PST PROTECTION DESIGN AND SETTINGS

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SOC / StO / PROTECTION EQUIPMENT SUBGROUP

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ABBREVIATIONS

ATB	Ampere-turn-balanced
ATP	Alternative transients program
BPU	Base power unit
CB	Circuit breaker
CT	Current transformer
DH PST	Delta-hexagonal phase shifting transformer
EHV	Extra-high voltage
EMTP	Electromagnetic transients program
ENTSO-E	European Network of Transmission System Operators for Electricity
FAT	Factory acceptance test
HiL	Hardware-in-the-loop
HV	High voltage
IEEE	Institute of Electrical and Electronics Engineers
KCL	Kirchhoff's current law
OHL	Overhead line
OLTC	On-load tap changer
PAR	Phase angle regulator
POTT	Permissive overreaching transfer trip
PSCAD	Power systems computer aided design
PSSE	Power system simulator for engineering
PST	Phase shifting transformer
RTDS	Real-time digital simulator
SAT	Site acceptance test
TSO	Transmission system operator
UMEC	Unified magnetic equivalent circuit
V/f	Voltage-to-frequency ratio
VT	Voltage transformer

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1 INTRODUCTION

Phase shifting transformers (PSTs) are used to modify the power flow of a transmission line through the change of the line end voltage angle.

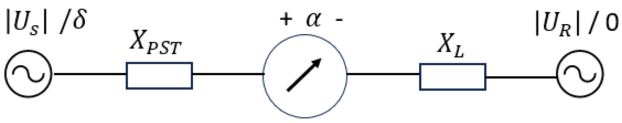

FIGURE 1. PHASE SHIFTING TRANSFORMER IN A TWO-NODE POWER SYSTEM

$$P = \frac{|U_r||U_s|}{X_L + X_{PST}} \sin(\delta + \alpha)$$

FIGURE 2. ACTIVE POWER (P) IN THE TRANSMISSION LINE WITH A PHASE SHIFTING TRANSFORMER

Therefore, PSTs are commonly installed in transmission lines where it is necessary to change the power load flow to avoid overloads in parallel circuits or in interconnections of two different power systems.

Although the usual application of the PSTs is to connect them in series with the transmission line, they can also be connected directly to two different busbars.

The aim of this report is to present the state of the art of protection functions and the usual protection schemes for PSTs, as well as the common practices adopted by the TSO members of ENTSO-E.

For this purpose, the development of load-current calculation for the different types of PST has been undertaken, as it has a significant impact on the stability of the main protection functions.

An example of phasor current and setting calculations for a differential and distance protection scheme for a dual-core PST is included as an easy reference guide that can be applied to other PSTs.

Information from ENTSO-E members on the use, protection systems and experiences with PSTs has been gathered through a questionnaire, and the main conclusions are included in this report.

2 PHASE SHIFTING TRANSFORMERS: OPERATING PRINCIPLE

TYPES OF PHASE SHIFT TRANSFORMERS

Although there are several design principles, a PST can be single or dual core. These two types can also be symmetrical or asymmetrical.

Symmetrical PSTs present current phasors for line and source ends with the same magnitudes, while
2.1 asymmetrical PSTs present current phasors for line and source ends with different magnitudes.

2.1.1 SINGLE CORE

The single core is probably the simplest type of PST. The advantage of this solution is that it does not require a separate excitation transformer, thereby reducing costs and space in the substation.

In a single-core PST, the on-load tap changer (OLTC) and the regulating windings are connected in series with the power system. The short-circuit impedance of the PST varies between a maximum and zero (at a phase-angle shift of 0°).

For this reason, additional impedance, typically a serial reactor connected to the load-side terminals, might be necessary to protect the OLTC from short-circuit currents.

Thus, they are directly exposed to system disturbances and fault currents, which may require a costly OLTC, and the overall dimensions of the individual PSTs can compromise their transportability.

For these considerations, the use of these PST, even if they are simpler in construction, is limited to powers of about 200MVA and high-voltage (HV) levels.

2.1.1.1 ASYMMETRICAL TYPE

The asymmetrical type is the simpler solution, with the general principle for obtaining a phase shift being to connect a segment of one phase to another.

To obtain an additional 90˚ of voltage ΔV, a delta-connected winding offers the simplest solution.

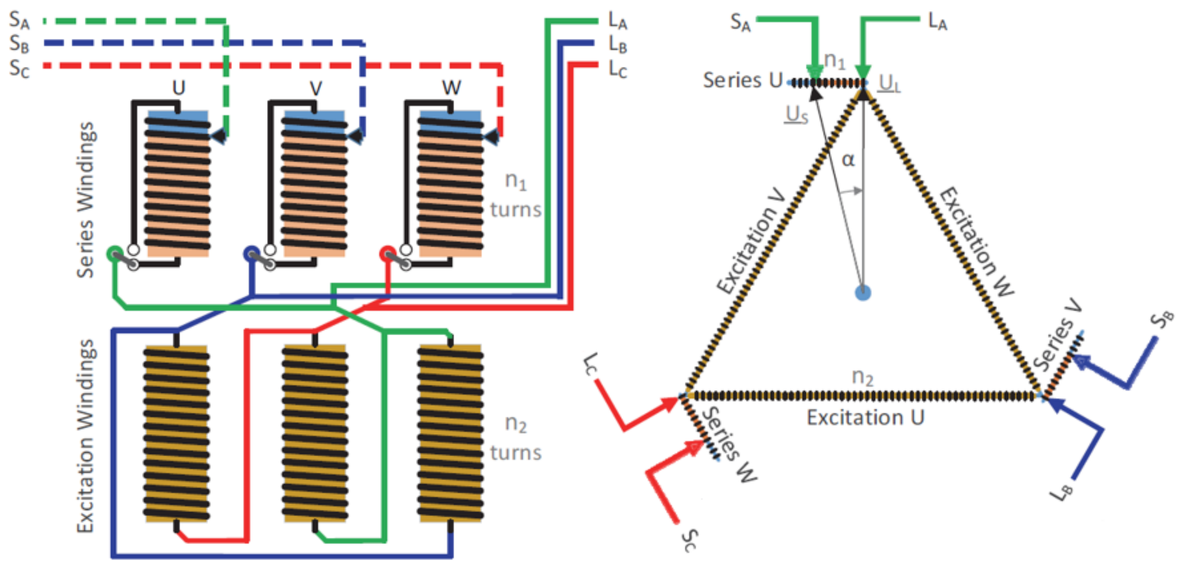

FIGURE 3. SINGLE-CORE ASYMMETRICAL PHASE SHIFTING TRANSFORMER [1]

In this designed solution, only one-half of the tapped winding can be used. However, in this case, the load voltage increases relative to the source voltage as the phase angle increases.

2.1.1.2 SYMMETRICAL TYPE

The single-core symmetrical type is also known as a standard/extended-delta single-core PST due to the shape of its phasor diagram, as shown in Figure 4.

The secondary winding of phase $V_B - V_C$ is split up into two halves and is connected in series with phase V_A.

In the symmetrical type, the voltage magnitude under no-load conditions is identical on both the source and load sides, and the phase-angle shift α has no effect.

In this transformer type, commutation between the advance and retard modes is performed by two switches per phase. This differs from the single switch in the asymmetrical type, in which the series windings are split into two dual-core windings.

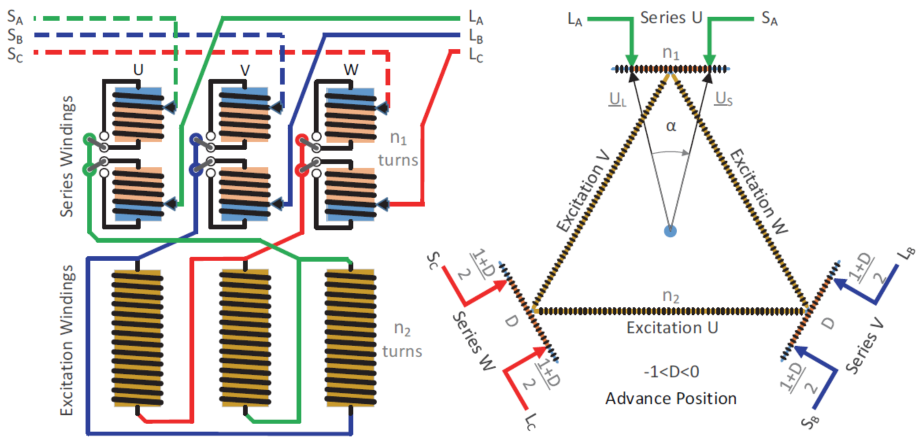

FIGURE 4. SINGLE-CORE SYMMETRICAL PHASE SHIFTING TRANSFORMER [1]

Figure 5 illustrates the distribution of current and voltage phasors within the symmetric PST. It should be noted that the phasor diagram has been plotted without considering the voltage drop in the unit. It should also be noted that the currents in the two halves of the series winding are not in phase, but this provides a sufficient indication to understand the functionality.

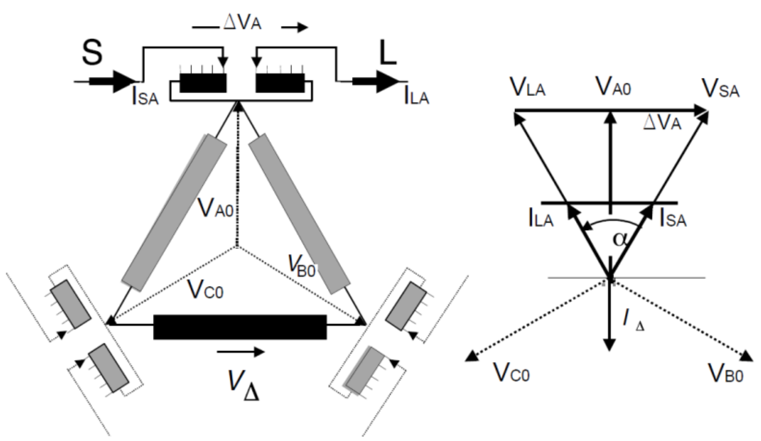

FIGURE 5. SINGLE-CORE SYMMETRICAL PHASOR DIAGRAM [1]

Where:

$V_{SA} = V_{A0} + \Delta V_A/2$ (1)
$V_{LA} = V_{A0} - \Delta V_A/2$ (2)
$\Delta V_A = V_{SA} - V_{LA}$ (3)
$V_{SA} = V_{LA} = V$ (4)
$V_0 = V \cdot cos\left(\frac{\alpha}{2}\right)$ (5)
$\Delta V = 2 \cdot V \cdot sin\left(\frac{\alpha}{2}\right)$ (6)
$V_\Delta = \sqrt{3} \cdot V_0 = \sqrt{3} \cdot V \cdot cos\left(\frac{\alpha}{2}\right)$ (7)
$I_S = I_L = I$ (8)
$I_\Delta = part\ of\ the\ current\ that\ is\ transferred\ to\ the\ excitation\ winding$

$$V_\Delta \cdot I_\Delta = \frac{\Delta V}{2} \cdot I_{SA} + \frac{\Delta V}{2} \cdot I_{LA} = \frac{\Delta V}{2} \cdot (I_{SA} + I_{LA}) = \frac{\Delta V}{2} \cdot \left(2 \cdot I \cdot cos\left(\frac{\alpha}{2}\right)\right) \Rightarrow$$
$$I_\Delta = \frac{\Delta V}{V_\Delta} \cdot I \cdot cos\left(\frac{\alpha}{2}\right) = \left(\frac{2}{\sqrt{3}}\right) \cdot I \cdot sin\left(\frac{\alpha}{2}\right) \quad (9)$$

These quantities are determined by the rated characteristics of the PST:

$P_S = 3 \cdot V_{LA} \cdot I_L \Rightarrow rated\ through\ output\ power$ (10)
$P_T = 3 \cdot \Delta V_{LA} \cdot I_{LA} \Rightarrow rated\ total\ power$ (11)

2.1.1.3 DELTA-HEXAGONAL

A single-core PST with symmetrical tuning is called a delta-hexagonal (DH PST). In this scheme, the excitation system is configured in a zig-zag arrangement of three windings and provides an OLTC with linear adjustment (without a change-over selector).

The existence of this scheme is due to advancements in OLTC technology. It promises to be much more economical to build and install than previous designs, thereby improving the economic viability of deploying these devices on the transmission grid.

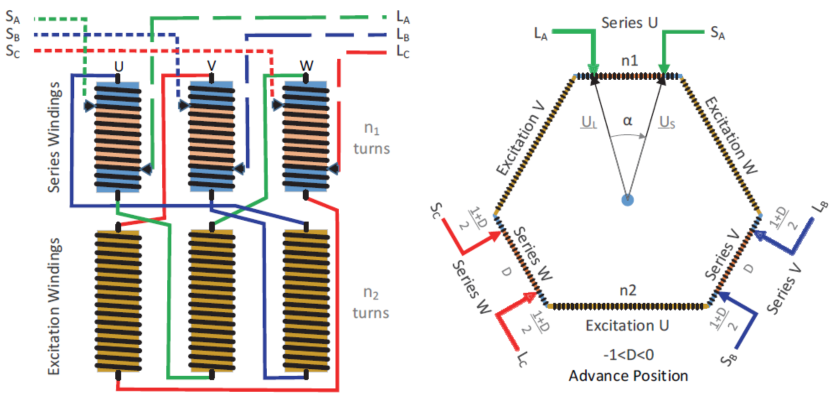

FIGURE 6. DELTA-HEXAGONAL PHASE SHIFTING TRANSFORMER [1]

In a DH PST, there are two OLTCs with three-phase taps. Each tap moves its three terminals along the series windings, creating a phase shift between the source and load ends. When the taps pass each other, the transformer switches the operation from retard to advance mode, or vice versa.

2.1.2 DUAL CORE

The dual-core PST comprises two power transformers: *the serial core* and *excitation core*.

- *Serial core*:

This core is a power transformer with at least two windings. One or more windings are serially (serial) connected to the line, while one or more windings are delta-connected to the second power transformer unit (excitation core).

The currents from the delta winding are 90 degrees out of phase with the line currents flowing through the serial windings. An A/R switch (ARS) that fixes the advance or retard voltage angle by changing the current polarity of the regulation windings can be installed in the delta winding.

- *Excitation core*:

This core is a power transformer with at least two windings. One or more windings are connected to the delta windings of the serial core, and, in addition to the tap changer, it can include an ARS that also fixes the advance or retard voltage angle, thus serving as the regulation windings. When an ARS is installed in the excitation core, the polarity of the regulation winding currents remains unchanged; instead, the polarity of the regulation winding voltage reverses.

One or more windings are the excitation winding, where currents flow 90 degrees out of phase with the line currents through the serial winding, which is then connected again to the serial winding, fixing the voltage angle at this line end.

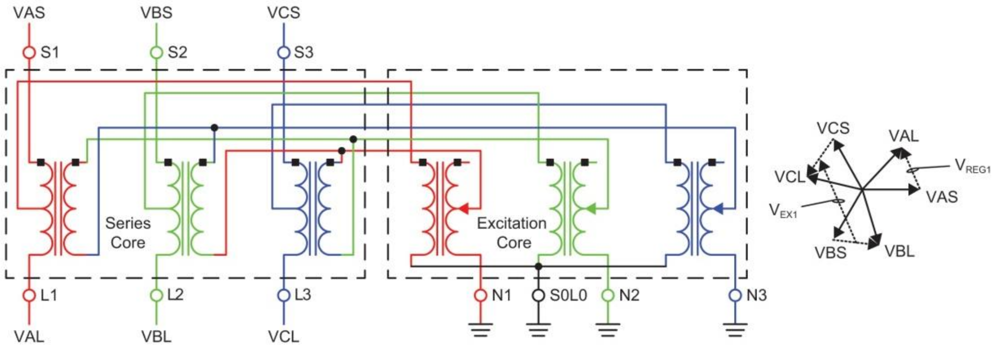

FIGURE 7. DUAL-CORE SYMMETRICAL PHASE SHIFTING TRANSFORMER [2]

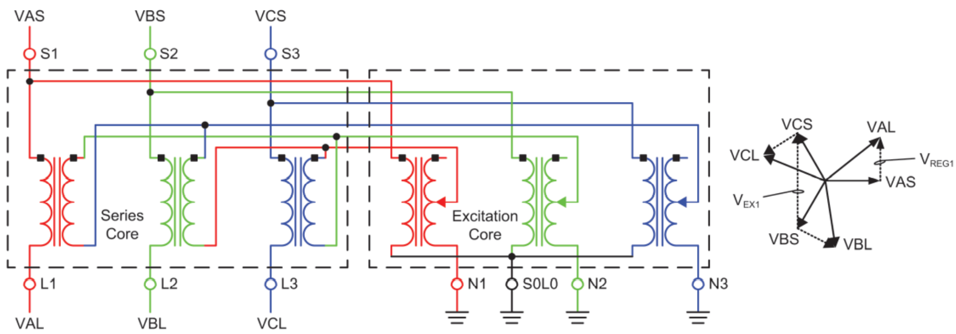

FIGURE 8. DUAL-CORE ASYMMETRICAL PHASE SHIFTING TRANSFORMER [2]

The main protection function, together with the electromechanical protection built into the transformer, is differential transformer protection (87T). Two examples for dual-core winding phasor current calculation are shown in Sections 2.1.2.1 and 2.1.2.2. In both examples, the source phasor currents are taken as the reference to determine the advance or retard position of line phasor currents.

2.1.2.1 DUAL-CORE ASYMMETRICAL WINDING PHASOR CURRENT CALCULATION UNDER BALANCED AND LINEAR CONDITIONS

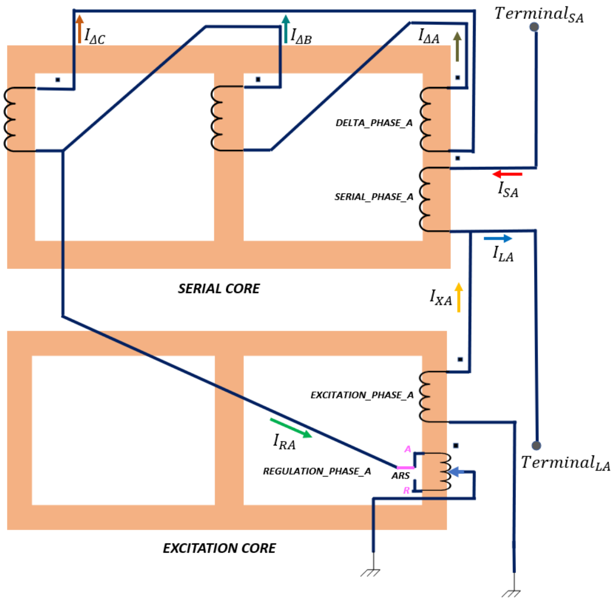

FIGURE 9. PHASE A WINDING CURRENTS OF A DUAL-CORE ASYMMETRICAL PHASE SHIFTING TRANSFORMER WITH AN ADVANCED/RETARD SWITCH IN THE EXCITATION CORE

In Figure 9, not all winding phasor currents are shown for simplicity.

The equations for the magnetic circuits of the serial core according to Hopkinson's law are:

$$N_s \cdot I_{SA} - N_\Delta \cdot I_{\Delta A} = \mathcal{R}_{A_{SER\ CORE}} \cdot \phi_{A_{SER\ CORE}} \quad (12)$$

$$N_s \cdot I_{SB} - N_\Delta \cdot I_{\Delta B} = \mathcal{R}_{B_{SER\ CORE}} \cdot \phi_{B_{SER\ CORE}} \quad (13)$$

$$N_s \cdot I_{SC} - N_\Delta \cdot I_{\Delta C} = \mathcal{R}_{C_{SER\ CORE}} \cdot \phi_{C_{SER\ CORE}} \quad (14)$$

Where:

$N_s = number\ of\ turns\ of\ primary\ winding\ of\ the\ serial\ core$

$N_\Delta = number\ of\ turns\ of\ delta\ winding\ of\ the\ serial\ core$

$I_{SA-SB-SC} = phasor\ currents\ of\ the\ serial\ winding\ of\ the\ serial\ core.$

$I_{\Delta A-\Delta B-\Delta C} = phasor\ currents\ of\ delta\ winding\ of\ the\ serial\ core$

$\mathcal{R}_{A-B-C_{SER\ CORE}} = reluctance\ of\ magnetic\ circuit\ for\ phases\ A, B\ and\ C\ of\ the\ serial\ core$

$\phi_{A-B-C_{SER\ CORE}} = phasor\ magnetic\ flux\ of\ phases\ A, B\ and\ C\ of\ the\ serial\ core$

To simplify the calculation, under linear conditions, the reluctance can be neglected and the product of $\mathcal{R} \cdot \phi \approx 0$ and therefore:

$$N_s \cdot I_{SA} - N_\Delta \cdot I_{\Delta A} = 0 \quad (15)$$

$$N_s \cdot I_{SB} - N_\Delta \cdot I_{\Delta B} = 0 \quad (16)$$

$$N_s \cdot I_{SC} - N_\Delta \cdot I_{\Delta C} = 0 \ (17)$$

Then, delta winding currents can be approximated by:

$$I_{\Delta A} = \frac{N_s}{N_\Delta} \cdot I_{SA} \ (18)$$

$$I_{\Delta B} = \frac{N_s}{N_\Delta} \cdot I_{SB} \ (19)$$

$$I_{\Delta C} = \frac{N_s}{N_\Delta} \cdot I_{SC} \ (20)$$

Applying Kirchhoff's law in delta windings, we obtain the currents of the regulation windings.

As these currents from regulation windings are composed of the delta current windings, finally we can express them referenced to the source currents flowing into the serial windings:

$$I_{RA} = I_{\Delta B} - I_{\Delta C} = \frac{N_s}{N_\Delta} \cdot I_{SB} - \frac{N_s}{N_\Delta} \cdot I_{SC} = \frac{N_s}{N_\Delta} \cdot (I_{SB} - I_{SC}) = I_{SA} \cdot \sqrt{3} \cdot \frac{N_s}{N_\Delta} \cdot e^{-i\frac{\pi}{2}} \ (21)$$

$$I_{RB} = I_{\Delta C} - I_{\Delta A} = \frac{N_s}{N_\Delta} \cdot I_{SC} - \frac{N_s}{N_\Delta} \cdot I_{SA} = \frac{N_s}{N_\Delta} \cdot (I_{SC} - I_{SA}) = I_{SB} \cdot \sqrt{3} \cdot \frac{N_s}{N_\Delta} \cdot e^{-i\frac{\pi}{2}} \ (22)$$

$$I_{RC} = I_{\Delta A} - I_{\Delta B} = \frac{N_s}{N_\Delta} \cdot I_{SA} - \frac{N_s}{N_\Delta} \cdot I_{SB} = \frac{N_s}{N_\Delta} \cdot (I_{SA} - I_{SB}) = I_{SC} \cdot \sqrt{3} \cdot \frac{N_s}{N_\Delta} \cdot e^{-i\frac{\pi}{2}} \ (23)$$

Applying Hopkinson's law to the excitation core in the case of the ARS in the advance position (line currents in advanced position with respect to source currents), we obtain:

$$N_R \cdot I_{RA} - N_X \cdot I_{XA} = \mathcal{R}_{A_{EXC\,CORE}} \cdot \phi_{A_{EXC\,CORE}} \approx 0 \ (24)$$

$$N_R \cdot I_{RB} - N_X \cdot I_{XB} = \mathcal{R}_{B_{EXC\,CORE}} \cdot \phi_{B_{EXC\,CORE}} \approx 0 \ (25)$$

$$N_R \cdot I_{RC} - N_X \cdot I_{XC} = \mathcal{R}_{C_{EXC\,CORE}} \cdot \phi_{C_{EXC\,CORE}} \approx 0 \ (26)$$

Where:

$N_R = number\ of\ turns\ of\ regulation\ winding\ of\ the\ excitation\ core$

$N_X = number\ of\ turns\ of\ excitation\ winding\ of\ the\ excitation\ core$

$I_{RA-RB-RC} = currents\ of\ regulation\ winding\ of\ the\ excitation\ core$

$I_{XA-XB-XC} = currents\ of\ excitation\ winding\ of\ the\ serial\ core$

$\mathcal{R}_{A-B-C_{EXC\,CORE}} = reluctance\ of\ magnetic\ circuit\ of\ phases\ A, B\ and\ C\ of\ the\ excitation\ core$

$\phi_{A-B-C_{EXC\,CORE}} = magnetic\ flux\ of\ phases\ A, B\ and\ C\ of\ the\ excitation\ core$

Then, the currents from excitation with ARS in advance position windings can be written as:

$$I_{XA} = \frac{N_R}{N_X} \cdot I_{RA} = \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot (I_{SB} - I_{SC}) = I_{SA} \cdot \sqrt{3} \cdot \frac{N_s \cdot N_x}{N_\Delta \cdot N_H} \cdot e^{i\frac{\pi}{2}} \ (27)$$

$$I_{XB} = \frac{N_R}{N_X} \cdot I_{RB} = \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot (I_{SC} - I_{SA}) = I_{SB} \cdot \sqrt{3} \cdot \frac{N_s \cdot N_x}{N_\Delta \cdot N_H} \cdot e^{i\frac{\pi}{2}} \ (28)$$

$$I_{XC} = \frac{N_R}{N_X} \cdot I_{RC} = \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot (I_{SA} - I_{SB}) = I_{SC} \cdot \sqrt{3} \cdot \frac{N_s \cdot N_x}{N_\Delta \cdot N_H} \cdot e^{i\frac{\pi}{2}} \ (29)$$

Applying Hopkinson's law to the excitation core in the case of the ARS in retard position in the same way as in Eqs. (24), (25) and (26), the currents from excitation windings can be expressed as:

$$I_{XA} = \frac{N_R}{N_X} \cdot I_{RA} = \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot (I_{SC} - I_{SB}) = I_{SA} \cdot \sqrt{3} \cdot \frac{N_s \cdot N_x}{N_\Delta \cdot N_H} \cdot e^{-i\frac{\pi}{2}} \quad (30)$$

$$I_{XB} = \frac{N_R}{N_X} \cdot I_{RB} = \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot (I_{SA} - I_{SC}) = I_{SB} \cdot \sqrt{3} \cdot \frac{N_s \cdot N_x}{N_\Delta \cdot N_H} \cdot e^{-i\frac{\pi}{2}} \quad (31)$$

$$I_{XC} = \frac{N_R}{N_X} \cdot I_{RC} = \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot (I_{SB} - I_{SA}) = I_{SC} \cdot \sqrt{3} \cdot \frac{N_s \cdot N_x}{N_\Delta \cdot N_H} \cdot e^{-i\frac{\pi}{2}} \quad (32)$$

Finally, line currents can be expressed as functions of source currents and the number of turns of the serial, delta, regulation and excitation windings.

Applying Kirchhoff's law to the connection point of serial and excitation windings and the line, we obtain in the case of ARS in advance position:

$$I_{LA} = I_{SA} + I_{XA} = I_{SA} + \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot (I_{SC} - I_{SB}) = I_{SA} \cdot \left(1 + \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot \sqrt{3} \cdot e^{i\frac{\pi}{2}}\right) \quad (33)$$

$$I_{LB} = I_{SB} + I_{XB} = I_{SB} + \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot (I_{SA} - I_{SC}) = I_{SB} \cdot \left(1 + \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot \sqrt{3} \cdot e^{i\frac{\pi}{2}}\right) \quad (34)$$

$$I_{LC} = I_{SC} + I_{XC} = I_{SC} + \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot (I_{SB} - I_{SA}) = I_{SC} \cdot \left(1 + \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot \sqrt{3} \cdot e^{i\frac{\pi}{2}}\right) \quad (35)$$

In the case of ARS in retard position:

$$I_{LA} = I_{SA} + I_{XA} = I_{SA} + \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot (I_{SC} - I_{SB}) = I_{SA} \cdot \left(1 + \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot \sqrt{3} \cdot e^{-i\frac{\pi}{2}}\right) \quad (36)$$

$$I_{LB} = I_{SB} + I_{XB} = I_{SB} + \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot (I_{SC} - I_{SA}) = I_{SB} \cdot \left(1 + \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot \sqrt{3} \cdot e^{-i\frac{\pi}{2}}\right) \quad (37)$$

$$I_{LC} = I_{SC} + I_{XC} = I_{SC} + \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot (I_{SA} - I_{SB}) = I_{SC} \cdot \left(1 + \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot \sqrt{3} \cdot e^{-i\frac{\pi}{2}}\right) \quad (38)$$

Under balanced operation and taking currents from the source terminal as known phasors, the phasor currents from the delta, regulation and excitation windings and line terminal of the asymmetrical PST can be expressed as follows:

- Source phasor currents:

$$I_{SA_{DUAL\_CORE\_ASYM}} =| I_{SA_{DUAL_{CORE_{ASYM}}}} |\cdot e^{i(\omega t + \varphi)} \quad (39)$$

$$I_{SB_{DUAL\_CORE\_ASYM}} = I_{SA_{DUAL_{CORE_{ASYM}}}} \cdot e^{i\left(\frac{2\pi}{3}\right)} \quad (40)$$

$$I_{SC_{DUAL\_CORE\_ASYM}} = I_{SA_{DUAL_{CORE_{ASYM}}}} \cdot e^{i\left(\frac{\pi}{3}\right)} \quad (41)$$

- Line phasor currents:

$$I_{LA} = I_{SA_{DUAL\_CORE\_ASYM}} \cdot (1+\beta) \ \ (42)$$

$$I_{LB} = I_{LA_{DUAL\_CORE\_ASYM}} \cdot e^{i\frac{2\pi}{3}} \ \ (43)$$

$$I_{LC} = I_{LA_{DUAL\_CORE\_ASYM}} \cdot e^{i\frac{\pi}{3}} \ \ (44)$$

- Regulation phasor currents:

$$I_{RA_{DUAL\_CORE\_ASYM}} = I_{SA_{DUAL\_CORE\_ASYM}} \cdot \alpha \ (45)$$

$$I_{RB_{DUAL\_CORE\_ASYM}} = I_{RA_{DUAL\_CORE\_ASYM}} \cdot e^{i\frac{2\pi}{3}} \ \ (46)$$

$$I_{RC_{DUAL\_CORE\_ASYM}} = I_{RA_{DUAL\_CORE\_ASYM}} \cdot e^{i\frac{\pi}{3}} \ \ (47)$$

- Excitation phasor currents:

$$I_{XA_{DUAL\_CORE\_ASYM}} = I_{SA_{DUAL\_CORE\_ASYM}} \cdot \beta \ (48)$$

$$I_{XB_{DUAL\_CORE\_ASYM}} = I_{XA_{DUAL\_CORE\_ASYM}} \cdot e^{i\frac{2\pi}{3}} \ \ (49)$$

$$I_{XC_{DUAL\_CORE\_ASYM}} = I_{XA_{DUAL\_CORE\_ASYM}} \cdot e^{i\frac{\pi}{3}} \ \ (50)$$

Where:

$$\beta = \sqrt{3} \cdot \frac{N_s \cdot N_x}{N_\Delta \cdot N_H} \cdot e^{\xi i\frac{\pi}{2}}$$

$$\alpha = \sqrt{3} \cdot \frac{N_s}{N_\Delta} \cdot e^{-i\frac{\pi}{2}}$$

$$\xi = \pm 1 \rightarrow ARS\ switch\ in\ advance\ (+1)\ or\ retard\ (-1)\ position$$

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2.1.2.2 DUAL-CORE SYMMETRICAL CURRENT CALCULATION EXAMPLE UNDER BALANCED AND LINEAR CONDITIONS

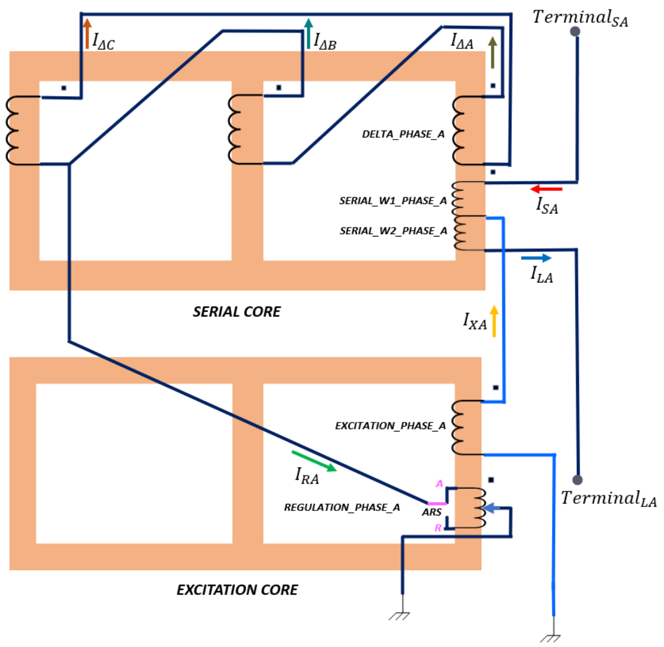

FIGURE 10. PHASE A WINDING CURRENTS OF A DUAL-CORE SYMMETRICAL PHASE SHIFTING TRANSFORMER WITH ADVANCED/RETARD SHIFT IN THE EXCITATION CORE

In Figure 10, not all the phasor currents are shown for simplicity.

The equations of the magnetic circuits of the serial core according to Hopkinson's law are:

$$N_s \cdot I_{SA} + N_s \cdot I_{LA} - N_\Delta \cdot I_{\Delta A} = \mathcal{R}_{A_{SER\ CORE}} \cdot \phi_{A_{SER\ CORE}} \quad (51)$$

$$N_s \cdot I_{SB} + N_s \cdot I_{LB} - N_\Delta \cdot I_{\Delta B} = \mathcal{R}_{B_{SER\ CORE}} \cdot \phi_{B_{SER\ CORE}} \quad (52)$$

$$N_s \cdot I_{SC} + N_s \cdot I_{LC} - N_\Delta \cdot I_{\Delta C} = \mathcal{R}_{C_{SER\ CORE}} \cdot \phi_{C_{SER\ CORE}} \quad (53)$$

Where:

$N_s = number\ of\ turns\ of\ the\ primary\ winding\ of\ the\ serial\ core.$

$N_\Delta = number\ of\ turns\ of\ delta\ winding\ of\ the\ serial\ core.$

$I_{SA-SB-SC} = phasor\ currents\ of\ serial\ winding\ 1\ of\ the\ serial\ core.$

$I_{LA-LB-LC} = phasor\ currents\ of\ serial\ winding\ 2\ (equal\ to\ line\ currents) of\ the\ serial\ core.$

$I_{\Delta A-\Delta B-\Delta C} = Phasor\ currents\ of\ delta\ winding\ of\ the\ serial\ core.$

$\mathcal{R}_{A-B-C_{SER\ CORE}} = Reluctance\ of\ magnetic\ circuit\ of\ phases\ A, B\ and\ C\ of\ the\ serial\ core.$

$\phi_{A-B-C_{SER\ CORE}} = Phasor\ magnetic\ flux\ of\ phases\ A, B\ and\ C\ of\ the\ serial\ core.$

To simplify the calculation, under linear conditions, the reluctance can be neglected and the product of the reluctance and magnetic flux $\mathcal{R} \cdot \phi \approx 0$, and therefore:

$$N_s \cdot I_{SA} + N_s \cdot I_{LA} - N_\Delta \cdot I_{\Delta A} = 0 \ (54)$$

$$N_s \cdot I_{SB} + N_s \cdot I_{LB} - N_\Delta \cdot I_{\Delta B} = 0 \ (55)$$

$$N_s \cdot I_{SC} + N_s \cdot I_{LC} - N_\Delta \cdot I_{\Delta C} = 0 \ (56)$$

Then, delta winding currents can be approximated by:

$$I_{\Delta A} = \frac{N_s}{N_\Delta} \cdot (I_{SA} + I_{LA})\ (57)$$

$$I_{\Delta B} = \frac{N_s}{N_\Delta} \cdot (I_{SB} + I_{LB})\ (58)$$

$$I_{\Delta C} = \frac{N_s}{N_\Delta} \cdot (I_{SC} + I_{LC})\ (59)$$

Applying Kirchhoff's law in the delta windings, we obtain the currents of the regulation windings.

As these currents from regulation windings are composed of the delta current windings, finally, we can express them referenced to the line and source terminal currents flowing into the serial windings:

$$I_{RA} = I_{\Delta B} - I_{\Delta C} = \frac{N_s}{N_\Delta} \cdot (I_{SB} + I_{LB}) - \frac{N_s}{N_\Delta} \cdot (I_{SC} + I_{LC}) = \frac{N_s}{N_\Delta} \cdot [(I_{SB} - I_{SC}) + (I_{LB} - I_{LC})]\ (60)$$

$$I_{RB} = I_{\Delta C} - I_{\Delta A} = \frac{N_s}{N_\Delta} \cdot (I_{SC} + I_{LC}) - \frac{N_s}{N_\Delta} \cdot (I_{SA} + I_{LA}) = \frac{N_s}{N_\Delta} \cdot [(I_{SC} - I_{SC}) + (I_{LC} - I_{LC})]\ (61)$$

$$I_{RC} = I_{\Delta A} - I_{\Delta B} = \frac{N_s}{N_\Delta} \cdot (I_{SA} + I_{LA}) - \frac{N_s}{N_\Delta} \cdot (I_{SB} + I_{LB}) = \frac{N_s}{N_\Delta} \cdot [(I_{SA} - I_{SB}) + (I_{LA} - \quad {}_{LB})]\ (62)$$

Applying Hopkinson's law to the excitation core in the case of the ARS in advance position, we obtain:

$$N_R \cdot I_{RA} - N_X \cdot I_{XA} = \mathcal{R}_{A_{EXC\ CORE}} \cdot \phi_{A_{EXC\ CORE}} \approx 0\ (63)$$

$$N_R \cdot I_{RB} - N_X \cdot I_{XB} = \mathcal{R}_{B_{EXC\ CORE}} \cdot \phi_{B_{EXC\ CORE}} \approx 0\ (64)$$

$$N_R \cdot I_{RC} - N_X \cdot I_{XC} = \mathcal{R}_{8_{EXC\ CORE}} \cdot \phi_{0_{EXC\ CORE}} \approx 0\ (65)$$

Where:

$N_R = number\ of\ turns\ of\ regulation\ winding\ of\ the\ excitation\ core$

$N_X = number\ of\ turns\ of\ excitation\ winding\ of\ the\ excitation\ core$

$I_{RA-RB-RC} = currents\ of\ regulation\ winding\ of\ the\ excitation\ core$

$I_{XA-XB-XC} = currents\ of\ excitation\ winding\ of\ the\ serial\ core$

$\mathcal{R}_{A-B-C_{EXC\ CORE}} = reluctance\ of\ magnetic\ circuit\ of\ phases\ A, B\ and\ C\ of\ the\ excitation\ core$

$\phi_{A-B-C_{EXC\ CORE}} = magnetic\ flux\ of\ phases\ A, B\ and\ C\ of\ the\ excitation\ core$

Then, the currents from excitation with ARS in advance position windings can be expressed as:

$$I_{XA} = \frac{N_R}{N_X} \cdot I_{RA} = \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot [(I_{SB} - I_{SC}) + (I_{LB} - I_{LC})]\ (66)$$

$$I_{XB} = \frac{N_R}{N_X} \cdot I_{RB} = \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot [(I_{SC} - I_{SA}) + (I_{LC} - I_{LA})]\ (67)$$

$$I_{XC} = \frac{N_R}{N_X} \cdot I_{RC} = \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot [(I_{SA} - I_{SB}) + (I_{LA} - I_{LB})]\ (68)$$

Applying Hopkinson's law to the excitation core in the case of the ARS in retard position, the currents from the excitation windings can be expressed as:

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$$I_{XA} = \frac{N_R}{N_X} \cdot I_{RA} = \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot [(I_{SC} - I_{SB}) + (I_{LC} - I_{LB})] \ (69)$$

$$I_{XB} = \frac{N_R}{N_X} \cdot I_{RB} = \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot [(I_{SA} - I_{SC}) + (I_{LA} - I_{LC})] \ (70)$$

$$I_{XC} = \frac{N_R}{N_X} \cdot I_{RC} = \frac{N_R}{N_X} \cdot \frac{N_s}{N_\Delta} \cdot [(I_{SB} - I_{SA}) + (I_{LB} - I_{LA})] \ (71)$$

Unlike the asymmetrical PST, the symmetrical PST currents of delta, regulation and excitation windings depend on the line and source terminal currents, and therefore the solution of the equations and the final expressions of I_{LA}, I_{LB} and I_{LC} is slightly more complex.

We will use a different approach than the one for the asymmetrical PST to find the phasor currents.

Applying Kirchhoff's law to the connection point in the serial core with ARS in advance position, the following is obtained:

$$I_{LA} = I_{SA} + I_{XA} = I_{SA} + \frac{N_R}{N_X} \cdot I_{RA} = I_{SA} + \frac{N_R}{N_X} \cdot (I_{\Delta B} - I_{\Delta C}) = I_{SA} - i \cdot \frac{N_R}{N_X} \cdot \sqrt{3} \cdot I_{\Delta A} \ (72)$$

$$I_{LB} = I_{SB} + I_{XB} = I_{SB} + \frac{N_R}{N_X} \cdot I_{RB} = I_{SB} + \frac{N_R}{N_X} \cdot (I_{\Delta C} - I_{\Delta C}) = I_{SB} - i \cdot \frac{N_R}{N_X} \cdot \sqrt{3} \cdot I_{\Delta B} \ (73)$$

$$I_{LC} = I_{SC} + I_{XC} = I_{SC} + \frac{N_R}{N_X} \cdot I_{RC} = I_{SC} + \frac{N_R}{N_X} \cdot (I_{\Delta A} - I_{\Delta B}) = I_{SC} - i \cdot \frac{N_R}{N_X} \cdot \sqrt{3} \cdot I_{\Delta C} \ (74)$$

Combining Eqs. (54), (55) and (56) and (72), (73) and (74), $I_{\Delta A}$, $I_{\Delta B}$ and $I_{\Delta C}$ can be expressed in terms of I_{SA}, I_{SB} and I_{SC}, N_S, N_Δ, N_R and N_X:

$$N_s \cdot I_{SA} + N_s \cdot \left(I_{SA} - i \cdot \frac{N_R}{N_X} \cdot \sqrt{3} \cdot I_{\Delta A}\right) = N_\Delta \cdot I_{\Delta A} \Rightarrow 2 \cdot N_s \cdot I_{SA} - i \cdot \frac{N_R \cdot N_s}{N_X} \cdot \sqrt{3} \cdot I_{\Delta A} = N_\Delta \cdot I_{\Delta A} \Rightarrow$$

$$I_{\Delta A} = \left(\frac{2 \cdot N_s}{N_\Delta + i \cdot \sqrt{3} \cdot \frac{N_R \cdot N_s}{N_X}}\right) \cdot I_{SA} = K \cdot I_{SA} \ (75)$$

$$N_s \cdot I_{SB} + N_s \cdot \left(I_{SB} - i \cdot \frac{N_R}{N_X} \cdot \sqrt{3} \cdot I_{\Delta B}\right) = N_\Delta \cdot I_{\Delta B} \Rightarrow 2 \cdot N_s \cdot I_{SB} - i \cdot \frac{N_R \cdot N_s}{N_X} \cdot \sqrt{3} \cdot I_{\Delta B} = N_\Delta \cdot I_{\Delta B} \Rightarrow$$

$$I_{\Delta B} = \left(\frac{2 \cdot N_s}{N_\Delta + i \cdot \sqrt{3} \cdot \frac{N_R \cdot N_s}{N_X}}\right) \cdot I_{SB} = K \cdot I_{SB} \ (76)$$

$$N_s \cdot I_{SC} + N_s \cdot \left(I_{SC} - i \cdot \frac{N_R}{N_X} \cdot \sqrt{3} \cdot I_{\Delta C}\right) = N_\Delta \cdot I_{\Delta C} \Rightarrow 2 \cdot N_s \cdot I_{SC} - i \cdot \frac{N_R \cdot N_s}{N_X} \cdot \sqrt{3} \cdot I_{\Delta C} = N_\Delta \cdot I_{\Delta C} \Rightarrow$$

$$I_{\Delta C} = \left(\frac{2 \cdot N_s}{N_\Delta + i \cdot \sqrt{3} \cdot \frac{N_R \cdot N_s}{N_X}}\right) \cdot I_{SC} = K \cdot I_{SC} \ (77)$$

Again, using Eqs. (54), (55) and (56) and combining with (75), (76) and (77) I_{LA}, I_{LB} and I_{LC} can be expressed in terms of I_{SA}, I_{SB}, I_{SC}, N_S, N_Δ, N_R and N_X:

$$N_s \cdot I_{SA} + N_s \cdot I_{LA} = N_\Delta \cdot K \cdot I_{SA} \Rightarrow I_{LA} = \left(\frac{N_\Delta}{N_S} \cdot K - 1\right) \cdot I_{SA} = \left[\frac{N_\Delta}{N_S} \cdot \left(\frac{2 \cdot N_s}{N_\Delta + i \cdot \sqrt{3} \cdot \frac{N_R \cdot N_s}{N_X}}\right) - 1\right] \cdot I_{SA} \Rightarrow$$

$$I_{LA} = \left(\frac{1 - i \cdot \sqrt{3} \cdot \frac{N_R \cdot N_s}{N_X \cdot N_\Delta}}{1 + i \cdot \sqrt{3} \cdot \frac{N_R \cdot N_s}{N_X \cdot N_\Delta}}\right) \cdot I_{SA} \quad (78)$$

$$N_s \cdot I_{SB} + N_s \cdot I_{LB} = N_\Delta \cdot K \cdot I_{SB} \Rightarrow I_{LB} = \left(\frac{N_\Delta}{N_S} \cdot K - 1\right) \cdot I_{SB} = \left[\frac{N_\Delta}{N_S} \cdot \left(\frac{2 \cdot N_s}{N_\Delta + i \cdot \sqrt{3} \cdot \frac{N_R \cdot N_s}{N_X}}\right) - 1\right] \cdot I_{SB} \Rightarrow$$

$$I_{LB} = \left(\frac{1 - i \cdot \sqrt{3} \cdot \frac{N_R \cdot N_s}{N_X \cdot N_\Delta}}{1 + i \cdot \sqrt{3} \cdot \frac{N_R \cdot N_s}{N_X \cdot N_\Delta}}\right) \cdot I_{SB} \quad (79)$$

$$N_s \cdot I_{SC} + N_s \cdot I_{LC} = N_\Delta \cdot K \cdot I_{SC} \Rightarrow I_{LC} = \left(\frac{N_\Delta}{N_S} \cdot K - 1\right) \cdot I_{SC} = \left[\frac{N_\Delta}{N_S} \cdot \left(\frac{2 \cdot N_s}{N_\Delta + i \cdot \sqrt{3} \cdot \frac{N_R \cdot N_s}{N_X}}\right) - 1\right] \cdot I_{SC} \Rightarrow$$

$$I_{LC} = \left(\frac{1 - i \cdot \sqrt{3} \cdot \frac{N_R \cdot N_s}{N_X \cdot N_\Delta}}{1 + i \cdot \sqrt{3} \cdot \frac{N_R \cdot N_s}{N_X \cdot N_\Delta}}\right) \cdot I_{SC} \quad (80)$$

Note that in Eqs. (75), (76) and (77), there is a division between two conjugate phasors, which leads to a phasor:

$$\left(\frac{1 - i \cdot \sqrt{3} \cdot \frac{N_R \cdot N_s}{N_X \cdot N_\Delta}}{1 + i \cdot \sqrt{3} \cdot \frac{N_R \cdot N_s}{N_X \cdot N_\Delta}}\right) = | 1 | \cdot e^{i\left(2 \cdot atg\left[\xi \cdot \sqrt{3} \cdot \frac{N_S \cdot N_x}{N_\Delta \cdot N_H}\right]\right)} \quad (81)$$

This is consistent with the fact that for a symmetrical PST, the magnitudes of I_{SA}, I_{SB}, I_{SC} are equal to the magnitudes of I_{LA}, I_{LB} and I_{LC} respectively.

Under balanced operation and taking currents from the source terminal as known phasors, the phasor currents from the delta, regulation and excitation windings and the line terminal of the symmetrical PST can be expressed as:

$$I_{SA_{DUAL\_CORE\_ASYM}} = | I_{SA_{DUAL_{CORE_{ASYM}}}} | \cdot e^{i(\omega t + \varphi)} \quad (82)$$

$$I_{SB_{DUAL\_CORE\_ASYM}} = I_{SA_{DUAL_{CORE_{ASYM}}}} \cdot e^{i\left(\frac{2\pi}{3}\right)} \quad (83)$$

$$I_{SC_{DUAL\_CORE\_ASYM}} = I_{SA_{DUAL_{CORE_{ASYM}}}} \cdot e^{i\left(\frac{\pi}{3}\right)} \quad (84)$$

$$I_{LA_{DUAL\_CORE\_SYM}} = I_{SA_{DUAL\_CORE\_SYM}} \cdot e^{i\delta} \quad (85)$$

$$I_{LB_{DUAL\_CORE\_SYM}} = I_{LA_{DUAL\_CORE\_SYM}} \cdot e^{i\frac{2\pi}{3}} \quad (86)$$

$$I_{LC_{DUAL\_CORE\_SYM}} = I_{LA_{DUAL\_CORE\_SYM}} \cdot e^{i\frac{\pi}{3}} \quad (87)$$

$$I_{XA_{DUAL\_CORE\_SYM}} = i \cdot \sqrt{3} \cdot K \cdot I_{SA_{DUAL\_CORE\_SYM}} \quad (88)$$

$$I_{XB_{DUAL\_CORE\_SYM}} = I_{XA_{DUAL\_CORE\_SYM}} \cdot e^{i\frac{2\pi}{3}} \quad (89)$$

$$I_{XC_{DUAL\_CORE\_SYM}} = I_{XA_{DUAL\_CORE\_SYM}} \cdot e^{i\frac{\pi}{3}} \quad (90)$$

$$I_{HA_{DUAL\_CORE\_SYM}} = I_{LA_{DUAL\_CORE\_SYM}} - I_{SA_{DUAL\_CORE-SYM}} \quad (91)$$

$$I_{HB_{DUAL\_CORE\_SYM}} = I_{HA_{DUAL\_CORE\_SYM}} \cdot e^{i\frac{2\pi}{3}} \quad (92)$$

$$I_{HC_{DUAL\_CORE\_SYM}} = I_{HA_{DUAL\_CORE\_SYM}} \cdot e^{i\frac{\pi}{3}} \quad (93)$$

Where:

$$\delta = 2 \cdot atg\left[\xi \cdot \sqrt{3} \cdot \frac{N_s \cdot N_x}{N_\Delta \cdot N_H}\right]$$

$$K = \frac{1}{\frac{N_\Delta}{N_s} - i \cdot \xi \cdot \sqrt{3} \cdot \frac{N_R}{N_X}}$$

$$\xi = \pm 1 \rightarrow ARS\ in\ advance\ (+1)\ or\ retard\ position\ (-1)$$

3 Protection functions and schemes of phase shifting transformers

Main protection function of phase shifting transformers

3.1.1 Non-adaptive 87PST protection function

The classic approach to protecting dual-core PSTs is based on the use of at least two different
3.1 differential protection systems:

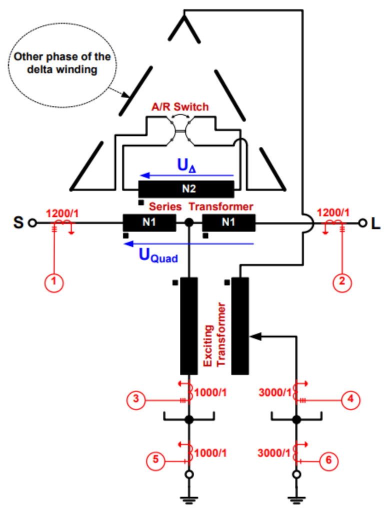

Fig 6: Traditional IEEE Scheme [5]

Figure 11. Example of a traditional Institute of Electrical and Electronics Engineers (IEEE) scheme for phase shifting transformer protection [3]

- 87P primary winding differential:

  There is a differential protection that covers the primary windings of the serial core and the primary windings of the excitation core.

  As there is an electrical connection between the serial and excitation windings, Kirchhoff's current law (KCL) protection applies. This protection does not require any current compensation, as it covers the primary windings; therefore, the transformer connection group and turn ratio do not apply to set up this function.

  This function is also not affected by inrush currents, overexcitation currents or serial core saturation due to close-in external faults to the PST.

  As KCL is not able to detect turn-to-turn faults, the detection of these faults relies on a 63 sudden pressure relay (63SPR) or a Buchholz relay.

- 87S secondary winding differential:

  This is differential protection for the secondary winding of the excitation unit and ampere-turn-balanced (ATB) protection for the serial unit.

  Therefore, it provides protection for turn-to-turn faults on serial windings and protection to winding ground faults in the regulating winding of the excitation core (not for all the winding turns to ground faults, so there might be a lack of sensitivity for close to the neutral connection winding to ground faults).

Note that saturation of the serial core can cause maloperation during external close-in PST faults.

3.1.2 SELF-ADAPTIVE 87PST PROTECTION FUNCTION

There are new approaches to protecting PSTs that simplify protection schemes. These algorithms use voltages and currents from the load and source sides to balance currents in a self-adaptive manner [4].

The need for buried CTs, a tap changer and the ARS position is removed as it only requires the installation of CTs and at least one VT in the source and line sides:

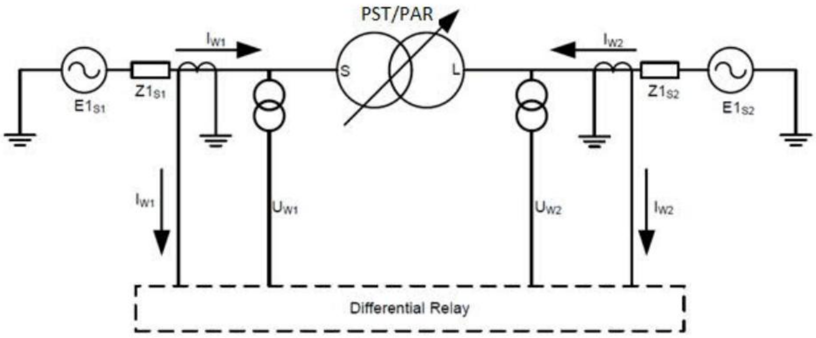

FIGURE 12. DIFFERENTIAL PROTECTION FOR AN ARBITRARY PHASE-SHIFTING TRANSFORMER [4]

Before the calculation of differential currents, the algorithm estimates the transformation ratio and phase-angle shift using positive-sequence currents and the selected voltages from the source and load ends:

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

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

FIGURE 13. DIFFERENTIAL CURRENT CALCULATION USING THE ESTIMATION OF THE TRANSFORMATION RATIO AND PHASE SHIFT ANGLE [4]

The applied matrices depend on the phase-angle shift and the need for zero-sequence suppression.

3.1.3 RESTRICTED EARTH FAULT DIFFERENTIAL PROTECTION 87R

Phase-to-ground faults located close to the winding ground connection result in small short-circuit currents, making fault detection challenging for protection devices [6].

Restricted earth fault differential protection function (87R) measures the zero-sequence currents in high/low voltage terminal windings (composing $I_{Residual}$) and the neutral current (namely, the operation quantity $I_{Operation}$). These quantities are used to implement a percentage differential protection [5][6].

Therefore, this protection function requires a CT located in the star grounding of the Wye-connected windings.

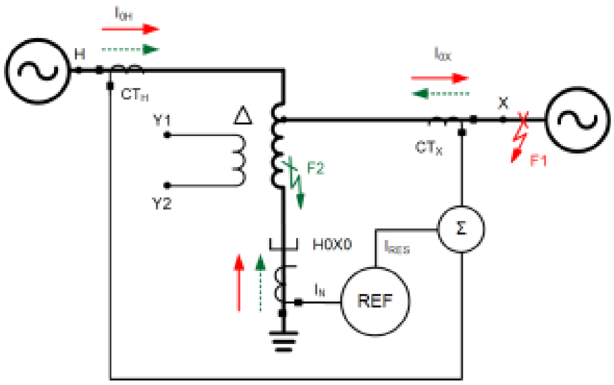

FIGURE 14. EXAMPLE OF AUTOTRANSFORMER EXPECTED ZERO-SEQUENCE CURRENTS FOR EXTERNAL/INTERNAL FAULTS [5]

3.1.4 EARTH TANK PROTECTION

Earth tank protection is used as the main transformer protection. The purpose of this protection is to detect all current flowing from the active part to the earth through the tank. Therefore, this protection detects only internal faults with a connection to the tank, whereas interturn faults are not detected.

The installation of an earth tank protection requires that the transformer be connected to ground via only one lead. A current transformer measures the current flowing from the tank to the earth in the lead, as shown in Figure 15:

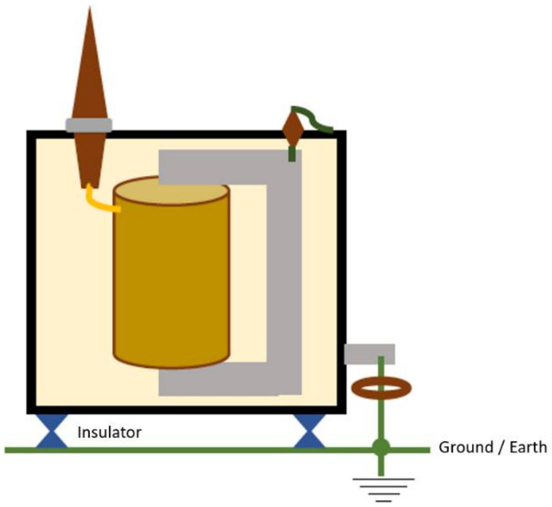

FIGURE 15. EXAMPLE OF AN EARTH TANK DESIGN (HV PART)

An instantaneous overcurrent element of a protective relay is connected to the current transformer and issues a trip command to the circuit breaker in the event of an earth-to-tank fault.

The power transformer must be connected to ground with only one lead. Otherwise, the fault current will flow to earth through multiple paths, and the current measured by the protective relay will not be

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sufficient to establish a trip command. To achieve this goal, the power transformer must be insulated from ground, as shown in Figure 15.

3.2 BACKUP PROTECTION FUNCTIONS OF PHASE SHIFTING TRANSFORMERS

3.2.1 21 DISTANCE PROTECTION

Distance protection (21) is used as a backup transformer protection (distance zones set in forward, reaching up to 80% of PST impedance, instantaneous time delay) and can provide a backup for busbar (distance zones set in reverse, overreaching the busbar, time-delayed operation) or line faults (distance zones set in reverse, over/underreaching the line, time-delayed operation), preventing the PSTs being connected to external short circuit in case of busbar protection or line protection failures.

It can be implemented on the source and line sides depending on the presence of VTs. The permissive overreaching transfer trip (POTT) teleprotection overreach scheme can be used to trigger an instantaneous trip in the event of internal fault detection.

A bypass circuit breaker is usually installed for PST maintenance, so the overhead line (OHL) can be energised while PST is out of service. In such cases, the PST’s impedance is removed from the system.

The reach of the distance zones in direction to the PST must take into account the minimum short-circuit reactance of the PST (X_{sc-PST}) that is dependent on the tap position of the regulating winding of the excitation unit) and the bypass (in case of existing) to avoid overreaching line faults or busbar faults.

The distance protections of the remote end of the line connected to the PST must also take X_{sc-PST} and bypass into account to avoid overreaching.

The need to protect all areas of the PST/bypass/line complex with at least two protections and possible backup is even more stringent in extra-high voltage (EHV) applications or in system schemes that include a bay dedicated to the bypass or line on more busbars.

Figure 16 illustrates a typical situation with a redundant protection system for all zones, applying the criteria described above.

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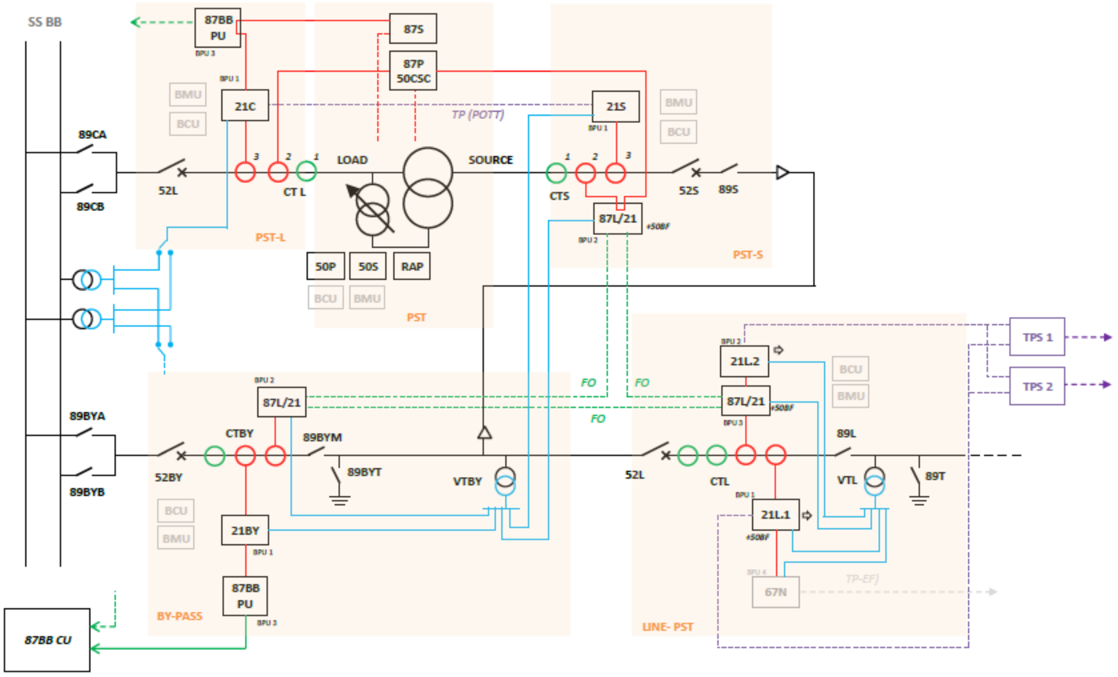

FIGURE 16. SINGLE-LINE SCHEME FOR PST APPLICATION IN A DOUBLE BB SS WITH A BYPASS BAY

Table 1 describes in detail the settings adopted and the commands provided for the various base power units (BPUs) that make up the entire protection system to have each part of the system protected with two protections.

Units	BPU	Protective function	Impedance zone (21)	Direction zone	Settings	Delay time	Start 50BF	Command
PST LOAD SIDE (PST-L)	BPU 1	Impedance Protection 21	Z1	Forward= PST	80% Zcc min _PST-	150 ms	Start 50BF BU 87BB (BPU3)	PST Block
			Z5	Forward = PST	125% di Zcc_PST- act. with Rx PT (POTT)	0 ms	Start 50BF BU 87BB (BPU3)	PST Block
			Z2	Reverse= SS BusBar	50% Z_L connect BB with $Z_{L<}$	300 ms	No	Trip 52PST-L
			Z3	Reverse= SS BusBar	120% Z_L connect BB with $Z_{L>}$	1,200 ms	No	Trip 52PST-L
			Z4	Reverse= SS BusBar	120% Z_L connect BB with $Z_{L>}$ x Kinf	3,500 ms	No	Trip 52PST-L
			Z5	Forward = PST	120%Zcc PST	4,000 ms	Start 50BF BU 87BB (BPU3)	Trip 52PST-L
	BPU 3	BU 87BB	-	-	-	-	-	Trip 52PST-L & 52PST-S
PST SOURCE SIDE (PST-S)	BPU 1	Impedance Protection 21	Z1	Forward = PST	70% Zcc min PST-	150 ms	Start 50BF BU 87BB (BPU3)	PST Block
			Z5	Forward = PST	125% di Zcc_PST- act. with Rx PT (POTT)	0 ms	Start 50BF BU 87BB (BPU3)	PST Block

			Z2	Reverse = Line/By	50% Z_{Lpst}	150 ms	-	Trip 52PST-L & 52PST-S
			Z3	Reverse = Line/By	120% Z_{Lpst}	1,200 ms	-	Trip 52PST-S
			Z4	Reverse = Line/By	=Z4 L_{pst}	3,500 ms	-	Trip 52PST-S
			Z5	Forward = PST	120%Xcc PST	4,000 ms	Start 50BF 87in BPU2	Trip 52PST-S
	BPU 2	87L -3 Ends (PST-L/BY-L_{pst})	-	Prot. Obj. = Line/By	-	0 ms	-	Trip 52PST-L & 52PST-S
		Impedance Protection 21 (backup 87L)	Z1	Forward = Line/By	2 ohm – active only with off 87L	170 ms	-	Trip 52PST-L & 52PST-S
			Z2	Forward = Line/By	10 ohm Use only for SOTF Function	5 s	-	Trip 52PST-L & 52PST-S
			Z3	OFF	-	-	-	-
			Z4	OFF	-	-	-	-
			Z5	OFF	-	-	-	-
		50 BF	BF	BF1	10% $I_R L_{pst}$ A	120 ms	Start by Zone dir. To PST	Trip 52PST-L & 52PST-S
Bypass PST	BPU 1	Impedance Protection 21	Z1	Forward = Line/By	50% di ZL_{pst}	170 ms	Start 50BF BU 87BB (BPU3)	Trip 52BY -
			Z2	Forward = Line/By	80% di ZL (use only for SOTF Function)	5 s	Start 50BF BU 87BB (BPU3))	
			Z3	Forward = Line/By	120% di ZL_{pst}	600 ms	Start 50BF BU 87BB (BPU3)	Trip 52BY
			Z4	Forward = Line/By	125% Z4 L_{pst}	3,500 ms	Start 50BF BU 87BB (BPU3))	Trip 52BY
			Z5	Reverse= SS BusBar	120% Z_L connect BB with $Z_{L>}$ x Kinf	4,000 ms	-	Trip 52BY
	BPU 2	87L -3 Ends (PST-L/BY-L_{pst})	-	Prot. Obj. = Line/By	-	0 ms	Start 50BF BU 87BB (BPU3))	Trip 52BY
		Impedance Protection 21 (backup 87L)	Z1	Forward = Line/By	2 ohm – active only with off 87L	170 ms	Start 50BF BU 87BB (BPU3))	Trip 52BY
			Z2	Forward = Line/By	2 ohm (use only for SOTF Function)	5 s	-	Trip 52BY
			Z3	OFF	-	-	-	-
			Z4	OFF	-	-	-	-
			Z5	OFF	-	-	-	-
	BPU 3	BU 87BB	-	-	-	-	-	Scatto 52BY

TABLE 1: EXAMPLE SETTINGS FOR DISTANCE PROTECTION WITH AND WITHOUT A BYPASS CIRCUIT BREAKER

3.2.2 50/51 PHASE OVERCURRENT PROTECTION

Instantaneous phase overcurrent protection (50) is usually applied to back up the 87T functions.

It must be considered that X_{sc-PST} varies with the tap position and in cases where X_{sc-PST} is close to zero, achieving selectivity between internal and external faults is very difficult.

The pickup current must be higher than the expected maximum PST inrush current, or set a time delay to block the function from inrush detection.

As in power transformers, phase-time overcurrent protection (51) might be coordinated with the PST damage curve to allow a certain level of PST overload.

3.2.3 50N/51N NEUTRAL OVERCURRENT PROTECTION

Instantaneous or time-neutral overcurrent protections (50N/51N) are commonly used as backup protections for power transformers.

Because ground-fault current flowing from power transformers' earthing can be caused by either internal or external faults, the use of time-delayed elements for neutral overcurrent protection is preferred.

As explained in [2], the magnitude of the zero-sequence impedance depends on the type and construction of the PST, with high zero-sequence impedance in shell-type or five-limb excitation cores in a dual-core PST, and low zero-sequence impedance in three-limb excitation cores in a dual-core PST.

Therefore, the application of neutral overcurrent elements is directly affected by the type and construction of the PST.

In a dual-core PST, 51N elements applied on the ground CT of the excitation winding can be implemented as backup protection for ground faults, taking into account whether PST acts as a source of ground-fault current for external fault coordination. For the regulation winding, 51N elements can also be applied, with no need to coordinate for external ground faults.

3.2.4 24 OVERFLUXING PROTECTION

The overexcitation protection function of transformers is designed to prevent damage from excessive excitation currents. This function does not operate in the event of a transformer fault but is intended to prevent a possible fault caused by overexcitation of the magnetic core.

The transformer core can typically be overexcited under conditions such as high voltage. This saturation results in an increase in the magnetising current, which can cause severe overheating and mechanical stress in localised areas of the magnetic core, potentially leading to core damage, insulation breakdown or even complete transformer failure. Overexcitation protection is implemented to prevent these detrimental effects and ensure the transformer's longevity and reliability.

The overexcitation protection function is also closely tied to the electrical supply frequency, as the excitation current in a transformer is directly influenced by the frequency of the applied voltage.

In normal operation, transformers are designed to operate at a specific frequency, which corresponds to the rated magnetic flux and excitation current. However, when the frequency deviates from the rated value, the transformer's magnetic flux is also affected. Lower frequency results in higher excitation current, which can lead to transformer core damage from overheating or excessive magnetisation.

In the context of overexcitation protection, the function monitors the voltage-to-frequency (V/f) ratio to detect conditions that could lead to overexcitation. When the V/f ratio exceeds a predetermined threshold, which could occur if the frequency drops or the voltage grows significantly, the protection relay activates to prevent overexcitation. By incorporating the V/f ratio into the overexcitation protection, the transformer is protected against the harmful effects of abnormal frequency and voltage conditions, ensuring proper operation even during transient events or irregular operating conditions.

The thermal characteristic curve can be user-defined and is based on a replica of the PST's thermal behaviour. If the threshold value of the characteristic is exceeded, the integration process for the thermal characteristic begins. When the time as a function of V/f is reached, tripping is initiated. The more the threshold is overreached, the faster the tripping is initiated. If the value drops below the pickup threshold, the thermal characteristics curve is reverted. The parametrised cooling time reduces the thermal storage to zero according to the cooling characteristic.

Phase-shifting transformers are specifically designed to modify the phase angle between the primary and secondary voltage. The transformer's design requires careful consideration of not only the voltage-to-frequency ratio (V/f) but also the phase shift.

3.2.4.1 Serial core overexcitation protection (24.1)

The purpose of this function is to detect the state of overexcitation (maximum flux) of the series unit, with the consequence of rapid overheating of the core due to the high iron losses. The protection operates by analysing the relationship between the existing voltage difference across the two sides of the series unit and the frequency. The detection of overexcitation based on indirect methods (e.g., the presence of a fifth harmonic) within differential protection equipment, which is typically used to avoid unwanted tripping of function 87, is not considered reliable for this purpose due to the size, characteristics and uniqueness of the PST.

The measured voltage for the 24.1 function is proportional to the vector difference between the two voltages (obviously on the same phase) present on both sides of the PST.

Two auxiliary isolation/adaptation voltage transformers, fed by secondary protection voltage transformers (VT1 and VT2) at both ends of the relevant PST, are therefore provided.

The secondary windings of the auxiliary transformers are appropriately connected in series to supply the voltage input for the 24.1 function. The auxiliary voltage transformer transformation ratio is designed to produce a 100/√3 V output voltage in the presence of the maximum nominal phase shift of the relevant PST.

The protection function 24.1 is blocked in the absence of one of the two measured voltages or in the event of tripping of the VT miniature circuit breaker.

3.2.4.2 Excitation core overexcitation protection V/F (24.2)

The purpose of this protection, as with the previous function, is to detect the state of overexcitation (maximum flux) of the exciting unit, with the consequence of rapid core overheating in the event of extraordinarily high network voltage. It operates by direct analysis of the relationship between voltage (in this case, the voltage applied to the exciting windings) and frequency.

Since the voltage at the ends of the exciting windings is not available, the network voltage (on the PST load side) is used as the measuring voltage (as shown in the single-line diagram).

The voltage actually present on the exciting windings is not easily calculated (this would have been the proper parameter for the 24.2 function), even with current compensation or other algorithms. The setting will therefore be referred to as the PST no-load operation mode (practically, the voltage on the exciting windings corresponds to the network voltage).

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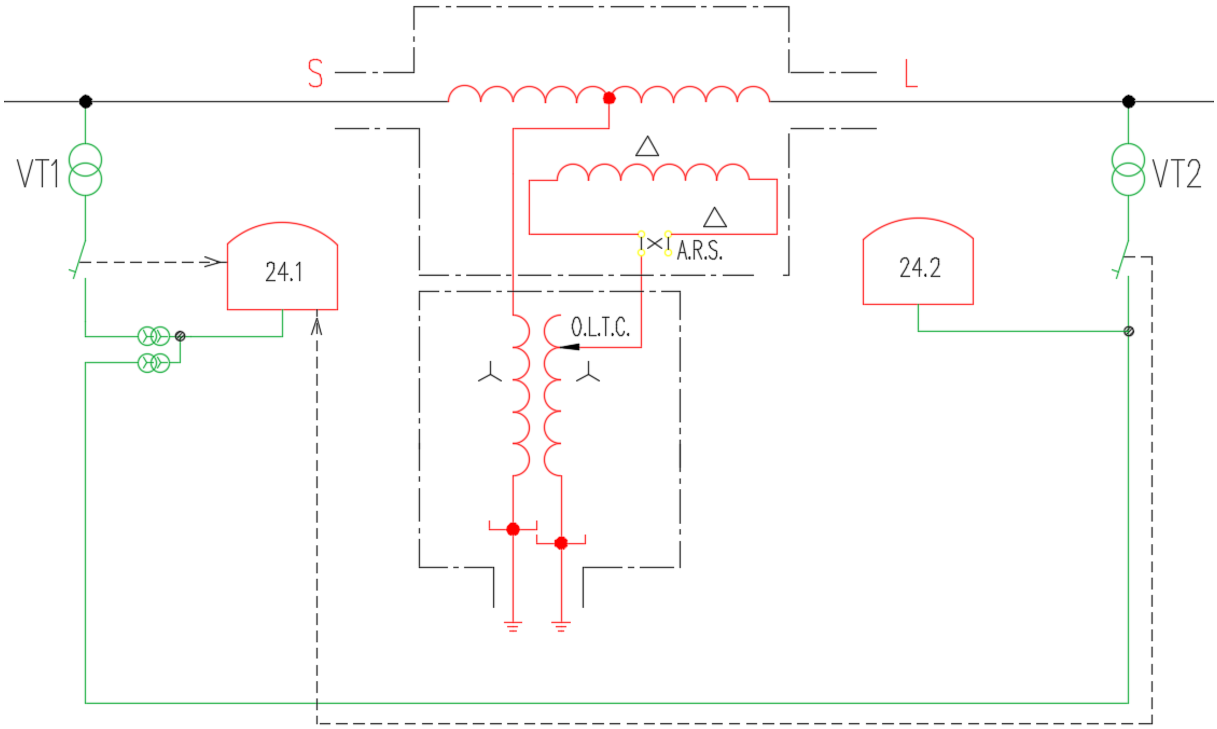

FIGURE 17. OVERFLUXING PROTECTION IN A DUAL-CORE PHASE SHIFTING TRANSFORMER

3.3 PROTECTION SCHEMES OF SINGLE-CORE PHASE SHIFTING TRANSFORMERS

As previously presented in Section 3.1.1, the general protection scheme for PSTs in a single-core configuration can use only one differential protection scheme, with source- and load-side CTs.

The design of PST differential protection systems must tolerate a continuous phase-angle shift between the source and load currents during power flow.

If no CTs are available, the differential relay's slope setting must accommodate the exciting current component at the full PST shift angle. Figure 18 shows the differential protection of a single-core PST design.

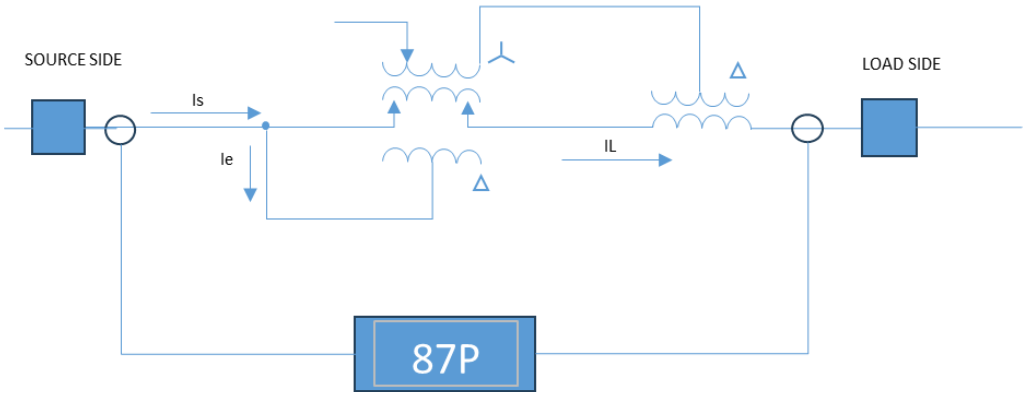

FIGURE 18. SINGLE-LINE SCHEME OF SINGLE-CORE PHASE SHIFTING TRANSFORMER PROTECTION (EXTENDED DELTA USE EXTERNAL CTS)

The minimum protective configuration shown has certain limitations, which must be carefully studied to avoid misoperation of the protection under load or through-fault conditions.

For balanced load or three-phase fault conditions, the phase shift of the phase angle regulator (PAR) transformer causes an error current to appear in the overall differential relay. The current error is proportional to the through current and varies with the phase shift.

The magnitude of the error current is:

$$I_d = 2/\sqrt{3} \cdot I_{thru} \cdot \sin\left(\frac{\delta}{2}\right) \quad (94)$$

Where δ is the angle between the source and load-side currents and I_{thru} is the magnitude of the source or load current.

PSTs operate by mixing currents and voltages from the three phases to produce an apparent phase shift.

For single-phase through currents, the PST does not achieve its rated phase shift. Instead, it produces a mixing of the single-phase current into an unbalanced three-phase current.

This effect can produce through-fault conditions in which an overall differential relay sees current in only one of its two input circuits, leaving it vulnerable to misoperation.

Unbalanced currents in PSTs can be analysed by means of symmetrical components:

- Positive-sequence currents are shifted by the set phase-angle shift of the PST.
- Negative-sequence currents are shifted opposite to the set phase shift.
- Zero-sequence currents are not shifted at all.

The problems illustrated above lead to the use of only CTs external to the PST, with desensitisation applied to 87P to make its operation safe. It is necessary to use gas and pressure detection systems for internal failures.

Usually, for medium-high power PSTs (which are therefore more expensive) and to increase the degree of safety and fault positioning detection, manufacturers install the CTs inside for each winding, as shown in Figure 19.**Error! Reference source not found.**

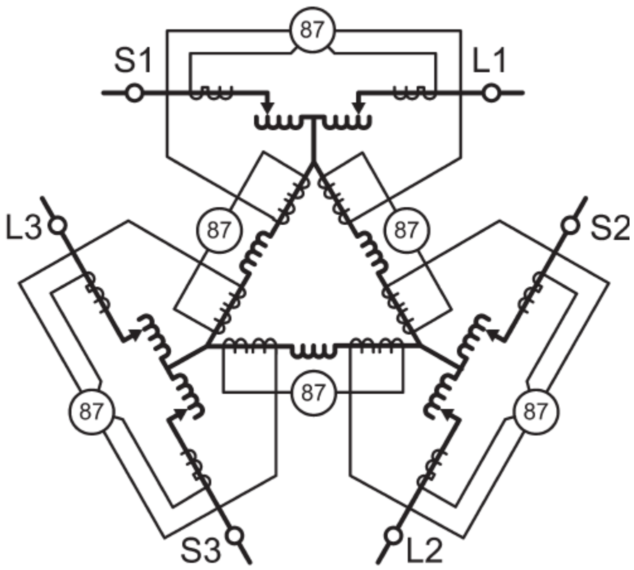

FIGURE 19. SINGLE-LINE SCHEME OF SINGLE-CORE PHASE SHIFTING TRANSFORMER PROTECTION (EXTENDED DELTA USE INTERNAL CTS) [1]

The system is based on both main protection and backup, using percent-restraint KCL-type differential relays (87) with a total of six single-phase differential zones, each protecting a single-phase winding with overlap at the delta winding.

Figure 20 illustrates the protection system adopted for a symmetrical single-core PST, with the coverage areas of each 87 function highlighted (diagram for one phase).

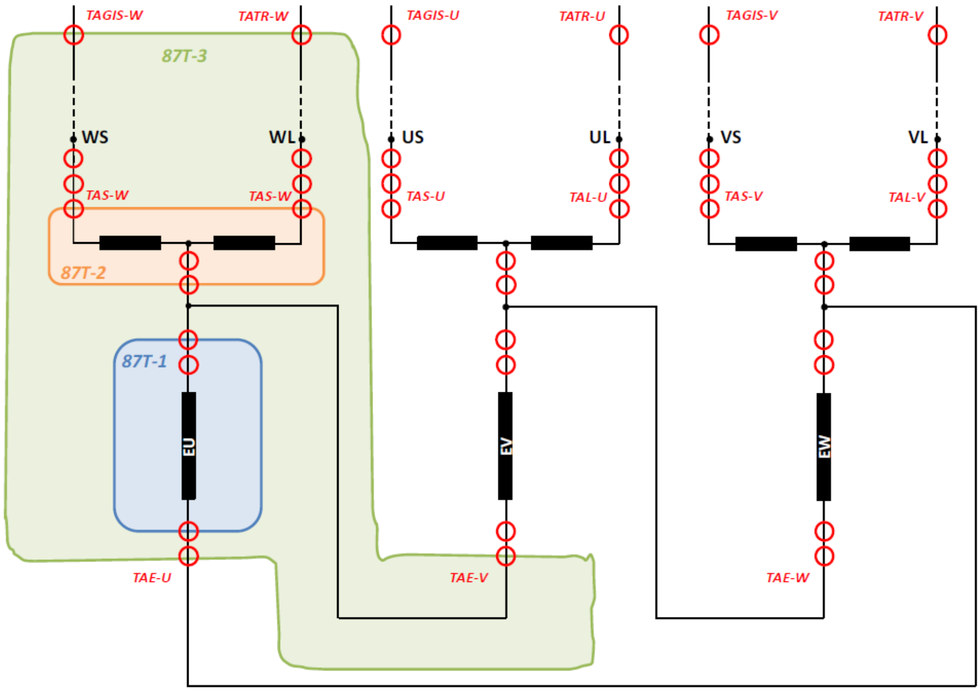

FIGURE 20. SINGLE-LINE SCHEME OF SINGLE-CORE PHASE SHIFTING TRANSFORMER PROTECTION COVER ZONES

Another possibility to protect the single-core PST is to use the tap changer position to reduce the number of currents and 87T functions, thereby simplifying the scheme, as explained in [7].

In this case, only source and load currents are needed, and the tap changer position is used to compensate for the phase shift angle and therefore balance the differential currents.

3.4 PROTECTION SCHEMES OF DUAL-CORE PHASE SHIFTING TRANSFORMERS

Figure 21 shows a simplified protection scheme that can be applied for either a dual-core symmetrical or asymmetrical PST.

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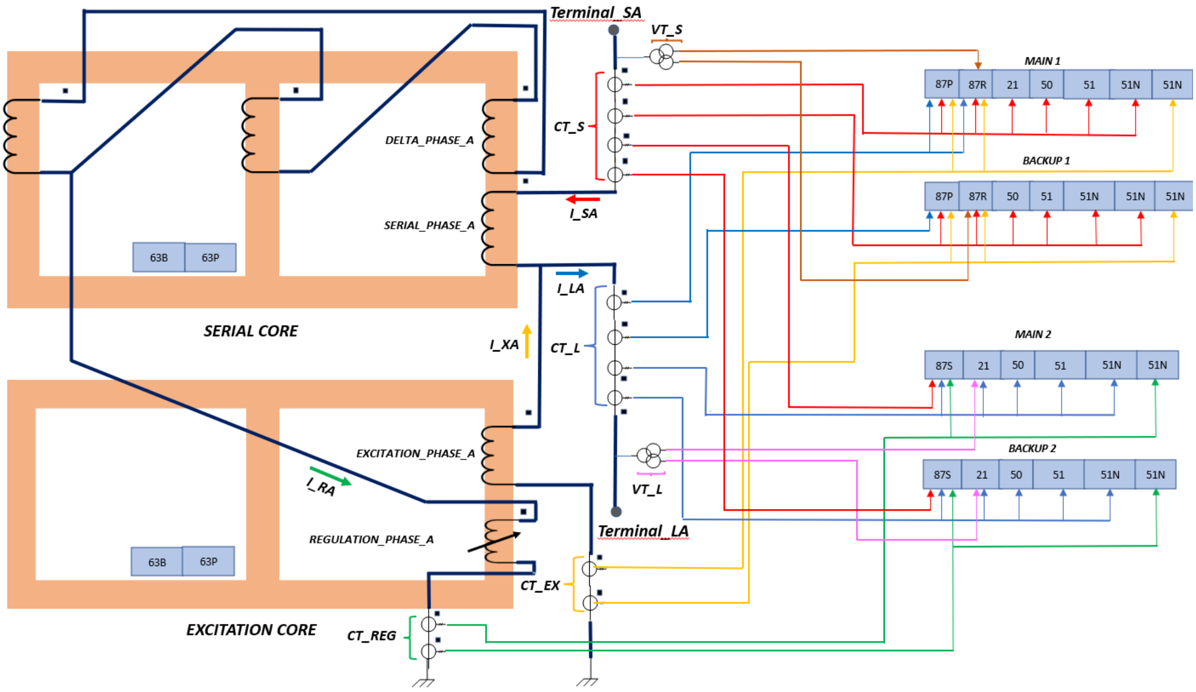

FIGURE 21. DUAL-CORE PHASE SHIFTING TRANSFORMER PROTECTION SCHEME

Four different protection systems are required to achieve redundancy:

- Main 1 and Backup 1:

These systems include the 87P and 87R for the serial and excitation windings, respectively, as the main protection functions. As backup protection functions, 21, 50, 51 and 51N are implemented.

- Main 2 and Backup 2:

These systems include the 87S for ATB for the serial winding and KCL for the regulation winding as the main protection functions. As backup protection functions, 50, 51 and 51N are implemented.

Electromechanical relays 63B and 63P are usually integrated into power transformers and complete the protection scheme.

4 APPLICATION EXAMPLE OF DUAL-CORE ASYMMETRICAL PHASE SHIFTING TRANSFORMER 87S PROTECTION SETTINGS

4.1 PHASE SHIFTING TRANSFORMER CHARACTERISTICS

For this example, an asymmetrical PST with the following characteristics is considered:

$S_{Rated-SERIAL\ CORE} = 1{,}270\ MVA$

$U_{Rated-SERIAL\ CORE} = 400kV$

$N_S = 106\ turns$

$N_\Delta = 120\ turns$

$S_{Rated-EXCITATION\ CORE} = 230\ MVA$

$U_{Rated-EXCITATION\ CORE} = 46.1kV$

$N_R = 17x6\ turns = 102\ turns \rightarrow 17\ taps - 6\ turns/tap$

$N_X = 885\ turns$

The location and the star grounding of CTs are according to**Error! Reference source not found.** Figure 21 for the 87S, being the CT ratio for $CT_S, CT_L, CT_{Reg} = 3{,}000/5\ A$.

The equations in Section 2.1.2.1 provide the primary current phasors for different power flows and tap positions with ARS in the advance or retard position:

TAP POSITION	POWER FLOW [PU]	I_SA		I_RA		I_XA		I_LA	
		MODULE [A]	PHASE [Deg]	MODULE [A]	PHASE [Deg]	MODULE [A]	PHASE [Deg]	MODULE [A]	PHASE [Deg]
1	0.3	549.926	0	841.375	-90	5.843	90	549.957	0.609
	0.5	916.544	0	1402.292	-90	9.738	90	916.595	0.609
	0.75	1374.815	0	2103.438	-90	14.607	90	1374.893	0.609
	1	1833.087	0	2804.583	-90	19.476	90	1833.191	0.609
	1.25	2291.359	0	3505.729	-90	24.345	90	2291.488	0.609
8	0.25	458.272	0	701.146	-90	38.953	90	459.924	4.858
	0.5	916.544	0	1402.292	-90	77.905	90	919.849	4.858
	0.75	1374.815	0	2103.438	-90	116.858	90	1379.773	4.858
	1	1833.087	0	2804.583	-90	155.81	90	1839.697	4.858
	1.25	2291.359	0	3505.729	-90	194.763	90	2299.621	4.858
17	0.25	458.272	0	701.146	-90	82.774	90	465.687	10.239
	0.5	916.544	0	1402.292	-90	165.548	90	931.374	10.239
	0.75	1374.815	0	2103.438	-90	248.322	90	1397.062	10.239
	1	1833.087	0	2804.583	-90	331.097	90	1862.749	10.239
	1.25	2291.359	0	3505.729	-90	413.871	90	2328.436	10.239

FIGURE 22. PHASE A CURRENTS IN ADVANCE POSITION

TAP POSITION	POWER FLOW [PU]	I_SA		I_RA		I_XA		I_LA	
		MODULE [A]	PHASE [Deg]	MODULE [A]	PHASE [Deg]	MODULE [A]	PHASE [Deg]	MODULE [A]	PHASE [Deg]
1	0.3	549.926	0	841.375	-90	5.843	-90	549.957	-0.609
	0.5	916.544	0	1402.292	-90	9.738	-90	916.595	-0.609
	0.75	1374.815	0	2103.438	-90	14.607	-90	1374.893	-0.609
	1	1833.087	0	2804.583	-90	19.476	-90	1833.191	-0.609
	1.25	2291.359	0	3505.729	-90	24.345	-90	2291.488	-0.609
8	0.25	458.272	0	701.146	-90	38.953	-90	459.924	-4.858
	0.5	916.544	0	1402.292	-90	77.905	-90	919.849	-4.858
	0.75	1374.815	0	2103.438	-90	116.858	-90	1379.773	-4,858
	1	1833.087	0	2804.583	-90	155.81	-90	1839.697	-4,858
	1.25	2291.359	0	3505.729	-90	194.763	-90	2299.621	-4,858
17	0.25	458.272	0	701.146	-90	82.774	-90	465.687	-10,239
	0.5	916.544	0	1402.292	-90	165.548	-90	931.374	-10,239

	0.75	1374.815	0	2103.438	-90	248.322	-90	1397.062	-10,239
	1	1833.087	0	2804.583	-90	331.097	-90	1862.749	-10,239
	1.25	2291.359	0	3505.729	-90	413.871	-90	2328.436	-10,239

FIGURE 23. PHASE A CURRENTS IN RETARD POSITION

4.2 87S SETTING CALCULATION

In an 87T power transformer, a winding serves as the reference, and the phasor currents are then compensated relative to it. This compensation is usually based on the rated power, rated voltage and transformer group connection.

Because the 87S protection function covers windings of different power transformers, it is more difficult to establish a reference winding and the way the phasor currents are compensated.

In this example, the 87S is a three-winding protection function in which magnitude and phase compensation are applied as explained in Sections 4.2.1 and 4.2.2.

4.2.1 MAGNITUDE COMPENSATION

The objective is that the sum of the magnitudes of the rated currents of the source and line terminals is equal to the magnitude of the rated current that circulates through the regulation winding under balanced conditions.

Although there is only one serial winding per phase, in 87S settings, it is considered as two windings (one for the source terminal and the other for the line terminal).

According to Section 4.1 and taking the source terminal as a reference winding and then its rated voltage as the magnitude used to scale the magnitude of the 87S phasor currents, we obtain:

$$U_{Rated\ Source\ Terminal_{87S}} = 400kV$$

$$U_{Rated\ Line\ Terminal_{87S}} = 400kV$$

$$U_{Referece_{87S}} = U_{Rated\ Source\ Terminal} = 400kV$$

$$I_{Referece_{87S}} = I_{CT\ Rated\ Secondary_{Source}\ Terminal} = 5\ A\ \Rightarrow as\ all\ CTs\ are\ 3000/5\ A$$

$$C_{Magnitud\ I_{Regulation}} = (|\ I_{Rated\ SA_{TAP17}}\ | + |\ I_{Rated\ LA_{TAP17}}\ |)/|\ I_{Rated\ RA}\ | = (1833A + 1833A)/(2804A) = 1.307$$

$$U_{Rated\ Regulation_{87S}} = U_{Rated\ Source\ Terminal} \cdot C_{Magnitud\ I_{Regulation}} = 400kV \cdot 1.307 = 522.8\ kV$$

Therefore, the 87S magnitudes compensated will be calculated as follows (only Phase A is shown for simplicity):

$$|\ I_{SA_{CompPU}}\ | = \frac{U_{Rated\ Regulation_{87S}}}{U_{Rated\ Reference\ Winding}} \cdot \frac{|\ I_{SA_{Secondary}}\ |}{I_{Reference_{87S}}} = \frac{400kV}{400kV} \cdot \frac{|\ I_{SA_{Secondary}}\ |}{5A} = \frac{|\ I_{SA_{Secondary}}\ |}{5A}$$

$$|\ I_{LA_{CompPU}}\ | = \frac{U_{Rated\ Regulation_{87S}}}{U_{Rated\ Reference\ Winding}} \cdot \frac{|\ I_{LA_{Secondary}}\ |}{I_{Reference_{87S}}} = \frac{400kV}{400kV} \cdot \frac{|\ I_{LA_{Secondary}}\ |}{5A} = \frac{|\ I_{LA_{Secondary}}\ |}{5A}$$

$$|\ I_{RA_{CompPU}}\ | = \frac{U_{Rated\ Regulation_{87S}}}{U_{Rated\ Reference\ Winding}} \cdot \frac{|\ I_{RA_{Secondary}}\ |}{I_{Reference_{87S}}} = \frac{400kV \cdot 1.307}{400kV} \cdot \frac{|\ I_{RA_{Secondary}}\ |}{5A} = 1.307 \cdot \frac{|\ I_{RA_{Secondary}}\ |}{5A}$$

4.2.2 PHASE COMPENSATION

According to the star grounding of the CTs, the current phasor diagram (in advance and retard position) under rated and balanced power load flow (from Terminal S to L) is as follows (only Phase A is shown for simplicity):

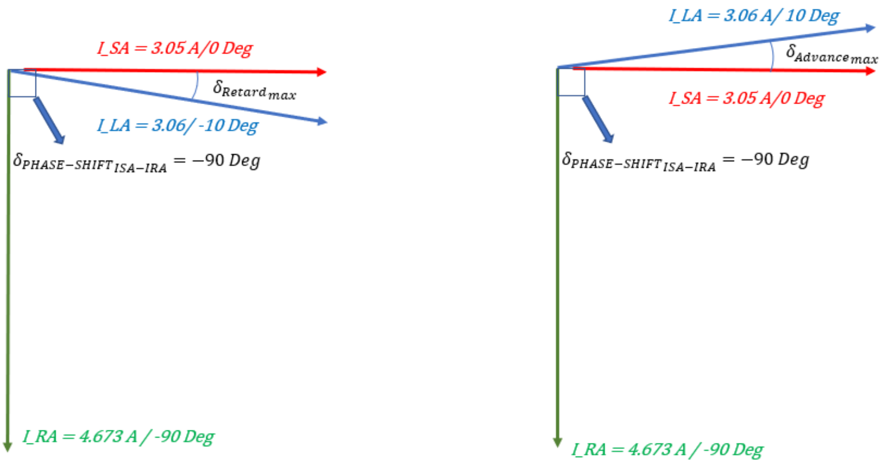

FIGURE 24. PHASOR A CURRENT DIAGRAM IN 87S FUNCTION

Then, the phase compensation to apply to the regulation winding is -90 degrees.

Finally, applying the magnitude compensation explained in Section 4.2.1 and the phase compensation, the phasor currents in 87S under balanced conditions will be:

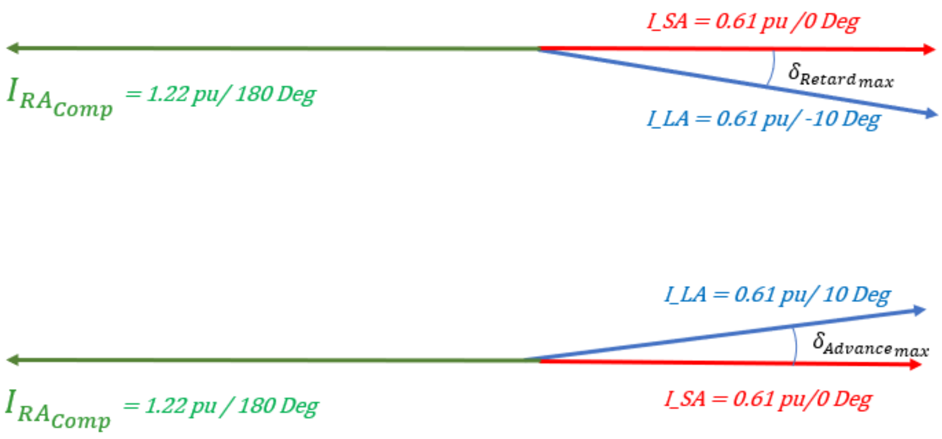

FIGURE 25. PHASE A PHASOR CURRENTS WITH MAGNITUDE AND PHASE COMPENSATION UNDER RATED BALANCED CONDITIONS

Note that the transformer protection devices apply matrix products to make the phase compensation. Therefore, any compensated phasor depends on the phasor currents of the other two phases:

Row	Degrees shift that would be cancelled		Wye	Delta	Double-Delta
0	ABC, 0*30° cw[a]	0°	$1\begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{bmatrix}$ Wye		$\frac{1}{3}\begin{bmatrix}2 & -1 & -1\\ -1 & 2 & -1\\ -1 & -1 & 2\end{bmatrix}$
	ACB, 0*30° ccw[b]	0°			
1	ABC, 1*30° cw	30°		$\frac{1}{\sqrt{3}}\begin{bmatrix}1 & -1 & 0\\ 0 & 1 & -1\\ -1 & 0 & 1\end{bmatrix}$ Delta A-B (DAB)	
	ACB, 1*30° ccw	330°			
2	ABC, 2*30° cw	60°	$1\begin{bmatrix}0 & 0 & -1\\ -1 & 0 & 0\\ 0 & -1 & 0\end{bmatrix}$		$\frac{1}{3}\begin{bmatrix}1 & -2 & 1\\ 1 & 1 & -2\\ -2 & 1 & 1\end{bmatrix}$
	ACB, 2*30° ccw	300°			
3	ABC, 3*30° cw	90°		$\frac{1}{\sqrt{3}}\begin{bmatrix}0 & -1 & 1\\ 1 & 0 & -1\\ -1 & 1 & 0\end{bmatrix}$	
	ACB, 3*30° ccw	270°			
4	ABC, 4*30° cw	120°	$1\begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ 1 & 0 & 0\end{bmatrix}$		$\frac{1}{3}\begin{bmatrix}-1 & -1 & 2\\ 2 & -1 & -1\\ -1 & 2 & -1\end{bmatrix}$
	ACB, 4*30° ccw	240°			
5	ABC, 5*30° cw	150°		$\frac{1}{\sqrt{3}}\begin{bmatrix}-1 & 0 & 1\\ 1 & -1 & 0\\ 0 & 1 & -1\end{bmatrix}$	
	ACB, 5*30° ccw	210°			
6	ABC, 6*30° cw	180°	$1\begin{bmatrix}-1 & 0 & 0\\ 0 & -1 & 0\\ 0 & 0 & -1\end{bmatrix}$		$\frac{1}{3}\begin{bmatrix}-2 & 1 & 1\\ 1 & -2 & 1\\ 1 & 1 & -2\end{bmatrix}$
	ACB, 6*30° ccw	180°			
7	ABC, 7*30° cw	210°		$\frac{1}{\sqrt{3}}\begin{bmatrix}-1 & 1 & 0\\ 0 & -1 & 1\\ 1 & 0 & -1\end{bmatrix}$	
	ACB, 7*30° ccw	150°			
8	ABC, 8*30° cw	240°	$1\begin{bmatrix}0 & 0 & 1\\ 1 & 0 & 0\\ 0 & 1 & 0\end{bmatrix}$		$\frac{1}{3}\begin{bmatrix}-1 & 2 & -1\\ -1 & -1 & 2\\ 2 & -1 & -1\end{bmatrix}$
	ACB, 8*30° ccw	120°			
9	ABC, 9*30° cw	270°		$\frac{1}{\sqrt{3}}\begin{bmatrix}0 & 1 & -1\\ -1 & 0 & 1\\ 1 & -1 & 0\end{bmatrix}$	
	ACB, 9*30° ccw	90°			
10	ABC, 10*30° cw	300°	$1\begin{bmatrix}0 & -1 & 0\\ 0 & 0 & -1\\ -1 & 0 & 0\end{bmatrix}$		$\frac{1}{3}\begin{bmatrix}1 & 1 & -2\\ -2 & 1 & 1\\ 1 & -2 & 1\end{bmatrix}$
	ACB, 10*30° ccw	60°			
11	ABC, 11*30° cw	330°		$\frac{1}{\sqrt{3}}\begin{bmatrix}1 & 0 & -1\\ -1 & 1 & 0\\ 0 & -1 & 1\end{bmatrix}$	
	ABC, 11*30° ccw	30°			

[a] cw = clockwise
[b] ccw = counter clockwise

[a] cw = clockwise
[b] ccw = counter clockwise

FIGURE 26. PHASE SHIFT COMPENSATION MATRIX [7]

In this case, the matrix of row 3 must be applied.

Unlike a dual-core symmetrical PST, an asymmetrical PST with magnitude and phase compensation for 87S, as explained in this document, will result in the presence of differential current under load-balanced conditions.

4.2.3 PICKUP AND SLOPE OF 87S

The stability of the 87S under external close-in faults, where saturation of the serial core can occur, often leads protection engineers to set higher pickups and slopes for 87S, thereby reducing the protection function's sensitivity.

In this example, the settings for the pickup and slope of 87S are:

$$87S_{Pickup} = 0.45\ pu \ \Rightarrow 1350\ A$$

4.3 $87S_{Slope} = 55\%$

The assessment of the 87S is analysed in Section 4.4.

DISTANCE PROTECTION SETTING CALCULATION

As mentioned in Section 3.2.1, the setting calculation for the backup distance protection stages must account for bypassing the PST.

In this section, the criteria for setting the calculation of the distance zone with directionality towards the PST of the line end (21-L PST) are shown as an example.

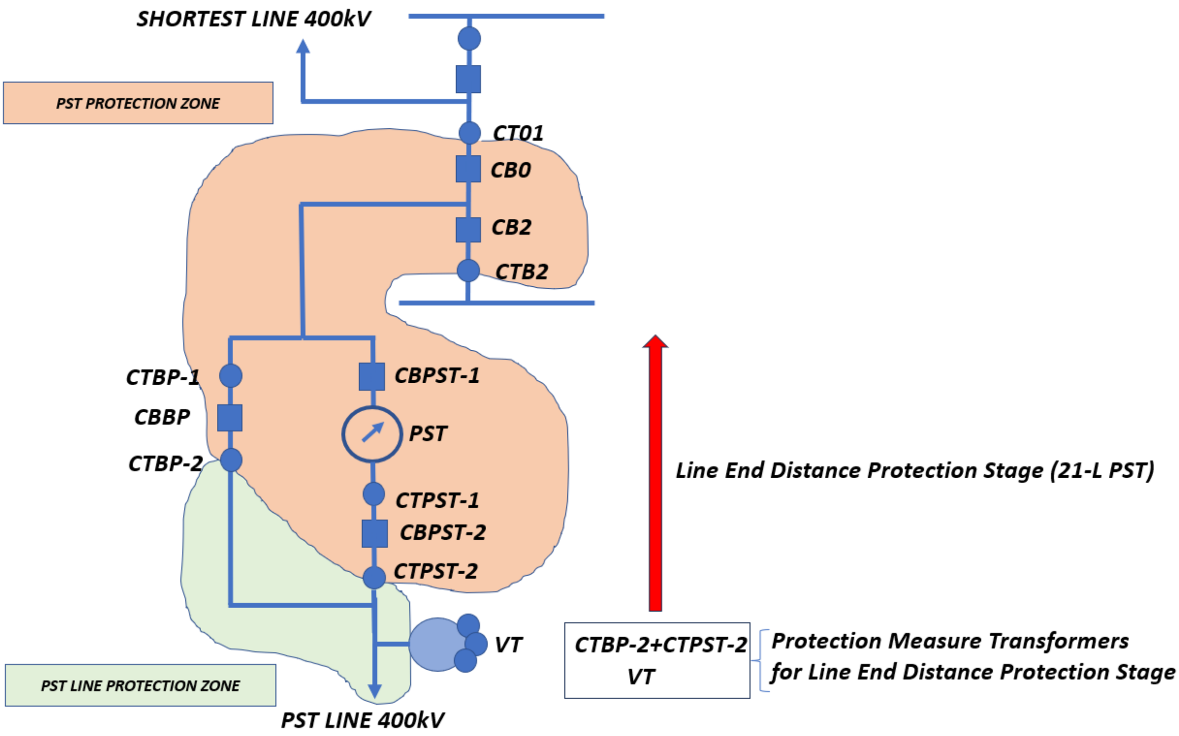

FIGURE 27. SIMPLIFIED DIAGRAM FOR 21L PHASE SHIFTING TRANSFORMER CALCULATION EXAMPLE

The protection function 21-L PST is primarily a backup protection for the terminal L PST against close-in faults. As shown in Figure 27, in case of a bypass circuit breaker (CB), the calculation of the reach of 21-L PST is affected, as coordination with 21-Z1 of the shortest line connected to the substation must be ensured.

Reactance and time delay for the operation of the 21-L PST depend on the use of a bypass CB to dynamically change the settings.

4.3.1 BYPASS CIRCUIT BREAKER NOT USED BY THE PROTECTION WHEN CHANGING THE DYNAMIC SETTING

In cases where no bypass CB position is used for the protection, the criteria adopted in the example for 21-L PST are as follows:

$$X_{21-L\,PST\_Ground} = 0.65 \cdot X_{LINE\ GND}$$

$$X_{21-L\,PST\_Phase} = 0.65 \cdot X_{LINE\ PHASE}$$

$$R_{21-L\,PST\_Ground} = 4.5 \cdot X_{21-L\,PST\_Ground}$$

$$R_{21-L\,PST\_Phase} = 3 \cdot X_{21-L\,PST\_Phase}$$

$$Time\ Delay\ 21 - L\ PST\ Ground = 200ms$$

$$Time\ Delay\ 21 - L\ PST\ Phase = 200ms$$

Where:

$X_{21-L\,PST\_Ground}$: $reactance\ reach\ of\ 21 - L\ PST\ for\ grounded\ faults$

$X_{21-L\,PST\_Phase}$: $reactace\ reach\ of\ 21 - L\ PST\ for\ ungrounded\ faults$

$R_{21-L\,PST\_Ground}$: $resistive\ reach\ of\ 21 - L\ PST\ for\ grounded\ faults$

$R_{21-L\ PST\_Phase}$: $resistive\ reach\ of\ 21-L\ PST\ for\ ungrounded\ faults$

$X_{LINE\ GND}$: $min.reactance\ seen\ for\ grounded\ faults\ on\ the\ lines\ connected\ to\ substation\ and\ bypass\ closed$

$X_{LINE\ PHASE}$: $min.reactance\ seen\ for\ ungrounded\ faults\ on\ the\ lines\ connected\ to\ substation\ and\ bypass\ closed$

Usually, if there is mutual coupling with other OHLs, $X_{LINE\ GND}$ could be lower than $X_{21-L\ PST\_Phase}$.

Since the bypass CB position is not used by the protection, the 21-L PST cannot operate instantaneously.

Note that the criteria of resistive reach of these quadrilateral distance elements are based on the maximum relation between reactive and resistive reach according to the per-unit distance of the protected line [8].

4.3.2 BYPASS CIRCUIT BREAKER USED BY THE PROTECTION TO MAKE DYNAMIC SETTING CHANGES

In cases where a bypass CB position is used for the protection to apply a dynamic setting change, the criteria adopted in the example for 21-L PST as follows:

4.3.2.1 SETTING GROUP 1 ACTIVE WHEN BYPASS CIRCUIT BREAKER CLOSED:

$$X_{21-L\ PST\_Ground\_Setting\_Group1} = 0.65 \cdot X_{LINE\ GND}$$

$$X_{21-L\ PST\_Phase\_Setting\_Group1} = 0.65 \cdot X_{LINE\ PHASE}$$

$$R_{21-L\ PST\_Ground\_Setting\_Group1} = 4.5 \cdot X_{21-L\ PST\_Ground\_Setting\_Group1}$$

$$R_{21-L\ PST\_Phase\_Setting\_Group1} = 3 \cdot X_{21-L\ PST\_Phase\_Setting\_Group1}$$

$$Time\ Delay\ 21-L\ PST\ Ground_{Setting\_Group1} = 200ms$$

$$Time\ Delay\ 21-L\ PST\ Phase_{Setting\_Group1} = 200ms$$

Where:

$X_{21-L\ PST\_Ground\_Setting\_Group1}$: $reactance\ reach\ of\ 21-L\ PST\ for\ grounded\ faults$

$X_{21-L\ PST\_Phase\_Setting\_Group1}$: $reactance\ reach\ of\ 21-L\ PST\ for\ ungrounded\ faults$

$R_{21-L\ PST\_Ground\_Setting\_Group1}$: $resistive\ reach\ of\ 21-L\ PST\ for\ grounded\ faults$

$R_{21-L\ PST\_Phase\_Setting\_Group1}$: $resistive\ reach\ of\ 21-L\ PST\ for\ ungrounded\ faults$

$X_{LINE\ GND}$: $min.reactance\ seen\ for\ grounded\ faults\ on\ the\ lines\ connected\ to\ substation\ and\ bypass\ closed$

$X_{LINE\ PHASE}$: $min.reactance\ seen\ for\ ungrounded\ faults\ on\ the\ lines\ connected\ to\ substation\ and\ bypass\ closed$

Usually, if there is mutual coupling with other OHLs, $X_{LINE\ GND}$ could be lower than $X_{21-L\ PST\_Phase}$.

4.3.2.2 SETTING GROUP 2 ACTIVE WHEN BYPASS CIRCUIT BREAKER OPEN:

$$X_{21-L\ PST\_Ground\_Setting\_Group2} = 0.65 \cdot X_{ZERO\_PST}$$

$$X_{21-L\ PST\_Phase\_Setting\_Group2} = 0.65 \cdot X_{POSITIVE\_PST}$$

$$R_{21-L\ PST\_Ground\_Setting\_Group2} = 4.5 \cdot X_{21-L\ PST\_Ground\_Setting\_Group2}$$

$$R_{21-L\,PST\_Phase\_Setting\_Group2} = 3 \cdot X_{21-L\,PST\_Phase\_Setting\_Group2}$$

$$Time\ Delay\ 21 - L\ PST\ Ground_{Setting\_Group2} = 0ms$$

$$Time\ Delay\ 21 - L\ PST\ Phase_{Setting\_Group2} = 0ms$$

Where:

$X_{21-L\,PST\_Ground\_Setting\_Group2}$: $reactance\ reach\ of\ 21 - L\ PST\ for\ grounded\ faults$

$X_{21-L\,PST\_Phase\_Setting\_Group2}$: $reactance\ reach\ of\ 21 - L\ PST\ for\ ungrounded\ faults$

$R_{21-L\,PST\_Ground\_Setting\_Group2}$: $resistive\ reach\ of\ 21 - L\ PST\ for\ grounded\ faults$

$R_{21-L\,PST\_Phase\_Setting\_Group2}$: $resistive\ reach\ of\ 21 - L\ PST\ for\ ungrounded\ faults$

$X_{ZERO\ PST}$: $min.\ zero\ sequence\ reactance\ of\ PST$

$X_{POSITIVE\_PST}$: $mi.\ positive\ sequence\ reactance\ of\ PST$

4.4 FAULT SIMULATIONS

A similar dual-core asymmetrical PST has been modelled in a hardware-in-the-loop (HiL) system [9] to assess the performance of the 87S protection function.

The dual-core asymmetrical PST shown in Section 4.1 was implemented in a 400 kV system, similar to that shown in the one-line diagram in Figure 27.

The most important aspect to highlight in the modelling is the use of the unified magnetic equivalent circuit (UMEC) transformer model [10] [11], which accurately represents the different magnetic circuits involved.

The UMEC transformer model also allows simulation of internal winding faults.

The UMEC model parameterisation was based on data provided by the manufacturer of the PST.

This section shows the simplified disturbance recorders in case of internal and external faults to the PST.

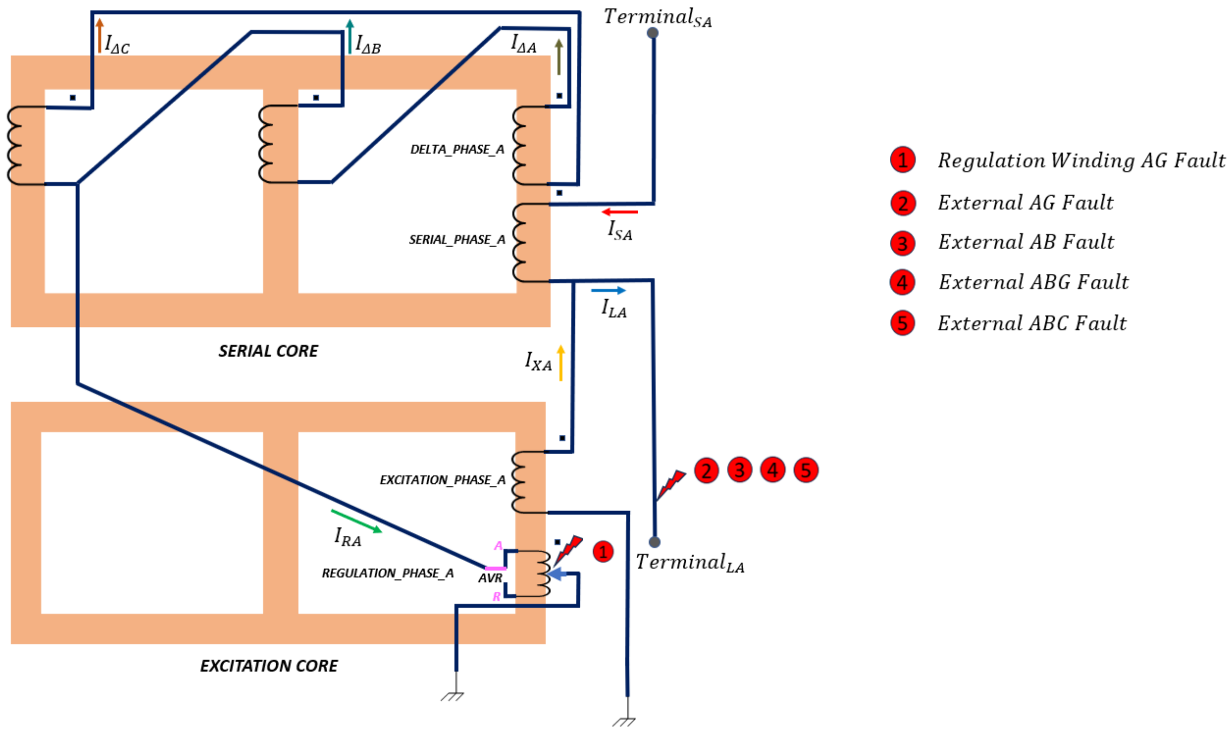

FIGURE 28. FAULTS SIMULATED IN THE MODEL OF A DUAL-CORE ASYMMETRICAL PHASE SHIFTING TRANSFORMER

The single phase to ground fault for the regulation winding has been considered the most likely to occur.

To assess the stability of the 87S, various external close-in faults to the PST have been simulated.

In the next sections, the current waveforms of the source, line, and regulation windings and the magnitudes of the 87S differential and restrain currents are shown for the different faults simulated, all with the PST operating at Tap 17, corresponding to the maximum phase shift.

In 87S tripping mode, the tripping is always three poles. For understanding the phase-segregated measuring mode of 87S, the tripping signals for Phases A, B and C are shown in the disturbance records.

Under a faulty, unbalanced condition, the differential current in the three phases will increase, as the compensation applied to the phasor currents in Section 4.2 cannot fully stabilise 87S due to the serial and excitation core connections and the possible saturation of the serial core.

For this reason, it is important to have models to simulate internal and external faults, assess the 87S performance and change the calculated setting if needed based on the simulation results.

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4.4.1 AG REGULATION WINDING FAULT

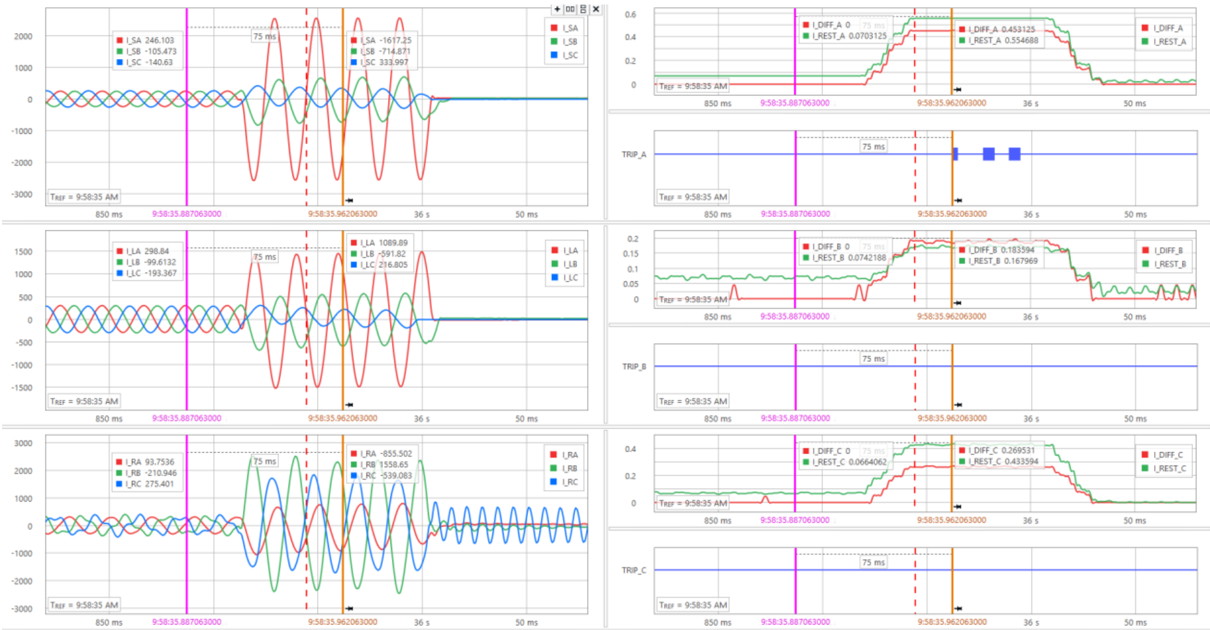

FIGURE 29. REGULATION WINDING AG FAULT

This fault has been applied within the regulation winding and represents the maximum sensitivity of 87S settings, approximately to a short circuit of Turn 46 to ground, covering 45% of the winding (considering the turn connected to the ground as the Turn 1 and the turn connected to the terminal of the transformer as the turn 102) to detect internal faults, generating a Phase A trip command.

Note that there are higher regulation winding currents in Phases B and C (as explained in Eq. (22) and (23) in Section 2.1.2.1; Phase B and C regulation currents are commonly composed of Phase A delta current) than the regulation Phase A winding current under fault.

4.4.2 AG EXTERNAL CLOSE-IN FAULT

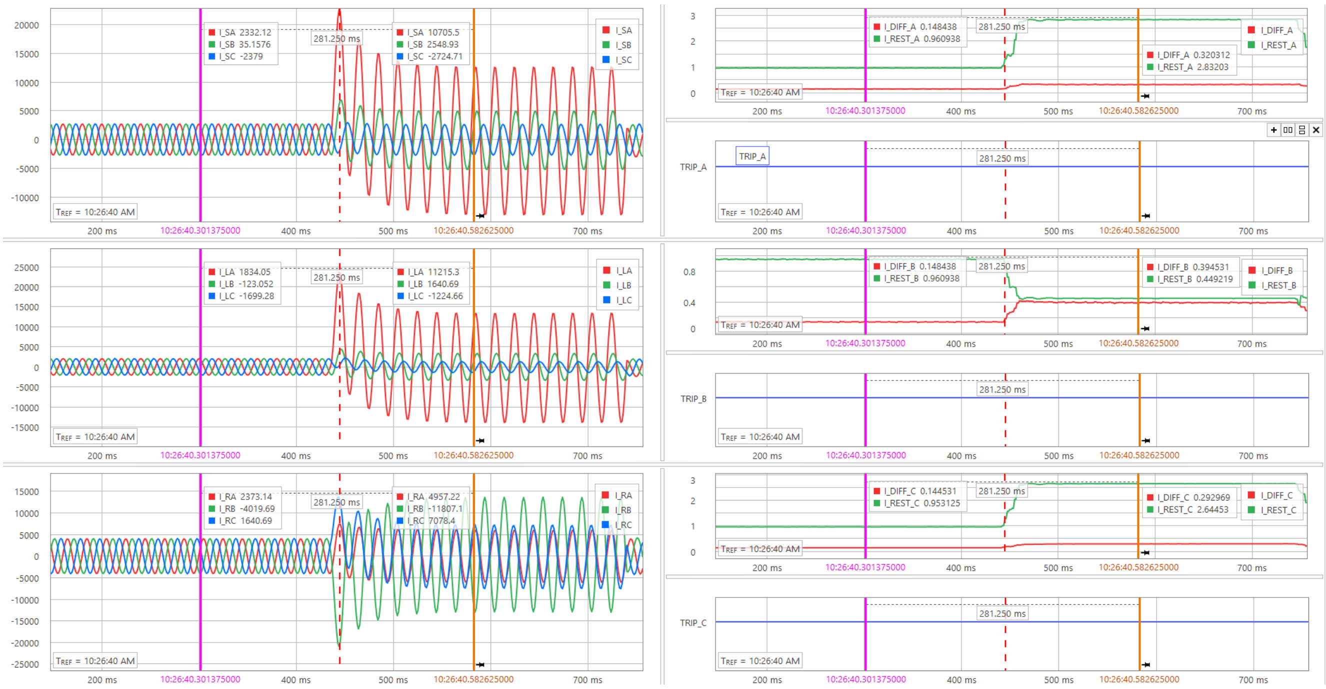

FIGURE 30. AG EXTERNAL PST CLOSE-IN FAULT

Although there is differential current in the three phases, it is insufficient to pick up 87S, being stable for this external fault.

4.4.3 AB EXTERNAL CLOSE-IN FAULT

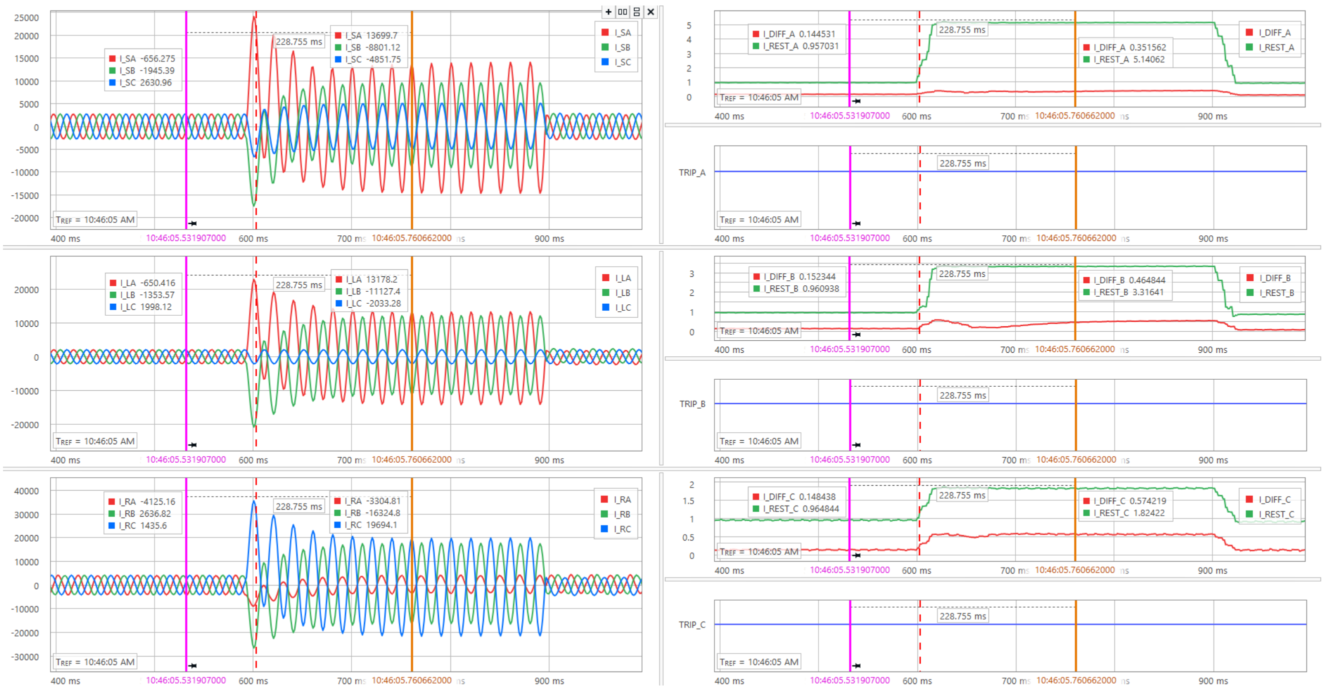

FIGURE 31. AB EXTERNAL PST CLOSE-IN FAULT

In this case, there is a differential current in Phases B and C that picks up the 87S, but the restraining currents are high, making 87S stable for this external close-in fault.

4.4.4 ABG EXTERNAL CLOSE-IN FAULT

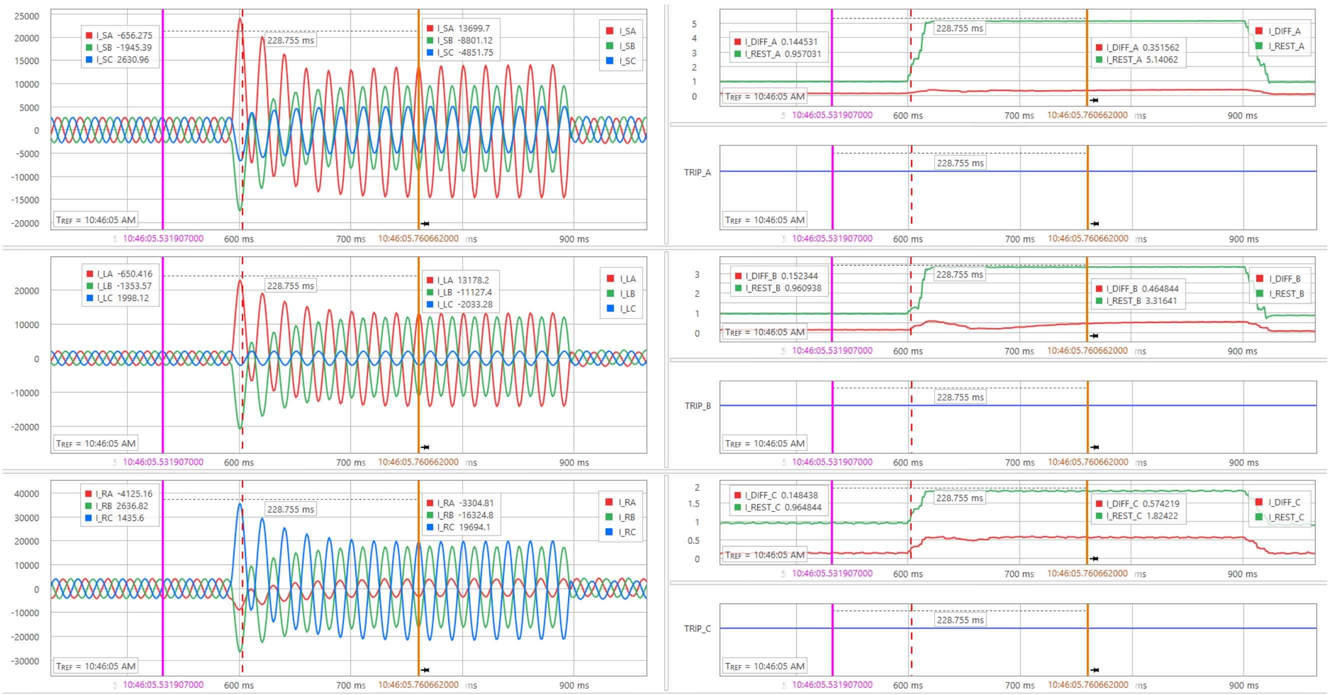

FIGURE 32. ABG EXTERNAL PST CLOSE-IN FAULT

Similar to Section 4.4.3, there is a differential current in Phases B and C that picks up the 87S, but the restraining currents are high, making 87S stable for this external close-in fault.

4.4.5 ABC EXTERNAL FAULT

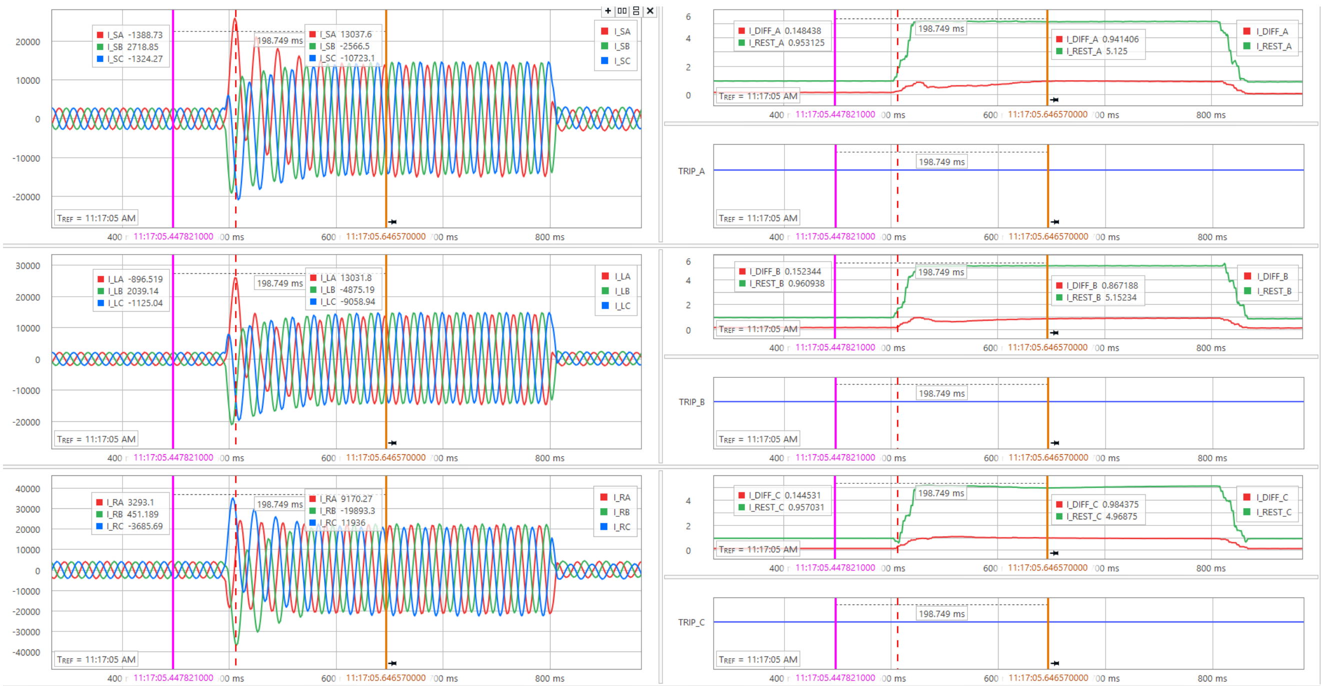

FIGURE 33. ABG EXTERNAL PST CLOSE-IN FAULT

In this case, there is a differential current in Phases A, B and C that picks up the 87S, but the restraining currents are high, making 87S stable for this external close-in fault.

5 TRANSMISSION SYSTEM OPERATOR QUESTIONNAIRE

This chapter presents the TSOs' answers to the questionnaire regarding the application, protection and field experience of PSTs.

PART 1: APPLICATION

5.1.1 Q1.1 IN YOUR GRID, ARE THERE ANY PSTS? Q1.2 SPECIFY THE NUMBER AND CHARACTERISTICS OF PSTS.

5.1

TSO	Q1.1	Q1.2
1	Yes (x16)	(x14) Dual Core ** No data available of Sym/Asym, (x2) Single Core
2	Yes (x2)	(x2) Dual Core Asymmetrical
3	Yes (x2)	(x2) Dual Core Symmetrical
4	No	NA
5	Yes (x5)	(x5) Dual Core Symmetrical
6	No	NA
7	Yes (x10)	(x9) Dual Core Symmetrical, (x1) Dual Core Asymmetrical
8	Yes (x3) (To put in service in future)	(x2) Dual Core Symmetrical, (x1) Single Core Symmetrical
9	Yes (x2)	(x1) Dual Core Symmetrical, (x1) Single Core Asymmetrical
10	Yes (x2) and (x1) Dual Core Symmetric under construction	(x2) Dual Core Symmetrical, (x1) Dual Core Asymmetrical
11	Yes (x2 In Project)	(x2) Dual Core Symmetrical
12	Yes (x4)	(x4) Dual Core Asymmetrical
13	Yes (x4)	(x4) Dual Core Symmetrical
14	No	NA
15	Yes (x10)	(x6) Dual Core Symmetrical, (x2) Dual Core Asymmetrical, (x2) Single Core Symmetrical
16	Yes (X7) ** Only Data Available for 4 PSTs.	(x4) Single Core Asymmetrical
17	Yes (x2)	(x2) Dual Core Symmetrical
18	No	NA
19	Yes (x3)	(x2) Dual Core Asymmetrical, (x1) Dual Core Symmetrical

TABLE 2. TSOS' ANSWERS TO Q1.1 AND Q1.2

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The main conclusions of Q1.1 and Q1.2 are summarised as follows:

- There are 69 PSTs in operation:
  - 65 Dual-core PSTs:
    - 36 symmetrical
    - 12 asymmetrical
    - 14 information not available
  - 10 Single-core PSTs:
    - 3 symmetrical
    - 5 asymmetrical

5.1.2 Q1.3 Which criteria are used to decide whether to install a PST?

TSO	Q1.3
1	Power Flow
2	Power Flow
3	Power Flow
4	NA
5	Power Flow
6	NA
7	Power Flow
8	Power Flow
9	Power Flow
10	Power Flow
11	Power Flow
12	Power Flow
13	Power Flow
14	NA
15	Power Flow
16	Power Flow
17	Power Flow
18	NA
19	NA

Table 3. TSOs' answers to Q1.3

Naturally, the main criteria to decide to install PST are based on modifying the power flow in:

- Corridors
- Interconnection lines of different grids
- Mixed lines

- Between different voltage level grids:
    - Evacuation of power from renewable power plants
    - Reduce overload at a specific voltage level in the grid.

5.1.3 Q1.4 Do you use PSTs with a dedicated winding to supply auxiliary circuits?

TSO	Q1.4
1	No
2	No
3	No
4	NA
5	No
6	NA
7	No
8	No
9	No
10	Partly
11	No
12	Yes
13	No.
14	NA
15	No
16	No
17	No
18	NA
19	No

Table 4. TSOs' answers to Q1.4

It is not common practice to use dedicated windings to supply auxiliary circuits.

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PART 2: PROTECTION SCHEME AND SETTING

5.2.1 Q2.1 SPECIFY THE STANDARD PROTECTION SCHEMES THAT USUALLY APPLY TO THE DUAL-CORE PST IN YOUR GRID.

TSO	Q2.1
1	Earth Tank (Main) and Buchholz (Backup)
2	Serial Core: 87T,50,51 (Main); 21,50,51 (Backup); Excitation Core: 87T,50,51 (Main); 21,50,51 (Backup); * (Different type of PST)
3	21 (S and L sides of Serial Core), Branch Point Differential and Flux Balance Differential * (Asked for SLD)
4	NA
5	Serial Core: 87P (Main); 21-Source Side,51,51N (Backup); Excitation Core: 87S (Main); 21-Load Side,51,51N (Backup);
6	NA
7	NA
8	Serial Core: 87P (Main 1); 87PST, 87RGF,51N (Main2); 21,51 (Backup); Excitation Core:87S (Main 1); 87PST, 87RGF,51N (Main2); 21,51 (Backup);
9	SU: 87T,50,51 (Main) and 50/51 (Backup). Not 87T for Excitation Core); * (Different type of PST)
10	Serial Core: 87P, 21-Source Side,50,50-Tertiary; Excitation Core: 87S, 21-Source Side,50,50-Tertiary
11	Serial Core : 87P,2x50,3x51,1x51N; Excitation Core : 87S,2x50,3x51,1x51N
12	Serial Core: x2 (87B,51,51N,51-Auxiliary Services) (Main1 and Main2); x2(21,67,51,68,59) (Backup1 and Backup2); Excitation Core: 2x(87T, 87N, 51N) (*Different Type of PST)
13	Serial Core and Excitation Core : 2x (87P,87S,50-ARS,24 Serial Core, 24 Excitation Core) (Main 1 and Main 2) and x1(87S-Sensitive-Secondary-Windings,50ARS); Serial Core : 21, 50-51 Source Side, 50 OLTC Blocking (Backup); Excitation Core : 50-51 Excitation Winding, 50N-51N Excitation Winding, 50-51 Regulation Winding, 50N-51N Regulation Winding)
14	NA
15	Serial Core: 87P (Main) 21-Source Side, 21-Load Side x2 (50,51,50N,51N) (Backup); Excitation Core: 87S (Main),50-51N Excitation Winding, 50-51N Regulation Winding (Backup); Serial-Excitation Core: 87S-Sensitive-Secondary-Windings (Main)
16	NA
17	Serial Core: 87P, 21-Source Side,21-Load Side, 51,51N; Excitation Core: 87S,51,51N (Excitation and Regulation Windings)
18	NA
19	Serial Core: x2(87P, 21-Source Side,21-Load Side,50,51,51N); Excitation Core: x2(87S,50,51,51N)

TABLE 5. TSOS' ANSWERS TO Q2.1

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There is a wide variety of solutions, but in general, the IEEE PST protection scheme explained in Section 3.1.1 is commonly used as the main protection system for dual-core PSTs:

- 8 TSOs use the IEEE PST protection scheme.
- 1 TSO is using a new approach.
- 3 TSOs have a different type of PST (connection of two shunt power transformers), implementing classic 87T and 87B as the main protection functions.
- 2 TSOs use the 87S sensitive secondary protection function.
- 1 TSO does not use any 87 function and implements an earth tank as the main protection.

Regarding the backup protection functions:

- 21 source and 21 load commonly used.
- 50,51 and 51N for the windings of the serial and excitation core.

5.2.2 Q2.2 SPECIFY THE STANDARD PROTECTION SCHEMES THAT USUALLY APPLY TO THE SINGLE-CORE PST IN YOUR GRID.

TSO	Q2.2
1	Same as Dual Core
2	NA
3	NA
4	NA
5	NA
6	NA
7	NA
8	87T
9	87T
10	NA
11	NA
12	NA
13	NA
14	NA
15	87T
16	Adaptive PST
17	NA
18	NA
19	NA

TABLE 6. TSOS' ANSWERS TO Q2.2

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Only five TSOs have a single-core PST:

- TSO 1 does not use any 87T and implements earth tank protection.
- TSOs 8, 9 and 15 use classic 87T protections functions.
- TSO 16 uses a new approach (87PST).

5.2.3 Q2.3 Does the protection scheme use buried CTs (not in the bushing)? If so, what is your experience regarding the behaviour of these buried CTs?

TSO	Q2.3
1	No
2	No
3	Yes/No problems.
4	NA
5	No answer
6	NA
7	Yes/Problems in one PST (not compensated buried CT cause trip after commissioning)
8	No
9	No
10	Yes/No problems.
11	Yes/No problems.
12	NA
13	Yes/Overexcitation in Inrush
14	NA
15	Yes/Problems with high current external faults.
16	Yes/No problems.
17	Yes/No problems.
18	NA
19	Yes/No problems.

Table 7. TSOs' answers to Q2.3

Nine TSOs use buried CTs:

- 3 TSOs faced problems:
  - ➢ Maloperation for external faults and inrush currents.

5.2.4 Q2.4 Do you use protection overfluxing protection (ANSI 24) on the serial Unit or the Excitation Unit? If so, how do you measure the voltage across the windings of the units?

TSO	Q2.4
1	No
2	No
3	No
4	NA
5	No
6	NA
7	No, but planned in future
8	Yes
9	No
10	No
11	No
12	No
13	Yes
14	NA
15	No
16	No
17	No
18	NA
19	No

Table 8. TSOs' answers to Q2.4

Only two TSOs use overfluxing protection, and one TSO intends to use it in the future.

5.2.5 Q2.5 In case of using one transformer differential protection dedicated for the excitation core (87S), explain how you compensate the differential current.

TSO	Q2.5
1	NA
2	Phase Shift of Regulation Winding Current and inversion of polarity of Bus or Load Side current.

3	Phase Shift of Regulation Winding Current and inversion of polarity of Bus or Load Side current.
4	NA
5	Phase Shift of Regulation Winding Current and inversion of polarity of Bus or Load Side current.
6	NA
7	NA
8	NA
9	NA
10	Increase Pickup 87T to not operate in maximum tap. No compensation. 87PST in future.
11	No dedicated 87 for Excitation Core.
12	External device changing the direction of the current and interrupts its arrival at the protection function depending on the angle regulator tap. For angle taps with a few turns covered by the excitation winding currents, the device interrupts the current measurement for the protection function. For angle taps with a greater number of turns, the device allows current measurement. When the tap is at a negative angle, the device reverses the current. (Busbar connected PST)
13	ARS connected to relay to block 87 during operation and position too. Increase Pickup 87T to not operate in maximum tap. No compensation. Polarity internally changes in relay.
14	NA
15	Phase Shift of Regulation Winding Current and inversion of polarity of Bus or Load Side current. In one case, Tap Position wired to protection to change 87T characteristic (Pickup and/or Slope) dynamically.
16	NA
17	ARS connected to relay to block 87 during operation.
18	NA
19	Phase Shift of Regulation Winding Current and inversion of polarity of Bus or Load Side current. Phase shift and inversion of CT Star ground polarity. One PST increase pickup and Slope 87S.

Table 9. TSO´s answers to Q2.5

The main conclusions are summarised as follows:

- Four TSOs use the phase shift of the regulation winding to invert the polarity of the bus or load-side current, as explained in Section 4.2.2.
- Five TSOs increase 87S pickup, slope or Block 87S in ARS switching or maximum tap.
- One TSO uses an external device to change or interrupt the current to the protection based on the tap position (for shunt connected PST).

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5.2.6 Q2.6 Have you changed or do you plan to change the protection scheme thanks to the availability of new protection algorithms? If so, which ones?

TSO	Q2.6
1	No
2	No
3	No
4	NA
5	No
6	NA
7	No
8	No
9	No
10	Yes
11	No
12	No
13	No
14	NA
15	No
16	No
17	No
18	NA
19	Yes

Table 10. TSOs' answers to Q2.6

Only two TSOs are planning to change protections to adaptive 87PST.

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5.2.7 Q2.7 Do you have models of your PSTs for simulating internal and external faults and assessing protection algorithms' performance? Q2.8 If so, which software do you use for modelling PSTs?

TSO	Q2.7	Q2.8
1	Partially. No for internal faults.	Excel or Matlab for external faults
2	No	NA
3	No	NA
4	NA	NA
5	No	NA
6	NA	NA
7	No	NA
8	Yes	PSCAD (But only for power flow)
9	No	NA
10	Yes	EMTP, ATP and PSCAD
11	Partially. No for internal Faults.	External Faults with NEPLAN.
12	No answer	No answer
13	No	PSSE for external faults.
14	NA	NA
15	No	NA
16	Partially. No for internal Faults.	Digsilent model as Autotransformer for external fault
17	Partially. No for internal Faults.	CAPE for External Fault
18	NA	NA
19	Yes	RTDS

Table 11. TSOs' answers to Q2.7 and Q2.8

The main conclusions are summarised as follows:

- 7 TSOs have models for simulating faults:
  - Only two TSOs have models to simulate internal faults.
- Short-circuit calculation software for protection settings and software for power flow analysis used for external fault short-circuit current calculation:
  - Neplan, Cape, Digsilent
  - PSCAD, PSSE
- Transient analysis software or HiL systems used for internal and external fault calculation:
  - EMTP ATP, RTDS

5.2.8 Q2.9 Are the settings and implementation in the protection devices made by the manufacturer of the PST or by the TSO? Q2.10 Are the factory acceptance test (FAT) and site acceptance tests (SAT) tests of the protection system made by the manufacturer of the PST or by the TSO?

TSO	Q2.9	Q2.10
1	By TSO	By TSO
2	By TSO	By Manufacturer
3	By TSO	By TSO
4	NA	NA
5	By TSO and Supplier	By TSO and Supplier
6	NA	NA
7	By TSO	By TSO
8	By vendors	By TSO
9	By TSO	By TSO
10	By TSO	By TSO
11	By TSO.	By TSO
12	By TSO	By manufacturer and TSO
13	By manufacturer.	By TSO and manufacturer
14	NA	NA
15	By TSO.	By C&P System Manufacturer
16	By TSO	By TSO
17	By manufacturer.	By Extenal Company and TSO
18	NA	NA
19	By TSO	By TSO

Table 12. TSOs' answers to Q2.9 and Q2.10

The main conclusions are summarised as follows:

- The calculation is entirely the responsibility of the vendors for three TSOs.
- FAT and SAT tests:
  - Commonly made or participated in by TSOs.
  - Supplier or external companies usually involved.

5.2.9 Q2.11 For your protection system: Do you have full redundancy for all kind of faults? Please describe if not.

TSO	Q2.11
1	Earth Tank (Main), Buchholz and 21 (Backup)
2	Yes
3	Yes. 87T and 21 for 220kV and 87T and 50/51 110kV
4	NA
5	Yes.
6	NA
7	Yes.
8	Yes
9	Yes for Serial Core.
10	Yes for the future 87PST
11	Yes.
12	Yes.
13	Yes.
14	NA
15	Yes.
16	NA
17	Yes
18	NA
19	Yes

Table 13. TSOs' answers to Q2.11

The majority of TSOs consider that their protection schemes have redundancy for all types of faults.

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5.2.10 Q2.12 Do you know if your protection system has weaknesses for some kind of faults (including external faults)? Please give examples.

TSO	Q2.12
1	No
2	No
3	Yes. Incorrect trip for External Fault
4	NA
5	No answer
6	NA
7	Interturn Faults in Excitation Unit (See by Buchholz)
8	NA
9	No.
10	No.
11	No.
12	NA
13	NA
14	NA
15	Block 87T during switching ARS
16	Selectivity Problems with 21-Z2
17	No
18	NA
19	Interturn Faults in Excitation Unit (See by Buchholz), and incorrect trip for close-in external faults.

Table 14. TSOs' answers to Q2.12

Five TSOs state there are weaknesses for some kind of faults or in the protection scheme:

- Winding interturn faults in the excitation core are not detected by 87S but are detected by Buchholz.
- Maloperation for external close-in faults due to saturation of the serial core.
- Selectivity problems with 21-Z2.
- Necessity of blocking 87T in case of ARS switching.

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PART 3: FIELD EXPERIENCE

5.3

5.3.1 Q3.1 HOW LONG HAVE THE PSTS AND THEIR PROTECTION SYSTEMS BEEN IN OPERATION?

TSO	Q3.1
1	25 Years
2	PST1 (1984 and PS since 2000), PST2 2005
3	22 Years
4	NA
5	Since 2006
6	NA
7	2007, 2008 (3), 2010 (2), 2020 (3)
8	Not In operation (2024 Expected)
9	Since 2016
10	1980 (1) and 2009 (1)
11	NA
12	Since 2006
13	2016 (1) and 2017 (1)
14	NA
15	2003
16	2018
17	2010
18	NA
19	2011

TABLE 15. TSOS' ANSWERS TO Q3.1

Many TSOs have PSTs in operation for more than 10 years, so they have experience in operating and maintaining these transformers.

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5.3.2 Q3.2 Have the protection systems always operated correctly? Q3.3 If not, can you briefly describe the events and the corrective actions performed?

TSO	Q3.2	Q3.3
1	Yes	NA
2	Yes	NA
3	No in 110kV	87S Trip. Reduce Sensitivity
4	NA	NA
5	Yes	No
6	NA	NA
7	No	Yes (Not I0 Filtering Enable)
8	NA	NA
9	Yes	NA
10	Yes	NA
11	NA	NA
12	No	NA
13	Unexpected Operation of the Primary Winding	Overexcitation of CT on Neutral Side
14	NA	NA
15	No. 87T Trip for External Fault.	CT Replace
16	Yes (external Busbar Fault and Protection Stable)	NA
17	Trip during Overloading	Increase 51 pickup
18	NA	NA
19	No. 87T Trip for External Fault	Apply Phase Shift and CT Star Inversion polarity

Table 16. TSOs' answers to Q3.2 and Q3.3

There have been maloperations in some cases:

- 87S trip for external faults
- Trip under overload conditions

However, in general, the operation of the protection systems seems correct thus far.

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5.3.3 Q3.4 Do you compare the short-circuit current (fault current level and waveforms) of the simulation models with real events? Q3.5 If so, can you briefly describe whether the model and the real event match?

TSO	Q3.4	Q3.5
1	No	No
2	No	NA
3	No	No. Only models for Power flow
4	NA	NA
5	No	NA
6	NA	NA
7	NA	NA
8	NA	NA
9	No	No answer
10	No	NA
11	NA	NA
12	NA	NA
13	No	NA
14	NA	NA
15	No	NA
16	No	NA
17	No	NA
18	NA	NA
19	Yes	Yes. Models are accurate according to real events.

Table 17. TSOs' answers to Q3.4 and Q3.5

Only one TSO compares real events with the simulation models and states that the models are accurate according to real events.

6 CONCLUSIONS

PSTs are electrical machines whose implementation in the transmission networks is not widespread. Any PST installation project is designed specifically for a given set of needs, so it is complicated to have a standard solution.

This report shows that there are very few PSTs installed on European transport networks.

The protection of PSTs is complex due to the nature of load and short-circuit currents for internal and external faults, which may be compensated to stabilise the 87T protection functions applied.

Many TSOs follow the IEEE guidelines for protecting the PSTs, which require 87P and 87S functions to protect the serial and excitation cores in dual-core PSTs.

Apart from the classic way of protecting PSTs of IEEE, new adaptive algorithms are emerging that reduce the number of protection devices and functions [4].

Some TSOs are using dynamic models to simulate the performance of protection systems in the event of internal or external faults and heavy load conditions.

These studies help verify the evolution of short-circuit currents and other electromagnetic magnitudes, thereby enabling a better understanding of the performance of the protection systems of these electrical machines.

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