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Protecting Phase-Shifting Transformers: A Comprehensive Approach

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SUMMARY

The power transmission grid is undergoing significant transformations driven by increased energy demand, deregulation, and integrating renewable energy sources, necessitating improved control of power flows. Phase-shifting transformers (PSTs) play a crucial role in regulating power flow within the transmission network, offering a simple, reliable, and cost-effective means of controlling active power. However, protecting PSTs presents unique challenges that require a deep understanding of the magneto-electric circuit of these transformers and current flow through different windings, the impact of load tap changer (LTC) and advanced retard switch (ARS), and the appropriate protection schemes. This article outlines the essential requirements for PST protection, including the effects of CTs and PTs location, short circuit and through fault protection, thermal overload, overcurrent, neutral/ground overcurrent, LTC and ARS impacts, inrush effects on differential protection, and the use of Buchholz and LTC sudden pressure relays (SPRs). Addressing these protection requirements and implementing suitable schemes improves the protection system security, enhancing PST's availability and ensuring secure and efficient power flow control within the transmission network.

KEYWORDS

Phase-shifting transformer (PST), regulation winding, phase-shift angle, two-core symmetric, load tap changer (LTC), advance-retard switch (ARS), turn-to-turn fault, Kirchhoff's current law (KCL), Ampere-turns balance (ATB), permissive overreaching transfer trip (POTT)

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INTRODUCTION

Phase-shifting transformers (PSTs) are commonly used to efficiently control active power flow in electric transmission networks. They achieve this by regulating the voltage phase-shift angle between source and load terminals using a positive or negative quadrature-phase voltage injection. This regulation allows PSTs to perform various functions, such as relieving line overloads, adjusting parallel-line load sharing, and facilitating energy transfers in interconnected grids. The voltage phase-shift angle is controlled by a series transformer unit that injects a phase-shifted voltage source into the line segment. A shunt or main transformer unit powers this series transformer unit. The configuration of the shunt and series transformer windings determines the amount of phase shift introduced. This article outlines the fundamental principles of active power control using PSTs, the different categories of PSTs, and the protection requirements for these transformers.

A PST regulates the active power flow by controlling the angle (δ) between source and load buses or terminals. The PST obtains the quadrature voltage for regulating a specific phase from the phase-to-phase voltages of the other two phases. For example, the quadrature voltage that controls the A-phase power flow in retard or advanced mode will be obtained from phases B and C (U_{BC}) or C and B (U_{CB}), respectively. Depending on the design, polarity inversion, also known as the advanced or retard mode, can be selected using either the LTC's reversing change-over selector or a separate advanced-retard switch (ARS). The amount of phase angle shift is governed by the load tap changer (LTC) located at the exciting or shunt unit's secondary winding. The LTC adjusts the magnitude of the quadrature voltage, which is impressed on the delta secondary winding of the series unit. The exciting unit's secondary voltage is then induced into the series unit's primary winding as a booster voltage (ΔU). Depending on the direction of the power flow, the booster voltage (ΔU) can be adjusted either in retard mode (-δ) or advanced mode (+δ). In the advanced phase regulation mode, the load terminal voltage (U_L) leads the source terminal voltage (U_S), whereas in the retard mode, the load terminal voltage (U_L) lags behind the source terminal voltage (U_S). The PST can introduce higher or lower impedances to achieve the advanced or retard mode, respectively, as discussed in [1][2].

ACTIVE POWER FLOW CONTROL

The active power flow (*P*) through a branch with inductive reactance (*X*) is determined by the power angle equation:

$$P = (U_i * U_j / X) \, Sin(\delta)$$

Where:

P is the active power flow, U_i and U_j are the voltages at the sending and receiving ends of the line, and δ is the load angle (the difference of phases between U_i and U_j of the line, $\delta = (\theta_i - \theta_j)$)

The active power flow can be adjusted by modifying the voltages U_i and U_j, the reactance X, and the load angle δ. However, voltage adjustments have limited control due to voltage regulation constraints. Alternatively, significant adjustments can be achieved by changing the branch reactance through series compensation using capacitor banks. The load angle δ plays a crucial role in altering the extent and direction of active power flow.

The concept of load angle adjustment using a PST is illustrated in Fig. 1. Parallel branches *I* and *II* have the same parameters (i.e., identical branch reactance, $X_I = X_{II} = X$), and the power flow across the network results in voltages U_i and U_j at the sending and receiving end with a load angle difference of δ (Fig. 1b). The power angle equation calculates the active power (P_I) through the branch *I*.

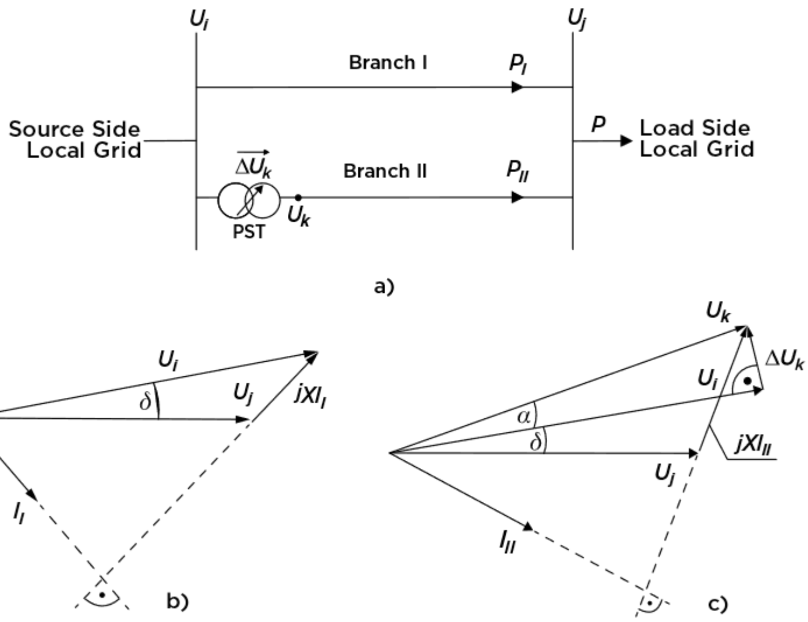


Fig. 1. Active power flow control in PST by adjusting δ: a) system one-line with a series and a shunt unit, b) phasor diagram for branch *I*, c) phasor diagram for branch *II* [3]

A PST is installed on branch *II* to enhance active power flow control. Adding a perpendicular voltage ΔU_k to the initial voltage U_i means the load terminal voltage, U_k ($U_k = U_i + \Delta U_k$) is developed at the series transformer unit's load terminal [refer to Fig. 1 c)] [3]. This adjustment modifies the load angle to ($\delta + \alpha$). The active power (P_{II}) in branch II can be calculated using the modified voltage U_k and load angle ($\delta + \alpha$) as:

$$P_{II} = (U_k * U_j / X)\ Sin(\delta + \alpha)$$

Since $(\delta + \alpha) > \delta$, the active power flow P_{II} is greater than P_I. The booster voltage, ΔU_k, can be adjusted within a range of (-α) to (+α), allowing for fine control of the active power flow.

CATEGORIES OF PSTS

PSTs can be classified into various types: symmetric or non-symmetric, quadrature or non-quadrature, single-core or two-core, and single-tank or dual-tank design. References [2][4] provide a more detailed grouping of PSTs into five categories.

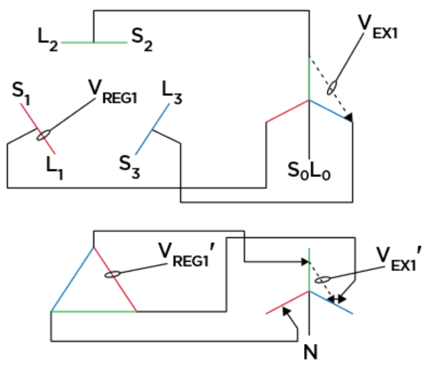
1. Single-core asymmetric, with tap winding outside the delta
2. Single-core symmetric, with tap winding outside the delta
3. Single-core, symmetric, polygon (delta hexagonal)
4. Two-core symmetric with a wye-wye exciting unit (conventional)
5. Two-core, asymmetric with a wye-wye exciting unit (quadrature booster)

PSTs are available in various designs, offering different types of regulation, such as fixed or variable phase shifts and options with or without voltage regulation [1][2][4]. The most commonly used PST types are the two-core symmetric with wye-wye exciting units and the single-core symmetric polygon PSTs. In the past, the hexagonal connection was popular for fixed phase shift applications to avoid the need for LTCs and mitigate associated operational issues. However, other PST types have also been employed. For high-power devices, symmetric two-core designs are often preferred due to their flexibility in selecting the step voltage and current of the regulating winding, allowing optimization based on voltage and current ratings of the LTC.

It's worth noting that the structural characteristics of PSTs and the physical location and configuration of CTs can influence the sensitivity and protection range of differential protection under the same fault condition, leading to some differences [5].

TWO-CORE SYMMETRIC PST WITH WYE-WYE EXCITING UNIT

This article mainly focuses on the protection philosophy of two-core symmetric type PSTs, providing a comprehensive understanding of the design. Specifically, the two-core symmetric PST with the wye-wye exciting unit is illustrated in Figs. 2a) and 2b) displaying the nameplate and three-line diagram [2][4]. In this design, the excitation core's primary winding is tapped to the midpoint of the series core's primary winding. An LTC regulates each phase of the excitation core's secondary winding to control the secondary voltage of the series core winding. The series core's secondary winding is connected in delta and receives a quadrature voltage of ±90° out of phase with the midpoint to ground voltage between the S and L terminals.



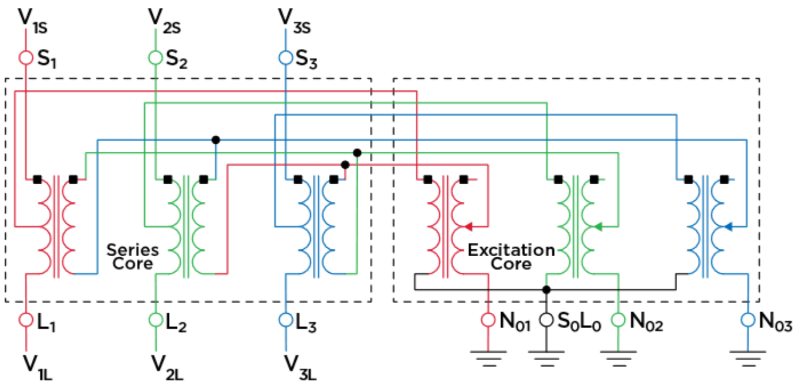


Fig. 2a). 2-Core PST's nameplate diagram   Fig. 2b). 3-line diagram in the advanced position

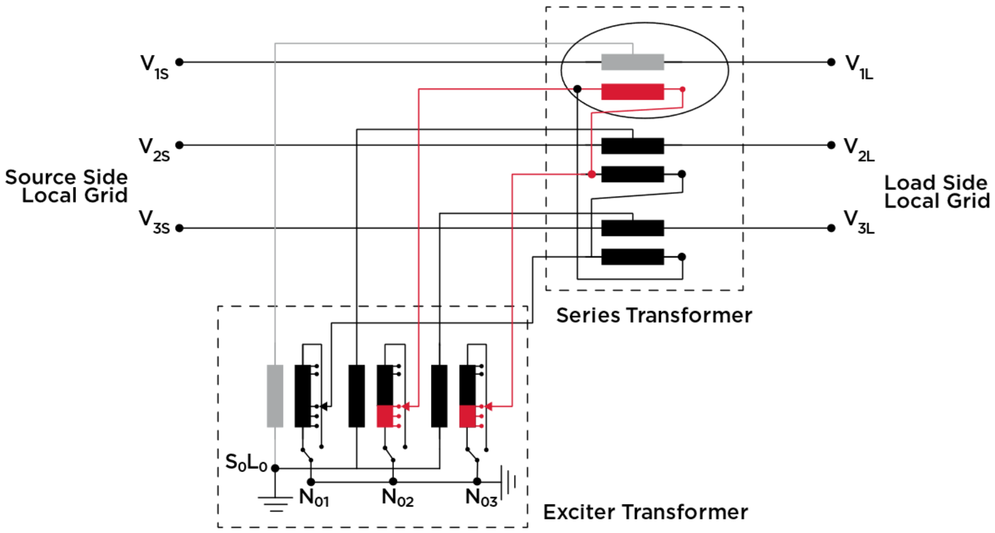


Fig. 3. Winding arrangement of a 2-core symmetric PST in the advanced position

The winding arrangement of a symmetric two-core PST is shown in Fig. 3 [6], where the excitation core is powered by the source voltage tapped from the midpoint of the series core's primary winding. The exciter or main transformer unit is designed to handle power based on the range of phase-shift angle regulation. However, the exciting winding requires a unique protection scheme, as the conventional power transformer differential scheme may not be sensitive enough to detect faults in this winding.

IMPACT OF CTS AND VTS LOCATION ON PST PROTECTION

The physical location of current transformers (CTs) and potential transformers (PTs) significantly influences the effectiveness of protection for phase-shifting transformers (PSTs). Careful consideration must be given to the specification and placement of these devices during the selection and design of the PSTs. CTs can be of the bushing, non-bushing, or standalone types. Non-bushing CTs, when buried inside the PST due to space limitations, can introduce measurement errors due to stray flux or magnetic proximity effects, requiring proper shielding to prevent relay misoperation.

Fig 4. a) Bushing CT and b) Non-bushing CT

In two-core PST designs, CTs placed on each phase between the winding and wye neutral connection can offer differential protection. However, locating CTs to protect the PST as two discrete transformers through a differential protection scheme can be challenging due to the internal leads of the exciting windings remaining inside the tanks [2].

Voltage transformers (VTs) serve multiple functions in PST protection schemes, such as providing polarization for distance or directional elements in Permissive Overreaching Transfer Trip (POTT) schemes. VTs also contribute to angle compensation of sequence component differential elements, sync check for reclosing load side circuit breakers, sensing LTC voltage/position, and acting as external fault detectors to block or desensitize differential protection. The voltage polarizing sensitivity in distance relays is predetermined, and if the voltage falls below this level, the relay function will only produce output via memory action [7].

OVERVIEW OF PST PROTECTION

PSTs, similar to standard power transformers, necessitate sensitive, fast, reliable, and secure protection. Ensuring high sensitivity is crucial for detecting partial winding faults near the neutral of a wye-grounded transformer, such as turn-to-turn or ground faults. Challenges arise in fault detection and management of factors like CT saturation, inrush currents, and over-excitation, which can affect the reliable and secure operation of PSTs. Immediate tripping is necessary to prevent internal damage, and thermal overloading must be addressed to avoid premature failure.

In addition to these considerations, PSTs may have unique characteristics, such as variable phase shift and susceptibility to through-fault damage. Therefore, when designing a protection system for PSTs, the transformer construction (single-core or two-core) and the type of PST (symmetrical or asymmetrical) must be considered.

Typical protection schemes for PSTs involve Kirchhoff's Current Law (KCL) and Ampere-Turns Balance (ATB) differential protections, overcurrent and neutral/ground overcurrent protections, Buchholz and LTC sudden pressure relay, and POTT protection schemes. Each scheme requires careful consideration depending on the specific type of PST being utilized, and the selection of the appropriate protection scheme should be finalized during the design stage.

Overall, it is crucial to thoroughly analyze the protection requirements of PSTs during the planning phase to ensure the implementation of a fast, reliable, and secure protection system.

SHORT CIRCUIT PROTECTION FOR PSTS

Short-circuit protection for PSTs is commonly achieved through differential protection systems based on KCL and ATB. KCL differential schemes are utilized when the primary equipment within the protection zone is electrically connected, while ATB schemes are employed when they are magnetically linked. PSTs typically use ATB-type differential protection, which is effective in detecting partial winding faults, such as turn-to-turn faults.

In some cases where traditional ATB protection cannot be applied to PSTs, KCL-type differential protections are used, like restricted earth fault (REF) protection for grounded wye windings. REF schemes monitor the sum of the $3I_0$ current entering the neutral of a grounded wye winding and the $3I_0$ current exiting the phase terminals of the same winding [2].

Transformer manufacturers offer protection and monitoring schemes for PSTs based on industry standards, such as IEEE Std C57.12.00 or IEC 60076-5, IEC/IEEE Std 60076-57-1202, and IEEE Std C57.135 or IEC 62032. They determine the most critical short-circuit conditions for each PST winding or active part, considering the significant impedance variations that can occur during tap changes. The PST design must consider the maximum system short-circuit fault levels expected throughout the PST unit's lifespan [1].

THROUGH FAULT PROTECTION FOR PSTS

Protecting PSTs against through-faults presents challenges due to their varying impedance, which depends on the tap position of the regulating winding and the type of PST construction. In a two-core PST, through-faults will affect only the series core when on the neutral tap, but when off-neutral, the windings of the excitation core are also exposed to through-fault currents [2]. On the other hand, a single-core PST has zero impedance on the neutral tap, resulting in a high ratio between external fault currents and the rated PST current, particularly in low-fault current impedance systems [1].

When selecting tap changers and evaluating winding forces, it is crucial to consider the impact of fault currents. The short-circuit current withstand capabilities of PSTs shall adhere to IEEE Std C57.12.00 or IEC 60076-5 unless otherwise agreed upon by the user and manufacturer before completing the PST design [1].

THERMAL OVERLOAD PROTECTION FOR PSTS

Protecting PSTs against thermal overload is more complex compared to conventional transformers. The number of turns carrying current and generating I^2R losses in a PST varies significantly depending on the tap position of the LTCs. In a two-core PST, thermal load flow primarily affects the series core when on the neutral tap. The current in the excitation core and the amount of I^2R heating also vary with loading and tap position. Single-core PSTs have complex thermal characteristics.

To address these challenges, manufacturers should define thermal overload limits and implement thermal model protection schemes. Direct temperature measurement using fiber-optic probes in the hottest spots of the windings is particularly useful for accurate temperature estimation, especially in detecting rapid hot spot rises caused by cooling system failures in the series windings.

The thermal overload capability of PSTs must comply with the requirements specified in IEEE C57.135 and C57.12.00 or IEC 60076-7. Additionally, the manufacturer should define and agree with the purchaser on additional overload requirements for retard operation before finalizing the PST design.

IMPACT OF LTC AND ARS IN PST DIFFERENTIAL PROTECTION

Phase shift angle regulation in PSTs is achieved by using LTC taps. The regulating winding can add or subtract turns to control in-phase, advance, or retard operation. Switching between advance and retard modes is accomplished by reversing the connection of one PST winding through the LTC or a separate Advance Retard Switch (ARS). Reference [1] describes several PST configurations, some with ARS and multiple LTCs for tap changes. In most cases, the differential protection is not affected by the transition between advance and retard modes.

For two-core PST designs, the method of winding connection inversion to achieve an advance/retard transition can be done through an ARS in the series transformer secondary winding or one or more LTC reversing change-over selectors, and sometimes an ARS in the exciter transformer secondary winding. The primary winding KCL-type differential is not affected by changes in the secondary winding connections of either transformer, as it only uses primary winding currents. However, the secondary winding ATB differential balances currents through the series transformer core. The measured series transformer primary winding currents are adjusted through CT compensation and tap settings to replicate the secondary delta currents, relying on a fixed turns ratio and angular relationship between the series primary winding currents and those in the delta-connected secondary [2].

When the winding connection is reversed in the exciter transformer secondary winding, the differential remains balanced, as the relationship between the primary winding currents and the delta-connected secondary currents in the series transformer remains unaffected, as discussed in [2].

However, if the winding connection is inverted in the series transformer secondary winding, the relationship between the currents in the primary winding and the delta-connected secondary changes, requiring two separate differential compensation settings, one for advance mode and the other for retard operation mode. Special accommodations may be necessary to ensure dependable and secure secondary winding differential protection throughout the range of tap positions and operation modes.

INRUSH IMPACT ON PST DIFFERENTIAL PROTECTION

The impact of inrush on differential protection in PSTs depends on the type of differential element used. Generally, KCL differential elements are immune to inrush currents as they cancel out within the protected zones. On the other hand, ATB differential elements and sequence component differentials can be affected during partial cycle saturation, leading to disruption in the differential operation.

Inrush with Single-Core PSTs:

Single-core PSTs, like the extended delta and delta hexagonal types, have delta-configured windings that experience inrush currents when energized with the full system phase-to-phase voltage. KCL-type differential elements for each winding remain unaffected. While ATB-type differentials are rarely used, if applied, their potential impact from inrush should be carefully analyzed. Sequence component differential elements are susceptible to misoperation during inrush and require traditional inrush security techniques.

Inrush with Two-Core PSTs:

Two-core PSTs typically employ two sets of differential relays: the primary winding differential relay (87P) and the secondary winding differential relay (87S). The 87P provides primary winding protection against faults, while the 87S offers phase and ground fault protection for the secondary windings.

The 87P, a KCL-type differential relay, is generally immune to inrush currents. However, inadequate mitigation of proximity effects on the CTs near the neutral end of the primary winding in the excitation transformer can lead to errors and misoperation.

The 87P does not detect faults in the secondary windings, which is where the 87S comes into play. The 87S utilizes an ATB differential, measuring the compensating current in the secondary winding of the series core. When the PST is energized on the neutral tap, the series core remains unexcited, and inrush current impact is minimized. However, if the PST is energized off the neutral, inrush current effects may arise, requiring traditional inrush security techniques.

Inrush currents can have varying impacts on differential protection in PSTs, depending on the type of differential element employed. It is vital to analyze the effects of inrush currents and implement appropriate traditional inrush security techniques to ensure robust and reliable protection. By addressing these considerations, the effectiveness of differential protection in PSTs can be significantly enhanced.

OVERCURRENT PROTECTION

Phase overcurrent protection can be utilized as a secondary protection scheme alongside the primary protection of Differential protection. However, applying instantaneous overcurrent protection becomes challenging when the PST is at the neutral tap position and its impedance is zero. In such cases, it becomes impossible to differentiate between internal and external faults based solely on the magnitude of the current.

If the minimum impedance of the PST is not zero in its minimum impedance position, it may be feasible to apply an instantaneous overcurrent function. In such cases, the internal fault current should exceed the external fault current by at least 30% [2]. Nevertheless, it is crucial to consider the security of the instantaneous overcurrent protection during PST energization when high inrush currents can occur.

When applying instantaneous overcurrent protection, it is crucial to consider the maximum inrush current value. Setting the pickup value at 1.5 to 2 times higher than the maximum inrush current helps avoid nuisance tripping and provides adequate protection for the PST.

Typically, the inrush current (in KA) is calculated as a multiple of the transformer-rated current based on the equivalent MVA of the PST as follows.

$$I_{Inrush} = (M * MVA_{EQ}) / ((\sqrt{3})*kV)$$

Where:
MVA_{EQ} is the equivalent MVA of the PST
kV is the phase-to-phase voltage of the PST
M is the inrush factor

The value for *M* can vary among manufacturers but commonly falls between 6 and 10 times the rated current.

In cases where a simple instantaneous overcurrent function is not feasible and voltage transformers (VTs) are accessible on both sides of the PST, instantaneous directional overcurrent protection with directional comparison logic can be employed. The selection of the specific type of directional comparison logic is crucial, with sensitivity and security during external faults and inrush being the primary influencing factors.

For satisfactory protection of the PST, the phase time overcurrent relay elements should be set to permit temporary overloading. These elements can have a pickup value of approximately 2.0 times or greater than the maximum continuous current rating of the PST. It is important to coordinate the settings of these relay elements with the PST damage curve and the source/line side relay settings to ensure adequate PST protection [2].

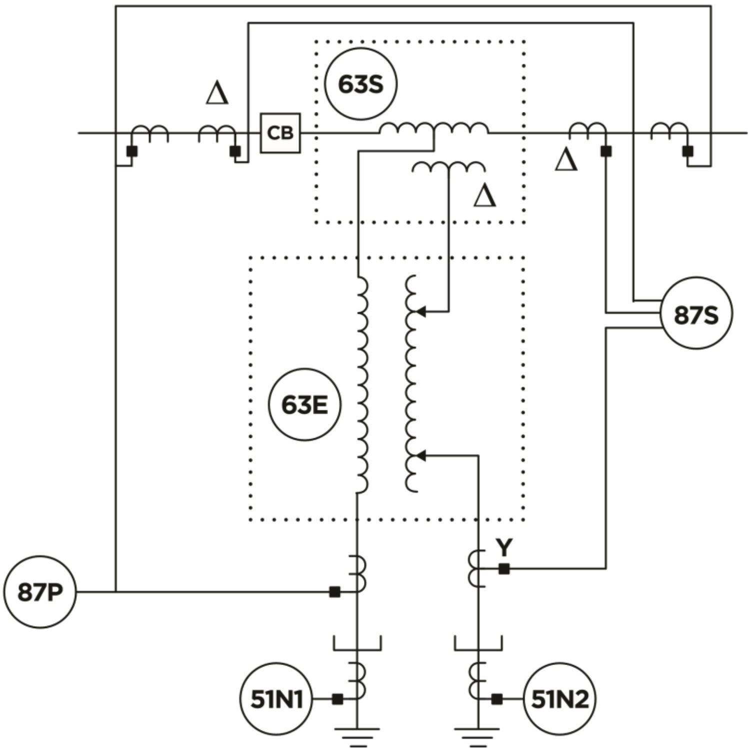
NEUTRAL/GROUND OVERCURRENT PROTECTION

The selection of neutral or ground overcurrent protection for PSTs depends on the type and design of the transformer. Directional ground time overcurrent protection can be applied to any PST configuration's source and load terminals. However, this method may not provide comprehensive backup protection for ground faults within the PST.

For PSTs that act as a zero-sequence source during system ground faults, coordination between the exciter transformer primary winding neutral time overcurrent elements (51N1) and external ground overcurrent elements, such as the line-side ground overcurrent relay, can be established. However, coordination with external ground overcurrent elements is unnecessary for PSTs that do not function as a zero-sequence source during system ground faults.

In the case of a two-core PST, inverse time-neutral overcurrent protection can be employed on the exciter transformer primary winding neutral CTs to provide backup ground fault protection for the PST. However, the exciter unit's secondary winding neutral overcurrent elements do not require coordination with line-side ground overcurrent elements. These elements respond solely to internal faults within the exciting transformer and should not be considered as backup protection for external faults [2].

When setting up the pickups for exciter transformer primary and secondary windings' neutral overcurrent elements, it is crucial to do so sensitively, considering unbalanced magnetizing inrush currents [2].



87P: Primary winding differential protective relay
87S: Secondary winding differential protective relay
51N1: Exciting transformer primary ground backup
51N2: Exciting transformer secondary ground backup
63S SPR: Series transformer sudden pressure relay
63E SPR: Exciting transformer sudden pressure relay

Fig. 5. Relaying options for protecting a two-core symmetric PST [8]

BUCHHOLZ AND LTC SUDDEN PRESSURE RELAY

Buchholz relays are commonly used in series and exciting transformers to detect internal faults. They monitor changes in oil pressure or the accumulation of gases resulting from insulation failure or arcs. Sudden Pressure Relays (SPRs) are also installed in the LTC compartments of the exciting-unit transformer. These relays protect against turn-to-turn faults that may not be detected by the PST's differentials, distance, or overcurrent protection functions. They operate when the pressure inside the transformer tank increases at a rate beyond the safe limits set by the manufacturer. SPR relays are highly sensitive to low- or high-energy arcs within the transformer LTC.

DIFFERENTIAL PROTECTION FOR PSTS

Differential protection plays a crucial role in safeguarding electrical equipment, including phase-shifting transformers (PSTs). There are two common types of differential protection: KCL and ATB differentials.

KCL-type differential protection is primarily used for protecting busbars or machine stators in the primary protection zone. It ensures that the sum of currents entering and leaving the zone is zero. In some cases, it may also be applied to protect the primary winding of a PST. Considering severe short-circuit conditions and impedance swings, the transformer manufacturer provides specialized protection and monitoring schemes for PSTs.

The 87P-KCL relay protects winding to the ground and winding to winding faults involving the primary windings only, as shown in Fig. 6. It will not detect turn-to-turn faults or faults on the secondary windings of the series or excitation cores. The 87P relay is unaffected by series-unit winding saturation caused by overvoltages during nearby external faults [2].

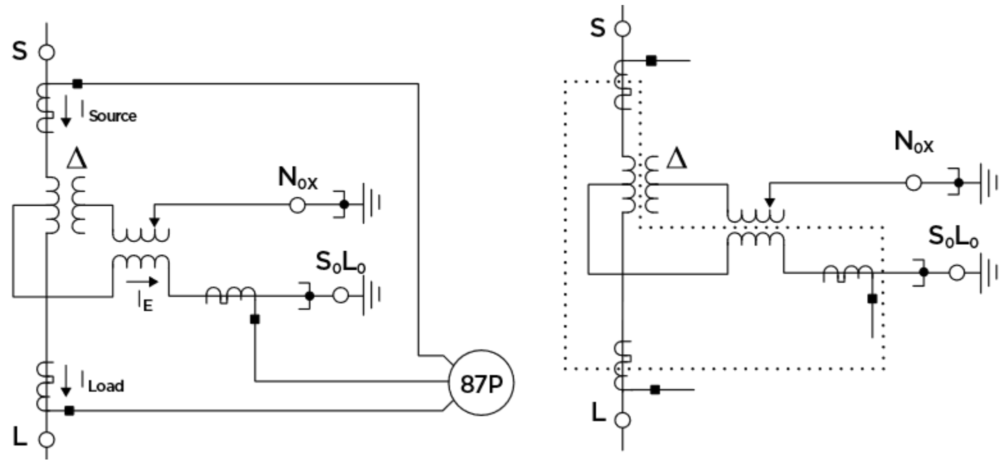
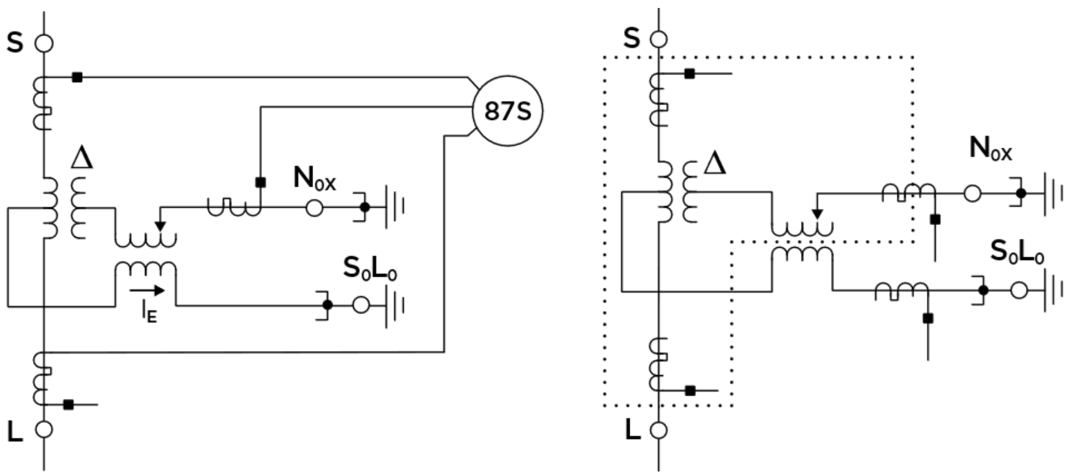


Fig. 6. 87P-KCL relay connections and zone of protection [2]

On the other hand, ATB-type protection is typically used for protecting a transformer's primary and secondary windings. It monitors the ampere-turns balance (ATB) on a magnetic core, swiftly responding to partial winding faults like turn-to-turn faults. The sum of ampere-turns within a protection zone is maintained at zero (AT1+AT2= 0 or $N_1 * I_1 + N_2 * I_2 = 0$).

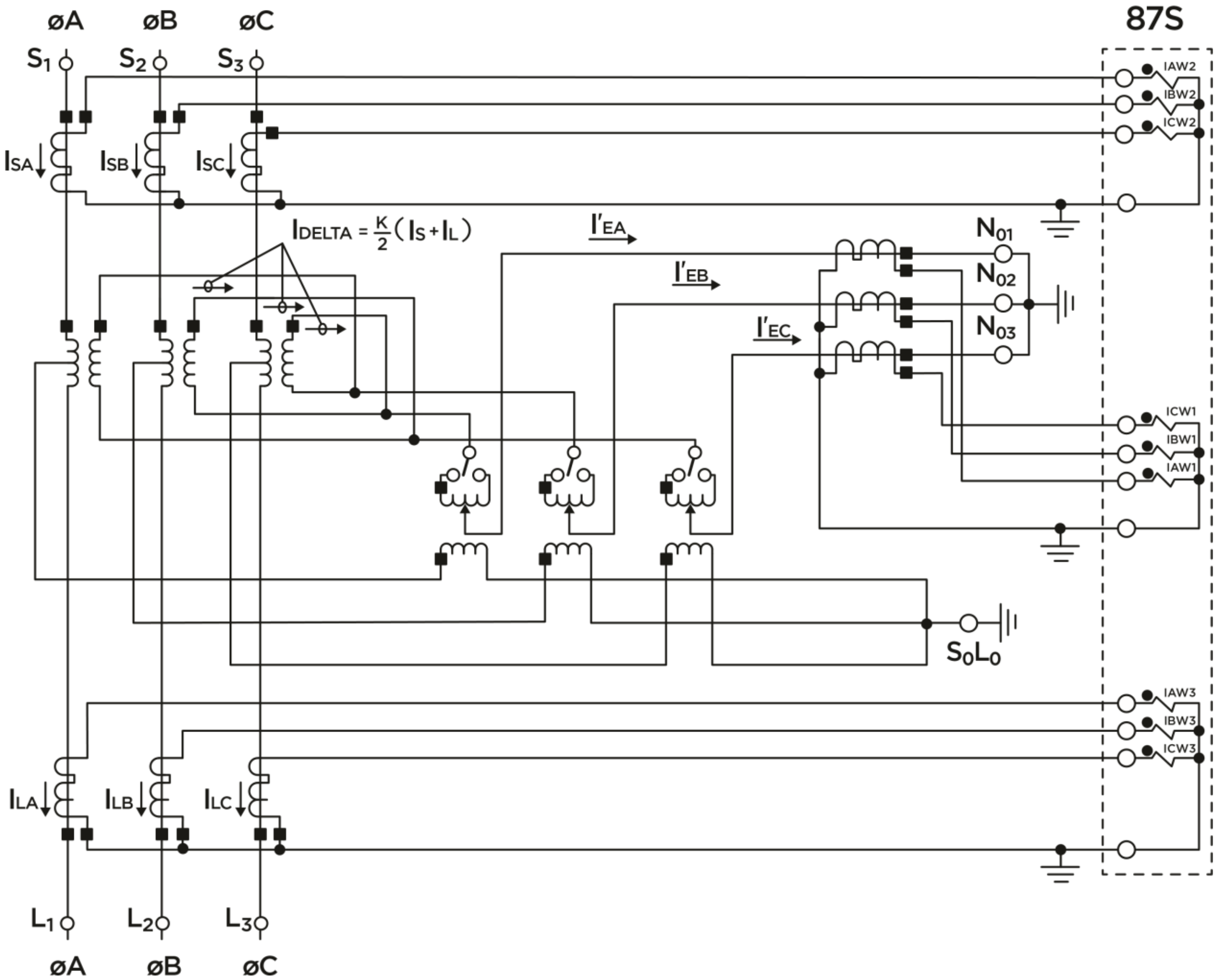
The 87S-ATB relay is provided by a percent restrained differential relay with a zone of protection defined by source and load bushing CTs and the exciter core secondary winding CTs, as shown in Figs. 7 and 8. The CT polarity shown in Figs. 7 and 8 is one possible connection option; alternatively, the load-side CTs can be connected with the opposite polarity, provided the relay supports angular compensation. The choice between delta and wye-connected CTs depends on the selected phase compensation method.



Note: N_{0X} CTs may be internal CTs rather than bushing CTs for some applications.

Fig. 7. 87S-ATB relay connections and zone of protection [2]

The 87S-ATB relay protects winding to ground, winding to winding, and turn-to-turn faults involving the series unit windings. It may lack sensitivity to detect winding-to-ground faults close to the neutral connection of the excitation secondary winding. The 87S relay will not respond to turn-to-turn faults in the secondary of the excitation transformer.



Notes: a) N_{0X} CTs may be internal CTs rather than bushing CTs for some applications.
b) I'_{EA}, I'_{EB}, and I'_{EC} are the exciting unit secondary A, B, and C phase lead currents, respectively.

Fig. 8. 87S-ATB three-phase relay connections [2]

Unlike conventional transformers with an AT unbalance range within ±10%, PSTs can have an AT unbalance of up to ±100% due to their phase shift. Adjustments of tap compensation factors in real-time are necessary for adequate protection. Detecting partial winding faults, such as turn-to-turn or turn-to-ground, requires high sensitivity. Therefore, many protection systems for PSTs rely on KCL-type differential elements, where traditional ATB protection cannot be applied to detect turn-to-turn faults and use sudden pressure relays (63SPR) or Buchholz relays for turn-to-turn fault protection.

Protecting single-core PSTs with ATB differential elements poses additional challenges. Balancing the current flow and number of turns in each winding segment for different tap positions is complex, even with real-time compensation. Special attention is given to addressing partial winding faults, considering the tap board lead and tap changer connections in series between the S and L bushings of the PST. Further guidance on single-core PST protection can be found in [2].

CONCLUDING REMARKS

Phase-shifting transformers (PSTs) are essential for the effective regulation of power flows in today's evolving energy landscape. They provide a reliable and cost-effective solution for controlling active power in transmission systems where rapid controls are unnecessary for stability.

Understanding the intricate magneto-electric circuit of PSTs and comprehending the current flow within their windings is of utmost importance for power engineers, particularly when developing detailed specifications and implementing effective protection strategies for PSTs. Reference [4] serves as a comprehensive guide, providing valuable insights into critical design aspects such as active power flow control principles, different categories of PSTs, essential design considerations, optimal circuit arrangements, operational factors, and project-specific requirements.

The present article has explored the essential protection requirements for PSTs, covering various aspects such as the strategic placement of CTs and PTs, practical strategies for short circuit and through fault protection, considerations for thermal overload protection, challenges related to overcurrent and neutral/ground overcurrent protection, and the impact of LTCs and ARS. Additionally, we have analyzed the effectiveness of Buchholz and LTC sudden pressure relays (SPRs) in detecting internal faults and the influence of inrush effects on the performance of differential protection schemes for PSTs.

By addressing these protection requirements and implementing appropriate schemes, we enhance the security of the protection system and ensure the reliable and efficient regulation of power flows within the transmission network. The knowledge gained from this paper provides valuable insights for improving the performance of PSTs and ensuring their availability in critical power systems.

Based on the insights presented in this paper, it is evident that there is a need for continued study into differential protection and POTT schemes for PSTs. Exploring these areas in greater detail and addressing the implementation challenges will lead to a deeper understanding and improved methodologies. Such research efforts will contribute to advancing the field of power engineering and further enhancing the performance and reliability of PSTs in power transmission systems.

By collectively addressing the challenges associated with PSTs and implementing robust protection strategies, protection engineers can ensure the reliable and secure operation of transmission systems and contribute to the overall stability and efficiency of the power grid.

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