APPLICATION OF STANDARD 87T DIFFERENTIAL PROTECTION ON PHASE-SHIFTING TRANSFORMERS

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Abstract

This paper describes a universal, current-based, differential protection for any phase-shifting transformer (PST) – or phase-angle regulating transformer (PAR) – having variable phase-angle shift and variable turns ratio. The use of standard transformer differential protection for such applications was considered impossible in the currently applied protective relaying standards and practices. This universal differential protection method only requires stand-alone current and voltage transformers on the two sides of the protected phase-shifting transformer. Thus, any buried current transformers within the tank of the protected transformer are not required regardless of the transformer construction details and internal on-load tap-changer configurations. At the same time, the actual position of any built-in on-load tap-changer is not required as an input into the differential protection. The differential protection is self-adaptive. It automatically learns and adjusts to the actual transformation ratio and phase-angle shift across the protected power transformer. Thus, any phase-shifting transformer regardless of its construction principles (symmetrical or asymmetrical) and design details (single-core, double-core or even of any complex design) can be entirely protected by using such differential protection.

Introduction

The common characteristic for all types of three-phase power transformers is that they introduce a phase-angle shift Θ between the no-load voltages and between the through-going currents from the two sides of the transformer. The only difference between standard power transformers, special converter transformers and phase-shifting power transformers (PSTs) is that:

1) Standard three-phase power transformers introduce a fixed phase-angle shift Θ of n*30° (n=0, 1, 2, …, 11) between their terminal no-load voltages where n is defined by the transformer vector group at manufacturing;
2) Special converter transformers introduce a fixed phase-angle shift Θ different from 30° or a multiple of 30° between their terminal no-load voltages (for example 22.5°); and
3) Phase-shifting transformers introduce a variable phase-angle shift Θ between their terminal no-load voltages (for example ±24° in total, having ±32 OLTC steps of approximately 0.75° per each step).

For more info about such power transformer classification see reference [1].

As shown in reference [1], strict rules only exist for phase-angle shift between positive-, negative- and zero-sequence components from the two sides of any three-phase power transformer, but not for individual phase quantities. By using these properties of the sequence components, it is possible to make a phase segregated differential protection for phase-shifting transformers just by measuring the currents and voltages on the two sides of the protected PST.

This is a truly adaptive protection as it “learns” and adjusts to the actual PST ratio and phase-angle shift on-line (automatic on-line compensation for actual transformation ratio and for actual phase-angle shift across the protected PST) without reading of actual OLTC position(s).

By doing so, a simple but effective differential protection for any PST can be achieved that protects the entire PST, and is very similar to already well-established numerical differential protection for standard two-winding power transformers (standard 87T function), as shown in Figure 1. By using this new functionality, the differential protection for any arbitrary PST, regardless of its construction details and number of built-in tap-changers, will be ideally balanced for all symmetrical and non-symmetrical through-load conditions as well as for all external faults. At the same time the position of any built-in on-load tap-changer is not required. However, to be able to balance the differential protection during light load conditions, a single-phase or three-phase VT input from the two PST sides is also required. Minimum pickup for such differential protection is typically set to 20% of the PST rating. This 87T-PST function makes the application of differential protection on any PST transformer very easy. It eliminates the need for any buried CTs within the PST tank as, for example, required by presently used protection schemes [2,3].

Installation of such differential protection on a 1200MVA; 50Hz; 400kV; ±24°; symmetrical double-core PST in Germany, and a 300MVA; 60Hz; 138kV; ±25°; symmetrical double-core PST in the USA will be presented in the paper. Finally, this paper shall also provide better understanding of differential protection principles for standard power transformers and PSTs to the wider protective relaying community.

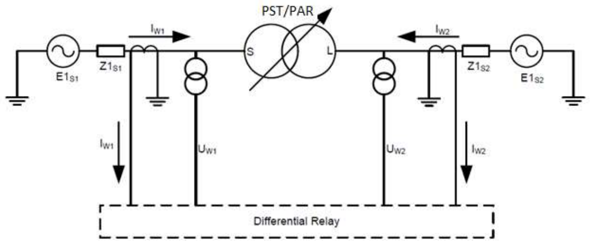


Figure 1: Differential protection arrangement for arbitrary Phase-Shifting Transformer

Used Methodology for the PST Differential Protection

Even in a healthy power transformer, the primary currents from two sides are generally not equal. This is due to the transformation ratio (i.e. no-load voltage ratio) and the phase-angle shift across the protected transformer. Therefore, the differential protection must first correlate the three-phase current sets from the two sides of the protected power transformer to each other before any calculation of the differential currents is performed.

Calculation of the fundamental frequency differential currents

For standard power transformers, the transformation ratio and the phase-angle shift are determined by the transformer design. These parameters are typically then entered as setting parameters into the differential protection function within the numerical IED for standard power transformers. However, for a PST, both the transformation ratio and the phase-angle shift may vary considerably during different operating conditions [1,4,5,7].

These variations are typically caused by using one or more on-load tap-changers (OLTCs) which are built-in inside the protected PST. Therefore, it is much more difficult to make a differential function which can accurately compensate for such variations. The new differential protection 87T-PST utilizes the measured currents and voltages from the two sides of the PST to estimate on-line these parameters, that is, transformation ratio and phase-angle shift. Note that the positions of any built-in OLTCs are not required for this estimation. By using current and voltage signals only, the function becomes self-adaptive and learns on-line the actual transformation ratio and phase-angle shift across the protected PST.

Before calculating any differential current, the power transformer actual phase shift and actual transformation ratio must be accounted for. Note that the first winding (W1 or S-side in case of a PST) is always taken as the reference side for the current magnitude compensation (i.e. the W2-side currents, or L-side in case of a PST, are transferred to W1-side using the transformation ratio) and for the phase-angle shift (i.e. the W2-side currents, or L-side in case of a PST, are rotated towards the W1-side by an angle θ). The following phasor based matrix equation is then used [1,7,10].

$$\begin{bmatrix} \overrightarrow{ID}_{L1} \\ \overrightarrow{ID}_{L2} \\ \overrightarrow{ID}_{L3} \end{bmatrix} = M_{W1}(0^{\circ}) * \begin{bmatrix} \overrightarrow{IL1}_{W1} \\ \overrightarrow{IL2}_{W1} \\ \overrightarrow{IL3}_{W1} \end{bmatrix} + Ratio * M_{W2}(\theta) * \begin{bmatrix} \overrightarrow{IL1}_{W2} \\ \overrightarrow{IL2}_{W2} \\ \overrightarrow{IL3}_{W2} \end{bmatrix} \quad (1)$$

where,

1) ID_{L1}, ID_{L2} and ID_{L3} are the three differential current phasors (in W1-side primary amperes) (differential current values in per-unit are obtained by dividing them with the set Base Current Value for W1)
2) $IL1_{W1}$, $IL2_{W1}$ and $IL3_{W1}$ are the W1-side current phasors (in primary amperes)
3) $IL1_{W2}$, $IL2_{W2}$ and $IL3_{W2}$ are the W2-side current phasors (in primary amperes)
4) M_{W1} and M_{W2} are three-by-three matrices with numerical coefficients as given below
5) *Ratio* is the actual transformation ratio between the two sides of the PST
6) θ is the actual phase-angle shift across the PST in degrees

The matrix coefficients are calculated on-line within the IED by using Equation (2), when the zero-sequence currents shall be removed [1,7,10].

$$M(\theta) = \frac{2}{3} * \begin{bmatrix} \cos(\theta) & \cos(\theta + 120^{\circ}) & \cos(\theta - 120^{\circ}) \\ \cos(\theta - 120^{\circ}) & \cos(\theta) & \cos(\theta + 120^{\circ}) \\ \cos(\theta + 120^{\circ}) & \cos(\theta - 120^{\circ}) & \cos(\theta) \end{bmatrix} \quad (2)$$

When the zero-sequence currents shall not be removed then a value of 1/3 shall be added to every matrix coefficient given in Equation (2). For more details see references [1,7,10].

Note that the bias current will be calculated in exactly the same way as for standard 87T differential protection. For more information see references [1,9].

Optional elimination of zero-sequence currents

To avoid unwanted trips for external earth-faults (i.e. external ground-faults), it might be necessary to subtract the zero-sequence current component from the fundamental frequency differential currents. The zero-sequence currents can be explicitly eliminated from the differential and bias current calculation by dedicated settings which are available for each of the two sides separately. The zero-sequence elimination is achieved by selecting the correct coefficient values for the two M matrices, as already described in a previous section of the paper. The following are three typical situations when zero-sequence current shall be removed on both PST sides:

1) If a protected PST incorporates a closed, tertiary, delta-winding.
2) If a protected PST has a "phantom tertiary effect" (3-legged core construction type).
3) If a protected PST is of an asymmetrical design.

Estimation of transformation ratio and phase-angle shift of the PST

The new differential protection continuously estimates on-line the actual transformation ratio and phase-angle shift across the protected PST by using positive-sequence currents and user selected voltages from the two sides of the protected transformer. The complex current ratio (CCR) is calculated all the time using Equation (3):

$$\overrightarrow{CCR} = \frac{-\overrightarrow{I_{W2}}}{\overrightarrow{I_{W1}}} = \frac{\left|\overrightarrow{I_{W2}}\right|}{\left|\overrightarrow{I_{W1}}\right|} * e^{j*\left(\measuredangle\overrightarrow{I_{W2}}+180^\circ-\measuredangle\overrightarrow{I_{W1}}\right)} = \frac{1}{I\_Ratio} * e^{j*I\_Angle} \tag{3}$$

where I_{W1} and I_{W2} are the positive-sequence current phasors from the two transformer sides and $j=\sqrt{-1}$.

Note that the W2-side positive-sequence current phasor shall be taken with a negative sign (i.e. turned around by 180°) due to the internally selected current directions which are shown in Figure 1. Actual phase rotation (i.e. phase sequence) in the protected power system (i.e. L1-L2-L3 or L3-L2-L1) can be entered as a setting and taken into account for sequence calculations.

The current-based transformation ratio (*I_Ratio*) can be now determined as the reciprocal value of the CCR magnitude and the current-based phase-angle shift (*I_Angle*) as the CCR angle value.

The complex voltage ratio (CVR) is calculated all the time by the differential protection using the following Equation (4):

$$\overrightarrow{CVR} = \frac{\overrightarrow{U_{W2}}}{\overrightarrow{U_{W1}}} = \frac{\left|\overrightarrow{U_{W2}}\right|}{\left|\overrightarrow{U_{W1}}\right|} * e^{j*\left(\measuredangle\overrightarrow{U_{W2}}-\measuredangle\overrightarrow{U_{W1}}\right)} = U\_Ratio * e^{j*U\_Angle} \tag{4}$$

where U_{W1} and U_{W2} are the two selected voltage phasors (one from each side). The differential protection will automatically compensate for the $\sqrt{3}$ factor, which may be required depending on whether phase-to-earth or phase-to-phase voltages from the two sides are used. The protection as well automatically compensates for inherent phase-angle shift between the selected phasors if voltages from different phases are selected (for example, U_{L1} from W1-side and U_{L3} from W2-side). For simplicity, such compensation factors are not shown in Equation (4). Now, the voltage-based transformation ratio (*U_Ratio*) can be determined as the CVR magnitude and the voltage-based phase-angle shift (*U_Angle*) as the CVR angle value.

When the W2 phasor is leading the W1 phasor, the angle will have positive sign and consequently, when the W2 phasor is lagging the W1 phasor, the angle will have negative sign. These rules are applicable for either the current- or voltage-based angles given above and correspond to the IEC/IEEE standard definition for phase-shifting transformers [5]. Thus, the I_Angle when the PST is loaded and the U_Angle when the PST is not loaded, will be positive for advanced mode of operation and negative for retard mode of operation. Therefore, they typically shall have the same value and sign as stated on the PST rating plate for individual OLTC positions [5]. However, such convention is only valid when positive-sequence voltages and currents, which is with phase rotation L1-L2-L3, are connected to the protected PST.

Once *I_Ratio*, *I_Angle*, *U_Ratio* and *U_Angle* are known, logic determines the actual used transformation ratio and phase-angle shift across the protected PST:

1) If any of the two positive-sequence current magnitudes is greater than 160% of the PST rated current, the old ratio and phase-angle are selected (that is, presently used values are frozen).
2) If both positive-sequence current magnitudes are in between 10% and 160% of the PST rated current, the values obtained from the current calculation are used.
3) If any of the two positive-sequence current magnitudes is less than 10% of the PST rated current, the values obtained from the voltage measurement shall be used if the voltages have appropriate magnitudes.

4) If any of the two voltage phasor magnitudes is greater than 120%, the old ratio and phase-angle are selected (that is, presently used values are frozen).
5) If both voltage phasor magnitudes are in between 70% and 120% of rated, the values obtained from the voltage calculation shall be used. Note that the automatic compensation for the $\sqrt{3}$ difference between phase-to-phase and phase-to-earth voltages is performed within the function.
6) If any of the two voltage phasor magnitudes is less than 70%, the default values determined by separate parameter settings are used.

Note also that the variation range for used turns ratio (DIFRATIO) and phase-angle shift (DIFANGLE) within the differential protection can be limited by end-user settings to ensure that the limits posed by PST construction details are never exceeded under any circumstances.

Once the to be used values for the transformation ratio (DIFRATIO) and phase-angle shift (DIFANGLE) are selected, they are further low-pass filtered. This filter is quite slow and has a time constant of 500ms. Theoretically, approximately five time constants must elapse before the filter output values will reach correct values after a step change on the filter input. On the other side, a typical modern OLTC operation can take around three to five seconds. Consequently, such time delay does not cause any practical problems.

However, when the whole differential protection is blocked via dedicated input, the filter time constant is reduced to 8ms. By doing this, the function is practically forced to learn the actual transformation ratio and phase-angle shift values very quickly. Such filter time constant reduction feature ensures that the differential protection behaves correctly during the following circumstances:

1) When the protection IED power supply is interrupted and then re-applied while the protected transformer is in-service
2) Any setting parameter within the IED is changed while the protected transformer is in-service
3) The differential protection IED shall be tested on a real-time digital simulator
4) The differential protection IED shall be tested by playing back captured recording files from an existing PST installation

For the third and fourth case, the binary input to block the function shall be pulsed for 50ms at the beginning of the injection (that is, during the pre-fault stage) to quickly learn the actual transformation ratio and phase-angle shift just before either the internal or the external fault conditions are injected into the tested IED. The only pre-request is that the pre-fault currents and voltages last longer than this blocking time (for example, longer than the above proposed 50ms).

There is also a binary input to force the use of default values, which are determined by setting parameters. There is also a further binary input to unconditionally force the use of the old values (values are frozen) for the transformation ratio and the phase-angle shift inputs into the low-pass filter. This is for example required during injection testing of the operating characteristic of the differential protection for a specific value of the transformation ratio and phase-angle shift. This will prevent the IED from compensating turns ratio and angle shift by using the injected currents during secondary testing.

After the low-pass filter the following two quantities are used in Equation (1):

1) DIFRATIO is used as Ratio in Equation (1)
2) DIFANGLE is used as the angle θ in Equation (1). Its value is multiplied by -1 due to different angle direction convention used for power transformers and inside the IED (i.e. clockwise for power transformers and anticlockwise for IEDs)

Calculation of the negative-sequence differential current

The negative-sequence based differential current is also calculated by using the following phasor equation:

$$\overrightarrow{ID_{NS}} = \overrightarrow{INS_{W1}} + \overrightarrow{INS_{W2}} * Ratio * e^{-j*\theta} \quad (5)$$

where ID_{NS} is the negative-sequence differential current phasor, and INS_{W1} and INS_{W2} are the negative-sequence current phasors from W1- and W2-sides respectively. Based on Equation (5) the following two features can be included:

1) Internal/external fault discriminator which helps to speed-up the differential protection operation in case of an internal fault by allowing by-pass of 2nd and 5th harmonic blocking criteria
2) Sensitive turn-to-turn fault protection which is capable to detect low-level internal faults, such as winding turn-to-turn faults with relatively small-time delay

Such negative-sequence based logic has been successfully used by traditional 87T transformer differential protection for quite some time, as described in references [6,9].

Instantaneous differential currents

The instantaneous differential current waveforms are also calculated by using Equation (1). Exactly the same matrix equation is used, but only the current phasors from the two sides are replaced by the raw current samples. The three instantaneous differential current waveforms are then used to check for blocking criteria such as 2nd harmonic blocking, 5th harmonic blocking and waveform blocking [1,7,9,10] which are required to restrain operation when the magnetic core(s) within the protected PST go into saturation, for example when the protected PST is energised.

What to do for 1½ breaker switchgear arrangement?

In some countries two breakers may be used on one or even both sides of the protected PST. For such switchgear arrangement the differential protection setup as shown in Figure 2 would be the best. The transformer bushing CTs which can be sized to the PST phase current rating shall be used for 87T-PST differential protection. This will ensure the most sensitive differential protection for the protected PST. At the same time these bushing CTs will practically not increase the investment cost at all.

The CTs associated with the circuit breakers, which typically have much higher primary current ratings than the PST itself, shall be used for 87B differential protection. Modern low-impedance busbar protection IEDs (87B) do allow to mix CTs of different primary ratings within the same protection zone and do have at least two differential zones available within a single IED.

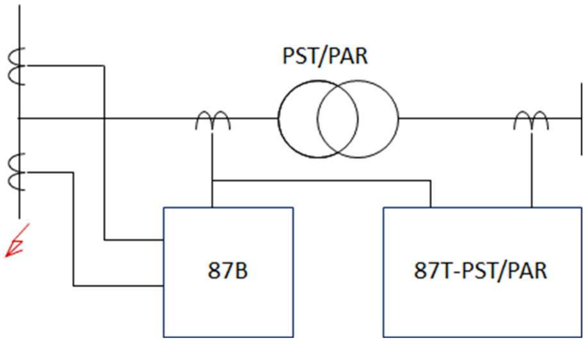


Figure 2: Proposed Differential Protection Arrangement for 1½ Breaker Scheme

Such protection arrangement will also provide very clear indication of the actual fault location. A similar setup shall be used when a 1½ breaker arrangement is used on both sides. A single two-zone 87B IED is able to handle both T-zones (3 CT inputs for T-zone on the S-side, and 3 CT inputs for the T-zone on the L-side of the PST).

Testing and Experience of new PST differential protection by TenneT

When TenneT was introduced to this new possibility for the PST protection, they found it to be quite interesting and they decided to put it through a specific test schedule before being approved to be used in their network. Different testing steps used by TenneT are described in the following sections.

Secondary injection testing by a test set

First the PST differential protection was completely tested by their standard test equipment in order to verify its basic features such as, for example: operating characteristic, operate time, 2nd and 5th harmonic blocking, negative-sequence based differential protection feature, etc. All these various tests were successfully completed.

Secondary injection of simulated external and internal fault conditions

The used test set software package also offers the possibility to simulate the power system under different operating conditions. This feature was used to simulate various operating conditions of the PST. The obtained current and voltage waveform signals were then injected into the differential protection. All these various tests were successfully completed, and the differential protection always behaved as expected.

Pilot installation of the differential protection

After that a pilot installation for the PST differential protection was arranged. It was installed on an existing dual-core, symmetrical PST having the following rated data: 1200MVA; 400/400kV; 50Hz; ±24°. This PST has 32 OLTC positions in advance and 32 OLTC positions in the retard direction. Due to large number of taps a separate advance-retard switch is also integrated within this PST. The excitation transformer does not have a permanently closed, tertiary delta-connected winding for this particular PST.

TenneT tries to avoid long copper cabling between the location of the protection relay and the primary assets like the circuit breaker, and current and voltage transformers. For such long distances of up to several hundreds of meters, a higher cable cross section would be needed. Even then, some issues can arise such as, for example, no reaction of a DC MCB associated with the tripping circuit to the breaker in case of a short circuit in the cable. Therefore, TenneT decided to locate the differential protection close to the S-side breaker and hard-wire the CT and VT signals from that PST side to the differential relay. At the same time, a separate Merging Unit (MU) was located close to the L-side breaker. Both CT and VT signals from the L-side were hard wired to this MU. Then the IEC61850-9-2 stream, containing both voltage and current signals, was connected to the differential protection via a dedicated fibre optic cable. This pilot installation set-up is shown in Figure 3.

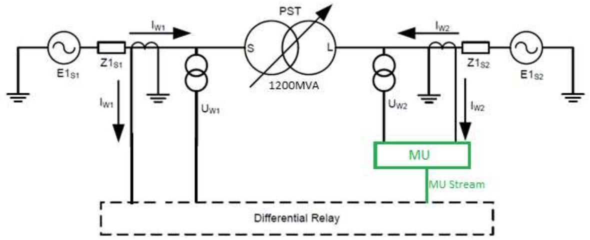


Figure 3: Simplified arrangement of the Pilot Installation

This pilot installation has been in full operation since March 2021. Since then, the PST was in operation at various loads and various OLTC positions. Even different positions of the advance-retard switch were used due to different operating conditions in the surrounding power system. Also, several primary faults in the PST vicinity have happened during this time. Despite all that the PST differential protection has remained fully stable.

The intention is to even send the trip command to the L-side breaker via this fibre optic cable using a GOOSE message between the IED and the MU in future commercial installations. Such digital solution also avoids mixing of the DC circuits between the two switchyards. Additionally, several hundreds of meters of copper cabling for CT, VT and tripping circuits are also completely avoided. Note that OLTC position has not been provided to the differential relay.

Protection Testing during PST FAT at the transformer factory

TenneT has several PSTs on order. Recently one of them had a FAT at the transformer factory. The PST differential protection scheme was shipped to the transformer factory, and it was connected to the PST during FAT. The same analogue input arrangements as in the pilot installation were used (see Figure 3). Many different DRs were captured during this FAT. For example, during short-circuit tests of the PST, all 65 tap positions were checked under load by tapping from position 32A to position 32R. Every tap transition was recorded by the differential protection. One such record is presented in Figure 4.

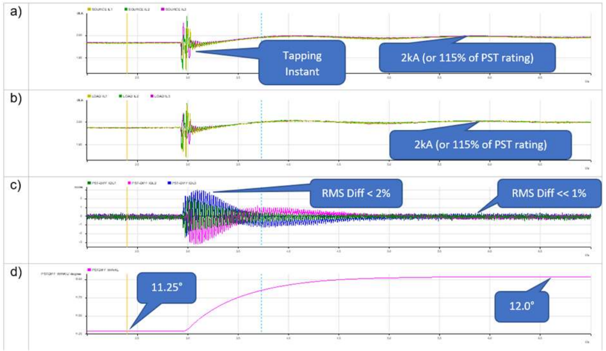


Figure 4: Recorded Tap Position Change under full load during PST FAT test

All presented signals come directly from the recordings captured by the target hardware [9] using twenty samples per fundamental power system cycle (i.e. 1kHz for 50Hz power system).

In Figure 4 the following signals are presented during a five second long time period:

a) The RMS values of the measured three-phase currents from the Source-side (i.e. W1) in primary kilo-amperes. Note that the used value range on the y-axis is quite small.
b) The RMS values of the measured three-phase currents from the Load-side (i.e. W2) in primary kilo-amperes. Note that the used value range on the y-axis is quite small.
c) The internally calculated three-phase instantaneous differential currents in percent of PST rating. Note that the used value range on the y-axis is quite small.
d) The internally calculated phase-angle shift across the PST in degrees (i.e. DIFANGLE value which is explained in a previous section of the paper).

As shown in Figure 4, during this FAT loading test the PST differential protection was capable to measure the phase-angle shift variation of 0.75 degrees. Relatively slow transition of the measured phase-angle shift between the two values is caused by the low-pass filtering, as explained in a previous section of the paper. The proper compensation resulted in differential currents much smaller than 1% during steady-state conditions when load currents were 115% of PST rating. During tapping the RMS differential current went transiently up to 2.0% which is practically a completely negligible value. This confirms that the differential function can properly measure the PST phase-angle shift and properly compensate for it based only on current measurements from the two PST sides.

Similar tapping tests were done during no-load conditions in the factory. These tests were used to verify that the differential protection can properly measure the PST phase-angle shift and properly compensate for it based only on voltage measurements from the two PST sides.

87T-PST protection primary testing for open-phase condition

TenneT has also arranged a primary testing of this pilot installation to verify 87T-PST function stability during an open-phase condition in the primary system. The PST was tapped to position 5-Advanced, which corresponds to phase-angle shift of 3.75° between S- and L-sides, and then a 40% load was arranged for the PST. At the same time, the PST was connected in series with a single 400kV OHL on the S-side. Then one pole (i.e. phase) of the OHL's circuit breaker was intentionally opened in order to verify the differential function stability. One record captured by the IED during such test is presented in Figure 5.

All presented signals come directly from the recording captured by the target hardware [9] using twenty samples per fundamental power system cycle (i.e. 1kHz for 50Hz power system).

In Figure 5 the following signals are presented during approximately a half second-long time period:

a) The RMS values of the measured three-phase currents from the Source-side (i.e. W1) in primary amperes. The PST load was around 700A (i.e. ~40%). Phase L1 on this side was opened during this test (its current magnitude dropped to zero during this test).

b) The RMS values of the measured three-phase currents from the Load-side (i.e. W2) in primary amperes. Note that phase L1 current magnitude on this side did not drop to zero but to approximately 46A during this test (i.e. $700A * sin(3.75^\circ) = 46A$).

c) The internally calculated three-phase instantaneous differential currents in percent of PST rating. Note that the used value range on the y-axis is quite small. The actual differential current values never exceeded 0.5% during the entire test.

d) The internally calculated phase-angle shift across the PST in degrees (i.e. DIFANGLE value which is explained in a previous section of the paper). Note that the used value range on the y-axis is extremely small. This angle was quite stable and had a value around 3.9° for the pre-test load conditions, and a value of 3.8° once phase L1 was opened on the S-side.

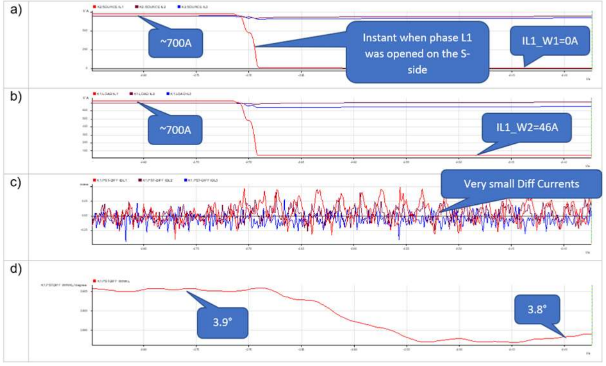


Figure 5: Recorded quantities during open-phase condition on S-side of the PST

As shown in Figure 5, during this open-phase test of the PST, the differential protection was fully stable and was not influenced at all on the S- or L-side of the PST by the open-phase condition.

It is also interesting to notice that there was no neutral current present in any of the two star-points during this entire test, which are available on this double-core PST, despite the fact that phase L1 was fully open on the S-side. This just confirms that a double-core PST without a closed tertiary delta-winding in the excitation transformer is NOT a zero-sequence current source despite direct (i.e. solid) connection to ground of both star points. For double-core PSTs having such design the zero-sequence current will simply be transferred from the S-side directly to the L-side for any external disturbances or asymmetrical operating conditions without any neutral current being present. However, the situation would be entirely different in case of a closed tertiary delta-winding being present in the excitation transformer.

Testing and Experience of new PST differential protection by ConEdison

Consolidated Edison Company of New York, Inc. (ConEdison) is one of the largest investor-owned utilities in the world. Founded in 1823 as the New York Gas Light Company, ConEdison provides electric, gas, and steam services to 9 million people over 604 square miles of New York City (NYC) and Westchester County in New York. Because of its dense service territory, ConEdison operates one of the most complex electric systems, with the use of PSTs to control the active power flow in their transmission system, while still providing extremely reliable electric services to customers in NYC.

One of their new 300MVA; 60Hz; 138kV; ±25°; symmetrical double-core PSTs was commissioned in 2022. This new PST is protected by two (2) different systems of comprehensive PST protective relays, and one (1) of them is a self-adaptive differential relay 87T-PST with integrated backup elements to protect the PST for any internal faults, and provides time delayed backup protection for external ground faults.

1) 87A (Self-Adaptive Phase Differential Element) – provides protection for all the windings within the PST for any fault.
2) 87Q (Negative Sequence Differential Element) – provides high-speed operation for internal faults, as well as sensitive turn-to-turn fault protection for the PST windings.
3) 51N (S0L0 Ground TOC Element) – provides ground fault protection for the primary windings of the PST, and provides backup protection for external ground faults.
4) 64T (J0 Ground TOC Element) – provides ground fault protection for the secondary windings of the PST.

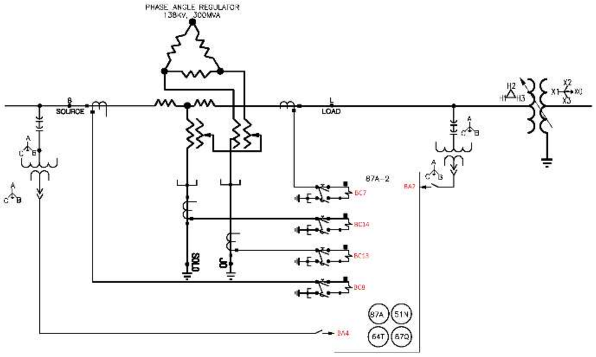


Figure 6: Single Line Diagram for PST/PAR Protection

Reference [11] describes how ConEdison designed a protection system to protect a PST where it was observed that many electromechanical relays would have been needed to provide the full PST protection for its primary and secondary windings for high- and low-level internal faults, and backup protection for external faults. In particular, Sudden Pressure and/or Buchholz relays would have had to be used to detect those low-level internal faults (i.e. winding turn-to-turn faults). These relays would have had to be designed with caution, because they are prone to mis-operate during high-level external faults. As a solution, these relays would have had to be supervised by an instantaneous phase overcurrent element (51FP) for security. With advanced digital relays with adaptive differential element (87A), a PST can be fully protected, including for those low-level internal faults.

Figure 7 & Figure 8 below are the COMTRADE screenshots that show that the Self-Adaptive Differential Elements remained secure during first energization of the PST, regardless of the high DC offset and 2nd harmonic content in the source-side inrush currents. Note: when the PST is energized (e.g. by closing the source-side CB), the load-side connected Dy1 transformer will also be energized (see Figure 6), as the PST's "load-side CB" is on the y-side of the Dy1 transformer.

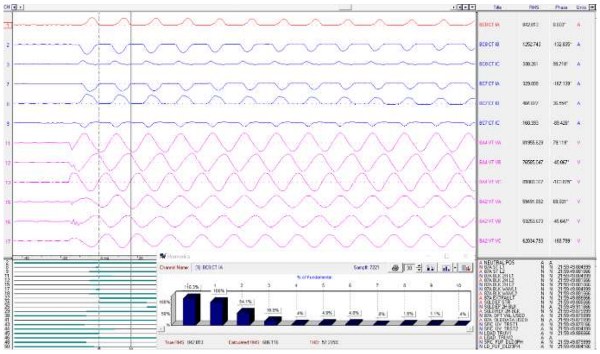


Figure 7: Energization of the PST - COMTRADE with Phase Quantities

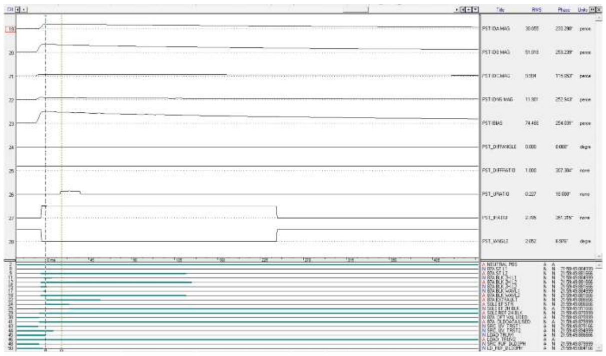


Figure 8: Energization of the PST - COMTRADE with Differential & Bias Quantities

Figure 9 shows the PST's OLTC tap position on the substation HMI screen, while it was operating in the -1 Retard mode. Based on the PST nameplate (Figure 10), if the PST is operating in -1 Retard mode, its phase shift between the Source and Load should be -1.6°. By using the source-side currents as reference (at 0°, currents into the source-side), the load-side currents should be at 178.4° = -1.6° + 180° (+180° as the load-side currents are flowing out from the load-side, i.e. away from the PST).

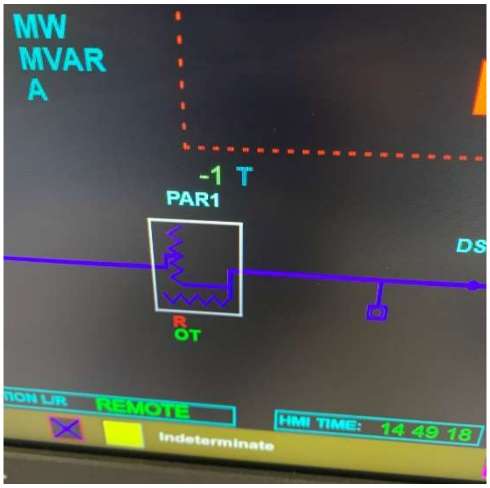
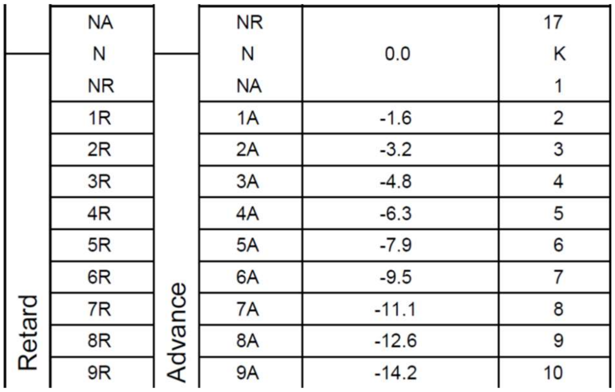


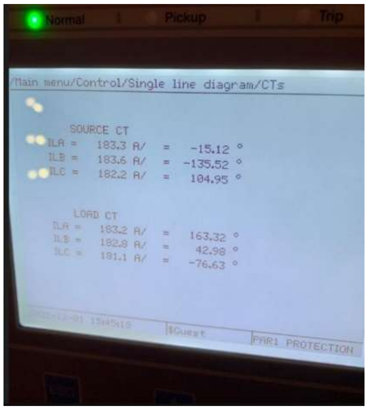
Figure 9: PST in -1 Retard Mode



	NA N NR		NR N NA	0.0	17 K 1
Retard	1R	Advance	1A	-1.6	2
	2R		2A	-3.2	3
	3R		3A	-4.8	4
	4R		4A	-6.3	5
	5R		5A	-7.9	6
	6R		6A	-9.5	7
	7R		7A	-11.1	8
	8R		8A	-12.6	9
	9R		9A	-14.2	10

Figure 10: PST Nameplate

Figure 11 below shows both Source and Load phase currents in complex form. The phase shift between the Source and Load currents are:
PhaseA: 15.12° + 163.32° = 178.44°
PhaseB: 135.52° + 42.98° = 178.50°
PhaseC: 104.95° + 76.63° = 178.42°



```
/Main menu/Control/Single line diagram/CTs

SOURCE CT
ILA =    183.3 A/   =    -15.12 °
ILB =    183.6 A/   =   -135.52 °
ILC =    182.2 A/   =    104.95 °

LOAD CT
ILA =    183.2 A/   =    163.32 °
ILB =    182.8 A/   =     42.98 °
ILC =    181.1 A/   =    -76.63 °

                    $Guest          PAR1 PROTECTION
```

Figure 11: Source & Load Phase Currents

Conclusion

The universal differential protection for phase-shifting transformers is presented. It only requires one three-phase current set and at least one phase-to-ground voltage as inputs from each side of the protected PST. Actual position of any internal OLTC is not required. Actual transformation ratio and phase-angle shift of the PST are estimated on-line by the IED.

Such differential protection is self-adaptive. It automatically learns and adjusts to the actual transformation ratio and phase-angle shift across the protected power transformer. Typically, minimum pickup of 20%, based on the PST rating, can be achieved for the differential protection. Such solution will protect the complete PST/PAR transformer against all internal faults. Negative-sequence based differential protection, which is also available, will provide additional sensitivity for low level turn-to-turn faults. At the same time, internally buried CTs within the protected power transformer tank are not required at all.

Consequently, any phase-shifting transformer regardless of its construction principles (symmetrical or asymmetrical) and design details (single-core, double-core or even of any complex design) can be entirely protected by using such differential protection scheme. If required even support for “Digital CTs and VTs” via merging units can also be provided as shown in this paper.

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