Protection of Phase Shifting Transformer(s) for Transgrid EnergyConnect Project – Concept and Application Considerations

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***Abstract*—Transgrid is installing five 300 kV, 200 MVA, two-core symmetrical phase shifting transformers (PST) in parallel at the Buronga Substation as part of the EnergyConnect project. The PSTs will provide a new interconnection between the New South Wales and South Australia transmission networks. PSTs provide the ability of bi-directional power flow control across the interconnection. They do so by changing the power system voltage angle across their "load" and "source" terminals by injecting a quadrature voltage between the two sides. The magnitude and direction of the injected quadrature voltage (or change in voltage angle) is controlled through a tap changer on a regulating winding.**

This paper presents the unique requirements and considerations for protecting two-core symmetrical PSTs against internal and external faults (shunt, turn-to-turn faults, through fault) and abnormal operation (thermal overloads). The requirements on location of current transformers (CTs) and voltage transformers (VTs) for creating different zones of protection are discussed. The influence of protection on PST design is highlighted with the placement of a CT within the tank of the PST. The physical design of a two-core PST consists of interconnected windings of two separate cores called the series and the excitation core. The PSTs in this project are connected to the transmission network through a breaker-and-a-half scheme on both sides at the Buronga Substation. The paper explains the principles of operation of the different protection functions implemented and describes the protection concept developed to protect both the series and excitation cores along with the connection to the busbar (Tee-point). The solution is implemented using a dual main X and Y protection scheme that uses two manufacturers with a diversity of protection principles. In particular, the protection functions in the relays are sequence component differential protection, phase differential protection with variable angle compensation, Kirchoff's current law (KCL)-based differential protection, ampere-turn balance (ATB)-based differential protection, restricted earth fault (REF) for primary winding of excitation core, and earth fault protection for regulating and tertiary winding.

The design and settings were validated as a complete solution on a Real Time Digital Simulation (RTDS®) platform by simulating shunt, turn-to-turn, and through faults at different locations within and outside the protection zone. The results presented not only validate the efficacy of the protection design but also demonstrate its sensitivity, security, and dependability. The first of the five transformers has been commissioned and placed in service. Commissioning of the remaining four transformers is expected to be completed in 2026.

***Keywords*—Two-core phase shifting transformer, sequence component differential protection, variable angle compensation, ampere-turn balance differential protection.**

I. Introduction

Project EnergyConnect (PEC) is a significant new transmission infrastructure project that connects Transgrid's Wagga Wagga Substation in New South Wales (NSW) to ElectraNet's Bundey/Robertstown Substation in South Australia (SA). It also includes a new transmission link from the Buronga Substation to the Red Cliffs Substation in Victoria. The total length of the transmission circuits is approximately 900 km. Fig. 1 shows the new transmission infrastructure being installed in this major project.

A new substation, named Dinawan, is being constructed between Coleambally and Jerilderie in the NSW Riverina region. The name "Dinawan," meaning emu, is derived from the language of the Wiradjuri people, the Traditional Custodians of the area.

The NSW (at Buronga) and SA (at Bundey) grids are now interconnected through a 327.4 km double-circuit overhead transmission line. At Transgrid's Buronga Substation, two synchronous condensers and five 200 MVA phase shifting transformers (PSTs) have been installed to facilitate and regulate power transfer between the NSW and SA networks.

Fig. 1. Overview of Project Energy Connect.

II. Background

Unlike traditional power transformers (step-up or step-down transformers), PSTs operate by varying the voltage angle between the "source" and "load" sides. While transformer differential protection in standard power transformers accounts for a fixed phase angle compensation across the transformer, the phase angle across the PST terminals varies based on the tap position. It is this varying phase angle that allows PSTs to regulate power flow. This requires novel approaches to protect them.

Angular shift across the PST is achieved by injecting a self-generated quadrature voltage onto the appropriate phases. The magnitude of the quadrature voltage determines the angle shift, and this in turn is controlled by the action of a tap changer. These transformers can be broadly classified into two categories: single-core and two-core design. These broad types can further be categorized as "symmetrical" or "asymmetrical" depending on the relationship between the source and load-side voltage magnitude under no-load conditions [1]. This paper explores the protection of a symmetrical, two-core PST.

III. Protection of Two-Core Symmetrical PSTs

There have been new developments in protection practices for PSTs in recent years. This project is probably one of the first to take full advantage of all the latest developments in addition to the traditional methods. This section details the comprehensive protection system design developed for this project.

The main deficiency in traditional PST protection system practices is that the differential elements are blind to turn-to-turn faults in the regulating winding [2] [3]. Mechanical sudden pressure and/or Buchholz relays were the only protection available to detect these faults. This gap in electrical protection of a PST is especially concerning given that the regulating winding has many taps and greater exposure to turn-to-turn faults than any fixed windings of a transformer.

There are now two special PST differential schemes available that are capable of electrical detection of all internal faults, including turn-to-turn faults. Both were applied in this application as part of a dual primary protection system—System X from one manufacturer, and System Y from a different manufacturer. The two methods are fundamentally different in principle but very similar in how they determine the variable phase shift across the PST for compensation. Both vendors' PST differential schemes use current transformers (CTs) and voltage transformers (VTs) at the terminals of the PST. Both are limited to two terminal zones, which factored into the different designs of System X and Y. Contrast this to traditional PST differential protection schemes that require use of CTs inside the PSTs.

Traditional protection schemes were also implemented in System X and System Y with slightly different configurations of the differential zones. The use of two different special PST differential schemes and traditional differential schemes takes advantage of the complementary nature of each differential element. Because of their different operating principles, each element is more responsive to certain fault types than others, and therefore fast and reliable detection of all internal faults is ensured. The various protection functions are described in the following subsections.

Fig. 2 shows a single-line diagram of the System X protection. The protection functions are implemented in two relays. Relay 87-OX is configured as an overall differential covering faults in the buswork using the traditional 87P, primary winding and 87S, secondary winding differentials required for a two-core PST. 87-PSTX provides protection for the PST only, including special PST differential elements.

Fig. 3 shows a single-line diagram of the System Y protection. Again, the protection functions are implemented in two relays. However, the protection is segregated into three subzones—the PST, the buswork from the breaker-and-a-half bays to the source terminals of the PST, and buswork from the breaker-and-a-half bays to the load terminals of the PST. Relay 87-BY is a high-speed percentage-restrained bus differential relay with two sets of three-phase differential elements. Relay 87-PSTY is configured with the special PST differential elements and the traditional PST differential elements. Segregating the PST protection from the bus protection eliminates compromises in optimizing protection for the bus versus the PSTs [4] [5].

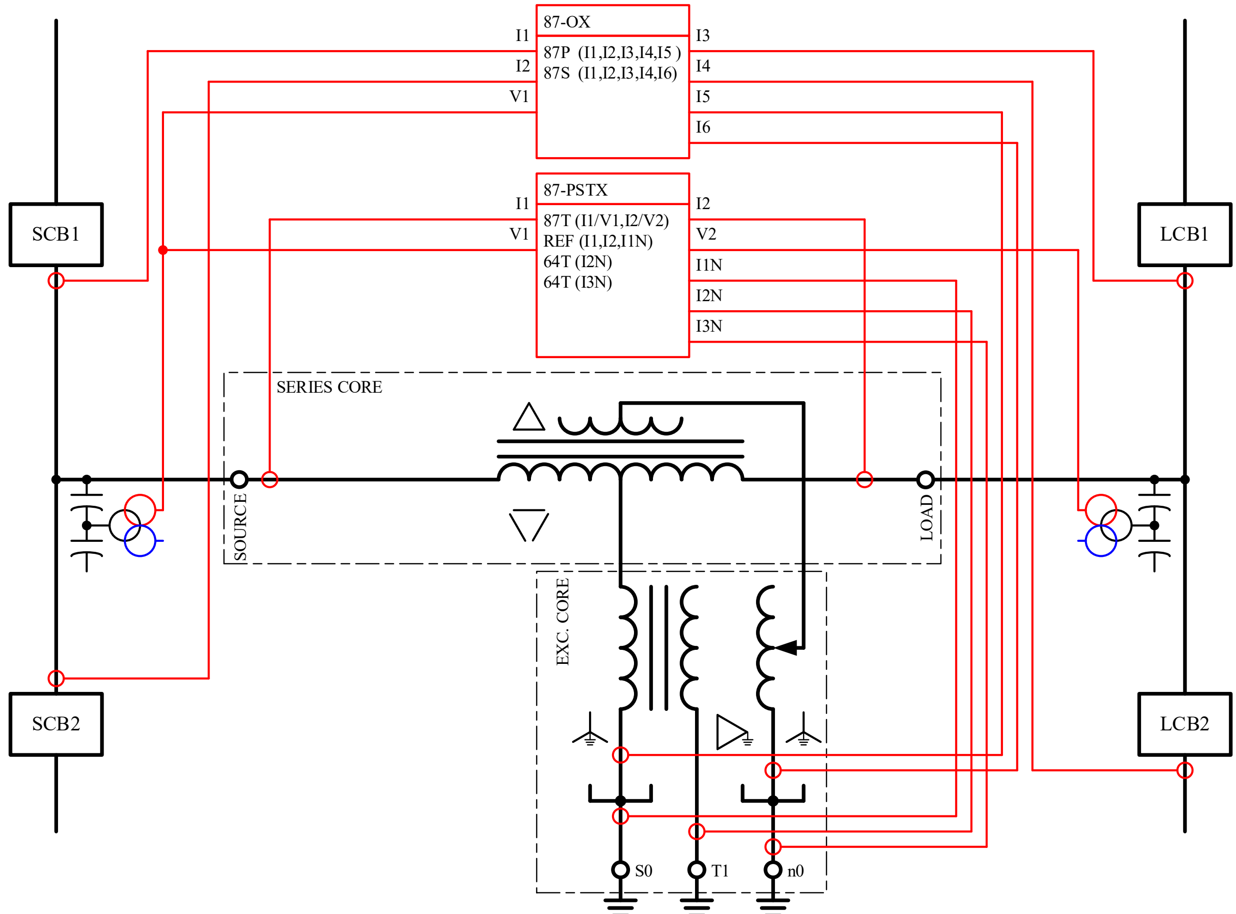

Fig. 2. System X single-line diagram.

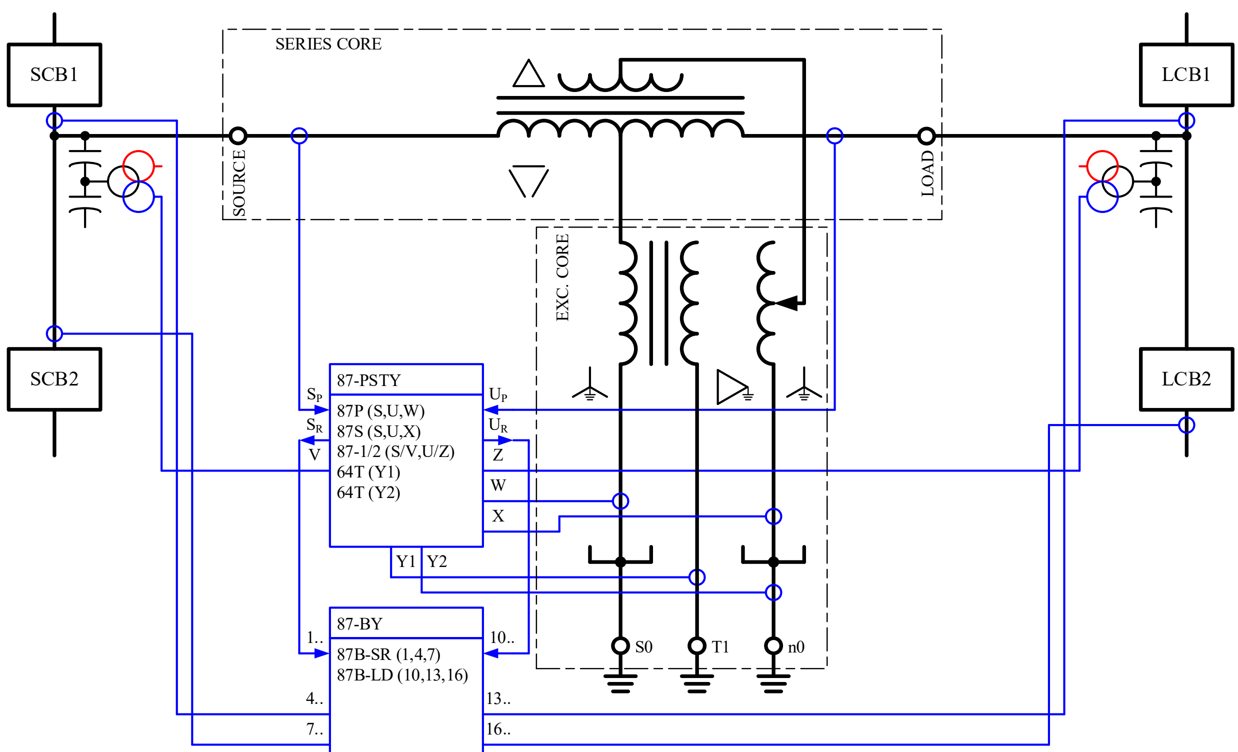

Fig. 3. System Y single-line diagram.

The different configurations of the zones are necessary because the relays from the two manufacturers have different capabilities. The special PST differential elements are discussed first (Sections 3.1 and 3.2). The traditional PST differential elements are discussed next. Finally, the elements for detecting ground faults in the PSTs are discussed. Bus differential protection is not discussed.

A. Sequence Component Differential Protection Elements (87-1/87-2) With Variable Phase Compensation

The first differential element developed specifically to accommodate the variable phase shift across a PST has been in use since 2006 [2]. The scheme uses symmetrical components to develop operate and restraint signals for the 87-1, positive-sequence differential element, and the 87-2, negative-sequence differential element. These are implemented in relay 87-PSTY, as shown in Fig. 3. This scheme is equally applicable to both single-core and two-core PSTs. This scheme has been steadily refined over the nearly two decades since it was first used. The following is a very brief description of the scheme. The reader is encouraged to read [1], [2], and [6] for more details.

The load-side positive- and negative-sequence components can easily be compensated to a position 180 degrees out of phase with the source side so that differential signals can be calculated. The scheme makes use of a fundamental attribute of symmetrical components theory: the phase shift of the negative-sequence components will be opposite of the positive-sequence components across a transformer. This principle is true whether the phase shift is an increment of 30 degrees, as with a traditional transformer, or variable as with a PST. The load-side positive-sequence component can be compensated by simply multiplying by a phasor of $1\angle -\Theta$ where Θ is the advance (positive sign) or retard (negative sign) angle position of the PST. The compensation phasor for the negative-sequence element is simply $1\angle \Theta$ [7].

A major improvement was made available in 2010 and reported in [1]. This development used electrical measurements to obtain the angle compensation factors. The relay uses a weighted average of the measured positive-sequence voltage angle and the measured positive-sequence current angle between the source and load sides. See Fig. 4 for the characteristic for determining the I1 angle weighting factor.

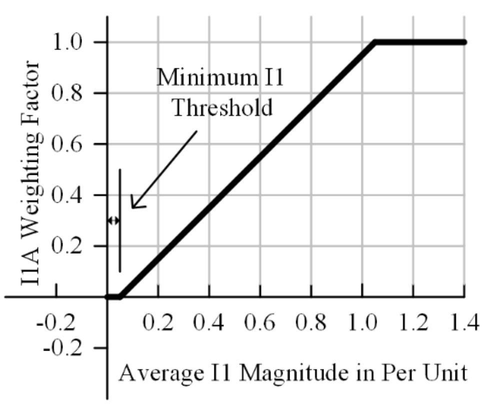

Fig. 4. I1 angle measurement weighting factor.

During conditions of no or low load flow, the current may be too low to get a reliable I1 angle difference reading. Under these conditions, the 87-1 and 87-2 elements use the measured V1 angle across the PST. As the load flow increases, the measured voltage angle becomes less accurate because the measured angle is the sum of the induced quadrature voltage and the voltage drop across the impedance of the PST. However, as the load flow increases, the current angle becomes more accurate. The weighted angle compensation factor is determined by (1).

$$\Theta = ANG_{I1} \bullet WT_{I1} + ANG_{V1} \bullet \left(1 - WT_{I1}\right) \tag{1}$$

where:

Θ is the angle compensation factor.

ANG_{I1} is the measured angle difference of the positive-sequence current across the PST.

WT_{I1} is the positive-sequence current weighting factor per Fig. 4.

ANG_{V1} is the measured angle difference of the positive-sequence voltage across the PST.

The result of (1) is then run through a smoothing filter to ensure that the angle compensation factor changes very slowly. A typical setting for the smoothing filter is 1.5 seconds to reach 95 percent of final value after a step change.

The 87-1 and 87-2 differential elements include a sensitive and a secure element. Fig. 5 shows the characteristics. The sensitive element is set with a relatively low slope (87nSLP1) and minimum pickup (87nMINP). Here, lower case "*n*" represents 1 for the 87-1 elements and 2 for the 87-2 elements. The sensitive element is also limited by the 87nIRS1 setting to relatively low levels of through-fault current. The sensitive element is blocked by external fault detector (EFD) logic and is only enabled after a reliable angle compensation factor is available.

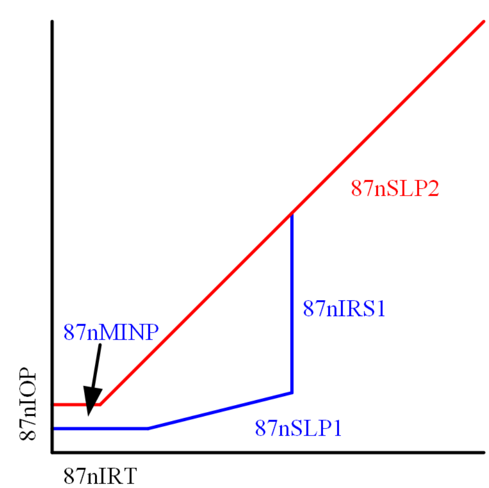

Fig. 5. Differential with sensitive (SLP1) and secure (SLP2) characteristics.

Examination of Fig. 5 shows that the secure element (red) uses a higher minimum pickup and slope than the sensitive element (blue). The secure element is in service at all times, protecting the PST when the EFD logic asserts or when a reliable angle compensation factor is not available. The secure slope (87nSLP2) is set above the worst-case error current if angle compensation is not available. That is, it maintains dependability under such conditions as loss of VT signals when current is too low to provide a reliable compensation angle. Use of two differential characteristics for each element ensures that dependability is not sacrificed to security.

Another advancement in recent years is the integration of the traditional PST differential elements, 87P and 87S, described in Sections 3.3 and 3.4, with the sequence component differentials in a single multifunction relay [6].

B. Phase Differential Protection Element (87T) With Variable Phase Compensation

The second special PST differential element to become available was based on the research presented in [8]. The concepts were developed and made available for use by the industry in recent years. This scheme is also equally applicable to both single-core and two-core PSTs. These differential elements are standard transformer differential elements with special compensation features to accommodate the continuously variable phase shift of a PST. A transformer differential element has several features not present in a bus or stator differential [6]. They must accommodate:

- Phase shift across the transformer introduced by different winding configurations, e.g., delta, wye, zig-zag—commonly referred to as phase compensation.
- Discontinuities in the zero-sequence network between each side of the transformer—commonly known as zero-sequence compensation.
- Different current magnitudes on each side of the transformer introduced by the transformation ratio—commonly referred to as magnitude or tap compensation.

Obviously, we would expect the special PST differential elements have a more sophisticated means of phase compensation and that is the case here. Phase compensation is often explained using (2).

$$\begin{bmatrix} Ia_{compensated} \\ Ib_{compensated} \\ Ic_{compensated} \end{bmatrix} = \left[\text{Compensation Matrix}\right] \bullet \begin{bmatrix} Ia \\ Ib \\ Ic \end{bmatrix} \qquad (2)$$

Compensated currents presented to the phase differential element on each side of the transformer are calculated by multiplying them by a 3 x 3 matrix called the compensation matrix [9]. Most transformer differential relays have a selection of fixed matrices with integer coefficients in each position.

For example, the compensation matrix for CTs that are connected in wye and connected to the differential element would be represented by the matrix shown in Fig. 6(a). The matrix shown in Fig. 6(b) represents the compensation matrix for CTs that are connected in delta with the A-Phase element receiving IA-IB, the B-Phase element receiving IB-IC, and the C-Phase element receiving IC-IA and compensation for the √3 magnitude increase. The delta matrix shown in Fig. 6(b) would compensate for a lagging 30 degrees phase shift relative to the reference terminal of the transformer. It also would remove zero-sequence current from the currents presented to the differential element.

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad \frac{1}{\sqrt{3}}\begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}$$

(a) (b)

Fig. 6. Example compensation matrices. (a) no angle compensation and without zero-sequence compensation, (b) 30-degree lag compensation with zero-sequence compensation.

The 87-PSTX relay uses generalized compensation matrices, as shown in Fig. 7. We can see that the matrix coefficients are a function of Θ, which is the phase angle that must be compensated.

The reader can use the $M(\Theta)$ matrix with Θ = 0° and find that it provides the same matrix as Fig. 6(a). Similarly, one can use the $M0(\Theta)$ matrix with Θ = 30° and find that it provides the same matrix as Fig. 6(b).

$$M(\theta) = \frac{1}{3} \bullet \begin{bmatrix} 1+2\bullet cos(\theta) & 1+2\bullet cos(\theta+120°) & 1+2\bullet cos(\theta-120°) \\ 1+2\bullet cos(\theta-120°) & 1+2\bullet cos(\theta) & 1+2\bullet cos(\theta+120°) \\ 1+2\bullet cos(\theta+120°) & 1+2\bullet cos(\theta-120°) & 1+2\bullet cos(\theta) \end{bmatrix} \qquad (a)$$

$$M0(\theta) = \frac{2}{3} \bullet \begin{bmatrix} cos(\theta) & cos(\theta+120°) & cos(\theta-120°) \\ cos(\theta-120°) & cos(\theta) & cos(\theta+120°) \\ cos(\theta+120°) & cos(\theta-120°) & cos(\theta) \end{bmatrix} \qquad (b)$$

Fig. 7. Generalized compensation matrices. (a) without zero-sequence removal, (b) with zero-sequence removal.

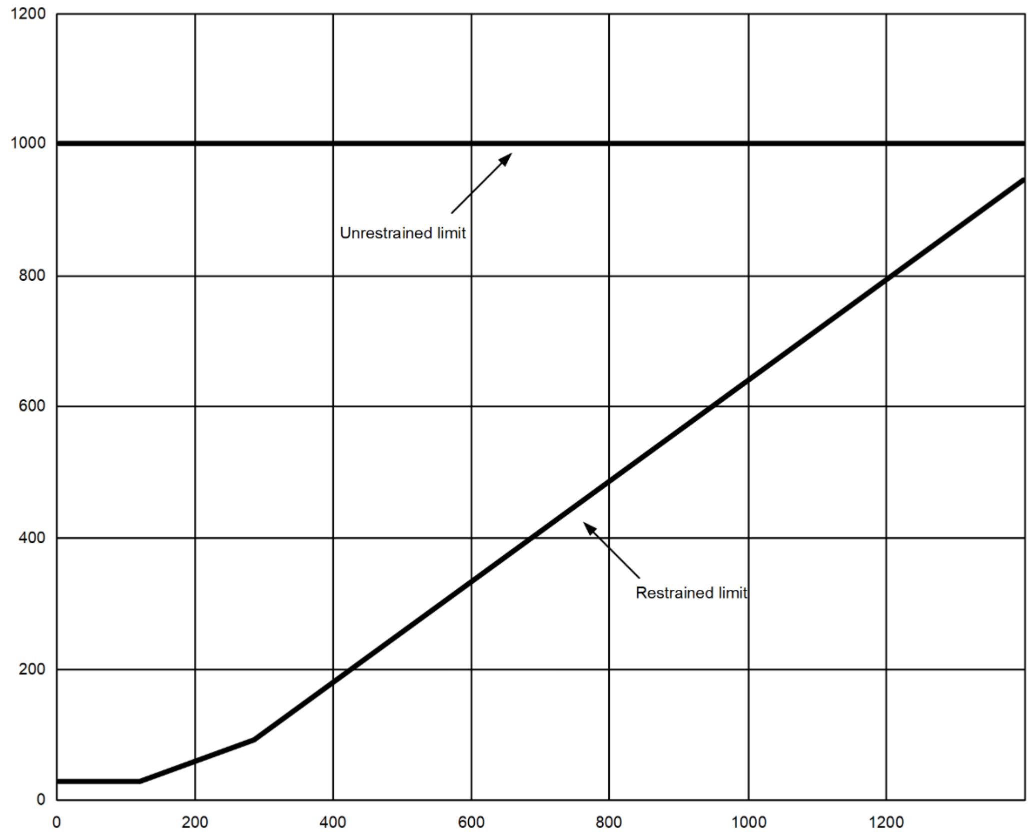

Fig. 8. Dual slope differential characteristic for 87T element in relay 87-PSTX.

Like the 87-1 and 87-2 elements previously described, the 87-PSTX relay uses voltage and current angle readings, along with a smoothing filter, to obtain Θ for use in the compensation matrices. The smoothing filter for these elements has a 0.5 second time constant (it takes three time constants to reach 95 percent of the final value). The compensated currents are used to develop operate and restraint signals, which are used with a dual slope characteristic, shown in Fig. 8, to determine if the transformer should be tripped. Because there is only one differential element per phase, this relay uses a much shorter time constant in the smoothing filter to obtain a valid angle for compensation upon start up.

The relay uses a logic switch to switch between sources of determining Θ. For example, the relay may start out using voltage if the source and load-side voltages are in the range of 70 to 120 percent of nominal. Once the source and load-side currents reach a magnitude in the range of 10 to 160 percent of nominal, the switch changes to using the current angle. If neither the voltage nor the current signals are in range, the logic switches to a user settable default value. We were concerned that this element could be vulnerable to misoperation in the case that load flow is low and the relay is in a loss-of-voltage alarm condition. Switching to an arbitrary value for Θ under such conditions would result in incorrect compensation for the PST position and the element could trip.

To mitigate the risk, we block the PST differential element (87T) in the 87-PSTX relay if both the current and voltage qualification conditions are deasserted. To mitigate the reduction in dependability, we implemented the 87P and 87S elements as overall zones in the 87-OX relay instead of using the approach in System Y of creating separate PST and bus subzones. The traditional PST differential elements are not dependent on VT signals for security.

C. Primary Winding Differential Protection Element (87P)

Primary winding protection is provided by 87P, a percentage-restrained differential protection element with the protection zone determined by CTs on the source side, load side, and exciter core primary winding, as shown in Fig. 2 and Fig. 3. The 87P elements are implemented in 87-OX and 87-PSTY relays. This protection works on the principle of Kirchoff's current law (KCL) and hence there is no requirement for angle compensation and harmonic restraint or blocking for inrush. See [1] and [3] for details on this protection.

D. Secondary Winding Differential Protection Element (87S)

Secondary winding protection is provided by 87S, a percentage-restrained differential protection element with the protection zone determined by CTs on the source side, load side, and exciter core secondary winding, as shown in Fig. 2 and Fig. 3. The 87S elements are implemented in 87-OX and 87-PSTY relays. This protection works on the principle of ampere-turn balance (ATB) around the magnetic circuit of the series core, which requires compensation settings for phase angle and magnitude according to the winding configuration of the series transformer [1] [3]. To set the magnitude compensation for this element, the ratio of the series transformer must be known. This information is typically not shown on the transformer nameplate and thus must be obtained from the transformer design reports. Equation (3) shows the equation to calculate the current in the secondary winding of the series transformer. This is the magnitude of the current inside the delta.

$$I_{DELTA}=\frac{N}{2}I_{SOURCE}+\frac{N}{2}I_{LOAD} \quad (3)$$

where:

I_{DELTA} is the phase current through the series core delta winding.

I_{SOURCE} is the phase current through source side.

I_{LOAD} is the phase current through load side.

N is the series core turns ratio.

Current inside the delta winding is not directly measured. Instead, current in the secondary windings of the excitation core (regulating windings) is used. Because the secondary winding of the excitation core is connected to provide a quadrature voltage to the secondary of the series transformer, the currents in the source and load terminal CTs must be compensated by plus and minus 90 degrees. The source and load currents must also include zero-sequence compensation because the series transformer passes zero-sequence currents through its primary windings, whereas the secondary winding currents do not see this zero-sequence current because of the delta connection. Because the series transformer secondary current is measured in the leads connecting the delta winding to the phase CTs above the star-point in the regulating winding, a √3 factor must be included in calculating the magnitude compensation factors [1] [4].

E. Transformer Earth Fault Protection Elements (REF and 64T)

Restricted earth fault (REF) protection for the primary winding provides protection for single-line-to-ground (SLG) faults and uses the CTs on the source side, load side, and neutral bushing (S0), as shown in Fig. 2. The REF element is implemented in the 87-PSTX relay only. A separate REF scheme is not necessary in a PST application that uses 87P protection because the 87P element uses the current at the neutral end of the winding. This gives it the same sensitivity advantage that an REF element enjoys for faults near the neutral of the winding. However, because the 87-PSTX relay does not have the 87P element, it was decided to implement REF so that the 87-PSTX relay has elements to detect all types of internal faults to the PST.

Ground fault overcurrent protection on the secondary and tertiary windings is provided using the CT on the neutral bushings, as shown in Fig. 2 and Fig. 3. The secondary winding of the series core is delta connected, so there is no normal path for zero-sequence current to flow. Similarly, the delta tertiary winding is corner grounded. Any current flowing in these bushings indicates a winding-to-ground fault so the elements can be set sensitively with little or no delay.

IV. System Modelling and Validation

To validate the performance of the protection system, we want to perform hardware-in-the-loop testing using an RTDS Simulator. To do this we need to accurately model the PST characteristics as well as the surrounding transmission network and instrumentation transformers.

We use the PST design review and test report to build our model. These documents include series and exciting core characteristics such as the MVA rating, winding voltages, impedance, number of taps, the angle design value, measured angles, and excitation characteristics.

The modelling process starts with the creation of a simplified model with a single PST and equivalent sources on the source and load side of the PST. This allows us to enter the PST parameters, test them, observe the behaviour, and make any adjustments required. Validation of the model is done by simulating the tests performed in the factory to obtain the impedances. For example, we apply a three-phase short-circuit on one side of the PST and then adjust the voltage to measure the impedance. As seen in Fig. 9, this project's PST impedance on neutral is 49 ohms for both the calculated and measured and is 62.62 ohms at full advanced and retard. The model was limited to assuming a linear variation in impedance with tap position. The result was that there was a slight difference in impedance of the model versus the PST design report as the tap position moved off neutral but did not deviate past a 2.5 ohms difference.

Similarly, we open circuit one side of the PST and measure the angle difference between the source and load side. This allows us to verify the winding voltages and tap positions are correct as we step along the tap positions. The calculated and measured angle difference match quite well, as shown in Fig. 10, with an error of less than one degree, except for at the extreme tap positions, which was just over two degrees. This was due to being unable to place the extreme tap position at the end of the windings. The tap changer in the transformer model was limited to only operating between 1 and 99 percent of the winding.

Once we are confident that the PST is modelled as required, it is then placed in the main model of the transmission system and duplicated to have all five PSTs in parallel.

Balanced and unbalanced faults were simulated at different locations, as shown in Fig. 11. Fault locations have been selected to demonstrate correct performance of the integrated protection system for PST and buswork under various internal and external faults. Simulation was performed for various levels and direction of power flow. Transformer energization was also simulated to demonstrate protection system security under inrush conditions. Fault locations 12 and 13 are out-of-zone faults and fault locations 14 and 15 are remote line faults to verify correct operation of external fault detectors and stability of overall differential protection (no operation). Fault locations 1 and 4 are to verify stability of the PST differential protection and correct operation of external fault detection logic. All other fault locations are internal faults and expected operation of the protection system for internal PST fault conditions is tabulated in Table I. Tests were also performed with of loss-of-voltage signals to the relays to understand the reliability of the protection for this condition.

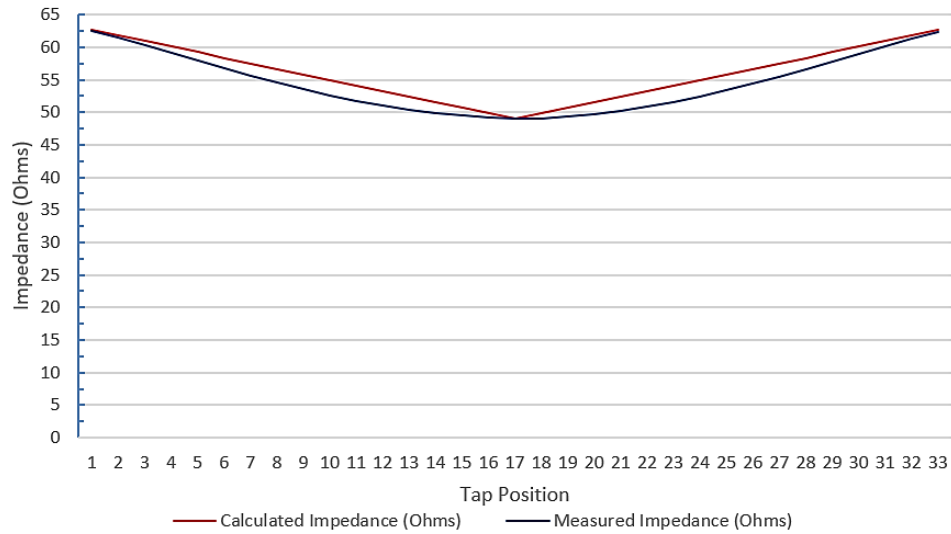

Fig. 9. PST impedance comparison.

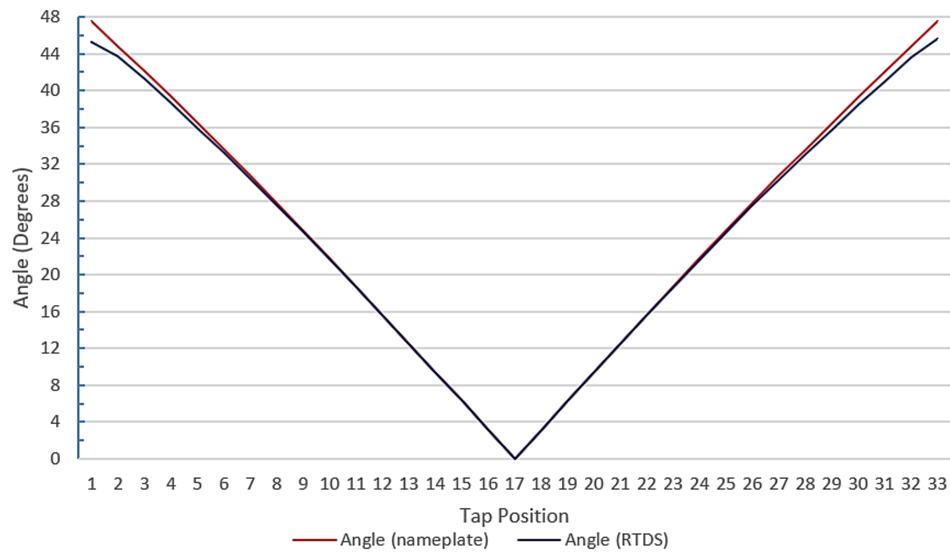

Fig. 10. PST angle comparison.

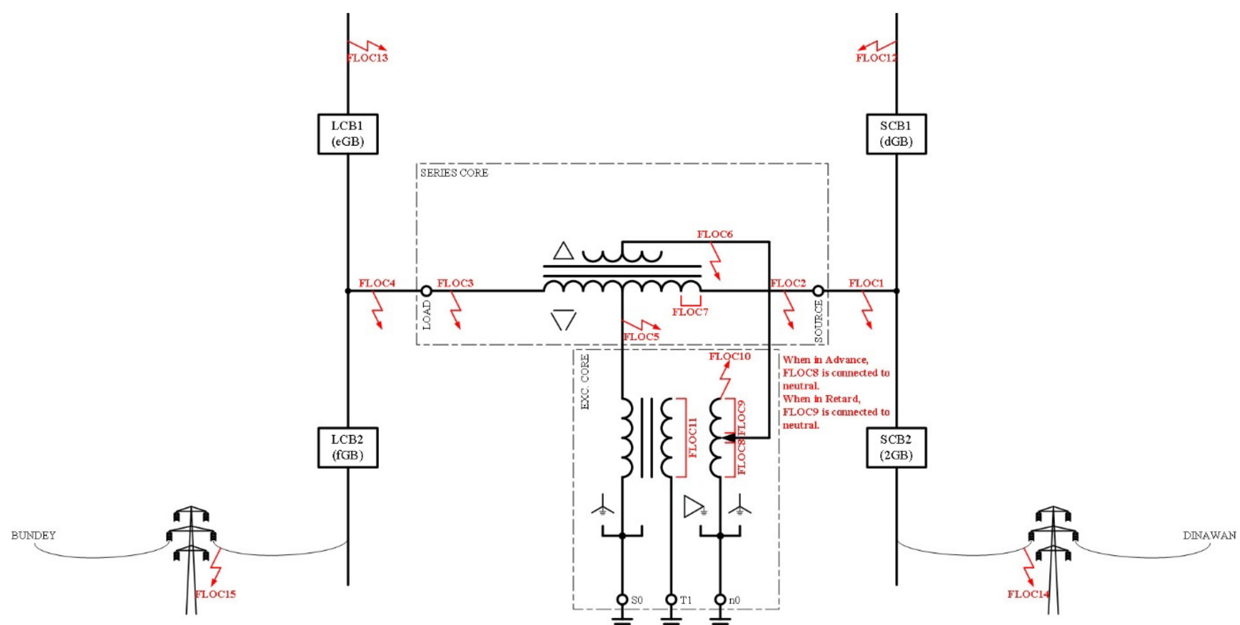

Fig. 11. PST fault simulations.

It should be noted that for certain fault types, like turn-to-turn faults at location 7 or faults within the series core delta winding at location 6, the 87-1 and 87-2 protection elements in the System Y relay and 87T differential protection in the System X relay have been shown as "protection element may operate" in Table I. This is because the sensitivity of the protection is dependent on the tap position, number of turns that are faulted for a turn-to-turn fault, or fault location within the series delta winding. Tests were performed with varying number of turns for fault location 7, and the protection successfully responded up to 35 percent of faulted turns. For the fault on the series delta winding, both System X and Y protection relays correctly picked up and operated.

The sensitivity of the protection is also validated while responding to faults within the tertiary winding, i.e., fault location 11. Both the 87T element in System X and the 87-1 and 87-2 protection elements in System Y correctly operated for this fault. Additional tests were conducted to determine the limits of sensitivity by adding fault resistance. The 87T protection system was set sensitive up to a fault resistance of 8 Ω, whereas the sequence component differential protection was sensitive up to 4 Ω fault resistance. As faults with such fault resistances are rare occurrences, sensitivity of the protection system based on the selected settings was deemed satisfactory.

Faults were also simulated on different points of the voltage wave (0, 30, 60, and 90 degrees) and all combinations of phase-to-phase, phase-to-ground, phase-to-phase-to-ground, and three-phase faults were considered. These simulations were repeated with PST in advanced, retard, and neutral tap positions. One such example with operating times of different relays with PST in retard tap position is shown in Fig. 12 for fault location 5. This, being an internal fault, was picked up by both transformer protection relays. The relay trip time of both System X and System Y protection relays was comparable with System Y slightly faster for almost all cases.

TABLE I OPERATION OF PROTECTION RELAYS

Fault Location	**System X Protection**		**System Y Protection**	
	Operated	**Not Operated**	**Operated**	**Not Operated**
FLOC 1	87P, 87S	87T, REF, 64T(I2N), 64T(I3N)	87BY-S	87P, 87S, 87-1/2, 64T(Y1), 64T(Y2), 87BY-L
FLOC 2	87P, 87S, REF*	87T, 64T(I2N), 64T(I3N)	87P, 87S, 87-1/2	64T(Y1), 64T(Y2), 87BY-S, 87BY-L
FLOC 3	87P, 87S, REF*	87T, 64T(I2N), 64T(I3N)	87P, 87S, 87-1/2	64T(Y1), 64T(Y2), 87BY-S, 87BY-L
FLOC 4	87P, 87S	87T, REF, 64T(I2N), 64T(I3N)	87BY-L	87P, 87S, 87-1/2, 64T(Y1), 64T(Y2), 87BY-S
FLOC 5	87P, 87T, REF*	87S, 64T(I2N), 64T(I3N)	87P, 87-1/2	87S, 64T(Y1), 64T(Y2), 87BY-S, 87BY-L
FLOC 6	87S, 87T, 64T(I3N)*	87P, 64T(I2N)	87S, 87-1/2†, 64T(Y2)*	87P, 64T(Y1), 87BY-S, 87BY-L
FLOC 7	87S, 87T†	87P, REF, 64T(I2N), 64T(I3N)	87S, 87-1/2†	87P, 64T(Y1), 64T(Y2), 87BY-S, 87BY-L
FLOC 8	87T	87P, 87S, REF, 64T(I2N), 64T(I3N)	87-1/2	87P, 87S, 64T(Y1), 64T(Y2), 87BY-S, 87BY-L
FLOC 9	87T	87P, 87S, REF, 64T(I2N), 64T(I3N)	87-1/2	87P, 87S, 64T(Y1), 64T(Y2), 87BY-S, 87BY-L
FLOC10	87S, 87T, 64T(I3N)*	87P, REF, 64T(I2N)	87-1/2, 87S, 64T(Y2)*	87P, 64T(Y1), 87BY-S, 87BY-L
FLOC11	87T	87P, 87S, REF, 64T(I2N), 64T(I3N)	87-1/2	87P, 87S, 64T(Y1), 64T(Y2), 87BY-S, 87BY-L
FLOC12, FLOC13, FLOC14, FLOC15	–		87P, 87S, 87T, REF, 64T(I2N), 64T(I3N)	–

* Protection operates for earth fault.
† Protection element may operate.

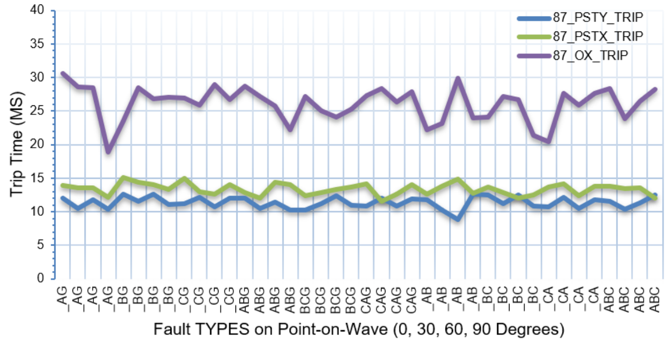

Fig. 12. Consolidated trip times for System X and System Y relays at fault location 5 for different types for point-on-wave (0, 30, 60, and 90 degrees).

V. Summary and Conclusion

This paper presents details of a comprehensive state-of-the-art protection system for a two-core symmetrical phase shifting transformer. Protection functions in the selected relays complement each other and provide protection for all types of faults. The efficacy of the developed solution was successfully demonstrated on an RTDS test platform by simulating different external and internal faults. Protection system sensitivity was demonstrated with at least one protection function responding to every fault, and protection system security was highlighted with protection restraining for external faults and inrush conditions. The dependability of the protection system was demonstrated by the difficult-to-detect faults like turn-to-turn faults or faults within the embedded tertiary winding; these faults were correctly picked up by the protection system.

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VII. Biographies

Michael J. Thompson received his B.S., magna cum laude, from Bradley University in the USA in 1981 and an M.B.A. from Eastern Illinois University in the USA in 1991. Upon graduating, he served nearly 15 years at Central Illinois Public Service (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. He is an IEEE Fellow, past Chair of the IEEE PES Power System Relaying and Control Committee, past Chair of the Substation Protection Subcommittee of the PSRC, and 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.

Gurinder Saluja holds a BE in Electrical Engineering from Delhi University and a Master of Technology in Power System from the Indian Institute of Technology, Delhi, India. He is a member of CIGRE Australia B5 panel and has extensive expertise in the generation and transmission of power systems. At present, he serves as the Secondary Design Manager at Transgrid, Australia, overseeing the design and standards for Protection, Control, and Communication systems within the organization.

Ashish Ahuja received his B.E, first class with distinction, from Delhi College of Engineering, India in 2003 and MS from Kansas State University, USA in 2006. Upon graduating he joined Black & Veatch in Kansas City, USA. Prior to joining Schweitzer Engineering Laboratories in 2020, he worked at Siemens Ltd in Gurgaon, India. He is working as a senior engineer in SEL Engineering Services in Melbourne, Australia.

Chido Chandakabata received his B.Sc. with honours in Electrical Engineering from the University of Zimbabwe in 2004. He started his career as a Graduate Engineer at Zimbabwe Electricity Supply Authority (ZESA), later moving to the role of Protection Design Engineer. Prior to joining Schweitzer Engineering Laboratories (SEL), he worked for Schneider Electric where he was involved in delivering key projects across Australia and the Asia-Pacific region. He currently holds the position of Senior Engineering Manager. His current research interests are in advanced synchrophasor applications, high-speed protection and control systems and digital secondary systems design and integration.

Jordan A. Bell received his BSEE from Washington State University in 2006. He joined Schweitzer Engineering Laboratories, Inc. (SEL) in 2008 as a protection engineer in the SEL Engineering Services, Inc. (SEL ES) group. He is currently a senior engineer working on event report analysis, relay settings and coordination, fault studies, and model power system testing with a real-time digital simulator. He is a registered professional engineer in the state of Washington and a member of IEEE.

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