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 (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 (i.e. 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 (i.e. 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-changers 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 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.

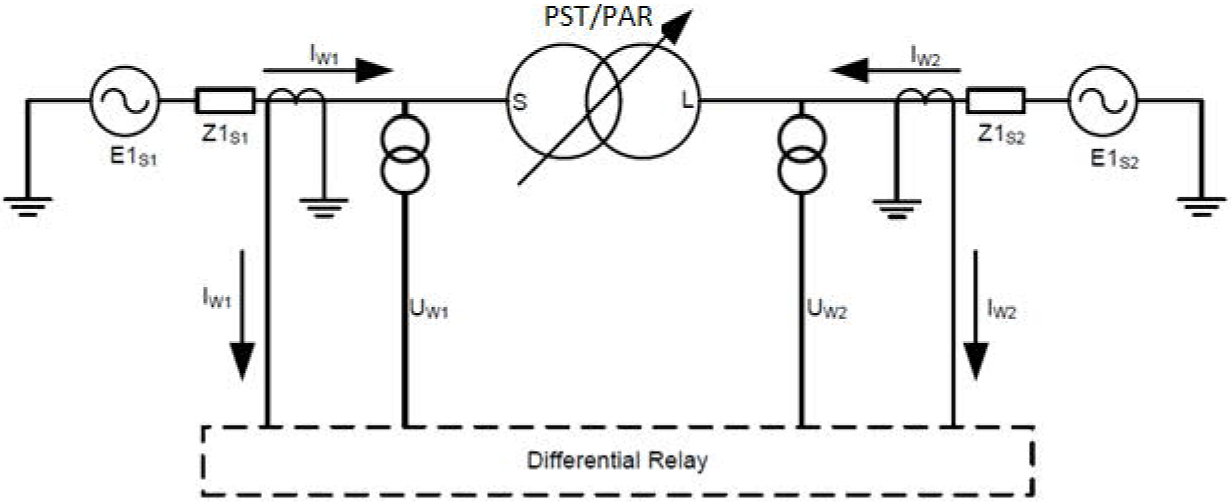

Figure 1: Differential protection arrangement for arbitrary Phase-Shifting Transformer

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 shifting (i.e. 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 two 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 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):

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

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):

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

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 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, that is with phase rotation L1-L2-L3, are connected to the protected PST.

Once these four values are known, the logic shown in Figure 2 is used to determine the actual transformation ratio and the phase-angle shift across the protected PST. Selection of Logic #1, shown in Figure 2, works with the priorities as described below:

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.

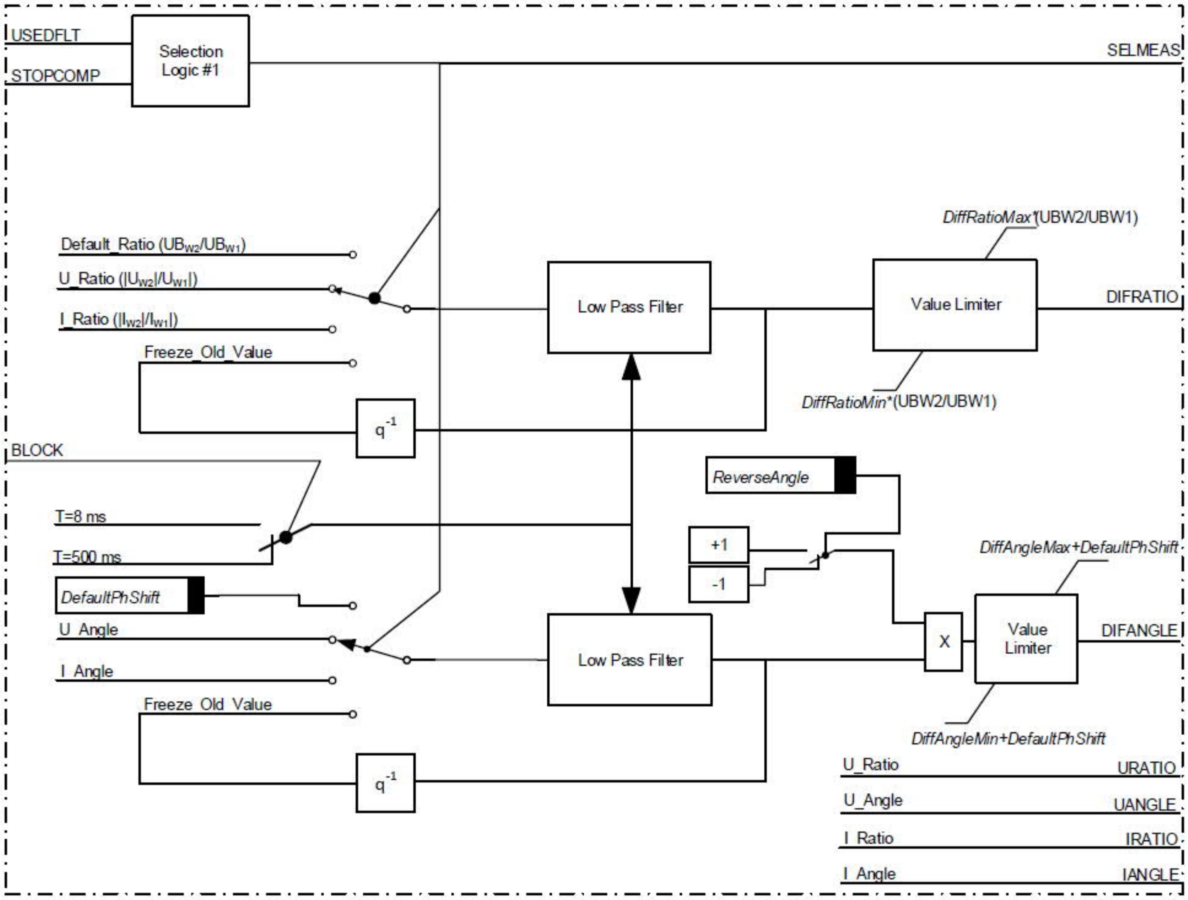

Figure 2: Simplified logic to determine the actual transformation ratio and phase-angle shift

Once values for the transformation ratio and the phase-angle 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, as shown in Figure 2, 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 function shall be pulsed for 50 ms 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 50 ms).

A binary input, named USEDFLT as shown in Figure 2, is there to force the use of default values, which are determined by setting parameters. A further binary input, named STOPCOMP which is also shown in Figure 2, is there 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) from the logic given in Figure 2:

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)

Note also that values for DIFRATIO, DIFANGLE, *I_Ratio*, *I_Angle*, *U_Ratio*, *U_Angle* and all differential and bias currents are provided as service values from the function and can be read locally on the HMI and remotely via communication to facilitate operation and testing of the IED. Additionally, they can be even recorded in the Comtrade file during power system disturbance.

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.

Testing 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.

TenneT tries to avoid long copper cabling between the location of the protection relay and the primary assets like the circuit breaker, current and voltage transformer. 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 (i.e. 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.

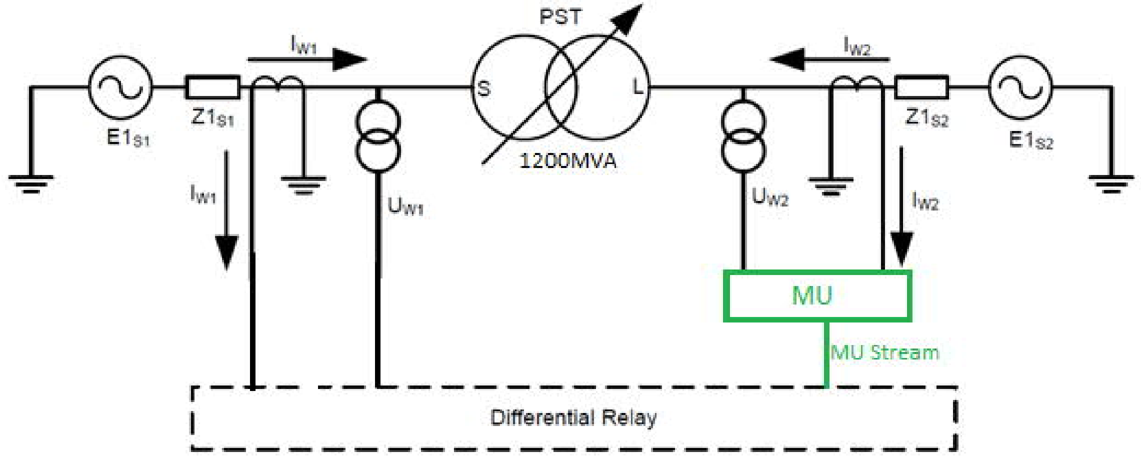

Figure 3: Simplified arrangement of the Pilot Installation

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 advanced-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.

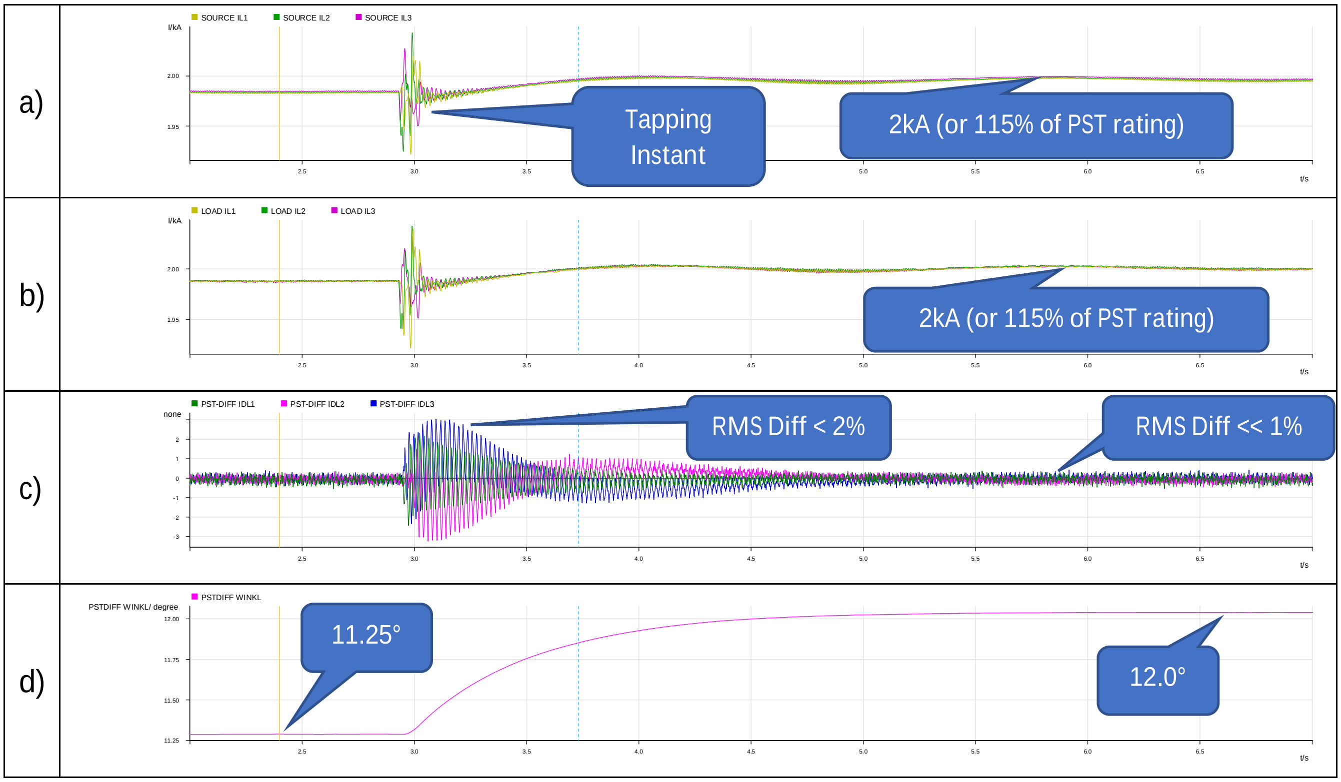

Figure 4: Recorded Tap Position Change under full load during PST FAT test

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 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 cause 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. 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.

New Protection Scheme for the Double Core PST

In addition to the differential protection the complete protection scheme for a double-core PST may also include a Restricted EF protection function 87N, other backup protection functions like 50/51, 51N, as well as metering and manual OLTC control as shown in Figure 5.

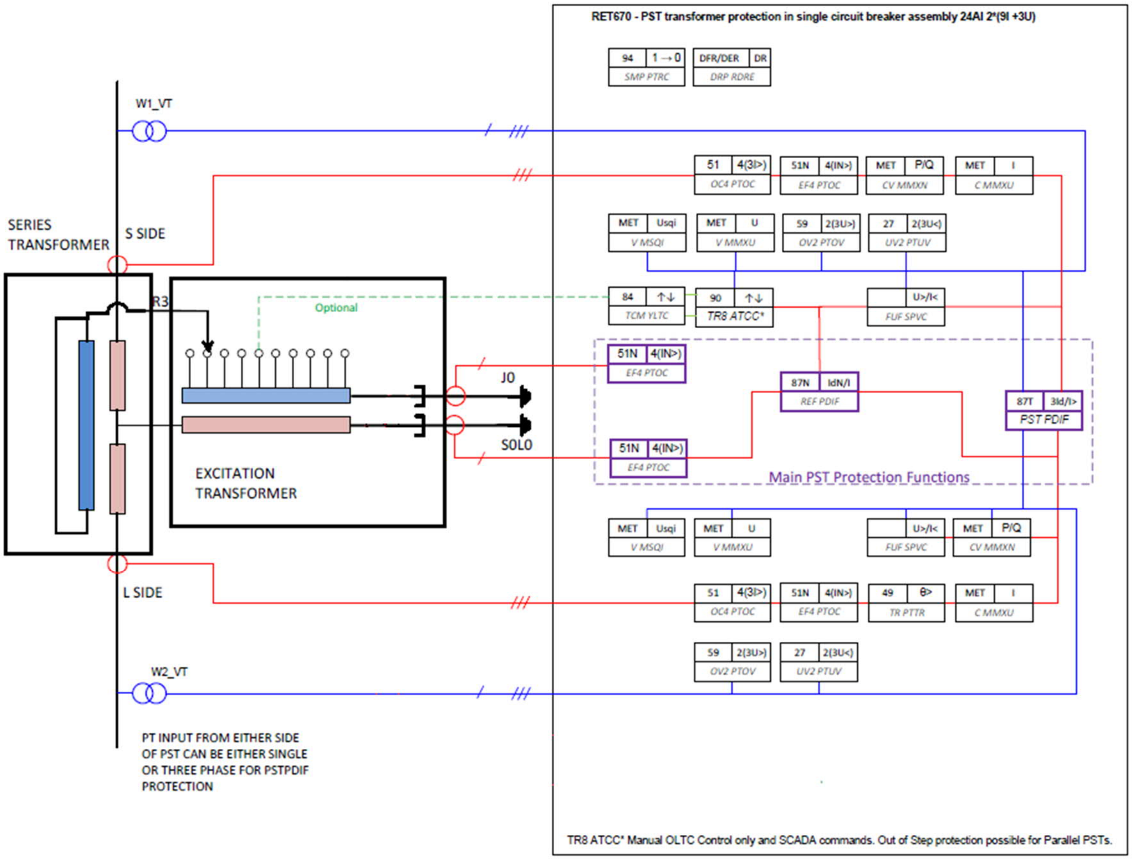

Figure 5: Proposed Protection Scheme for a Double-Core PST

Furthermore, over-excitation protection for series transformer and even an out-of-step protection for parallel operating PSTs can be achieved in the same IED. Likewise monitoring functionality for through-fault current monitoring, winding hot-spot temperature estimation, etc. can also be arranged within this IED.

When redundancy is required the proposed scheme can be either duplicated or a more traditional scheme, as described in references [2,3,4], can be used as a second protection scheme.

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 6 would be the best. The transformer bushing CTs which can be sized to the PST 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 relays (i.e. 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.

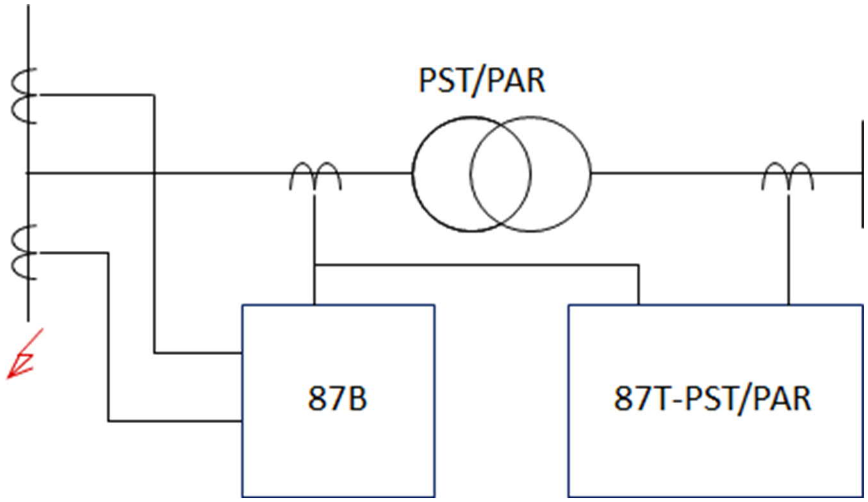

Figure 6: Proposed Differential Protection Arrangement for 1½ Breaker Scheme

Such protection arrangement will also provide very clear indication of the actual fault location. Similar setup shall be used in case when 1½ breaker arrangement is used on both sides.

Comparison between old IEEE Scheme and the New Scheme

A traditional scheme, as described in references [2,3,4], is often presently used for double-core PST protection. Two differential protections, often called 87P and 87S in the literature, are used. It is important to understand that these two differential protections are complementary to each other and actually not redundant to each other. Note also that both of these differential protections require a buried CT inside the protected PST tanks. Such CTs can often give trouble in the field due to improper design as described in reference [8]. Figure 7 shows which PST part is protected by which differential protection scheme.

As shown in reference [4] very specific values, which are not commonly available on the PST rating plate, are required to properly set the 87S protection. Some special/strange vector group settings/compensations are needed as well to be set for the 87S relay.
At the same time, to set the 87T-PST differential protection only the data readily available on the PST rating plate are needed. This simplifies the setting calculation procedures very much.

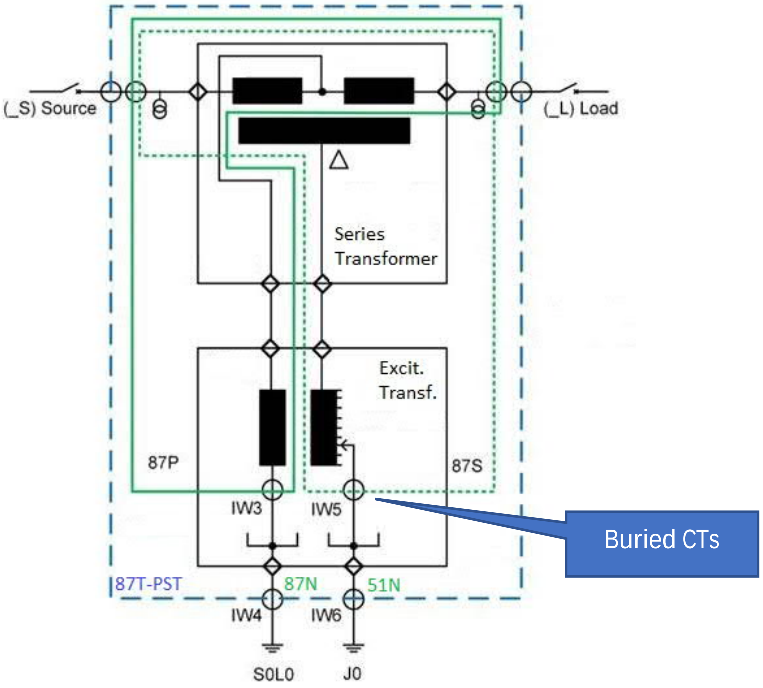

Figure 7: Comparison between 87T-PST and old IEEE Differential Protection Arrangements

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 are estimated on-line.

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.

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. Furthermore, PST control and monitoring can also be included. 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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