CIGRE US National Committee
2023 Grid of the Future Symposium

Protecting Phase-Shifting Transformers: A Comprehensive Approach

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October 10, 2023

Outline

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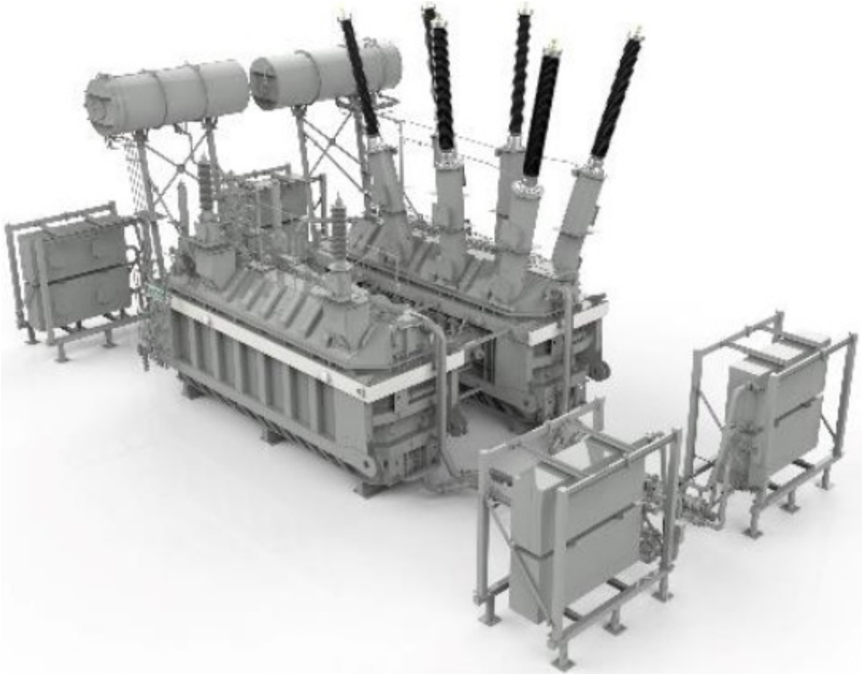
Background

- The modern power grid is evolving due to rising energy demand, deregulation, and the integration of renewable energy sources, requiring improved control of active power flows.
- PST plays an essential role in regulating power flow, offering a simple, reliable, and cost-effective means of controlling active power.
- Understanding PSTs' complex magneto-electric circuits and current flow within their windings is essential when developing specifications and implementing protection strategies for PSTs.
- This article focuses on enhancing protection requirements to bolster protection system security, ensuring PST's availability and efficient power flow control.

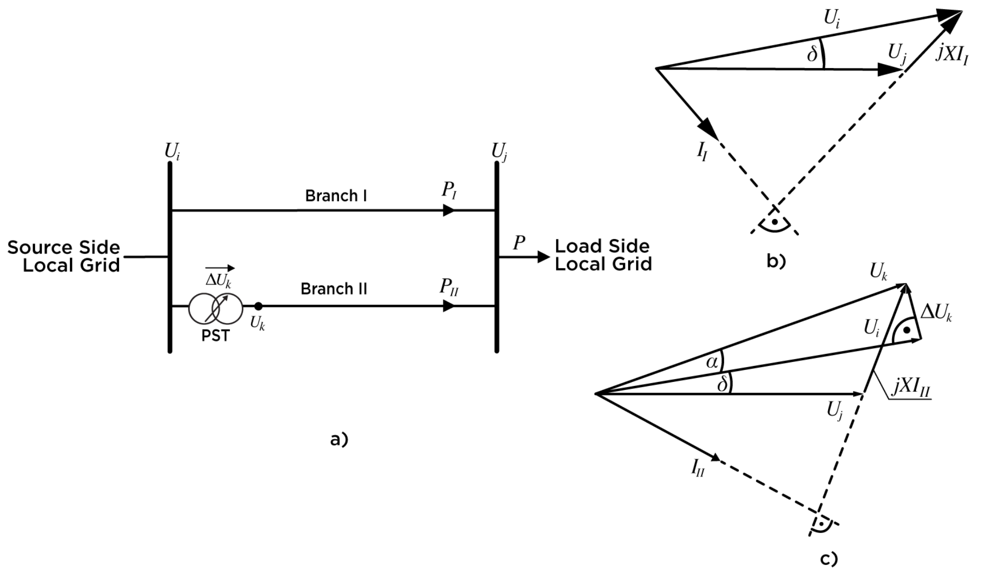
Phase-Shifting Transformers

Phase-shifting transformer (photo courtesy of ABB)



Phase-shifting transformer (photo courtesy of Siemens)

Principles of Active Power Control



Active power flow control by adjusting δ: a) system one-line with a PST, b) phasor diagram for branch-I, c) phasor diagram for branch-II [identical branch reactance, $X_I = X_{II} = X$]

- Active power flow (*P*) through a single branch of inductive reactance (*X*)

$$P = \frac{U_i U_j}{X} Sin\delta$$

- U_i, U_j – voltages at sending and receiving end, and δ – load angle (diff. of phases between U_i and U_j, $\delta = (\theta_i - \theta_j)$)

$$P_I = \frac{U_i U_j}{X} Sin\delta$$

$$P_{II} = \frac{U_k U_j}{X} Sin(\delta + \alpha) \quad \text{where, } U_k = U_i + \Delta U_k$$

- Since $(\delta + \alpha) > \delta$, $P_{II} > P_I$.
- ΔU_k (i.e., booster voltage) can be adjusted from (-α) to (+α)

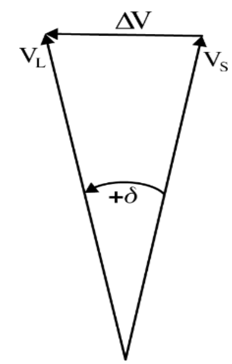
C1-108_2014: Improving the Cross-border Transmission Capacity of Polish Power System by Using Phase Shifting Transformers, *CIGRE 2014*

Types and Categories of PSTs

Symmetric or non-symmetric type; quadrature or a non-quadrature type with a single-core or a two-core design, and finally with a single tank or a dual tank design.

PSTs categories:

- Single-core asymmetric, with tap winding outside the delta
- Single-core symmetric, with tap winding outside the delta
- Single-core, symmetric, polygon (delta hexagonal)
- Two-core symmetric with wye-wye exciting unit (conventional)
- Two-core, asymmetric with wye-wye exciting unit (quadrature booster)

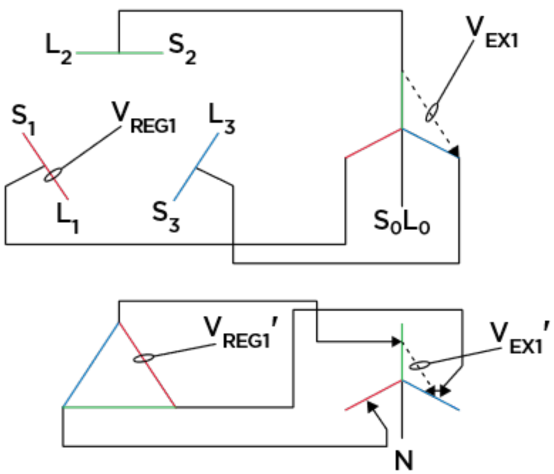


Quadrature voltage across a PST causes a shift in angle δ

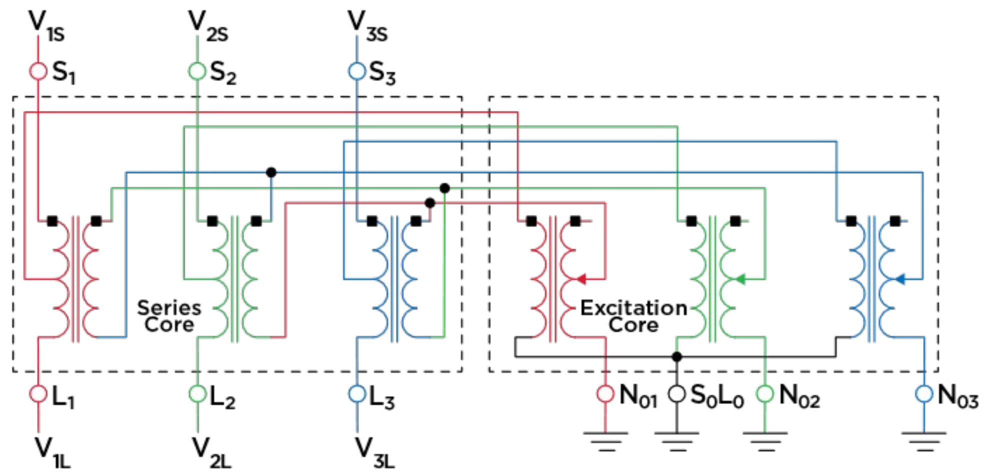
Available in various designs - such as fixed or variable phase shifts and options with or without voltage regulation.

IEEE Std C37.245:2018 Guide for the Application of Protective Relaying for phase-Shifting Transformers

Two-Core Symmetric PST- with Wye-Wye Exciting Unit (Conventional)



Nameplate diagram

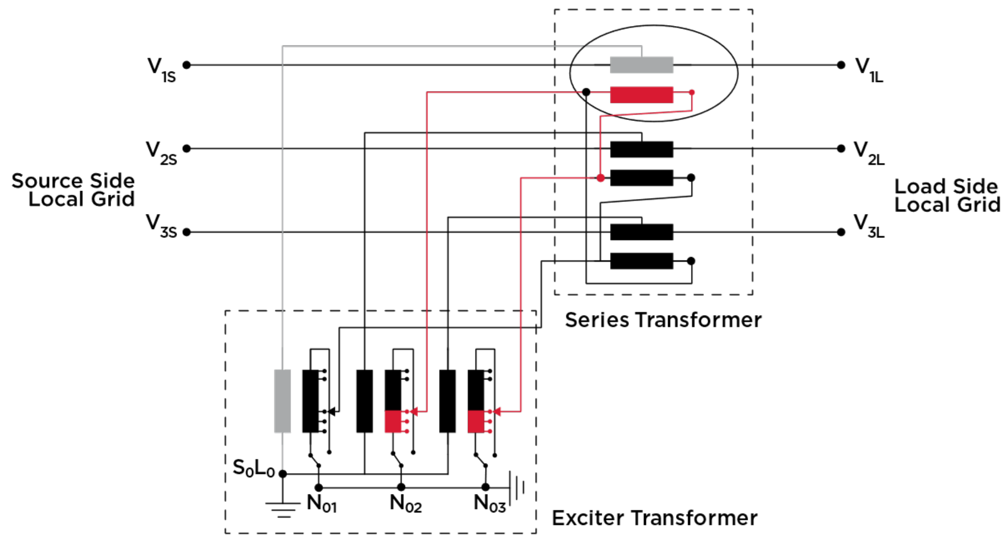


Three-line diagram of a two-core symmetric PST in the advanced position

IEEE Std C37.245:2018 Guide for the Application of Protective Relaying for phase-Shifting Transformers

T. Manna, "Design Considerations in Phase-Shifting Transformers to Enhance Loadability and Controllability of The Connected Grid," *2022 Grid of the Future Symposium, CIGRE USNC*, Chicago, Nov. 7-10, 2022.

Winding Arrangement of a Two-core Symmetric



Winding arrangement of a two-core symmetric PST in the advanced position

Exciter unit is powered by the source voltage supplied from the midpoint of the primary winding of the series transformer. This winding arrangement injects a booster voltage between the source and load bushings.

Phase-Shifting Transformers Application and Technology, ABB AG, Germany

T. Manna, "Design Considerations in Phase-Shifting Transformers to Enhance Loadability and Controllability of The Connected Grid," *2022 Grid of the Future Symposium, CIGRE USNC*, Chicago, Nov. 7-10, 2022.

Impact of CTs and VTs Location

- ► 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.

Bushing CT and Non-bushing CT

- ► VTs serve multiple functions, such as providing polarization for distance or directional elements.
- ► 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.

Key Considerations in PST Protection

- Unlike traditional power transformers, PSTs require sensitive, fast, reliable, and secure protection.
- High sensitivity is vital for detecting partial winding faults near the neutral, like turn-to-turn or ground faults.
- Challenges include managing CT saturation, inrush currents, and over-excitation, affecting reliable operation.
- Immediate tripping is crucial for preventing internal damage, and thermal overloading must be avoided.
- PSTs may possess unique characteristics, like variable phase shift and susceptibility to through-fault damage.
- Protection schemes encompass KCL differential and ATB differential, overcurrent, neutral/ground overcurrent, Buchholz and LTC sudden pressure relay, among others.

Short Circuit Protection

- 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 series winding.
- In some cases where traditional ATB protection cannot be applied to PSTs, KCL-type differential protection can be used for those cases.

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Through Fault Protection

- 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 [1].
- 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 [2]
- When selecting tap changers and evaluating winding forces, it is crucial to consider the impact of fault currents.

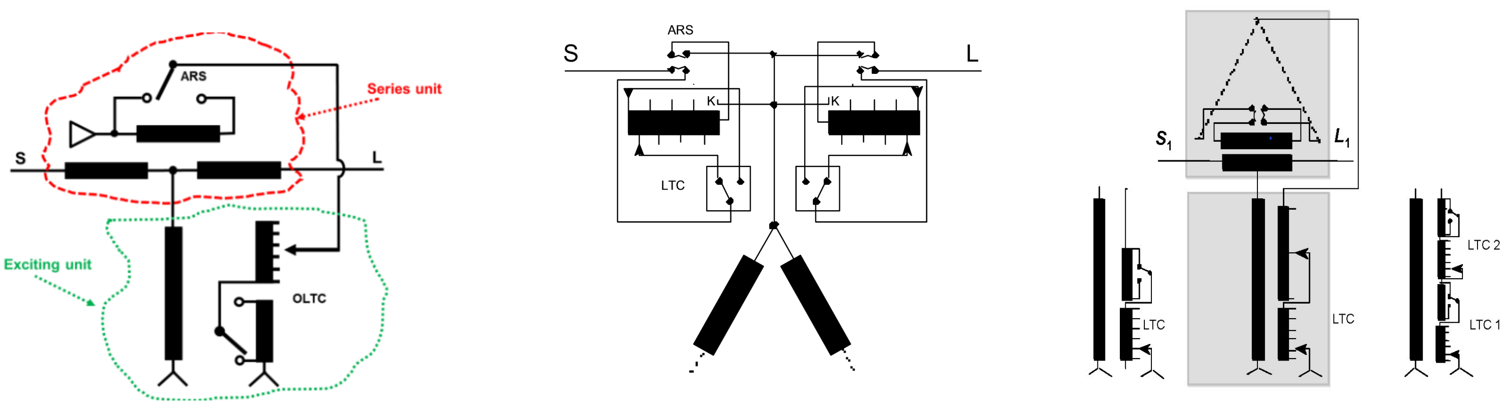
[1] IEEE Std C37.245:2018 Guide for the Application of Protective Relaying for phase-Shifting Transformers
[2] IEC 62032-2012/IEEE Std C57.135-2011 - Guide for the Application, Specification and Testing of Phase-Shifting Transformers

Thermal Overload Protection

- 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.

Impact of LTC and ARS on 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).
- In most cases, the differential protection is not affected by the transition between advance and retard modes.



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IEC 62032/IEEE Std C57.135:2012 Guide for the Application, Specification and Testing of Phase-Shifting Transformers

Impact of LTC and ARS on Differential Prot.(Cont'd)

- The primary winding KCL-type differential uses only primary winding currents, which will not be affected by changes in the secondary winding connections by either transformer's ARS or LTC switch.
- However, balancing of secondary ATB differential relies on a fixed and known turns ratio and angular relationship between the series primary winding current and those in the delta connected secondary. Any changes in the secondary connections may affect the differential balancing.
- Due to the change in connections by ARS in secondary delta winding, it requires two separate differential compensation settings, one for advance mode and the other for retard operation mode.
- When the winding connection is reversed in the exciter transformer secondary winding, the differential remains balanced.

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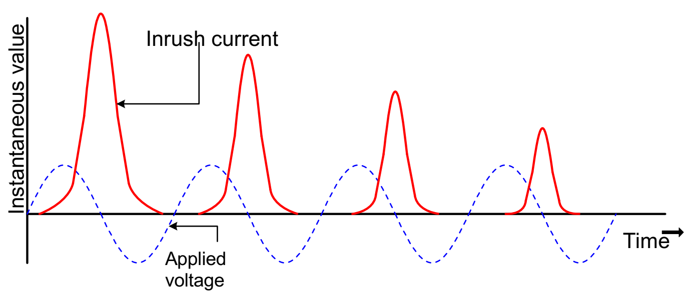
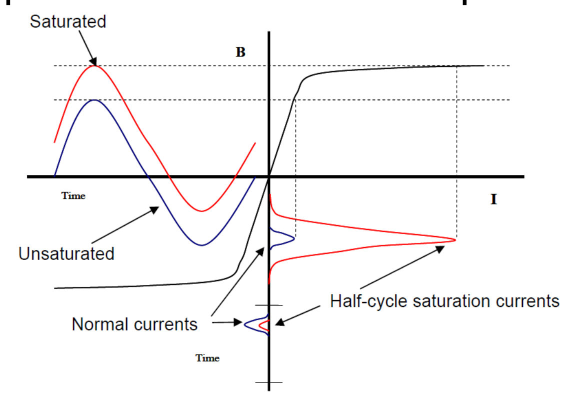
Inrush Impact on Differential Protection

- 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.



Typical magnetizing inrush current waveform



Part-cycle saturation of transformer cores under effect of dc

IEEE Std C37.245:2018 IEEE Std C37.91:2021 IEEE Std C57.163:2015

Inrush Impact on Differential Protection (Cont'd)

- The 87P of the two-core transformer provides primary winding protection against faults, while the 87S offers phase and ground fault protection for the secondary windings.
- The 87P is generally immune to inrush currents. However, inadequate mitigation of proximity effects on the CTs can lead to errors and misoperation.
- 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 the inrush current impact is minimized.
- However, if the PST is energized off the neutral, inrush current effects may arise, requiring traditional inrush security techniques.

Overcurrent Protection

- Phase overcurrent protection can be utilized as a backup of differential protection. However, applying instantaneous overcurrent protection becomes challenging when the PST is at the neutral tap position, and its impedance is zero.
- If the minimum impedance of the PST is not zero, it may be feasible to apply an instantaneous overcurrent function. However, it is crucial to consider the PST inrush current during PST energization.
- 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 phase time overcurrent relay element can be applied to protect PST; however, you need to consider allowing the temporary overload and coordinate with the PST damage curve.

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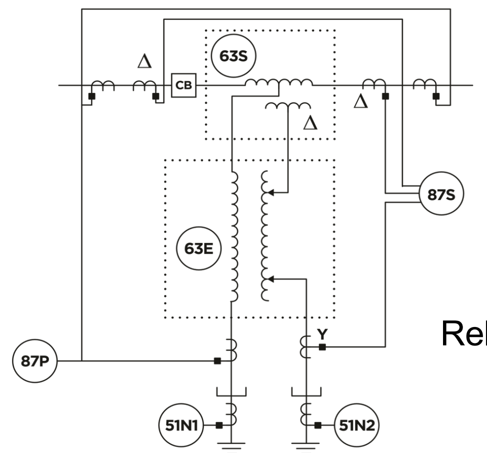
Neutral/Ground Overcurrent Protection

- Directional ground time overcurrent protection can be applied to any PST configuration's source and load terminals. However, ground instantaneous protection is not applied mostly due to the complexity of discriminating internal and external faults.

- 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.



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

Relaying options for protecting a two-core symmetric PST

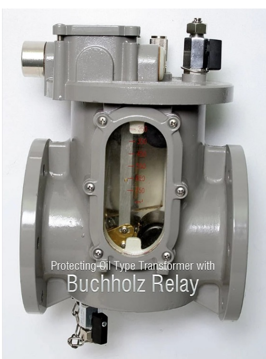
- However, the exciter unit's secondary winding neutral overcurrent elements do not require coordination with line-side ground overcurrent elements. These elements respond solely to internal faults within the exciting transformer.

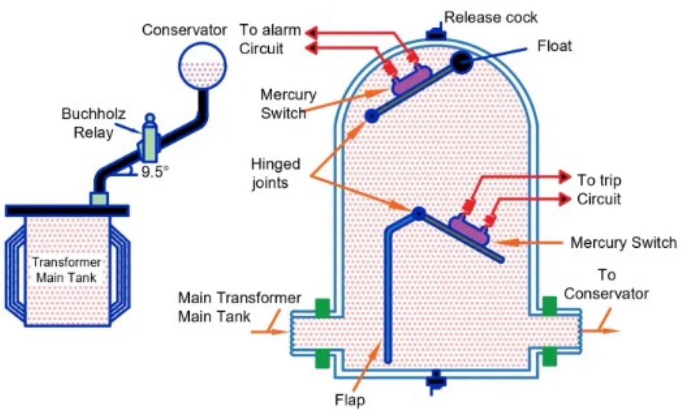
- When setting up the pickups for exciter transformer primary and secondary windings' neutral overcurrent elements, it is crucial to do so sensitively, considering unbalanced magnetizing inrush currents.

IEEE Std C37.245:2018

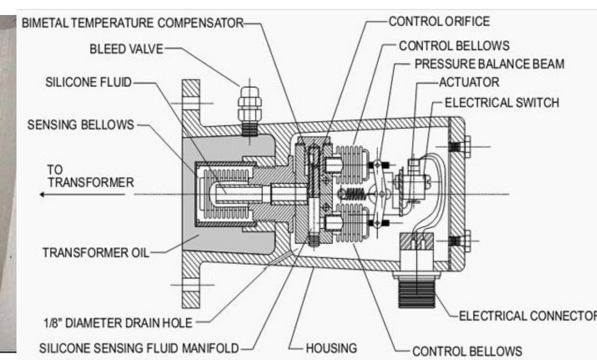
Buchholz and LTC Sudden Pressure Relay

- Buchholz relays are commonly used in PST to detect internal faults by detecting rapid oil flow or by detecting accumulating gases resulting from insulation failure or arcs.
- Sudden Pressure Relays (SPRs) are also installed in the series, exciting & LTC compartments of the exciting-unit transformer. These relays protect against turn-to-turn faults.
- SPRs 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.





Buchholz relay



Sudden pressure relay

IEEE Std C37.245:2018

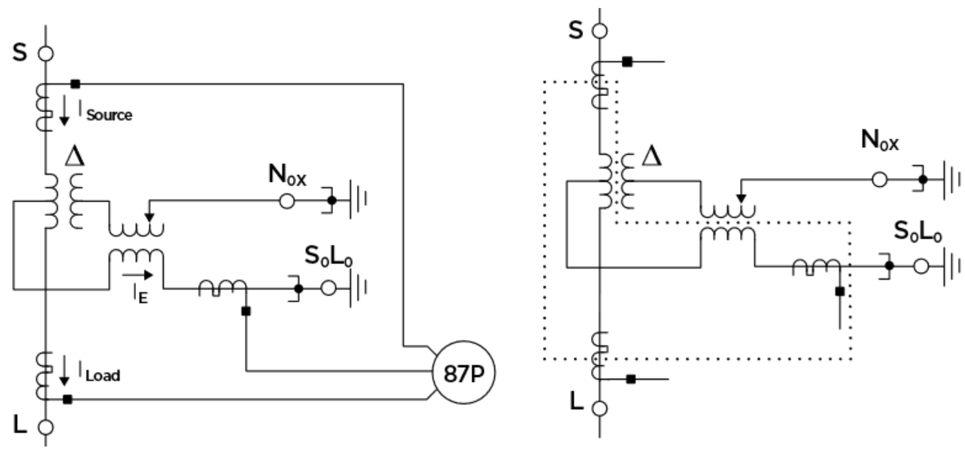
Images are taken from internet

KCL-Differential Protection

- The KCL-type differential protection is usually used to protect the primary winding of the series winding and the primary winding of the exciting unit using the current balancing theory, the sum of currents entering and leaving the zone is zero.

- The 87P-KCL relay protects winding to the ground and winding to winding faults involving the primary windings only.

- The 87P relay is unaffected by series-unit winding saturation caused by overvoltages during nearby external faults.



87P-KCL relay connections and zone of protection

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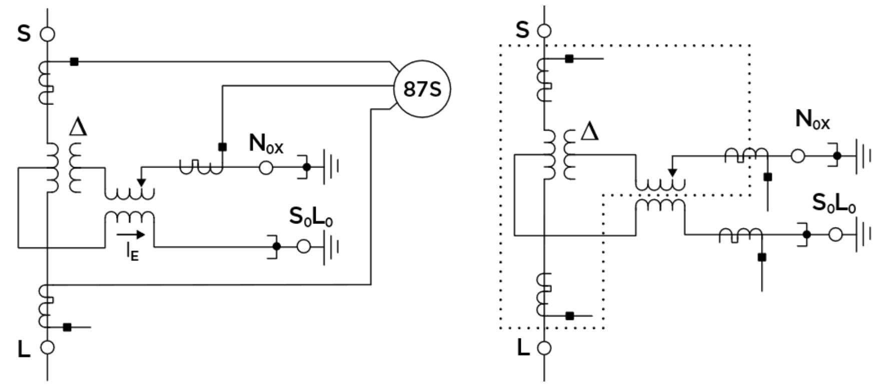
ATB-Differential Protection

- The ATB-type protection 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.



Note: N0X CTs may be internal CTs rather than bushing CTs for some applications.
87S-ATB relay connections and zone of protection

- 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.

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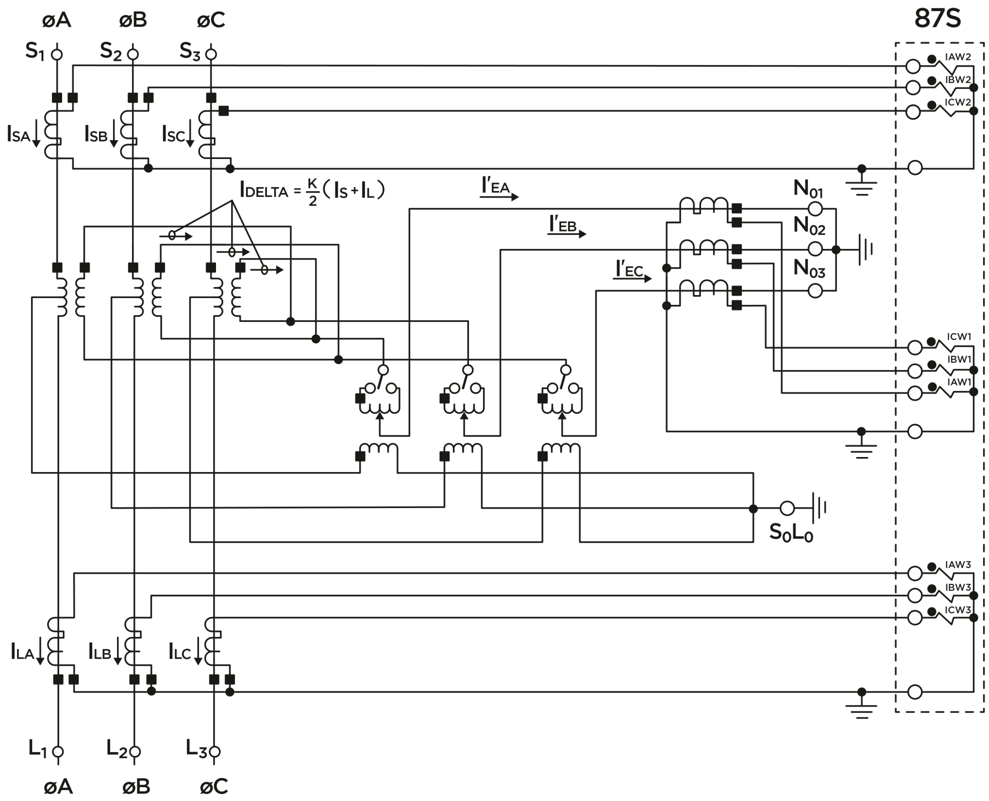
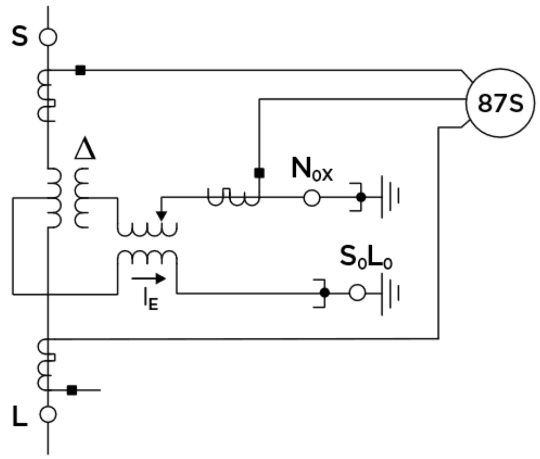
ATB-Differential Protection (Cont'd)





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

87S-ATB relay connections and zone of protection

IEEE Std C37.245:2018 Guide for the Application of Protective Relaying for phase-Shifting Transformers

Concluding Remarks

- PSTs provide a reliable and cost-effective solution for controlling active power.
- 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
- Understanding of challenges related to overcurrent and neutral/ground overcurrent protection, the impact of LTCs and ARS and inrush current effect and PST impedances on different winding configurations will help to choose correct protection.

References

[1] IEC 62032-2012/IEEE Std C57.135-2011 - Guide for the Application, Specification and Testing of Phase-Shifting Transformers

[2] IEEE Std C37.245: 2018 - Guide for the Application of Protective Relaying for Phase-Shifting Transformers

[3] C1-108_2014: Improving the Cross-border Transmission Capacity of Polish Power System by Using Phase Shifting Transformers, *CIGRE 2014*, www.e-cigre.org

[4] T. Manna, "Design Considerations in Phase-Shifting Transformers to Enhance Loadability and Controllability of The Connected Grid," *2022 Grid of the Future Symposium, CIGRE USNC*, Chicago, Nov. 7-10, 2022.

[5] Q. Tu et al., "Differential Protection Configuration for Phase Shifting Transformer," *2021 International Conference on Power System Technology* (*POWERCON*), Haikou, China, Dec. 8-9, 2021

[6] Phase-Shifting Transformers Application and Technology, ABB AG, Germany

[7] J. Andrichak and G. Alexander, "Distance Relays Fundamentals," *GER-3966*, GE Multilin, PA

[8] PSRC Working Group K1, "Protection of Phase Angle Regulating Transformers," Report to the Substation Subcommittee of IEEE PSRC, October 21, 1999.

[9] IEEE Std C57.12.00:2021 - Standard for General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers

[10] IEC/IEEE Std 60076-57-1202:2017 - Power transformers - Part 57-1202: Liquid immersed phase shifting transformers

[11] IEC 60076-5:2006 - Power transformers - Part 5: Ability to withstand short circuit

[12] IEC 60076-7:2018 - Power Transformers - Part 7: Loading guide for mineral oil-immersed power transformers

[13] IEC 62032:2012 - Guide for the Application, Specification and Testing of Phase-Shifting Transformers

[14] IEEE Std C37.91: 2021 - Guide for Protecting Power Transformers

Q&A

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