Guide to Primary Current Injection Testing of Phase-Shifting Transformers

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***Abstract*—The present trend of rapid growth and changes to the electric grid landscape of generation resources and loads has driven unprecedented demand for phase-shifting transformers (PST), which are needed to deliver granular, bi-directional regulation of active power flow through individual transmission paths. Prior to the most recent decade, PST installations were relatively rare, reflecting the limited availability of published engineering and operating guides regarding this unique and complex transformer type. For substation engineering and operations personnel who are relatively new to PSTs, this paper provides a comprehensive walkthrough of preparing and conducting primary current injection tests, necessary for validating the ratio and polarity of current transformers applied to two-core PSTs and their current differential protection systems. Through the recent experience New York Transco, LLC (NYT) gained from completing this testing for two parallel PSTs at a greenfield 345-kV substation, readers will learn the key considerations for preparing and conducting the tests, the calculations for sizing test equipment, the calculations of the expected current magnitudes and angles to validate test results, and valuable lessons learned from the testing experience.**

***Index Terms*—Primary, Current, Inject, Test, Phase, Shift, Transformer**

I. Introduction

Current differential schemes employed for transformer protection rely on accurate comparisons of current magnitude and phase angle to maximize sensitivity for detecting in-zone faults, allowing for pickups to be set well below the rated load of the transformer. As a tradeoff to this degree of protection sensitivity, current differential schemes are especially susceptible to mis-operation due to incorrect current transformer (CT) polarity, CT ratio, or relay settings. Common implementation errors, as well as various techniques that can be applied to identify these errors during commissioning, after load pickup, or after fault events, are discussed extensively in [1].

PSTs are uncommon and have more complex winding arrangements, CT arrangements, and current differential protection system designs compared to more common transformer types [2]. These factors present a greater risk for errors in the protection equipment installation and relay settings that could result in mis-operation. An unplanned outage of a PST and its regulated tie-line, due to a protection system mis-operation, can significantly impact system stability, imposing a great deal of pressure on the owner's engineering and operations teams to quickly identify and conclusively address, problems with the protection installation.

For current-based protection schemes, primary current injection is the most comprehensive method available for verifying the protection installation. Primary current injection testing involves applying an alternating-current source and load to the primary terminals of the transformer and verifying secondary currents measuring at connected protection and monitoring devices. Readers seeking general familiarity with the planning, execution, and value of primary injection tests should review the comprehensive guide presented in [3].

Factory acceptance testing of PSTs performed by the manufacturer customarily includes polarity and ratio testing of CTs and their secondary winding circuits wired back to the termination cabinet. Once the PST transformers are delivered and installed, the field commissioning team has practically no access to the CTs inside the transformer tank without disassembling the oil-filled throat connections between the series and exciter transformers. For a fully-assembled PST, primary current injection testing is the sole method for field testing both the polarity and ratio of this portion of the CT circuit. A dc-kick test can be performed to check the polarity of a CT primary core and secondary circuit, but it does not verify the CT ratio [1].

Between the transformer termination cabinet and the relay inputs in the substation control enclosure, the continuity and polarity of CT secondary winding burden circuits can be verified via secondary current injection testing. This testing is logistically simpler to execute than primary current injection testing, but it tests only a portion of the total protection installation.

Relay protection element testing can verify proper application of relay settings under various simulated normal operation and fault scenarios. This testing is typically performed by connecting the relay test set current leads to the test switches on the panel and injecting secondary currents into relay inputs. The scope of this testing generally does not include injection of secondary currents from points further upstream from the relay panel, such as at the transformer termination cabinet CT terminal blocks.

As a key last validation step ahead of energizing equipment, primary current injection tests should be performed to test the complete protection system installation and catch any errors that were not found during the array of piecewise commission tests. This comprehensive test is especially important for validating the relatively complex magnitude and angle

compensation settings required for PST differential protection schemes.

II. Test Setup Considerations

Primary current injection testing requires a source generator to apply voltage to the tested equipment, a load to draw current through the tested equipment, and devices to measure current, such as relays, meters, or phasing measurement tools. Refer to Figure 1 for an example of a PST substation and primary current injection testing application that we will prepare and analyze through the course of this paper.

For tests involving transformers, the transformer's short-circuit impedance provides sufficient load, and short-circuit conductors are applied between the load terminals of the transformer and ground to complete the circuit for the current injection test. Generally, primary current injection testing of three-phase equipment is performed for all three phases simultaneously, i.e., by applying a three-phase short to ground. This approach draws a balanced load, reducing thermal stress on a three-phase generator; it increases the number of CTs that can be tested simultaneously, and provides balanced three-phase quantities that are more straightforward for validating relay differential schemes. Testing of neutral-branch CTs or inside-delta winding CTs require injecting zero-sequence currents, which can be fed by the three-phase generator by making a single-phase short-circuit-to-ground connection on the load side of the PST. The injected current should not exceed the continuous negative-sequence current capacity of the generator.

Given the short-circuit impedance of the transformer, judicious selection of the generator voltage and mega-Volt-Ampere (MVA) ratings will determine the magnitude of primary current injected through the transformer windings and CTs. The minimum current required for testing is dictated by the minimum secondary current that the relay or measurement tool can resolve accurately. Relay and meter specifications contained in manuals generally report current input accuracy ratings for secondary currents as low as 5 or 10% of nominal, an amount that can be difficult to supply through the primary winding of the CTs if the CT ratio is particularly high.

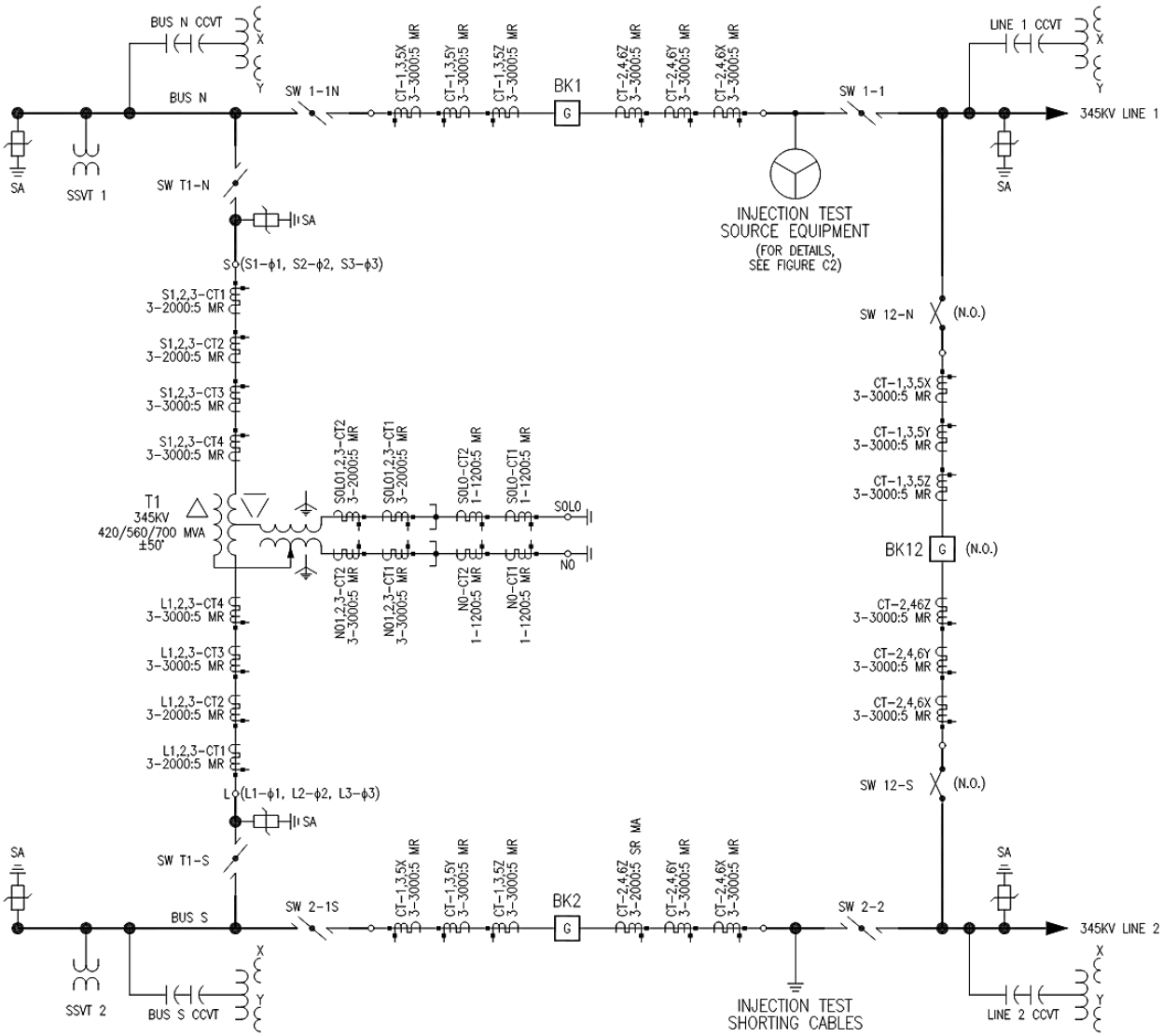


Figure 1. One-Line Diagram of Primary Current Injection Test Application.

From our experience, secondary currents as low as 2% of nominal have provided reasonable accuracy for verifying the polarity of secondary currents at the connected devices. Note however, that the relay will require at least one set of current or voltage inputs to measure a minimum current or voltage to establish a phase angle reference to compare to all other input currents. A typical minimum reference voltage is 5 V secondary, and the typical minimum reference current is 0.25 A secondary for a 5 A nominal relay. For sufficient resolution to distinguish ratio errors, a minimum secondary current of 0.25 A should be the goal. For context, consider a 2000:5 multi-ratio CT where the intended ratio to apply is 2000:5 (X1-X5 secondary connections), but the installed secondary circuit connections are X2-X5 (1600:5 ratio); in this scenario, an injected primary current of 100 A (5% of expected 2000 A nominal) will yield a secondary current error of merely 0.06 A. As a matter of due diligence, one should consult and confirm with the device manufacturer the minimum recommended currents to verify both ratio and polarity.

The current injected through the transformer windings to an externally applied short is limited by (1).

$$I_{INJECTED} = \frac{V_{APPLIED}}{Z_{SC}} \quad (1)$$

Where:

$I_{INJECTED}$	Current injected through the winding due to the applied voltage source
$V_{APPLIED}$	Voltage applied to the winding
Z_{SC}	Short-circuit impedance between the source and load terminals of the transformer

For a large PST, an applied voltage of several thousand volts may be the bare minimum needed to inject the necessary primary current through the windings and secondary currents through measurement devices. However, rental generators within North America are generally available only up to 600 V. For this reason, one should expect a generator step-up transformer bank to be included as part of the test supply equipment, along with medium-voltage cables to tie the transformer primary terminals to the station bus at the desired point of injection.

The current drawn through the transformer short-circuit load is predominantly lagging reactive, as the transformer short-circuit impedance consists almost entirely of the leakage reactance between windings. The corresponding generator load power factor would be nearly zero, and a synchronous generator's capacity to serve that load is limited by the rated temperature of the rotor winding insulation. The generator's load capacity during this overexcited operating scenario is not the nameplate MVA rating but typically less than 70% of the nameplate MVA, as is readily apparent from a typical generator capability curve. Power-factor-dependent generator capacity curves may not be readily available for the candidate generator, or may indicate an MVAR supply capability approaching a leading load factor of zero. To address these concerns, the test generator should be paired with an adequately sized variable capacitive load bank to offset the lagging power demand from the generator, ideally to completely negate the VAR demand. Test equipment rental companies can provide both the genset and the capacitive load bank on a single trailer. A critical benefit provided by a variable capacitive load bank compared to a fixed capacitor bank is its ability to vary the capacitive load by stepped amounts to maintain the generator VAR demand as close to zero as possible, even as the tested PST's short-circuit impedance varies over its tap position range. Minimizing the leading or lagging VAR demand from the generator may allow one to use a generator with a lower kVA rating. The current duty of interconnecting cables between the generator and the capacitor bank location is similarly reduced.

Beyond the concerns of the test source equipment ratings and location, one must furnish cables and connectors to apply the short-circuit to ground on the side of the PST opposite to where the test generator is connected. This distinction is made because, fundamentally, the PST can carry load in either direction, so it is not critical which sides the generator and shorts are connected to. For this paper, we assume the generator is connected at the source side and the short at the load side. The shorting cables should be connected at the furthest point one desires to inject current and verify CT quantities. It is advantageous to locate the generator further upstream of the PST source terminals and the shorts further downstream of the PST load terminals to, for example, test high- and low-side bus lead differential schemes bounded by breaker bushing CTs, along with verifying the PST differential protection schemes and associated CTs.

III. Test Equipment Sizing Calculations

Sizing the test generator, cables, step-up transformer, and other test equipment is a process of calculating the required voltage to apply to the PST source or load terminals to yield sufficient winding currents when a short-circuit load is applied. The three-phase short-circuit current flowing through the PST series winding (source-to-load) relative to the applied voltage can be determined by (2).

$$I_{SL} = \frac{V_{APP,LL}}{\sqrt{3} Z1_{SL}} \quad (2)$$

Where

I_{SL}	Current through the series winding (series transformer primary winding)
$V_{APP,LL}$	Line-to-line voltage applied to the PST (either source or load terminal)
$Z1_{SL}$	Equivalent source-to-load positive-sequence impedance of the PST at the considered on-load tap changer (OLTC) tap position, expressed in ohms

For an introduction to traditional two-core PSTs and a derivation of their winding voltage and current phasors, refer to Appendix A. The short-circuit impedance model of the two-core PST and the variation of impedance with respect to the OLTC tap position is covered in Appendix B.

A. Determine the Minimum Test Current

For a given current injected through the series windings, one must calculate and confirm that the current in all other windings exceeds the minimum magnitude necessary for accurate verification of the associated CT secondary current magnitudes

and phase angles at connected devices. Original equipment manufacturers of PSTs typically provide voltage and current tables for all windings and tap positions as part of their design submittals to the customer. The current ratios between windings could be scaled to the planned test current through the series winding to determine the magnitudes of currents in all other windings. However, as current angles also need to be verified during testing, it is ultimately necessary to solve the complex current phasors of all windings based on the PST winding arrangement and turns ratios. A detailed derivation of the winding voltage and current phasors is provided in Appendix A. A calculation of winding currents for an example PST is detailed in Appendix C.

B. Calculate the Generator Ratings

Once one establishes the minimum secondary current to be measured among all windings at the specific OLTC tap positions to be tested, consider the corresponding primary current that must be injected using the generator source. From (2), the injected current depends on the PST impedance and the voltage applied at the PST source terminal. The PST impedance varies with the OLTC tap position, where impedance is greatest at the extreme tap positions. The voltage applied at the PST source terminal depends on the generator's applied voltage, whether a step-up transformer is used to boost the voltage further, and any voltage drop due to the impedance between the generator and PST source terminals. A step-up transformer adds impedance to the test circuit, as do the cable leads between the generator, step-up transformer, PST under test, and three-phase short circuit to ground. Accounting for the voltage boost provided by the step-up transformer and the additional impedances in the primary current injection loop, the injected current can be calculated using (3).

$$I_{SL} = \frac{V_{LL,GEN}}{\sqrt{3}} \frac{V_{H,SUT}}{V_{X,SUT}} * \left[\frac{1}{Z1_{CAB,LV} + Z1_{HX,SUT} + Z1_{CAB,MV} + Z1_{SL} + Z1_{CAB,SC}} \right] \quad (3)$$

Where

- I_{SL} Current through the series winding (series transformer primary winding)
- $V_{LL,GEN}$ Line-to-line voltage applied by the generator
- $V_{H,SUT}$ H terminal-rated voltage of the generator step-up transformer at the applied tap position(s) of any applicable de-energized or OLTC(s)
- $V_{X,SUT}$ X terminal-rated voltage of the generator step-up transformer at the applied tap position(s) of any applicable de-energized or OLTC(s)
- $Z1_{CAB,LV}$ Positive-sequence impedance of the feeder cables between the generator and step-up transformer, reflected at the H terminals of the step-up transformer
- $Z1_{HX,SUT}$ Positive-sequence impedance of the generator step-up transformer reflected at the H terminals
- $Z1_{CAB,MV}$ Positive-sequence impedance of the feeder cables between the step-up transformer H terminals and the connection to the station bus where current is injected through the PST series winding
- $Z1_{SL}$ Equivalent source-to-load positive-sequence impedance of the PST at the considered OLTC tap position
- $Z1_{CAB,SC}$ Positive-sequence impedance of the shorting cables applied between all three phases and ground

For a sufficiently accurate calculation of injected current, one only needs to calculate the voltage drop using total impedance. Even for validating PST protection schemes, it is not necessary to solve the complex quantity of injected current or applied voltage from the real and reactive components of impedance between the generator and the PST. What matters is that the currents that the relay measures are of sufficient magnitude for verifying the input current CT ratio and angle, as well as the compensated currents and differential element operate and restraint currents.

C. Test Equipment Sizing Calculation Example

The calculation process, considerations, and most impactful constraints for sizing the primary current injection test equipment are best illustrated through the detailed calculation example, provided in Appendix C, considering a 345 kV, 700 MVA, ±50° PST. (A one-line diagram of the test equipment ratings and connections is presented in Figure C4).

The sizing calculations determined the minimum generator ratings to be approximately 1,000 kVA and 480 V, paired with a step-up transformer rated 1,000 kVA, 480/4,160 V. Applying approximately 4,160 V to the PST short-circuit load when at maximum tap position will draw approximately 70 A primary current through the PST series winding, yielding a minimum secondary current of approximately 0.15 A among all relay inputs. Both the required applied voltage and short-circuit power demand increase with increasing PST MVA, angle range, and impedance. As such, even a marginal increase in secondary current at the relay inputs for this example test scenario would require a substantial increase of applied primary voltage and power demand, beyond the ratings of commonly available portable temporary power equipment.

As the PST's short-circuit load is almost entirely lagging reactive, we must ensure that the generator's rated VAR supply (overexcitation) capacity is not exceeded. A generator with a higher kVA rating could be selected, but a more optimal approach is to offset the generator's inductive load by including a variable capacitive load bank as part of the test equipment setup.

The generator must also be sized for sufficient temporary overload capacity to supply the step-up transformer inrush demand, comparable to the generator's published motor starting rating. While this inrush current demand is significant, the resulting voltage drop will proportionally reduce the inrush current demand. The authoring team's experience with a real-world test application, consisting of a mobile generator and

step-up transformer with matching nameplate apparent power ratings, demonstrated that the generator could successfully start on no load then energize the step-up transformer and PST separately without the generator protection tripping or prolonged frequency or voltage instability. One may also consider starting the generator while tied to the step-up transformer and PST, given that the short-circuit impedance of the step-up transformer in series with the PST magnetizing impedance will further reduce the voltage and consequently, the inrush current demand from the generator.

One should avoid energizing the capacitive load bank along with the step-up transformer, if possible. When energized simultaneously, the transient inrush interaction between the capacitor and transformer core magnetizing loads could possibly perturb a resonance condition and cause a severe overvoltage condition. To reduce the risk of any undesirable interactions, the step-up transformer and capacitive load banks should be energized separately, and the generator should be sized to carry the inrush demand of the transformer.

Once the targeted applied voltage and associated injected currents are established, it is important to account for the impedances of the connected test equipment and their reduction of voltage and injected current through the PST. For this example test application, the impedance of all the cables connecting the equipment and the short to ground constituted no more than 0.2% of the total impedance of the current injection loop. The step-up transformer impedance was 2.8% of the total loop impedance. The PST short-circuit impedance made up more than 97.0% of the total loop impedance. Therefore, the reduction in applied voltage and injected current was no more than 3% from the original target values based on 4,160 V applied at the PST.

IV. Test Validation Preparation

A final calculation exercise needed to prepare for testing is to lay out a table of expected winding current magnitudes and phase angles to be measured by the relays, which the test process aims to verify. These values can be determined using the formulas derived in Appendix A. The calculated currents depend primarily on:

1. PST voltage and MVA ratings
2. The PST no-load angle regulation range
3. The actual tap position applied during testing
4. CT ratios
5. Expected polarity of current transformers, as applied at each set of relay current inputs
6. For a dual-core PST, the series transformer winding turns ratio

Both primary and secondary currents should be reported for each winding, allowing one to validate primary currents injected by the generator and the secondary currents measured at the relays. The winding currents all depend on the magnitude and angle of primary current injected through the PST series winding, so the test validation spreadsheet needs to calculate all expected winding current magnitudes and angles relative to the magnitudes and angles of measured primary currents injected through the series winding. An example layout of a test validation spreadsheet, with calculation formula references and expected results, is provided in Appendix D. This example considers the same PST presented in the example calculations for test source equipment sizing (Appendix C).

V. Logistical Considerations for Testing

Concerning the operation of test equipment and the measurement and recording results, a few important requirements and final checks should be addressed.

1. The generator MVA and voltage capacity needed for primary injection testing of a large PST can range from several hundred kilo-volt-amperes (kVA) to several MVA. Availability for a rental generator in this size range is limited and will likely require one to make a reservation four to six months in advance.
2. One must plan where to place and connect the generator, the fuel tank, the feeder cable runs to the station bus, and the shorting cables from the load side of the bus to ground.
3. The equipment rental company may size and supply feeder cables appropriate for the generator size, but the length from the generator trailer to the overhead bus needs to be determined from the station arrangement plan and elevation drawings.
4. Plan the process for taking measurements, including the device commands or measurement tools needed to obtain verification quantities from each device.
5. It is important to prove the correct relationship between primary equipment phasing and relay/meter phasing. To that end, one should measure the magnitude of primary currents flowing out of the AC source on a per-phase basis and also measure their angles relative to a common reference. Typically, A-phase of the AC source is used as the angle reference. One should not use the relays alone to prove that current flowing in A-phase of the primary equipment, for example, is actually going to the A-phase of all the relays. Once the exact magnitude and phase angle of the primary currents are measured, one can measure the secondary current magnitudes and angles at the relay test switches using the phasing test set.
6. Assess the time for engineer verification of measurements and any possible need to correct errors found and retake measurements before disassembly and demobilization of test equipment. Fully validating the polarity of all CTs and their secondary wiring to all IEDs, can be a considerable effort. Comprehensive validation of ratio and angle of all CTs involved in the PST differential protection schemes can require injection testing at several tap positions (neutral, max advance, and max retard), yielding 100–200 current measurements from six or more IEDs. The time required to record all these measurements needs to be factored in not only the overall testing schedule but also the test equipment rental duration and the available generator fuel supply. In total, once test equipment was set up, all

measurements for a single PST took NY Transco's team two days to complete.

7. Verify the generator fuel consumption rate and verify adequate fuel is available to complete the tests.
8. Coordinate, with the equipment rental company or equipment owner, the availability and participation of a qualified and responsible test equipment operator.
9. Prior to energizing equipment, perform a visual inspection of the test equipment to verify all equipment appears to be in good working order and all equipment connections are correct (e.g. cable terminations, step-up transformer and PST winding tap positions).
10. Verify that the temporary grounding provisions for the genset, step-up transformer, capacitor bank, and equipment trailer have been installed in accordance with equipment owner requirements, equipment nameplate requirements, and utility safety practices.
11. Verify that the generator, step-up transformer, capacitor bank, and other equipment protections are installed and all breaker trip unit settings set appropriately for the application.
12. Research the operating instructions for the capacitive load bank to understand its load control interface, how the control system auxiliary voltage supply is derived (e.g., directly from the line or a separate aux source), its allowable load step sizes, and other necessary considerations.
13. Understand the limitations of the selected generator kVA ratings to supply the inrush demand of the capacitive load bank, inrush demand of the step-up transformer, and short-circuit demand of the PST. The generator should be first started on no load, then the generator breaker should be closed into the step-up transformer without the capacitive load bank connected, to reduce the risk of undesirable resonant interactions between this equipment. The inrush current demand of the transformer may be significant, but the voltage drop experienced at the generator will proportionally reduce the inrush current demand. The generator's capacity for temporary overload to supply the step-up transformer inrush demand, comparable to its published motor starting rating, should be confirmed before ordering equipment.

VI. Conclusion

Prior to the first energization of a PST, it is important to test all protection systems to ensure proper function. The most complete method available to test the current differential and other current-based protection schemes is via primary current injection. Nontrivial time and effort are required to prepare the sizing calculations, procure injection test equipment, set up the equipment, perform the testing, and verify measurements against calculated expected results. However, the effort to complete the testing is easily justified by the guaranteed avoidance of substantial time and effort needed to identify and resolve issues with the protection system installation after a trip event upon energization, which may include disassembly and modification of the PST bushings, CTs, or wiring, a process that can require more time than allowed by the remaining construction outage schedule. Pushing the energization of the PST to the next allowable outage window may delay the project's target in-service date until the seasonal low load period, possibly six months or more. Faced with those challenges, the authors hope that this paper has informed readers of the considerations and calculations for preparing these tests, and that planning and conducting the testing becomes a manageable effort for those who are engaged with testing and commissioning PSTs.

VII. Appendix A – Two-Core (Series-Exciter) PST Winding Phasor Relationships

PSTs can come in a wide variety of winding, core, and tap changer configurations, but their fundamental purpose is the same—to control the voltage angle between the source and load terminals by adding a quadrature voltage (i.e., one 90° out of phase) to a reference excitation voltage, as depicted in Figure A1. The quadrature voltage can be controlled by altering the turns ratios of regulating winding using OLTCs.

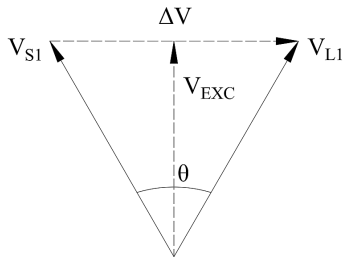


Figure A1. Source-to-Load Voltage Angle Shift of PST in Retard Position With Quadrature Voltage (ΔV).

A change to the voltage angle can increase or decrease power flow through a line according to (A1). The lagging voltage drop resulting from alternating-current flow through the impedance of a line can be offset by advancing the voltage angle across a PST, effectively decreasing the impedance of the line.

$$P_S = \frac{V_S * V_R * \sin\delta}{X_L} \quad \text{(A1)}$$

Where

- P_S Power transferred between sending and receiving ends
- V_S Sending end voltage magnitude
- V_R Receiving end voltage magnitude
- δ Angle between the sending and receiving voltages
- X_L Reactance of the line

Recognize that power flow on the transmission system is a complex relationship between the location of generating sources, loads, and the transfer paths between these points. The PST's regulation of voltage angle impacts the power transfer on not only the line it is connected to but also parallel transfer paths; the inverse is also true [2][4].

The voltage angle across a PST may be adjusted by operators to balance power flow among one or more parallel transmission paths, reducing the circulating current among them. Such functionality may be needed to reduce line overloads under high-load or contingency scenarios. Another possible

application is to regulate power flow along a contractually prescribed path.

The two-core PST is typically designed as separate two-winding transformers connected to apply the voltages to the high-voltage series windings, as indicated in Figure A2. It is possible to design both cores to fit in one common tank and may be more economical at lower MVA or voltage.

The winding connections and voltage vectors for both the series transformer (ST) and excitation transformer (ET) are depicted in Figures A2 and A3. The ST high-voltage winding is connected to the system, and load-flow current passes between the source (S) and load (L) terminals. The voltage angle between source and load is regulated by varying the quadrature voltage induced across the ST high-voltage windings, which is applied directly to the ST low-voltage excitation windings.

The quadrature voltage across each ST low-voltage winding is applied by direct phase-to-phase connection to the ET low-voltage windings. OLTCs in the ET low-voltage windings adjust the voltage applied to the ST low-voltage windings. To obtain the quadrature voltage, the B-phase and C-phase voltages of the ET regulating windings are connected across the ST A-phase low-voltage winding, which is induced in the A-phase ST high-voltage winding. Assuming A-B-C phase sequence, the load voltage angle can be advanced relative to the source voltage by connecting the ET low-voltage phasor "B" to the polarity terminal of the ST low-voltage A-phase winding and ET low-voltage phasor "C" to the non-polarity terminal of the ST low-voltage A-phase winding. From these connections, the ST A-phase low-voltage vector will induce the ET low-voltage phasor "B minus C" between ST S and L terminals. To retard the angle, the ET regulating windings are inverted via the OLTC reversing switch(es), and "B minus (minus C)," i.e., "C minus B" is instead applied between polarity and non-polarity terminals of the ST low-voltage winding. The voltages across the ET low-voltage regulating windings are induced from the ET high-voltage windings, which are connected to the midpoint of the ST high-voltage winding halves. The ET high-voltage windings are connected to the midpoint of the ST high-voltage windings to maintain a consistent quadrature voltage angle across the ST windings relative to the applied source voltage.

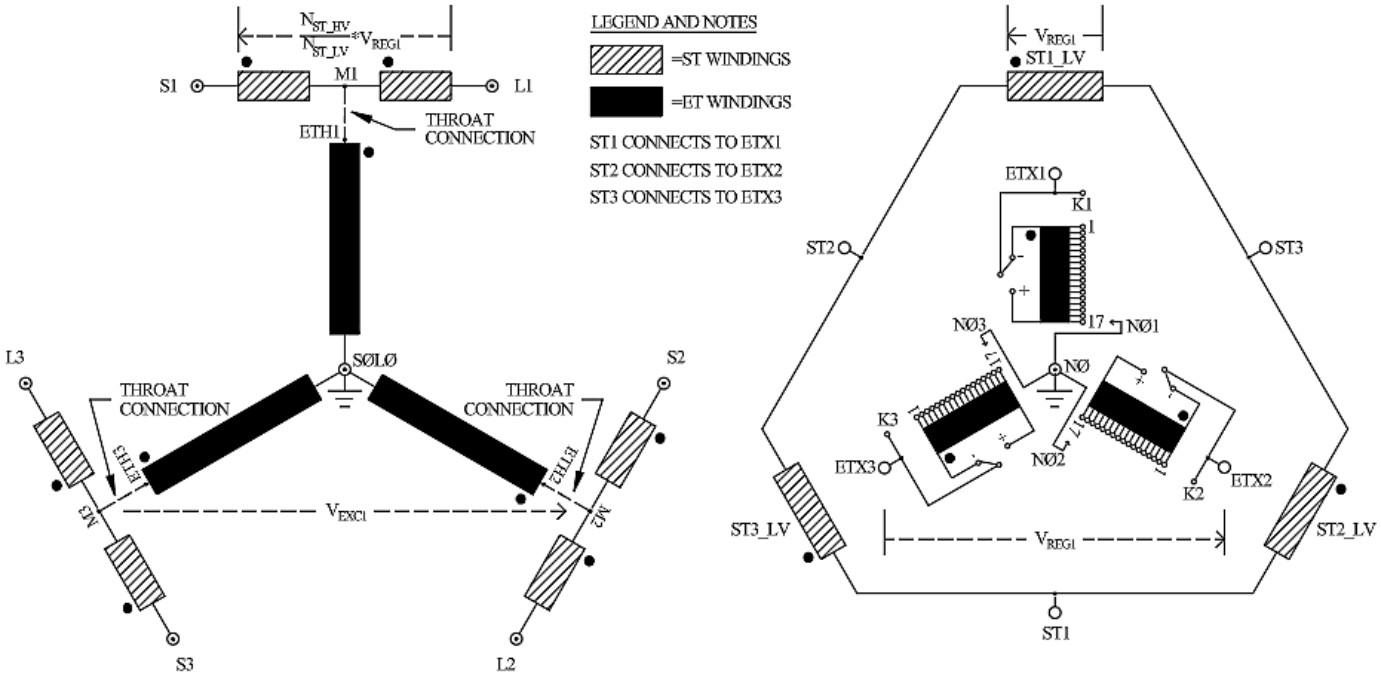


Figure A2. Two-Core PST Winding Connections, Tap Position 16A.

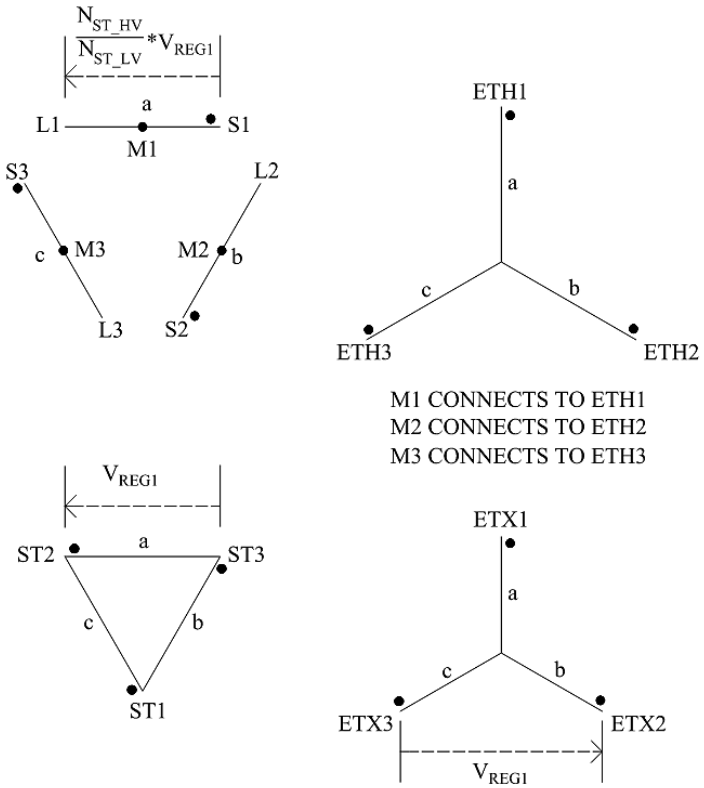


Figure A3. Two-Core PST Voltage Phasors, Tap Position 16A.

A. PST Rated Power

To further examine the voltage and current phasor relationships for this type of PST, we start by defining the apparent power rating of the overall PST from source-to-load terminals, see (A2).

$$S_{PST} = \sqrt{3} I_{S1} V s_{LL} \tag{A2}$$

Where

S_{PST} Apparent power rating of the PST
I_{S1} Design load-flow current
Vs_{LL} System voltage (line-to-line)

B. ST Series Winding Voltage

Neglecting impedance voltage drop due to current flow, the quadrature voltage induced from source to load can be determined from the basic voltage vector geometry in Figure A1, as shown in (A3).

$$\overrightarrow{V_{L1-S1}} = \frac{Vs_{LL}}{\sqrt{3}} 2 \sin\frac{\theta}{2} \angle[(\pm(90° + \left|\frac{\theta}{2}\right|)] \tag{A3}$$

Where

V_{L1-S1} Voltage across the ST high-voltage winding, between bushings S1 and L1

θ Angle shift applied to the voltage by the PST between bushings S1 and L1 under a no-load condition. (Throughout this paper, a positive value of theta indicates advance phase shift, and a negative value of theta indicates an applied retard phase shift)

The term $\pm(90° + \left|\frac{\theta}{2}\right|)$ is positive for an applied advance phase shift and is negative for an applied retard phase shift.

For example, given an applied phase shift of $\theta = 10°$ (advance), the angle of V_{L1-S1} is 95°.

The ST rated power is determined from the ST high-voltage winding voltage and current calculated in (A2) and (A3), as shown in (A4).

$$S_{ST} = 3 V_{L1-S1} I_{S1} \tag{A4}$$

Where

S_{ST} Apparent power rating of the ST

C. ST Series Winding Load Current

The ST series winding is split into two equal halves, connected at the midpoint to the ET primary winding. From this direct connection of windings, the current exiting the load terminal of the series winding is the summation of the source current (design load-flow current at the source reference angle) and the exciter primary winding current, which supplies the current for the phase angle shift. The result is that the load current magnitude is equal to the source current magnitude, but a phase angle shift is applied, as shown in (A5).

$$I_{L1} \angle(\theta + \phi) = I_{S1} \angle \phi + \overrightarrow{I_{ETH1}} \tag{A5}$$

Where

I_{L1} Current exiting the load terminal of the PST series winding

I_{ETH1} Current through the ET high-voltage winding, connected between the midpoint of the ST winding halves and the grounded neutral terminal (S0L0)

ϕ Angle of the source current relative to the source voltage due to the load power factor

Given the typical arrangement and connection of the load bushing CTs used by the PST differential relays (refer to the expected CT arrangement in Figure D1), the series winding current flow from source to load flows into the non-polarity side of the CTs, and the relay current inputs measure a current angle that is shifted 180° relative to the current phasor defined in (A5).

Also note that current flow through the PST windings produces a voltage drop due to the leakage reactance between the windings of the series and exciter cores, which causes an additional lagging angle β to be applied to the load current. This factor is not represented in (A5). Refer to [5] for a definition of this term and impact on load current angle under load. When specifying the rated angle regulation range of the PST, this factor is significant and should be accounted for. However, during primary current injection testing, it poses a negligible impact on the accuracy of measured current angles, as the lagging angle applied by this factor scales with load, and the load applied to the PST by the low-voltage generator test source is typically a minuscule fraction (less than 1%) of the PST rated power.

D. ST Secondary Winding Voltage

For extra high-voltage system applications or applications requiring a significant range of voltage angle regulation, the two-core PST has a distinct advantage over other well-established designs in that the OLTC connections are not exposed directly to system line voltage. This approach allows an OLTC with a lower voltage rating to be used, and the ST turns ratio can be selected to step up the OLTC line-to-line voltage to the quadrature voltage across the ST high voltage needed for the application, as can be seen using (A6).

$$\overrightarrow{V_{ST2-ST3}} = \overrightarrow{V_{L1-S1}} {}^{N_{ST2-ST3}}/_{N_{S1-L1}} \quad \text{(A6)}$$

Where

$N_{ST2-ST3}$ Number of turns in the ST low-voltage winding

N_{S1-L1} Number of turns in the ST high-voltage winding

Note that the ST turns (or voltage) ratio, ${}^{N_{S1-L1}}/_{N_{ST2-ST3,}}$ is not a standard item to include on the transformer nameplate per [6] or [7]. However, if the scope of primary current injection testing includes any CTs in the ST low-voltage windings, the ST voltage ratio is needed determine these currents. The ST turns ratio should be available in the manufacturer's transformer electrical design report provided to the customer. The customer can specify the ratio to be included on the transformer electrical data nameplate, which is more readily available than the electrical design report, especially after the initial PST installation has been completed.

E. ST Secondary Winding Current

The ST low-voltage winding current, $I_{ST2-ST3}$, is related to the currents in the series winding halves by the principle of ampere-turn balance, $I_1N_1 = I_2N_2$, fundamental to isolated windings sharing a common transformer core. Current through the series winding includes both the load-flow current and the exciting current that produces the phase shift across the series winding. Additionally, the source and load currents each flow through half of the total turns of the series winding. The summation of the series windings ampere turns equals the ampere turns produced in the ST secondary windings, as can be seen in (A7).

$$\overrightarrow{I_{ST2-ST3}}N_{ST2-ST3} = \frac{1}{2}N_{S1-L1}[I_{S1}\angle\phi + I_{L1}\angle(\theta+\phi)] \quad \text{(A7)}$$

F. ET Primary Winding Voltage

The nominal voltage of the ET high-voltage windings can be determined from the geometry between applied source voltage and the rated no-load voltage angle, as shown in (A8).

$$\overrightarrow{V_{ETH1}} = \frac{Vs_{LL}}{\sqrt{3}}\cos\frac{\theta}{2}\angle\left(\frac{\theta}{2}\right) \quad \text{(A8)}$$

Where

V_{ETH1} Rated line-to-neutral voltage of the ET high-voltage winding, connected between the mid-point of the ST winding halves and the grounded neutral terminal (S0L0)

The maximum voltage applied to this winding is equal to the applied source or load voltage when the PST is at the zero degrees no-load tap position.

G. ET Primary Winding Current

The ET high-voltage winding current, I_{ETH1}, is related to the source and load currents by applying Kirchhoff's current law (KCL) at the midpoint of the ST where the ET primary winding connects, as shown in (A9) [2].

$$I_{S1}\angle\phi + \overrightarrow{I_{ETH1}} + I_{L1}\angle(180° + \theta + \phi) = 0 \quad \text{(A9)}$$

Solving for I_{ETH1} yields (A10).

$$\overrightarrow{I_{ETH1}} = 2\sin\left(\frac{\theta}{2}\right)I_{S1}\angle \pm \left(90° + \left|\frac{\theta}{2}\right|\right) \quad \text{(A10)}$$

The term $\pm(90° + \left|\frac{\theta}{2}\right|)$ is positive for an applied advance phase shift and is negative for an applied retard phase shift. The KCL summation in (A9) establishes a nominal positive polarity for $\overrightarrow{I_{ETH1}}$ as flowing toward the ST midpoint. Given the typical arrangement and connection of the ET high-voltage winding CTs used by the PST differential relays (refer to Figure D1), the angle of ET winding current measured by the relay is consistent with the current phasor $\overrightarrow{I_{ETH1}}$ defined in (A9).

PST nameplate drawings commonly identify these winding currents as S0L01, S0L02, and S0L03. The winding neutral to ground connection is referred to as S0L0.

The ET high-voltage winding current is greatest when the PST is at the extreme tap positions.

H. ET Rated Power

The ET must be designed for both the maximum winding voltage and current duties, which separately occur at neutral

and maximum tap positions, respectively. The manufacturer also needs to design the ET for its greatest volt-ampere duty, which may be referred to as its "type power rating." This type power rating can be derived from (A8) and (A10) considering the maximum volt-ampere duty occurs at the maximum tap position, as can be seen using (A11).

$$S_{ET} = 3V_{ETH1}I_{ETH1} = 3\frac{Vs_{LL}}{\sqrt{3}}\cos\left(\frac{\theta}{2}\right)2\sin\left(\frac{\theta}{2}\right)I_{S1} \quad \text{(A11)}$$

Substituting (A3) and (A4) into (A11) yields the ET type power rating with respect to ST apparent power rating and no-load angle, as shown in (A12).

$$S_{ET} = S_{ST} * \cos\left(\frac{\theta}{2}\right) \quad \text{(A12)}$$

Where

S_{ET} type power rating of the ET

When the ST and ET are connected to form the PST, the effective power rating of the ET is its noncoincident maximum winding voltage and maximum winding current duty supporting the PST's apparent power [2]. By that definition, the ET effective apparent power rating is as follows in (A13).

$$S_{ET,eff} = 3V_{ETH1,max}I_{ETH1,max} = 3\frac{Vs_{LL}}{\sqrt{3}}2\sin\left(\frac{\theta}{2}\right)I_{S1} \quad \text{(A13)}$$

By inspection of (A3) and (A4), one may observe that the ET effective power rating is equal to the ST apparent power rating.

I. ET Secondary Winding Voltage

The ET regulating windings are connected line-to-ground to the corners of the ST delta-connected secondary windings. The equivalent line-to-line voltage of the regulating windings is equal to the ST secondary windings, as shown in (A14).

$$V_{ETX2-ETX3} = V_{ST2-ST3} \quad \text{(A14)}$$

Where

$V_{ETX2-ETX3}$ Rated line-to-line voltage of the ET low-voltage windings

J. ET Secondary Winding Current

The ET regulating winding current can be most easily determined by applying KCL about the node connecting the ET regulating winding to the corners of the delta-connected ST secondary windings, as can be seen using (A15). As defined in (A5), the current through each ST low-voltage winding is induced by the two halves of the ST primary winding of the same phase, scaled in magnitude by the ST turns ratio [2].

$$\overrightarrow{I_{ETX1}} = \frac{K}{2}\left[\left(\overrightarrow{I_{S3}} + \overrightarrow{I_{L3}}\right) - \left(\overrightarrow{I_{S2}} + \overrightarrow{I_{L2}}\right)\right] \quad \text{(A15)}$$

Where

K is the ST turns ratio $N_{S1-L1}/N_{ST2-ST3}$

$\overrightarrow{I_{ETX1}}$ Phase 1 current in the exciter low-voltage winding

$\overrightarrow{I_{S3}}$ Phase 3 source current vector, equal to the Phase 1 source current but lagging by 240°

$\overrightarrow{I_{L3}}$ Phase 3 load current vector, equal to the Phase 1 load current per (A5) but lagging by 240°

$\overrightarrow{I_{S2}}$ Phase 2 source current vector, equal to the Phase 1 source current but lagging by 120°

$\overrightarrow{I_{L2}}$ Phase 2 load current vector, equal to the Phase 1 load current per (A5) but lagging by 120°

Phase 2 and 3 ET low-voltage winding currents can be derived with the same basic approach; review [2] for details.

Equation (A15) can be reduced to an expression based on trigonometric identities for simpler solving using a calculator or spreadsheet formulas, as shown in (A16).

$$\overrightarrow{I_{ETX1}} = K\sqrt{3}\cos\left(\frac{\theta}{2}\right)I_{S1}\angle\left(90° \pm \frac{\theta}{2}\right) \quad \text{(A16)}$$

$\overrightarrow{I_{ETX1}}$ will always lead $\left(\overrightarrow{I_{S1}} + \overrightarrow{I_{L1}}\right)$ by 90 degrees. The KCL summation in (A15) establishes a nominal direction for $\overrightarrow{I_{ETX1}}$ as flowing from the KCL summation node toward the winding neutral. Given the typical arrangement and connection of the ET low-voltage winding CTs used by the PST differential relays (refer to Figure D1), the ET low-voltage winding currents flow into the non-polarity side of the CTs, and the relay current inputs will measure a current angle that is shifted 180° relative to the angle defined in (A16).

PST nameplate drawings commonly identify these winding currents as N01, N02, and N03. The winding neutral to ground connection is referred to as N0.

Neglecting the load current angle and impedance voltage drop due to load flow, the two-core PST voltage and current vectors are depicted in Figure A4.

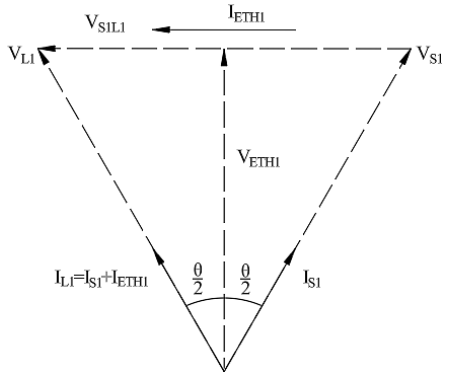


Figure A4. Two-core PST Voltage and Current Vectors, Neglecting Load-Flow low-Voltage Drop and Load Power Factor.

VIII. Appendix B – Two-Core PST Impedance

References [8], [9], and [10] provide derivations of the positive-sequence and zero-sequence impedances of the PST as a function of tap position, which simplify to the following set of equations (B1)–(B4).

$$Z1_{SL}(\theta = 0) = Z1_{ST} \quad \text{(B1)}$$

$$Z1_{SL}(\theta = max) = Z1_{ST} + Z1_{ET} \quad \text{(B2)}$$

$$Z1_{SL}(\theta) = Z1_{PST}(\theta = 0) + [Z1_{SL}(\theta = max) - Z1_{SL}(\theta = 0)]\left(\frac{\sin\frac{\theta}{2}}{\sin\frac{\theta=max}{2}}\right)^2 \quad \text{(B3)}$$

$$Z0_{SL} = Z1_{ST} \text{ for all tap positions} \quad \text{(B4)}$$

Where

$Z1_{SL}$ Positive-sequence impedance of the PST, between S and L terminals

$Z0_{SL}$ Zero-sequence impedance of the PST, between S and L terminals

$Z1_{ST}$ Positive-sequence impedance of the ST

$Z1_{ET}$ Positive-sequence impedance of the ET

For short-circuit modeling and analysis using phasor-based simulation software, the PST model is generally represented as positive- and zero-sequence impedances between the source and load terminals at the neutral tap position and the extreme tap positions; modeling the two-core PST as individual ST and ET impedances is not necessary.

Assuming a PST with equal range of regulation in advance and retard, the positive-sequence impedance at the extreme advance tap position is equal to the impedance at the extreme retard tap position.

For a typical two-core PST design, the positive-sequence impedance varies with tap position, while the zero-sequence impedance and zero-sequence shunt admittance remains almost constant across the tap position range [2].

An important caveat about (B1)–(B4) is that they do not account for the shunt branch of the zero-sequence impedance model. This shunt impedance may arise from a delta-connect set of tertiary windings in the ET or from the "phantom tertiary" effect, explained further in the next section.

A. Guide to Two-Core PST Short-Circuit Modeling

Despite the relative complexity of the two-core PST compared to other transformer designs, its symmetrical component model can be represented by the same equivalent T or pi model as the other transformer types. The positive-sequence and zero-sequence impedance T models for the two-core PST are presented in Figures B1 and B2. A typical naming convention used in short-circuit modeling software for each branch impedance and node is shown below inside each model block. The corresponding PST short-circuit model data represented by each branch is labeled above each block. These model components are discussed further in the following sections.

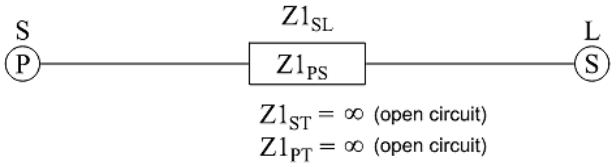


Figure B1. PST Positive-Sequence Impedance T Model.

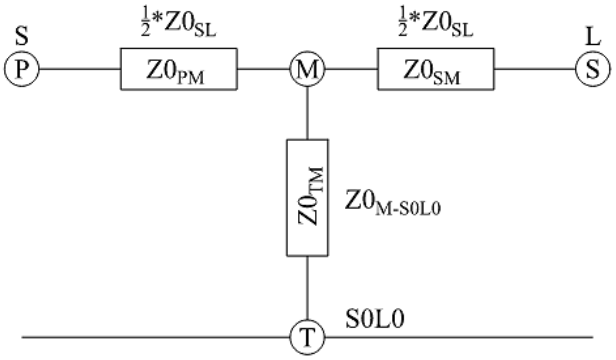


Figure B2. PST Zero-Sequence Impedance T Model.

B. Two-Core PST Positive-Sequence Impedance

The positive-sequence impedance of the PST is represented as a single lumped impedance between the S and L bushings of the ST. The negative-sequence impedance is equal to the positive-sequence impedance. At the neutral tap position, $Z1_{SL}$ equals the positive-sequence impedance of the ST; the ST impedance does not vary with tap position. At tap positions other than neutral, the overall PST positive-sequence impedance voltage drop depends on the ET impedance voltage drop. The ET positive-sequence impedance depends on the number of turns of the regulating winding connected via the OLTC, and thus the overall PST positive-sequence impedance varies by tap position. For short-circuit studies, it is important to obtain from the transformer manufacturer the positive-sequence impedance at the neutral tap position, maximum advance, and maximum retard tap positions.

C. Two-Core PST Zero-Sequence Impedance

The zero-sequence impedance model of the PST can be represented as either an equivalent T or pi model. First considering the ST on its own, zero-sequence voltage applied to the source or load bushings by the system will apply zero-sequence ampere turns of magnetomotive force (MMF) to the high-voltage series windings, which induce opposing zero-sequence ampere turns of MMF in the delta-connected secondary windings of the ST. Due to imperfect real-world coupling between windings, leakage flux will be present, which will produce a zero-sequence impedance voltage drop across the S and L bushings. The ST high-voltage series windings do not include a connection to earth, so the ST zero-sequence impedance model has an open circuit in the shunt branch. Note that even though the ET high-voltage windings provide connections from the ST high-voltage series windings' mid-points and ground, these connections do not influence the interaction between the zero-sequence currents flowing through the ST windings and the corresponding zero-sequence fluxes in the ST core.

The ET zero-sequence impedance model resembles that of a grounded-wye/grounded-wye (Yy0) transformer, which is represented as a series impedance between high- and low-voltage windings for both positive-sequence current and zero-sequence current. However, the direct connection of the ET wye-connected low-voltage regulating windings to the corners of the ST delta-connected low-voltage windings results in an open circuit to zero-sequence current flow between the ST low-voltage windings and ET low-voltage regulation windings. This connection isolates the path for zero-sequence current through the low-voltage regulating windings, in the case of a ground fault external to the PST or load unbalance. As a consequence, the ET core zero-sequence flux does not vary by tap position, and so the ET $Z0_{M\text{-}S0L0}$ does not vary with tap position.

A final aspect to discuss regarding the ET regulating windings' open circuit to zero-sequence current is that it provides no induced zero-sequence ampere turns to oppose those applied by the system to the ET high-voltage windings. In three-phase exciting transformers with three-limbed cores, zero-sequence voltage applied to the exciter primary windings

will produce zero-sequence flux in the three core limbs, which do not cancel and instead return through the air and the tank, and these mediums exhibit a higher reluctance to flux than the core. As reluctance is inversely proportional to inductance, the increased magnetic circuit zero-sequence reluctance results in a lower winding zero-sequence inductance and presents a stronger source of zero-sequence current through the S0L0 branch to external ground faults on the system. This phenomenon is commonly referred to as the "phantom tertiary" effect. Transformer cores may have a fourth or fifth limb to provide low-reluctance paths for the zero-sequence flux and reduce overall core flux density; such core designs yield a relatively weak phantom tertiary effect and greater M to S0L0 terminal zero-sequence excitation impedance.

If the ET design includes a set of delta-connected tertiary windings, the windings provide a path for zero-sequence current, and one should expect a relatively low zero-sequence impedance between the M and S0L0 terminals of the ET. For PST applications, tertiary windings may be necessary to facilitate factory short-circuit tests of PSTs with higher voltage and angle regulation ratings, where the test generator available for supply short-circuit test current has a lower rated voltage than the windings needing to be tested, as the tertiary windings provide a connection point for the generator and a means to boost the voltage applied to the higher-voltage windings.

From the perspective of one developing a short-circuit model for protection analysis, it is most important to recognize that depending on the core and winding design, the ET may or may not provide a significant source of zero-sequence current from ground through the excitation primary windings to external system ground faults. Given the variety of designs possible for PSTs among different manufacturers and applications, $Z0_{S\text{-}S0L0}$ should be tested and reported by the PST manufacturer so it can be accounted for accurately in the short-circuit model.

D. T Versus Pi Model for a Two-Core PST

Short-circuit analysis programs with a built-in PST model component typically use a pi representation of the PST zero-sequence impedance network, and so $Z0_{M\text{-}S0L0}$ would be split into two admittance halves, each half representing one of the two shunt branches of the pi. To evaluate coordination of S0L0 branch 51N protection elements with adjacent line or other zone ground overcurrent elements during external ground faults, it may be necessary to model the PST as a T model, which may be available in an autotransformer or three-winding transformer model component within the modeling software. The $Z0_{M\text{-}S0L0}$ branch zero-sequence current is represented by the autotransformer neutral current.

E. Calculation Using Example PST Impedance Data

The following example calculations, (B5)–(B14), define a T model of the PST positive-sequence and zero-sequences impedances based on example data, provided in Table B1, for a 700 MVA, 345 kV PST with ±50° no-load correction angle and ET utilizing a five-legged core.

TABLE B1. EXAMPLE PST IMPEDANCE DATA

Positive-Sequence Impedance Data

OLTC Tap Position	*Impedance Branch*	*%Z1*	*@ MVA*	*X/R Ratio*
16A	S-L	20	700	80
N	S-L	10	700	60
16R	S-L	20	700	80

Zero-Sequence Impedance Data

OLTC Tap Position	*Impedance Branch*	*%Z0*	*@ MVA*	*X/R Ratio*
All	S-L	10	700	60
All	M-S0L0	250	700	60

a) Positive-Sequence Impedance Model Calculations

At OLTC Tap Position N:

$$R1_{PS} = \mathrm{Z1\%} * \cos\left(\tan^{-1} X/R\right) \quad \text{(B5)}$$
$$= 0.10 \text{ pu} * \cos\left(\tan^{-1} 60\right) = 0.00167 \text{ pu}$$
$$X1_{PS} = \mathrm{Z1\%} * \sin\left(\tan^{-1} X/R\right) \quad \text{(B6)}$$
$$= 0.10 \text{ pu} * \sin\left(\tan^{-1} 60\right) = 0.09998 \text{ pu}$$
$$R1_{PT} = jX1_{PT} = R1_{ST} = jX1_{ST} = 1e12 \text{ pu} \quad \text{(B7)}$$

(Set to a very large number to represent an open circuit)

At OLTC Tap Position 16A/16R:

$$R1_{PS} = \mathrm{Z1\%} * \cos\left(\tan^{-1} X/R\right) \quad \text{(B8)}$$
$$= 0.20 \text{ pu} * \cos\left(\tan^{-1} 80\right) = 0.00250 \text{ pu}$$
$$X1_{PS} = \mathrm{Z1\%} * \sin\left(\tan^{-1} X/R\right) \quad \text{(B9)}$$
$$= 0.20 \text{ pu} * \sin\left(\tan^{-1} 80\right) = 0.19998 \text{ pu}$$
$$R1_{PT} = jX1_{PT} = R1_{ST} = jX1_{ST} = 1e12 \text{ pu} \quad \text{(B10)}$$

(Set to a very large number to represent an open circuit)

b) Zero-Sequence Impedance Model Calculations

At all OLTC tap positions:

$$R0_{PM} = R0_{SM} = 1/2 * \mathrm{Z0\%} * \cos\left(\tan^{-1} X/R\right) \quad \text{(B11)}$$
$$= 1/2 * 0.10 \text{ pu} * \cos\left(\tan^{-1} 60\right) = 0.00083 \text{ pu}$$
$$X0_{PM} = X0_{SM} = 1/2 * \mathrm{Z0\%} * \sin\left(\tan^{-1} X/R\right) \quad \text{(B12)}$$
$$= 1/2 * 0.10 \text{ pu} * \sin\left(\tan^{-1} 60\right) = 0.04999 \text{ pu}$$
$$R0_{TM} = \mathrm{Z0}_{M-S0L0} * \cos\left(\tan^{-1} X/R\right) \quad \text{(B13)}$$
$$= 2.50 \text{ pu} * \cos\left(\tan^{-1} 60\right) = 0.04166 \text{ pu}$$
$$X0_{TM} = \mathrm{Z0}_{M-S0L0} * \sin\left(\tan^{-1} X/R\right) \quad \text{(B14)}$$
$$= 2.50 \text{ pu} * \sin\left(\tan^{-1} 60\right) = 2.4997 \text{ pu}$$

2) Calculation Using Individual ST and ET Impedance Data

The following example, (B15)–(B27), calculates the ST and ET power ratings and positive-sequence impedances to validate overall T-model impedance data for the PST in the previous example.

PST rated power:

$$S_{PST} = \sqrt{3} I_{S1} V s_{LL} = 700\ MVA \text{ (given)} \quad \text{(B15)}$$

ST (and PST) rated current:

$$I_{S1} = \frac{700 \text{ MVA}}{\sqrt{3} * 345 kV} = 1{,}171.44\ A \quad \text{(B16)}$$

ST rated voltage:

$$V_{L1-S1} = \frac{V s_{LL}}{\sqrt{3}} 2 \sin\frac{\theta}{2} = \frac{345\ kV}{\sqrt{3}} 2 \sin\frac{50°}{2} = 168.36\ kV \quad \text{(B17)}$$

Keep in mind this is a single-phase voltage.

ST rated power:

$$S_{ST} = 3 * V_{L1-S1} I_{S1} = 3 * 168.36\ kV * 1{,}171.44\ A = 591.67\ MVA \quad \text{(B18)}$$

ET rated voltage:

$$V_{ETH1} = \frac{V s_{LL}}{\sqrt{3}} \cos\frac{\theta}{2} = \frac{345\ kV}{\sqrt{3}} \cos\frac{50°}{2} = 180.52\ kV_{L-N} \quad \text{(B19)}$$

In terms of line-to-line voltage,

$$V_{ETH1} = \sqrt{3} * 180.52\ kV_{L-N} = 312.67\ kV_{L-L} \quad \text{(B20)}$$

ET rated power:

$$S_{ET} = S_{ST} * \cos\frac{\theta}{2} = 591.67\ MVA * \cos\frac{50°}{2} = 536.24\ MVA \quad \text{(B21)}$$

ST positive-sequence impedance:

$$Z1_{SL}(\theta = 0) = Z1_{ST} = 0.10 \text{ pu @ } 700 \text{ MVA} \quad \text{(B22)}$$

Converting to ohms,

$$Z1_{ST} = 0.10\ pu \frac{(345\ kV)^2}{700 \text{ MVA}} = 17.00\ \Omega \quad \text{(B23)}$$

To determine $Z1_{ST}$ in per-unit of ST rated voltage and MVA,

$$Zbase_{ST} = \frac{(\sqrt{3} V_{S1-L1})^2}{S_{ST}} = \frac{(\sqrt{3} * 168.36\ kV)^2}{591.67\ MVA} = 143.72\ \Omega \quad \text{(B24)}$$

$$Z1_{ST,pu} = \frac{Z1_{ST}}{Zbase_{ST}} = \frac{17.00\ \Omega}{143.72\ \Omega} = 0.1183\ pu \text{ at } 591.67 \text{ MVA} \quad \text{(B25)}$$

ET positive-sequence impedance:

If $Z1_{ST}$ and $Z1_{ET}$ are expressed in per-unit on the common PST MVA base (700 MVA), they can be combined by simple summation of per-unit impedances without needing complex arithmetic.

$$Z1_{SL}(\theta = max) = Z1_{ST} + Z1_{ET} \quad \text{(B26)}$$

$$Z1_{ET} = Z1_{SL}(\theta = max) - Z1_{ST} \quad \text{(B27)}$$

$$= 0.20\ pu - 0.10\ pu = 0.10\ pu \text{ @ } 700 \text{ MVA}$$

Recognize that the direct connection of the ET and ST high-voltage windings makes an autotransformer. The ET contributes an equivalent voltage drop of 10% to the overall PST voltage drop from S to L terminals at 700 MVA through power. However, the actual two-winding ET impedance relative to the ET's rated power and winding current is greater by a scaling factor of $S_{PST}/\ *S_{ET}$, see (B28) and (B29).

$$Z1_{ET} = 0.10\ pu * S_{PST}/\ *S_{ET} \quad \text{(B28)}$$

$$= 0.10\ pu * 700 \text{ MVA}/536.24 \text{ MVA} = 0.1305\ pu$$

To express in ohms,

$$Z1_{ET} = 0.1305\ pu \frac{(V_{ETH1,L-L})^2}{S_{ET}} = 0.1305\ pu \frac{(312.67\ kV)^2}{536.24 \text{ MVA}} = 23.79\ \Omega \quad \text{(B29)}$$

IX. Appendix C – Test Equipment Sizing Calculations Example

This section provides a detailed calculation example of sizing primary injection test equipment for a PST with the ratings as follows:

Apparent power rating = 700 MVA

Rated source/load voltage = 345 kV

No-load angle regulation range = ±50°

$Z1_{SL}$ at neutral tap position = 10%

$Z1_{SL}$ at maximum tap position (16 Advance or 16 Retard) = 20%

$N_{S1-L1}/N_{ST2-ST3}$, ST turns ratio = 308/280 = 1.10

Source Bushing CT Ratio, Load Bushing CT Ratio = 2000:5

ET Primary Winding CT Ratio = 2000:5

ET Regulating Winding CT Ratio = 3000:5

One should first develop a table of winding currents to identify the winding with the lowest currents at the various tap positions (Table C1). Example calculations are provided for tap position 16A.

At Tap Position 16A

$$\text{No Load Angle} = -50°/16\ steps * 16 = -50°$$

$$I_{S1} = \frac{S_{PST}}{\sqrt{3} V s_{LL}} = \frac{700\ MVA}{\sqrt{3} * 345 kV \angle 0°} = 1171.4 \text{ A} \angle 0°$$

$$\overrightarrow{I_{ST2-ST3}} = \frac{[I_{S1}\angle\phi + I_{L1}\angle(\theta + \phi)]}{2} \frac{N_{S1-L1}}{N_{ST2-ST3}} = \frac{[1171.4\angle 0° + 1171.4\angle 50°]}{2} \frac{308}{280} = 1167.8\ A\angle 25°$$

$$\overrightarrow{I_{ETH1}} = -I_{S1}\angle\phi - I_{L1}\angle(180° + \theta + \phi) = 1171.4\angle 180° - 1171.4\angle(180° + 50°) = 990.1\ A\angle 115°$$

$$\overrightarrow{I_{ETX1}} = \frac{\frac{1}{2} N_{S1-L1}}{N_{ST2-ST3}\left[\left(\overrightarrow{I_{S3}} + \overrightarrow{I_{L3}}\right) - \left(\overrightarrow{I_{S2}} + \overrightarrow{I_{L2}}\right)\right]}$$

$$= \frac{308}{2 * 280}\begin{bmatrix}(1171.4\angle 120° + 1171.4\angle(120° + 50°)) \\ -(1171.4\angle - 120° + 1171.4\angle(-120° + 50°))\end{bmatrix} = 2022.7\ A\angle 115°$$

Note that the calculated ET low-voltage winding current angle represents current flowing through the windings toward neutral. However, given the typical arrangement and connections of CTs installed around these windings (reference

Figure D1), the current will enter the non-polarity terminal of the CTs, and the relay will measure current 180° out from the angle noted above.

Next, develop a table of secondary currents in each winding based on the turns ratios of CTs applied to each winding (Table C2). If we want to size the test source equipment to ensure a minimum injected current of 0.25 Asec for accurate verification of current magnitude and phase angle measured at devices, we can set the winding with the lowest current at each tap position to 0.25 Asec and scale the currents of all other windings according to the ratios of primary current between pairs of windings (Table C3).

Traditional differential protection for two-core PSTs consists of separate 87P and 87S schemes [2]. The 87P differential scheme involves source, load, and ET high-voltage winding currents. At neutral tap position, near zero current flows through the ET high-voltage windings. Conversely, the ET high-voltage winding currents are greatest when the PST is at maximum tap position. Therefore, for verifying the 87P differential scheme, testing should be performed with the PST at maximum tap position.

A traditional PST 87S differential current zone involves the currents from the source, load, and ET low-voltage (regulating) windings [2]. The ET low-voltage currents are greatest when the OLTC is at neutral tap position. Therefore, to verify the 87S differential scheme, testing should be performed with the PST at neutral tap position.

TABLE C1. EXAMPLE PST WINDING CURRENTS, PRIMARY AMPERES

	Equation Reference					
	(A3)	**(A2)**	**(A7)**	**(A10)**	**(A15)**	**(B1), (B2)**
Tap Position	**No Load Angle θ (deg)**	**I_{S1} (Apri)**	**$I_{ST2-ST3}$ (Apri)**	**I_{ETH1} (Apri)**	**I_{ETX1} (Apri)**	**$Z1_{SL}$ (%)**
16R	–50	1171.4	1167.8	990.1	2022.7	20.00
8R	–25	1171.4	1258.0	507.1	2178.9	12.62
1R	–3.125	1171.4	1288.0	63.9	2231.0	10.04
N	0.0	1171.4	1288.5	0.000	2231.8	10.00
1A	3.125	1171.4	1288.0	63.9	2231.0	10.04
8A	25	1171.4	1258.0	507.1	2178.9	12.62
16A	50	1171.4	1167.8	990.1	2022.7	20.00

TABLE C2. EXAMPLE PST WINDING CURRENTS, SECONDARY AMPERES

Tap Position	**No Load Angle θ (deg)**	**I_{S1} (Asec)**	**$I_{ST2-ST3}$ (Asec)**	**I_{ETH1} (Asec)**	**I_{ETX1} (Asec)**
16R	–50	2.93	2.92	2.48	3.37
8R	–25	2.93	3.15	1.27	3.63
1R	–3.125	2.93	3.22	0.16	3.72
N	0.0	2.93	3.22	0.00	3.72
1A	3.125	2.93	3.22	0.16	3.72
8A	25	2.93	3.15	1.27	3.63
16A	50	2.93	2.92	2.48	3.37

TABLE C3. EXAMPLE PST WINDING CURRENTS, SECONDARY AMPERES, NORMALIZED TO 0.25 ASEC FOR LOWEST WINDING CURRENT AT EACH TAP POSITION

Tap Position	**No Load Angle θ (deg)**	**$I_{S1}/I_{MIN} * 0.25$ (Asec)**	**$I_{ST2-ST3}/I_{MIN} * 0.25$ (Apri)**	**$I_{ETH1}/I_{MIN} * 0.25$ (Apri)**	**$I_{ETX1}/I_{MIN} * 0.25$ (Apri)**
16R	–50	0.296	0.295	0.250	0.340
8R	–25	0.577	0.620	0.250	0.716
1R	–3.125	4.583	5.039	0.250	5.819
N	0.0	0.250	0.275	0.000	0.318
1A	3.125	4.583	5.039	0.250	5.819
8A	25	0.577	0.620	0.250	0.716
16A	50	0.296	0.295	0.250	0.340

As the test source equipment voltage and power ratings needed to inject a specific current increases, as PST impedance increases, and PST impedance is greatest at maximum tap position, test source equipment sizing will generally be dictated by the voltage and power needed to inject required minimum currents through the PST when at maximum tap position.

From the calculations results of this example, a series winding current of 0.296 Asec (118.4 Apri) is needed to produce a minimum current of 0.25 Asec in all windings when testing the 87S differential scheme at neutral tap position and the 87P differential scheme at max tap position. From (1), the applied voltage required to inject this magnitude of series winding current is highest at the maximum tap position, i.e., 20% on a 700 MVA base.

$$\mathrm{V}_{APP,LL} = \sqrt{3} I_{SL} Z_{SL}$$
$$= \sqrt{3} * 118.4\ A * 20\% * {}^{345\ kV^2}/_{700\ MVA}$$
$$= 6.969\ \mathrm{kV}$$

One should consider the available voltage supplied by the generator source and whether the injected current through the PST is sufficient. In our example application, the need is clear for a step-up transformer to boost the applied voltage from the generator, as portable generators available on the rental market with rated voltage higher than 480 V are particularly uncommon. Common line-to-line distribution voltages in the desired range include 4.16 kV, 12.47 kV, and 13.8 kV. A transformer that steps up voltage to 4.16 kV would yield an injected current through the series winding at maximum tap position of 4.16/6.969 kV*118.4 A = 70.68 A, reducing the minimum secondary current injected in any of the windings to 0.149 Asec, i.e., through the ET high-voltage winding CTs.

The power demand from the generator is greatest when injecting the greatest current through the series winding. With 4.16 kV applied to the PST source terminals, the injected current will be greatest when the PST impedance is at a minimum, i.e., at neutral tap position.

$$I_{SL} = {}^{\mathrm{V}_{APP,LL}}\Big/_{\sqrt{3} Z_{SL}}$$
$$= {}^{4.16\ \mathrm{kV}}\Big/_{\sqrt{3} * 10\% * {}^{345\ kV^2}/_{700\ MVA}}$$
$$= 141.3\ \mathrm{A}$$

The revised power demand from the generator is

$$S_{GEN} = \sqrt{3} \mathrm{V}_{APP,LL} * I_{SL}$$
$$= \sqrt{3} * 4.16\ kV * 141.3\ A$$
$$= 1018\ \mathrm{kVA}$$

This lower injected current applied by a 4.16 kV source may be marginally acceptable, but once one accounts for the voltage drop between the generator and PST source terminals due to the impedance of the step-up transformer and connecting cables, the actual injected current will be even less. We will assess this impact in the following section. A more certain way to inject enough series winding current is to consider stepping up voltage to 12.47 kV, which would yield an injected current through the series winding of 211.7 A when the PST is at maximum tap position and a corresponding ET high-voltage winding CT secondary current of 0.447 Asec. Unfortunately, this increased injected current also increases the required apparent power rating of the step-up transformer and generator to 4,573 kVA.

Considering further the feasibility of a current injection test source using a 4.16 kV step-up transformer, we need to account for the impact of voltage drop from the generator to the PST through the impedance of the step-up transformer and cables. From (3),

$$I_{SL} = \frac{V_{LL,GEN}}{\sqrt{3}} \frac{V_{H,SUT}}{V_{X,SUT}}$$
$$* \left[\frac{1}{Z1_{CAB,LV} + Z1_{HX,SUT} + Z1_{CAB,MV} + Z1_{SL} + Z1_{CAB,SC}} \right]$$

For simplicity, this example calculation will estimate the voltage drop only based on total impedance and not precisely determine the real and reactive components of voltage drop based on the real and reactive components of impedance. As most of the impedance components consist of inductive reactance and negligible resistance, this simplification will yield sufficiently accurate results for sizing the test source equipment. The impedances will be expressed in per-unit on the PST's MVA and voltage base, which allows for more straightforward comparison of voltage drop contributions from the various components as well as the calculation of remaining voltage applied across the PST short-circuit impedance. The equipment voltage ratings and impedances defined for this calculation example are similar to the real-world testing application performed by NY Transco.

$V_{LL,GEN} = 480\ V$, the generator rated voltage

$V_{X,SUT} = 480\ V$, the step-up transformer secondary winding rated voltage

$V_{H,SUT} = 4{,}160$ V, the step-up transformer primary winding rated voltage

$Z1_{HX,SUT} = 5.75\%$ at 1,000 kVA, according to the step-up transformer nameplate ratings. Converted to per-unit on the PST MVA and voltage bases,

$$Z1_{HX,SUT_PU} = Z1_{HX,SUT} \frac{S_{PST}}{S_{SUT}} \frac{V_{SUT,LL}^2}{V_{PST,LL}^2}$$

$$Z1_{HX,SUT_PU} = 0.0575\ pu \frac{700\ MVA}{1.0\ MVA} \frac{4.16\ kV^2}{345\ kV^2} = 0.00585\ pu$$

$Z1_{CAB,LV} = 0.07855 \frac{\Omega}{1000\ ft}$ for 4/0 Cu Type W flexible temporary power cable, used to connect the generator to the secondary terminals of the step-up transformer. To support nameplate-rated loading of the 1000 kVA step-up transformer, 1202 A at 480 V, one would need 11 parallel runs of 4/0 Cu Type W, based on a single cable ampacity of 230 A at 75°C conductor temperature and derating by 50% for 10 or more parallel runs when rated in accordance with National Electric Code (NEC) Article 310. This number of cables is impractical to work with for this temporary installation of test equipment. By leveraging the capacitive load bank to offset the lagging

reactive load of the PST short-circuit impedance, we can reduce the test equipment loading to a small fraction of that otherwise needed. In the real-world test application completed by NY Transco, the rental equipment company provided eight runs of 4/0 Cu TYPE W for a 2500 kVA transformer, a total ampacity of only 1288 A at 75°C conductor temperature but more than enough for the current that was drawn through these cables with the capacitive load bank applied at the 4.16 kV side. The length of the furnished cable run was 50 ft., and the impedance of the parallel run of cables totaled

$$Z1_{CAB,LV} = 0.07855\,\frac{\Omega}{1000\ ft}\frac{50\ ft}{8\ runs} = 0.000491\ \Omega$$

Finally, convert the low-voltage cable impedance to the equivalent impedance seen at the high side of the generator step-up transformer and express in per-unit on the PST MVA and voltage base.

$$Z1_{CAB,LV} = Z1_{CAB,LV}\frac{{V_{H,SUT}}^2}{{V_{X,SUT}}^2}\frac{1}{Z_{BASE,PST}}$$

$$Z_{BASE,PST} = \frac{{V_{PST,LL}}^2}{S_{PST}}$$

$$Z1_{CAB,LV_PU} = 0.000491\ \Omega\frac{4{,}160\ V^2}{480\ V^2}\frac{700\ MVA}{345\ kV^2}$$

$$Z1_{CAB,LV_PU} = 0.000216864\ pu$$

$Z1_{CAB,MV}$=$0.1139\frac{\Omega}{1000\ ft}$ for 1/C 4/0 Cu Type SH flexible temporary power cable, used to connect the primary terminals of the step-up transformer to the safety grounding clamp or cluster grounding cable set that ultimately connects to the station bus or jumpers to the nearest PST or breaker. From the station layout plan and elevation section drawings, a cable length of 200 ft was determined necessary to route from the step-up transformer H bushings, down to the yard finished grade, laterally to the furthest phase of station bus, and up to a temporary grounding stud at the desired current injection point upstream of the high-voltage breaker that feeds the PST. This connection location was selected to allow testing of the breaker bushing CTs that are utilized for PST high-voltage bus lead differential protection, along with the PST bushing CTs used for the various PST protection and control systems. This cable impedance should also be converted to per-unit on the PST MVA and voltage base.

$$Z1_{CAB,MV_PU} = 0.1139\frac{\Omega}{1000\ ft}\frac{200\ ft}{1\ run}\frac{700\ MVA}{345\ kV^2}$$
$$= 0.000133914\ \text{pu}$$

$Z1_{SL_PU} = 0.2\ pu$ at maximum tap position, the short-circuit impedance of the PST between source and load terminals.

$Z1_{CAB,SC}$: A set of cables for applying the short-circuit connection, such as a temporary grounding cable set, could be selected for an ampacity matching that of the medium-voltage supply cables. For the simplicity of illustrating this example, assume that the short-circuit cable has the same impedance per 1,000 ft as the medium-voltage supply cable. The expected length of the short-circuit cable is closer to 50 feet to make the connection from the bus temporary grounding stud to the nearest structure's ground grid lead connection point.

$$Z1_{CAB,SC_PU} = 0.1139\frac{\Omega}{1000\ ft}\frac{50\ ft}{1\ run}\frac{750\ MVA}{345\ kV^2}$$
$$= 0.0000334785\ \text{pu}$$

With all equipment impedances defined on a common per-unit base, one may determine the current that can be injected through the PST series winding. When on maximum tap position,

$$I_{SL} = \frac{V_{LL,GEN}}{\sqrt{3}}\frac{V_{H,SUT}}{V_{X,SUT}}$$
$$*\left[\frac{1}{Z1_{CAB,LV_{PU}} + Z1_{HX,SUT_{PU}} + Z1_{CAB,MV_{PU}} + Z1_{SL_{PU}} + Z1_{CAB,SC_{PU}}}\right]$$
$$*\frac{1}{Z_{BASE,PST}}$$

$$I_{SL} = \frac{480\ V}{\sqrt{3}}\frac{4{,}160\ V}{480\ V}$$
$$*\left[\frac{1}{0.000217\ pu + 0.00585\ pu + 0.000134\ pu + 0.2\ pu + \ 0.0000335\ pu}\right]$$
$$*\frac{700MVA}{345\ kV^2}$$
$$I_{SL} = 68.5\ A$$

The impedance of all the cables connecting the equipment and the short to ground constitutes no more than 0.2% of the total impedance of the current injection loop. The step-up transformer impedance is 2.8% of the total loop impedance. The PST short-circuit impedance makes up more than 97.0% of the total loop impedance.

When the PST is on neutral tap position,

$$I_{SL} = \frac{480\ V}{\sqrt{3}}\frac{4{,}160\ V}{480\ V}$$
$$*\left[\frac{1}{0.000217\ pu + 0.00585\ pu + 0.000134\ pu + 0.1\ pu + \ 0.0000335\ pu}\right]$$
$$*\frac{700MVA}{345\ kV^2}$$
$$I_{SL} = 133.0\ A$$

The impedance of all the cables connecting the equipment and the short to ground constitutes no more than 0.19% of the total impedance of the current injection loop. The step-up transformer impedance is 1.9% of the total loop impedance. The PST short-circuit impedance makes up more than 97.9% of the total loop impedance.

Another observation one may make from the test system in Figure 1 is that the PST and injection test equipment are not the only equipment energized during testing. As primary injection testing ideally occurs after the station equipment, bus, and protection systems are fully installed, energization of the PST with the test generator also energizes other primary equipment such as voltage transformers, disconnect switches, breakers, buses and station service voltage transformers. All this equipment exhibits a stray capacitive load when energized, typically a shunt capacitance to ground; though some equipment also exhibits series stray capacitance, such as power transformers, PSTs, and circuit breakers utilizing grading

capacitors connected across open contacts. The capacitive load from this equipment is actually beneficial for test source sizing since the capacitive load offsets the inductive load of the tested transformer. However, the voltage applied to the equipment by the primary current injection test source is a small fraction of the system voltage. The resulting stray capacitive current demand is a couple milliamperes, a few thousandths of a percent of the total inductive load drawn by the transformer during the short-circuit current injection test. It is sufficient to conclude that equipment stray capacitive loads may be ignored when sizing test supply equipment.

At this point, the essential sizing calculations have been completed and established the following test equipment and ratings illustrated in Figure C4.

X. Appendix D – Example Measurement Validation Data Tables

This section provides an example layout of measurement validation data tables for primary current injection testing of a two-core PST with the following application parameters. PST winding and relay current input connections are depicted in Figure D1.

Apparent power rating= 700 MVA

Rated source/load voltage = 345 kV

No-load angle regulation range = ±50°

$Z1_{SL}$ at neutral tap position = 10%

$Z1_{SL}$ at maximum tap position (16 Advance or 16 Retard) = 20%

$N_{S1-L1}/N_{ST2-ST3}$, ST turns ratio = 308/280 = 1.10

Source Bushing CT Ratio, Load Bushing CT Ratio = 2000:5

ET Primary Winding CT Ratio = 2000:5

ET Regulating Winding CT Ratio = 3000:5

S0L0 CT Ratio = 1200:5

N0 CT Ratio = 1200:5

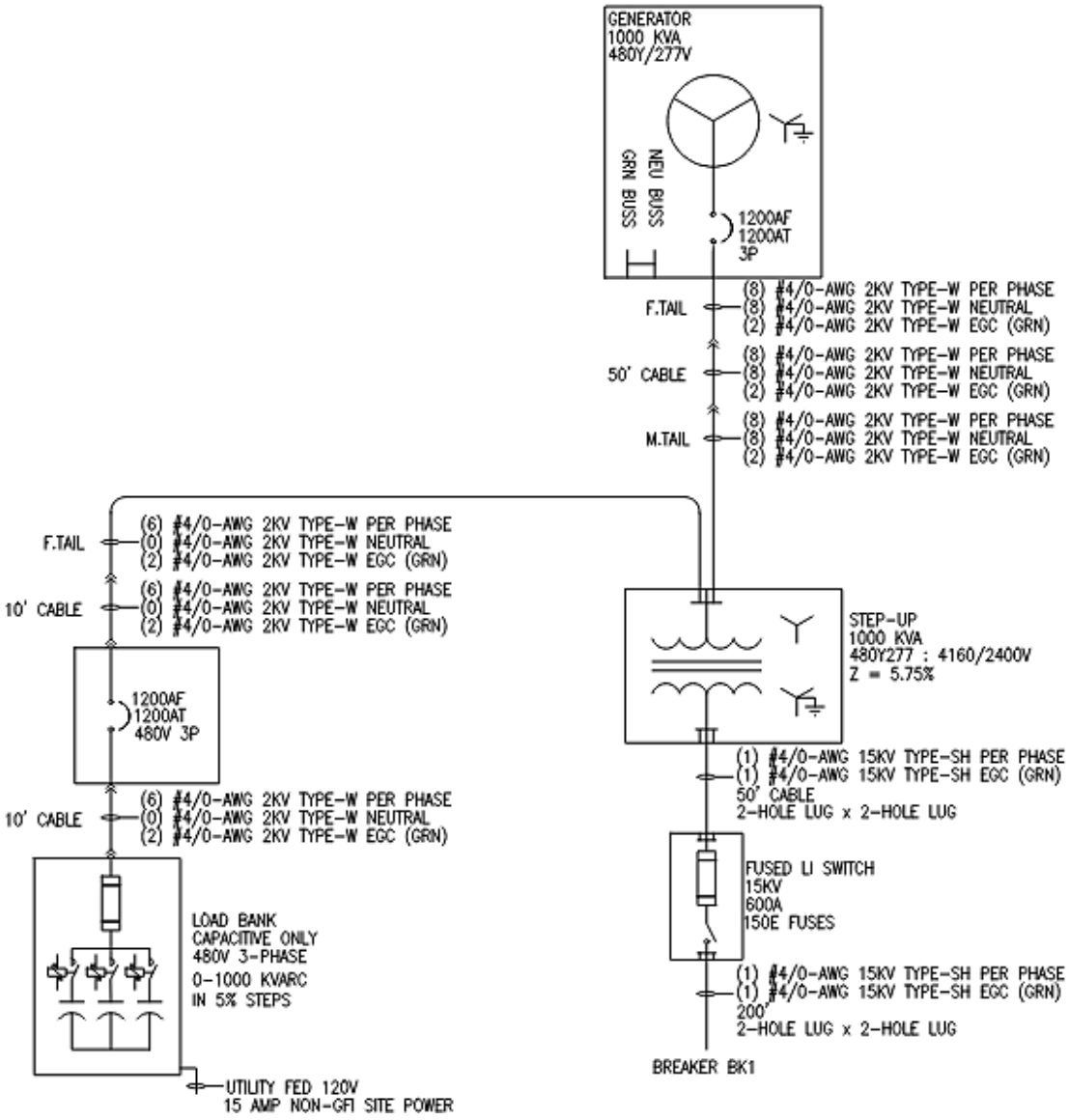


Figure C4. One-Line Diagram of Final Equipment Sized for Primary Injection Testing of Example PST Equipment.

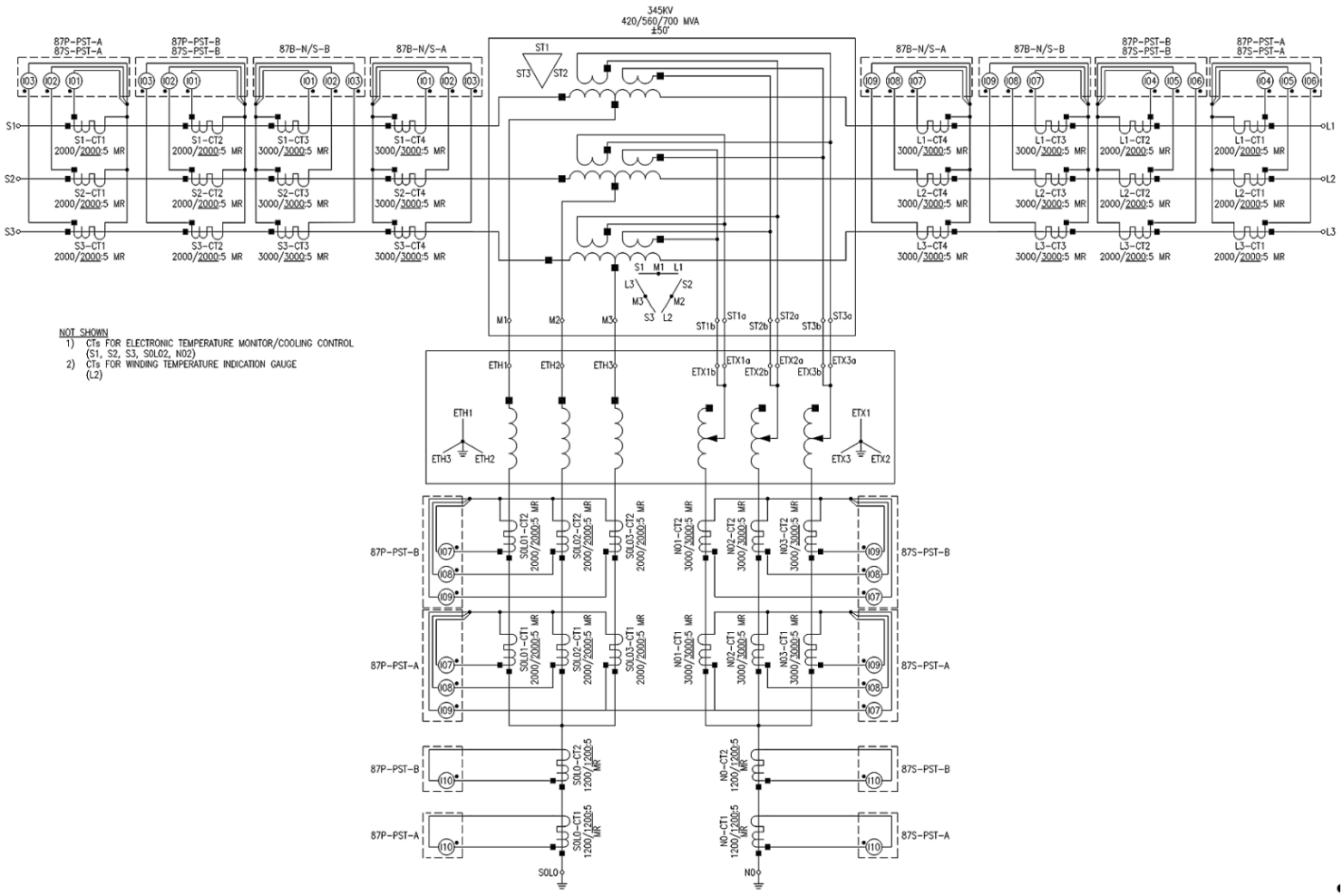


Figure D1. Three-Line Diagram of PST and Connected Relay Current Inputs.

A. PST 87P Differential Scheme – Measurement Validation Data

For testing the traditional PST 87P differential scheme current, Table D1 lays out the user input data and calculated expected measurements for the source, load, and ET primary winding currents. This table shows values for one phase of the PST. Copies of this table may be generated for the other phases.

B. PST 87S Differential Scheme – Measurement Validation Data

For testing the traditional PST 87S differential scheme current, Table D2 lays out the user input data and calculated expected measurements for the source, load, and regulating winding currents. This table shows values for one phase of the PST. Copies of this table may be generated for the other phases. Observe that the expected generator A-phase current is 90 degrees lagging the A-phase reference voltage due to the inductive load of the PST short-circuit impedance.

C. Example Relay Measurements Record Table

Relay measurement record tables should be prepared in advance of testing to identify the devices that need to be interrogated and the analog variable names that are attributed to the various PST winding current quantities. CT ratios should also be noted if measurements reported in secondary amperes, especially if multiple CT with different ratios are applied to a given winding.

Table D3 provides an example layout of relay quantities that may need to be measured when the PST is at a specific tap position and consistent current is supplied by the generator.

When comparing angles of the same phasor quantity across multiple relays, one should be aware that not all relays may have voltage inputs to provide a common reference angle. Relays with voltages inputs are commonly set to consider the phase A voltage angle the zero-degree reference angle. If a relay does not have voltage inputs wired and instead has A-phase current established as the reference angle, the current phasor angles measured by this relay will vary from those reported by the relay that does have voltage inputs wired and A-phase voltage configured to provide the phasor reference angle.

TABLE D1. PST 87P DIFFERENTIAL SCHEME – MEASUREMENT VALIDATION DATA

	Equation Reference								
	User Input	User Input	User Input	(A2)		(A5)		(A10)	
Tap Position	No Load Angle θ (deg)	Injected Current[1] (Apri)	Injected Current Reference Angle[2] (deg)	Expected I_{S1} (Apri)	Expected I_{S1} (Asec)	Expected I_{L1} (Apri)	Expected I_{L1} (Asec)	Expected I_{ETH1} (Apri)	Expected I_{ETH1} (Asec)
N	0.0	133.0	-90	133.0 @ -90°	0.333 @ -90°	133.0 @ 90°	0.339 @ 90°	0.0 @ 90°	0.000 @ 90°
16A	50	68.5	-90	68.5 @ -90°	0.171 @ -90°	68.5 @ 140°	0.171 @ 140°	57.9 @ 25°	0.145 @ 25°

[1]Current injected into PST source terminal, measured by generator

[2]The exact angle of current flowing through the source terminal will vary according to the angle reference used by the current measurement device, the load power factor, and the actual phase current being measured (e.g. S1, S2, and S3). The source current angle measured by the relay should be entered and used to calculate the angle of all other winding currents in relation to the source current angle.

TABLE D2. PST 87S DIFFERENTIAL SCHEME – MEASUREMENT VALIDATION DATA

	Equation Reference								
	User Input	User Input	User Input	(A2)		(A5)		(A14)	
Tap Position	No Load Angle θ (deg)	Injected Current[1] (Apri)	Injected Current Reference Angle[2] (deg)	Expected I_{S1} (Apri)	Expected I_{S1} (Asec)	Expected I_{L1} (Apri)	Expected I_{L1} (Asec)	Expected I_{ETX1} (Apri)	Expected I_{ETX1} (Asec)
N	0.0	133.0	-90	133.0 @ -90°	0.333 @ -90°	133.0 @ 90°	0.333 @ 90°	253.4 @ 180°	0.422 @ 180°
16A	50	68.5	-90	68.5 @ -90°	0.171 @ -90°	68.5 @ 140°	0.171 @ 140°	118.3 @ -155° (205°)	0.197 @ -155° (205°)

[1]Current injected into PST source terminal, measured by generator

[2]The exact angle of current flowing through the source terminal will vary according to the angle reference used by the current measurement device, the load power factor, and the actual phase current being measured (e.g. S1, S2, and S3). The source current angle measured by the relay should be entered and used to calculate the angle of all other winding currents in relation to the source current angle.

TABLE D3. EXAMPLE RELAY MEASUREMENTS RECORD TABLE – TAP POSITION 16A

Relay Designation	Relay Type	Relay Current Input Set	Associated CTs	CT Ratio	Genset IA Mag. (Apri)	Genset IA Ang. (deg)	Relay IA Mag. (A)	Relay IA Ang. (deg)	Relay IB Mag. (A)	Relay IB Ang. (deg)	Relay IC Mag. (A)	Relay IC Ang. (deg)
87P-PST-A	Make & Model	I01/I02/I03	PST S1,2,3 CT1	2000:5	68.5	-90	68.5	-90	68.5	150	68.5	30
87P-PST-A	"	I04/I05/I06	PST L1,2,3 CT1	2000:5	"	:	68.5	140	68.5	20	68.5	-100
87P-PST-A	"	I07/I08/I09	PST S0L01,2,3 CT1	2000:5	"	"	57.9	25	57.9	-95	57.9	145
87P-PST-A	"	I10	PST S0L0 CT1	1200:5	"	"	0	0	0	0	0	0
87S-PST-A	"	I01/I02/I03	PST S1,2,3 CT2	2000:5	"	"	68.5	-90	68.5	150	68.5	30
87S-PST-A	"	I04/I05/I06	PST L1,2,3 CT2	2000:5	"	"	68.5	140	68.5	20	68.5	-100
87S-PST-A	"	I07/I08/I09	PST N01,2,3 CT2	3000:5	"	"	118.3	-155	118.3	85	118.3	-35
87S-PST-A	"	I10	PST N0 CT2	1200:5	"	"	0	0	0	0	0	0

Relay Designation	Relay Type	Relay Current Input Set	Associated CTs	CT Ratio	Genset IA Mag. (Apri)	Genset IA Ang. (deg)	Relay IA Mag. (A)	Relay IA Ang. (deg)	Relay IB Mag. (A)	Relay IB Ang. (deg)	Relay IC Mag. (A)	Relay IC Ang. (deg)
87P-PST-B	“	System B Relay Inputs	System B Relay CTs	Various	Measurements from System B PST relays							
Bus Relays	“	Bus Relay Inputs	Various	Various	Measurements from Bus Relays (PST S1,2,3 CT3 and CT4; PST L1,2,3 CT3 and CT4; BK1 2,4,6 CTX and CTY; BK2 2,4,6 CTX and CTY)							
DFR	“	DFR Current Input Channels	Various CTs	Various	Measurements from DFR channels							

XI. References

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XII. Biographies

Ryan McMaster, IEEE Senior Member, has been a consulting engineer for electric utilities for the past 19 years, joining WSP (formerly POWER Engineers) in 2013. He is a member of the Electrical Studies and System Protection (ESSP) group, where he performs a variety of electrical system studies for transmission, substation, and generation projects. He has a background in protective relaying and substation protection and control design. Ryan received his B.S. in Electrical Engineering from Washington State University and is a licensed Professional Engineer in Washington, Oregon, Maine, and Pennsylvania.

Andrew Welch has more than 30 years of experience in the electrical industry and currently holds the position of Director of Operations and Maintenance at New York Transco, a New York based owner, operator, and developer of bulk electrical transmission facilities. Andrew has experience in heavy commercial and industrial construction, utility scale wind, and critical power generation, as well as electric utility testing, commissioning, and operations at facilities operating up to 345kV.

John Kelly has been in the electric utility industry for over 15 years and is currently an Operations Engineer for New York Transco. His background includes positions in field operations and protection engineering. He holds a Bachelor of Science in Computer Engineering from the State University of New York at New Paltz.

Michael Thompson received his B.S., magna cum laude, from Bradley University in 1981 and an MBA from Eastern Illinois University in 1991. Upon graduating, he served nearly 15 years at Central Illinois Public Service Company (now Ameren). Prior to joining Schweitzer Engineering Laboratories, Inc. (SEL) in 2001, he worked at Basler Electric. He is presently a distinguished engineer at SEL Engineering Services, Inc. (SEL ES), Inc. He is an IEEE Life Fellow, past Chair of the IEEE PES Power System Relaying and Control Committee (PSRC), and past Chair of the Substation Protection Subcommittee of the PSRC. Michael received the Standards Medallion from the IEEE Standards Association in 2016. He also served as a subject matter expert advising the System Protection and Control Working Group of the North American Electric Reliability Corporation for many years. Michael is a registered professional engineer in six jurisdictions, was a contributor to the reference book *Modern Solutions for the Protection Control and Monitoring of Electric Power Systems*, has published numerous technical papers and magazine articles, and holds four patents associated with power system protection and control.

James Silva received his B.S. and M.S. in Electrical Engineering from California Polytechnic State University, San Luis Obispo in 2005. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2008. He is presently a Senior Engineer - Protection at SEL Engineering Services, Inc. (SEL ES), Inc. with experience in power system protection and automation. James is a registered professional engineer in three states.

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