents by 30 degrees, as shown in Fig. 1. This is typically referred to as a DABY (or Dy1) connection or a YDAC (or Yd1) connection for a generator step-up transformer. For clarity, generator step-up transformers are represented as DACY transformers in this paper. For a more in-depth discussion of transformer connections, refer to [1] and [2].

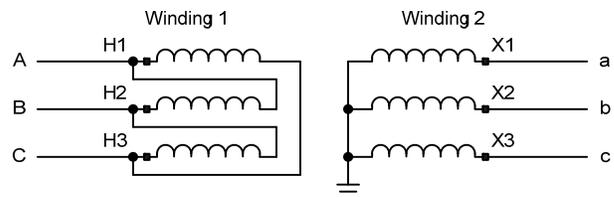


Fig. 1. DABY simplified three-line diagram.

The transformer nameplate should contain the information to derive the Winding 1 and Winding 2 connections shown in Fig. 1. The three-line ac connection diagram of the substation should show the phase-to-bushing connections to complete the phase connections shown in Fig. 1.

To determine the currents seen on the high-side and low-side terminals of the transformer in Fig. 1, we start with a balanced set of phasors representing the wye-side currents. We arbitrarily pick the A-phase current on the wye side at zero degrees. The phase rotation is assumed to be ABC. The high-side A-phase current is proportional to the difference between the A-phase current and the B-phase current on the low side of the transformer. The resulting high-side A-phase current is equal to the low-side A-phase to B-phase current

(therefore, the  $\sqrt{3}$  multiplier) multiplied by the transformer voltage ratio and leading the low-side A-phase current by 30 degrees. Performing similar analysis on the B and C phases results in Winding 1 delta currents and Winding 2 wye currents, as shown in Fig. 2. This phase angle relationship development is a critical step in the commissioning process and is important in selecting proper phase angle compensation settings.

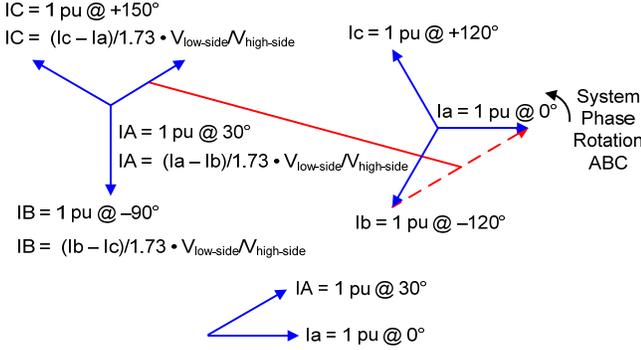


Fig. 2. Development of currents.

Note that the high-side system currents lead the low-side currents by 30 degrees, as it should be for the ANSI standard connection in Fig. 1.

Fig. 3 shows the complete three-line diagram for the connections described previously for a digital differential relay. Normally, the system A-phase current connects to the A-phase relay input (and B to B and C to C) in order for the relay meter function and faulted phase indication to be correct.

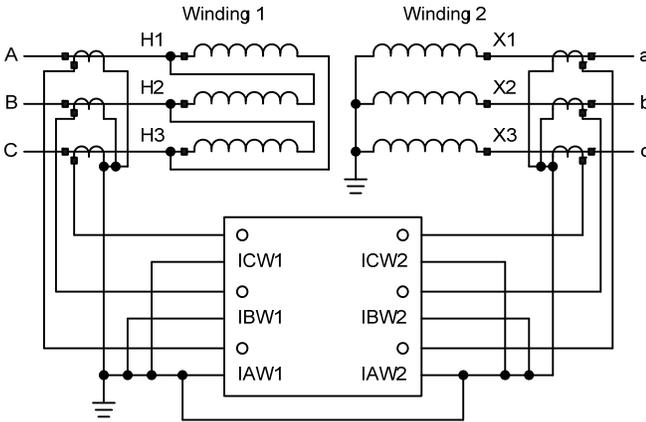


Fig. 3. Relay connections.

We also examine the DACY connection, which we typically find on a generator step-up transformer where the high-side wye winding is connected to the system and the delta winding is connected to the generator. The DACY connection is shown in Fig. 4. Developing the phasors from the system phasor as we did for the previous DABY example, we find that the high side lags the low side by 30 degrees.

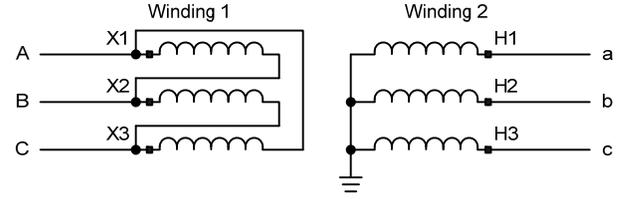


Fig. 4. DACY simplified three-line diagram.

### III. WINDING COMPENSATION

In order for the differential relay to properly sum the currents in and out of the differential zone, current mismatch and phase shift must be considered. The current mismatch from the power transformer ratio and CT ratios is solved by using tap settings so that the currents are compared on a per-unit basis. The tap for each winding is calculated using (1).

$$\text{TAP}_n = \text{MVA} \cdot \frac{1000}{\sqrt{3} \cdot \text{VLL}_n \cdot \text{CTR}_n} \cdot C \quad (1)$$

where:

C is 1 for wye-connected CTs and  $\sqrt{3}$  for delta-connected CTs.

MVA is the transformer rating.

VLL<sub>n</sub> is the line-to-line voltage of the winding in kV.

CTR<sub>n</sub> is the CT ratio for the winding.

Fig. 5 shows both tap and winding compensated currents in the relay.

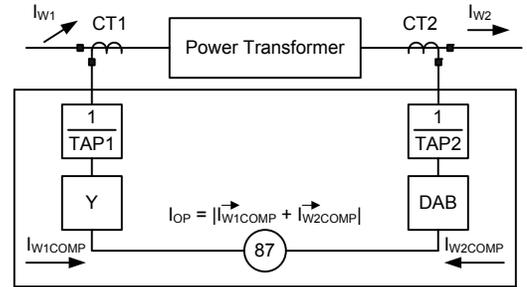


Fig. 5. DABY transformer and CT connection compensation.

In the DABY connection, if the CTs for Winding 2 are connected in wye, then we must correct for the phase shift through the transformer by combining the currents as they would be in the CTs of Winding 1. Referring to Fig. 3, we see that the Winding 1 A-phase current input sees a current proportional to  $I_A - I_B$  currents in Winding 2 current inputs. The  $I_A - I_B$  currents in Winding 2 must be divided by  $\sqrt{3}$  to scale the phase-to-phase current to a phase-to-neutral current. The A-phase Winding 2 compensation becomes (2).

$$\frac{1}{\text{TAP}_2} \cdot \frac{(\overline{IAW2} - \overline{IBW2})}{\sqrt{3}} \quad (2)$$

The compensation for B-phase and C-phase can be derived in a similar fashion. Winding 1 is the reference winding and requires no compensation.

Similarly, for the DACY connection in Fig. 4, we can derive that the A-phase winding compensation is the following:

$$\frac{1}{TAP2} \cdot \frac{(\overline{IAW2} - \overline{ICW2})}{\sqrt{3}} \quad (3)$$

The behavior of a single-slope percentage differential element can be analyzed based on the ratio of differential or operate current to restraint current. The operate current is the magnitude of the vector sum of the winding currents, and the restraint current is the average of the scalar sum of the winding currents. When the ratio of operate current to the restraint current exceeds the slope setting, the relay operate point will fall into the operate region of Fig. 6. A minimum operate current must be satisfied before the relay elements operate and is represented by the point at which the curve crosses the y axis.

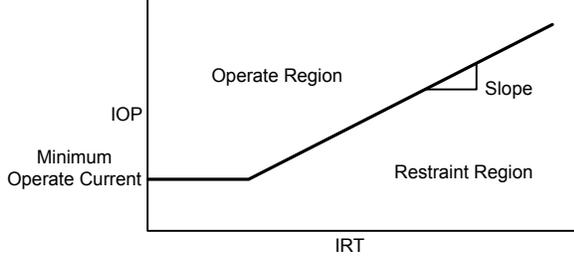


Fig. 6. Single-slope percentage differential characteristic.

For many transformer differential relays, the operate current and restraint current are represented by (4) and (5).

$$IOP = |\overline{IW1} + \overline{IW2}| \quad (4)$$

$$IRST = \frac{|\overline{IW1}| + |\overline{IW2}|}{2} \quad (5)$$

The slope of the characteristic line in Fig. 6 can be varied via a setting in the relay. Relays can have a single-slope, multiple-slope, or variable-slope characteristic. This paper only considers the single-slope characteristic. For a line that includes the origin, the slope is defined as the y-axis value divided by the x-axis value, or in this case:

$$SLOPE = \frac{IOP}{IRST} \quad (6)$$

Ignoring the effect of the tap settings, we can write the equations for the operate and restraint currents in terms of the per-unit currents applied to the inputs of the relay. For a DABY transformer, these equations are the following:

$$IOP1 = \left| \overline{IAW1} + \frac{(\overline{IAW2} - \overline{IBW2})}{\sqrt{3}} \right| \quad (7)$$

$$IRST1 = \frac{|\overline{IAW1}| + \left| \frac{(\overline{IAW2} - \overline{IBW2})}{\sqrt{3}} \right|}{2} \quad (8)$$

$$IOP2 = \left| \overline{IBW1} + \frac{(\overline{IBW2} - \overline{ICW2})}{\sqrt{3}} \right| \quad (9)$$

$$IRST2 = \frac{|\overline{IBW1}| + \left| \frac{(\overline{IBW2} - \overline{ICW2})}{\sqrt{3}} \right|}{2} \quad (10)$$

$$IOP3 = \left| \overline{ICW1} + \frac{(\overline{ICW2} - \overline{IAW2})}{\sqrt{3}} \right| \quad (11)$$

$$IRST3 = \frac{|\overline{ICW1}| + \left| \frac{(\overline{ICW2} - \overline{IAW2})}{\sqrt{3}} \right|}{2} \quad (12)$$

Equations for operate and restraint currents for the DACY transformer are the following:

$$IOP1 = \left| \overline{IAW1} + \frac{(\overline{IAW2} - \overline{ICW2})}{\sqrt{3}} \right| \quad (13)$$

$$IRST1 = \frac{|\overline{IAW1}| + \left| \frac{(\overline{IAW2} - \overline{ICW2})}{\sqrt{3}} \right|}{2} \quad (14)$$

$$IOP2 = \left| \overline{IBW1} + \frac{(\overline{IBW2} - \overline{IAW2})}{\sqrt{3}} \right| \quad (15)$$

$$IRST2 = \frac{|\overline{IBW1}| + \left| \frac{(\overline{IBW2} - \overline{IAW2})}{\sqrt{3}} \right|}{2} \quad (16)$$

$$IOP3 = \left| \overline{ICW1} + \frac{(\overline{ICW2} - \overline{IBW2})}{\sqrt{3}} \right| \quad (17)$$

$$IRST3 = \frac{|\overline{ICW1}| + \left| \frac{(\overline{ICW2} - \overline{IBW2})}{\sqrt{3}} \right|}{2} \quad (18)$$

Using these equations, we can evaluate the resulting slope calculations when different testing methods are applied.

#### IV. TRADITIONAL TWO-CURRENT TESTING METHOD

Commonly used two-current testing methods are based on testing practices applied to electromechanical differential relays without internal winding compensation. If these same tests are applied to microprocessor differential relays, the test results may be misleading. These methods use two current sources connected to the same phase of Winding 1 and Winding 2, as shown in Fig. 7. In this testing method, we test one phase or restraint element at a time.

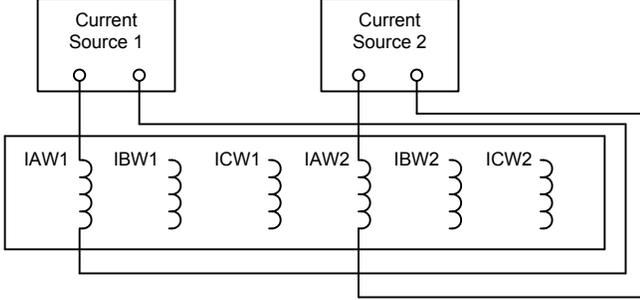


Fig. 7. Two-source test connections.

To test the percent restraint elements of a differential relay, we must first calculate test point values. When we test the restraint element, we must decide where on the characteristic curve shown in Fig. 8 we wish to test. Once we have determined the test values and applied them as shown in Fig. 7, we hope to observe a contact transition when the 87R element changes state. Because the 87R element is affected by each individual restraint element (the OR combination of 87R1, 87R2, and 87R3), its operation depends on the compensation settings in the differential relay. For the DABY compensation settings, injecting current into the A-phase of Winding 2 produces restraint and operate current in the 87R1 and 87R3 elements. Without current injected into the C-phase of Winding 1, the 87R3 element sees half of the restraint current. This results in the 87R3 element continuously plotting in the operate region while the 87R1 element is under test, as shown in Fig. 8. This is important to note because of the false operation of the 87R element when using a single-phase test.

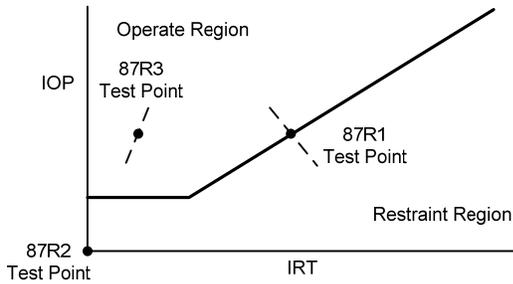


Fig. 8. Differential element trajectory for traditional two-source current injection.

For per-unit currents applied by Current Source 1 and Current Source 2, represented by  $I_1$  and  $I_2$  respectively, non-

zero operate and restraint currents are generated for the 87R1 and 87R3 elements, as shown in the following equations:

$$IOP1 = \left| \overline{I_1} + \frac{\overline{I_2}}{\sqrt{3}} \right| \quad (19)$$

$$IRST1 = \frac{\left| \overline{I_1} \right| + \left| \frac{\overline{I_2}}{\sqrt{3}} \right|}{2} \quad (20)$$

$$IOP2 = 0 \quad (21)$$

$$IRST2 = 0 \quad (22)$$

$$IOP3 = \frac{|\overline{I_2}|}{\sqrt{3}} \quad (23)$$

$$IRST3 = \frac{|\overline{I_2}|}{2\sqrt{3}} \quad (24)$$

For any non-zero current injected using Current Source 1, the 87R3 element plots at 200 percent, resulting in the 87R3 element operating for all test values, as shown in Fig. 8. The restraint element under test, in this case 87R1, must be isolated from the other restraint elements and monitored; the remaining restraint elements, 87R2 and 87R3, are ignored. Focusing only on the operation of the restraint element under test results in the same test results for a relay set for DABY or DACY compensation. The test does not verify the correct compensation settings and misses a very common cause of relay misoperations.

Test values calculated using this method do not correspond to actual fault conditions. A review of the distribution of currents through the transformer during external fault conditions may yield more suitable test connections and values.

#### V. REALISTIC UNBALANCED FAULTS

When realistic unbalanced through faults are applied to the wye side of delta-wye transformers, the resulting currents on the delta side of the transformers vary based on the winding connections. Fig. 9 shows an A-phase-to-ground (AG) external fault on the wye winding, resulting in non-zero current through the A- and C-phase bushings of the delta winding of a DABY transformer.

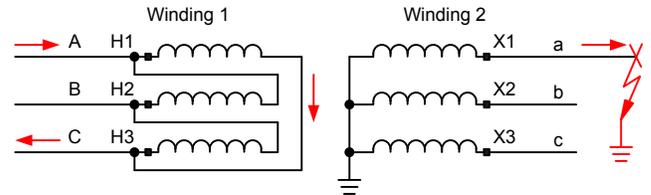


Fig. 9. DABY transformer with an AG fault just beyond the grounded wye winding.

In DACY transformers, a similar external AG fault on the wye side results in non-zero current through the A- and B-phase bushings on the delta side of the transformer. This difference in behavior between the DABY and DACY during unbalanced external fault conditions can be used to develop test techniques to verify winding compensation settings in digital differential relays.

## VI. ALTERNATE TWO-SOURCE TESTING

Realistic unbalanced fault currents can be reproduced and applied to three-phase digital transformer differential relays using as few as two or three current sources. Varying the magnitudes of the applied currents produces test values that plot along the set differential slope. Fig. 10 shows the connection of two current sources to simulate an AG fault on a DABY transformer.

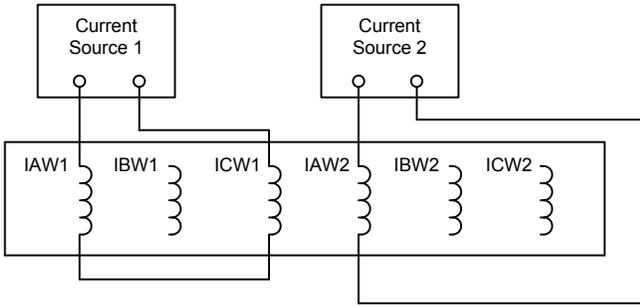


Fig. 10. Alternate two-current test connections for a DABY transformer.

The phasors associated with the applied AG through fault are shown in Fig. 11.

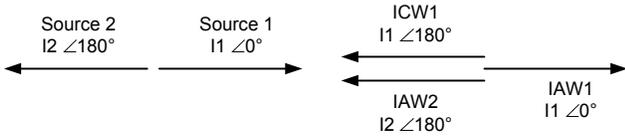


Fig. 11. Test current phasors for an AG fault through a DABY transformer.

For per-unit currents applied by Current Source 1 and Current Source 2, represented by  $I_1$  and  $I_2$  respectively, the resulting operate and restraint calculations are the following:

$$IOP1 = \left| \bar{I}_1 + \frac{\bar{I}_2}{\sqrt{3}} \right| \quad (25)$$

$$IRST1 = \frac{\left| \bar{I}_1 \right| + \left| \frac{\bar{I}_2}{\sqrt{3}} \right|}{2} \quad (26)$$

$$IOP2 = 0 \quad (27)$$

$$IRST2 = 0 \quad (28)$$

$$IOP3 = \left| -\bar{I}_1 - \frac{\bar{I}_2}{\sqrt{3}} \right| \quad (29)$$

$$IRST3 = \frac{\left| -\bar{I}_1 \right| + \left| -\frac{\bar{I}_2}{\sqrt{3}} \right|}{2} \quad (30)$$

Using these connections, the 87R1 and 87R3 differential elements should pick up and target nearly simultaneously. When a common trip output is used on a digital differential relay, special test settings and monitoring techniques are not required to isolate restraint elements under test. For a differential relay improperly set for DACY compensation, the 87R2 and 87R3 elements plot along the 200 percent slope (as shown in the following operate and restraint calculations), which results in tripping earlier than expected.

$$IOP2 = \left| \frac{-\bar{I}_2}{\sqrt{3}} \right| \quad (31)$$

$$IRST2 = \frac{\left| \frac{-\bar{I}_2}{\sqrt{3}} \right|}{2} \quad (32)$$

$$IOP3 = \left| -\bar{I}_1 \right| \quad (33)$$

$$IRST3 = \frac{\left| -\bar{I}_1 \right|}{2} \quad (34)$$

Verifying the slope of the differential elements using these connections also verifies the winding compensation settings of the relay.

## VII. ALTERNATE THREE-SOURCE TESTING

This test technique can be further improved with the addition of a third current source, as shown in Fig. 12. The pickup for elements 87R1 and 87R3 can be verified independently by applying a constant current source to Winding 2, while varying the Winding 1 source for the winding under test.

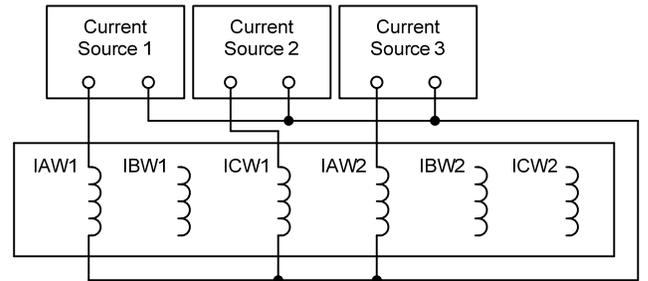


Fig. 12. Alternate three-current test connections for a DABY transformer.

For per-unit currents applied by Current Source 1, Current Source 2, and Current Source 3, represented by  $I_1$ ,  $I_2$ , and  $I_3$  respectively, the resulting operate and restraint calculations are the following:

$$IOP1 = \left| \bar{I}_1 + \frac{\bar{I}_3}{\sqrt{3}} \right| \quad (35)$$

$$IRST1 = \frac{\left| \bar{I}_1 \right| + \left| \frac{\bar{I}_3}{\sqrt{3}} \right|}{2} \quad (36)$$

$$IOP3 = \left| \bar{I}_2 - \frac{\bar{I}_3}{\sqrt{3}} \right| \quad (37)$$

$$IRST3 = \frac{\left| \bar{I}_2 \right| + \left| -\frac{\bar{I}_3}{\sqrt{3}} \right|}{2} \quad (38)$$

To test the 87R2 element, the connections should be modified to simulate a BG or CG fault. Table I shows the elements tested for each type of through fault applied.

TABLE I  
TEST CONNECTIONS FOR DABY TRANSFORMER  
USING THREE CURRENT SOURCES

Fault Type	Test Set Current Sources			Relay Elements		
	Source 1	Source 2	Source 3	87R1	87R2	87R3
AG	I <sub>AW1</sub>	I <sub>CW1</sub>	I <sub>AW2</sub>	Y	N	Y
BG	I <sub>BW1</sub>	I <sub>AW1</sub>	I <sub>BW2</sub>	Y	Y	N
CG	I <sub>CW1</sub>	I <sub>BW1</sub>	I <sub>CW2</sub>	N	Y	Y

Because only two or three currents are necessary to verify the winding compensation settings, older two- and three-source test sets can be used with these techniques. These techniques can be used with six-source test sets and automated test routines to apply unbalanced faults and test individual differential elements in digital differential relays.

## VIII. CONCLUSION

Traditional two-current testing methods apply unrealistic currents to digital transformer differential relays, requiring special test settings and ignoring differential elements that are not under test. These practices do not verify transformer compensation settings. For lightly loaded transformers, settings errors may go undetected for many years but can result in misoperations when additional loads are transferred to the transformer.

A review of the distribution of currents through delta-wye transformers during unbalanced external fault conditions yields test connections and techniques that verify transformer compensation settings without the use of special test settings. These testing methods can be performed with test sets with as few as two current sources.

## IX. REFERENCES

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## X. BIOGRAPHIES

**Edsel Atienza** received his BSEE from the University of Idaho in 2001. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2002 as an international field application engineer. In 2006, Edsel joined Tampa Electric as a substation operations engineer responsible for relay testing and maintenance. He returned to SEL in 2008, serving the southeastern United States as a field application engineer.

**Marion Cooper** is a field application engineer for Schweitzer Engineering Laboratories, Inc. He has over 30 years of protection and control experience, having worked for Georgia Power, Gulf Power, Florida Power Corporation (now Progress Energy), Areva T&D, and TRC Consulting. Marion has experience as a field relay engineer, relay settings engineer, protection and control design engineer, and an engineering manager. He received his BSEE from Auburn University. Marion is a Senior Member of IEEE and is a registered professional engineer in Florida. He has served on the IEEE Power System Relaying Committee (PSRC) and is a past member of the Georgia Tech Protective Relay Conference Planning Committee.