Application of Modern Differential to Fully Protect Various Types of Phase Shifting Transformers

Presented by:

JC Theron

Paper Authors:

Umar Khan, JC Theron - GE Vernova

Harjinder Sidhu – AltaLink, Canada

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Agenda

- Introduction/Objective
- Phase Shifting Transformer Theory
- Common Types of Phase Shifting Transformers
- Example of 2-Core Symmetrical PST
- Standard Transformer Differential
- Differential Protection of PSTs
  - Example of 2-Core PST Differential Method 1
  - Example of 2-Core PST Differential Method 2
- PST Differential Protection Aspects/Challenges
- Conclusion

Objective

While considering relaying technological application perspectives, objectives are:	To discuss differential protection methods for the protection of PSTs
	To discuss various issues and challenges related to the existing solutions
	To see the gaps between the available differential protection methods and protection requirements of the phase shifting transformers.

Objective

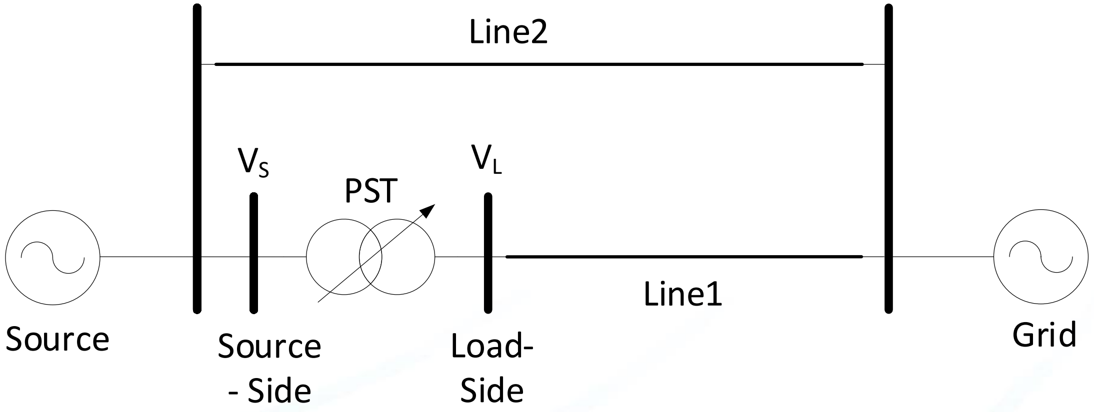
And to find the answers like:	Why a conventional power transformer differential principal established based on the ampere-turn relation is not fully applicable to PST?
	Do we need to revisit differential protection to fill the gaps?
	What are the design limitations of today transformer protection relay?
	Can a universal protection philosophy be established, which can be applied to conventional and special transformers including PSTs?

Phase Shifting Transformer Applications

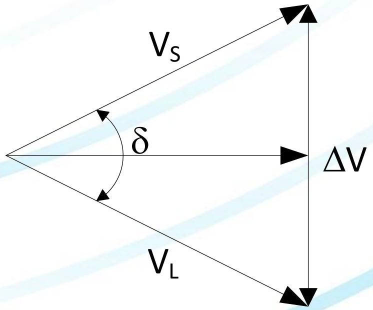
- Power Flow Management in Transmission Systems
- Optimizes power flow for efficiency in expansion of transmission networks and distributed generation.
- Controls active power flow over the transmission line through relative phase shift

Phase Shifting Transformer Theory

Active power flow over the transmission line

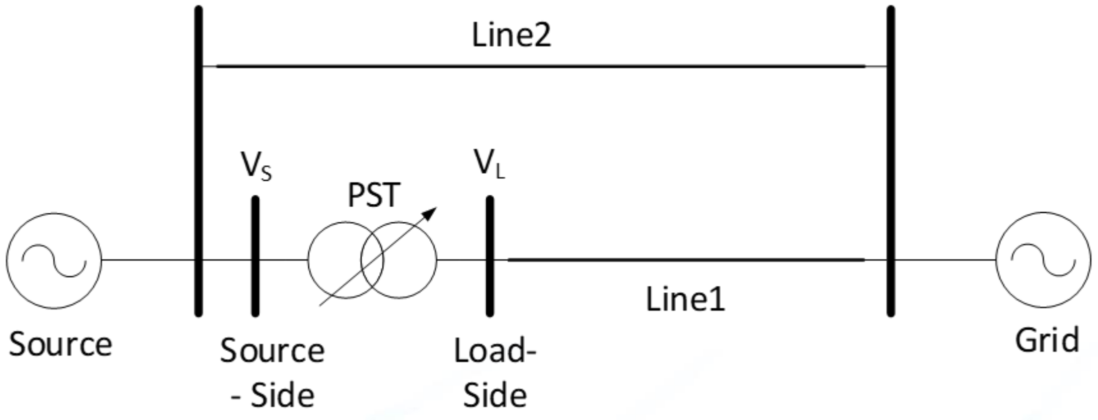


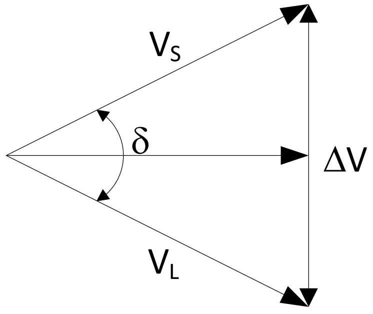
$$P = \frac{|V_1||V_2|}{Z} \sin \alpha$$



Phase Shifting Transformer Theory

Active power flow over the transmission line



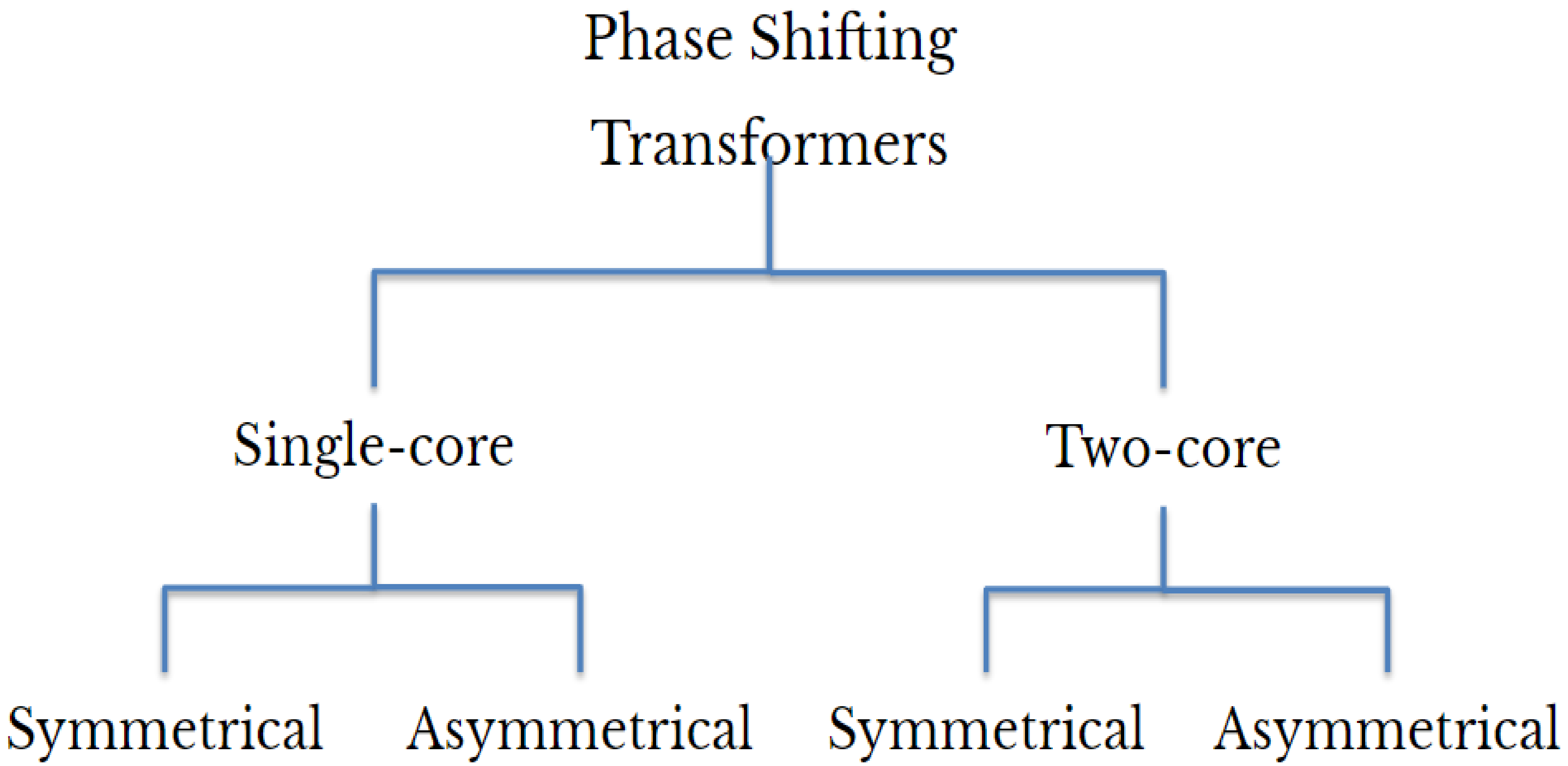


Active power can be controlled by varying

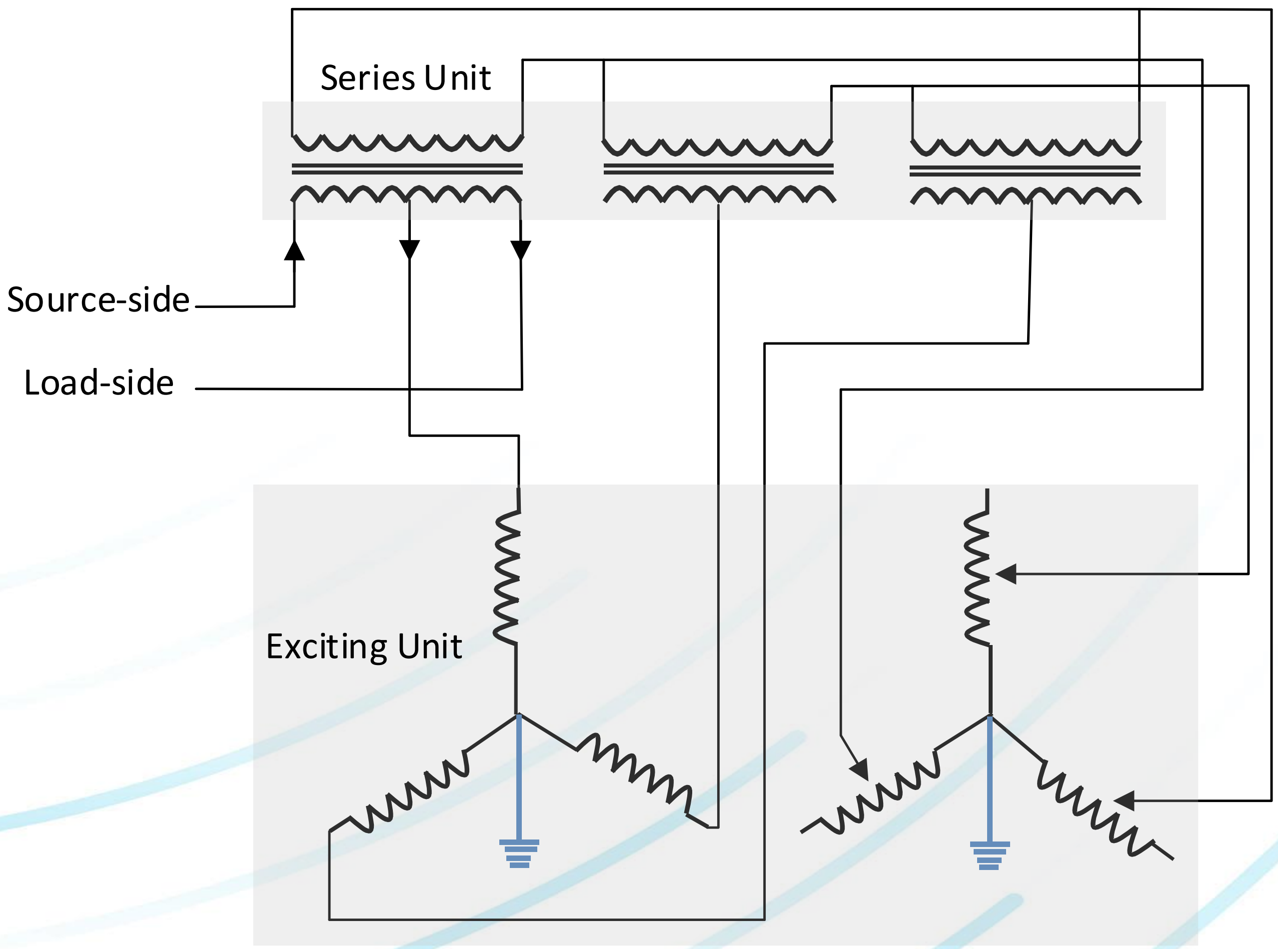
- ❑ Voltages → has more impact on reactive power
- ❑ Line impedance using capacitors bank in series
- ❑ Phase shift using phase shifting transformer

$$P = \frac{VS.VL}{ZL} sin\alpha$$

Common Types of PSTs

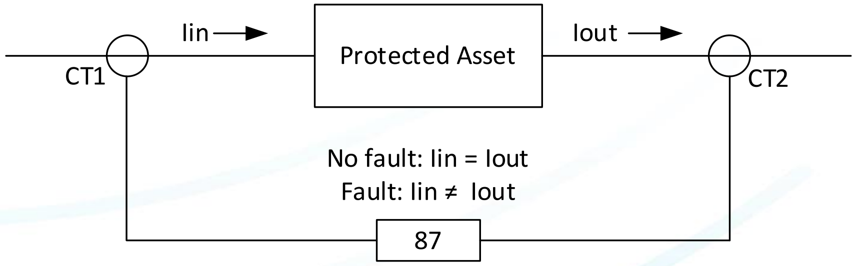


Example of 2-Core Symmetrical PST

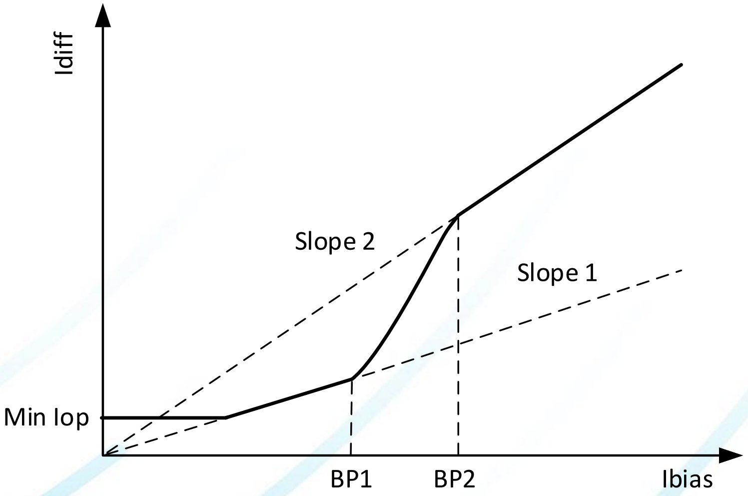


Standard Differential Protection

Schematic diagram of a two-winding transformer with differential relay

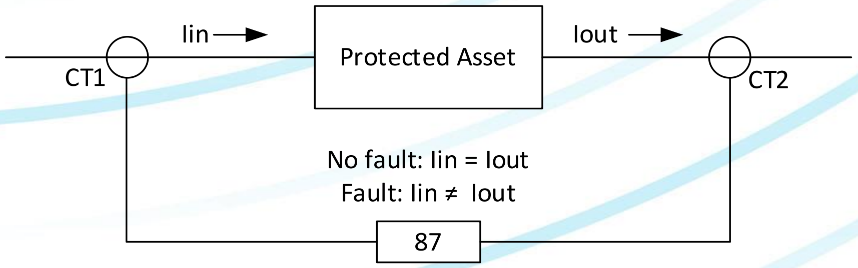


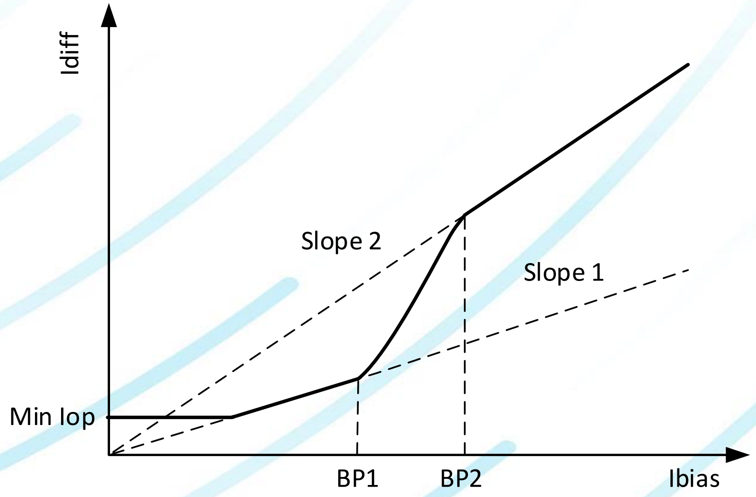
Percentage differential relay characteristic



Standard Transformer Differential Protection

- Differential Current is based on the ***ampere-turn balance*** of the magnetically-coupled windings
- Use as a ***main protection element*** in standard
- Provides ***speed and selectivity***
- Has ***security and dependability challenges*** in case of current transformer (ct) saturation, magnetizing inrush current, zero-sequence current, over excitation.





Differential Protection of PSTs

Differential Protection in Phase Shifting Transformers

- ❑ Dependent on PST type and construction
- ❑ Faces non-traditional challenges like
    - ✓ Non-standard phase shift,
    - ✓ high voltage saturation of windings,
    - ✓ turn-turn fault detection,
    - ✓ and current transformer location.
- ❑ Differential current measuring principles rely on both magnetic-coupled windings and electrically connected windings
- ❑ Two zones based differential current measuring principles suggested for a two-core symmetrical PST due to complex design.

Example of Two-Core Symmetrical PST Diff (1)

Method 1 – two zone-based solution

Zone 1 (87S) protection series unit and extends to secondary of Exciting Unit

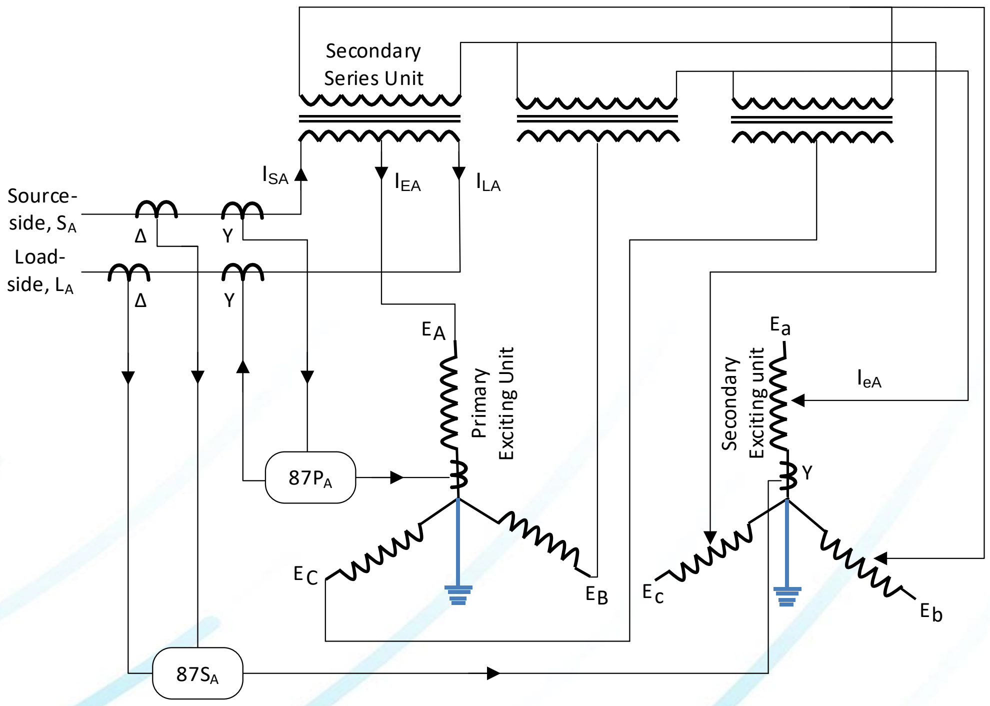
$$\begin{bmatrix} IdA\_87S \\ IdB\_87S \\ IdC\_87S \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{Ns} & \frac{1}{Ns} \\ \frac{1}{Ns} & 0 & -\frac{1}{Ns} \\ -\frac{1}{Ns} & \frac{1}{Ns} & 0 \end{bmatrix} \begin{bmatrix} ISA + ILA \\ ISB + ILB \\ ISC + ILC \end{bmatrix} - \begin{bmatrix} IeA \\ IeB \\ IeC \end{bmatrix}$$

Based on Ampere-turn Balance

Zone 2 (87P) protects primaries of Series and Exciting Units

$$IdA\_87P = |I_{SA} - I_{LA} - I_{EA}|$$
$$IdB\_87P = |I_{SB} - I_{LB} - I_{EB}|$$
$$IdC\_87P = |I_{SC} - I_{LC} - I_{EC}|$$

Based on Electrically Connected Circuit – like in busbar



Example of Two-Core Symmetrical PST Diff (1)

Method 1 – two zone-based solution

Zone 1 (87S) protects series unit and extends to secondary of Exciting Unit

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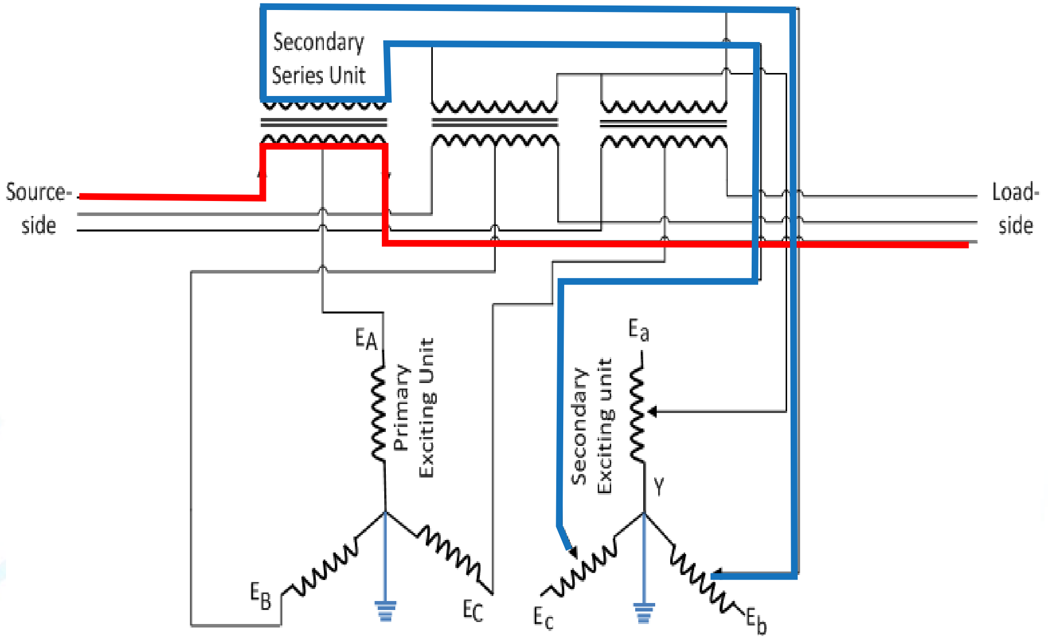
Based on Electrically Connected Circuit – like in busbar

Magnetically-coupled Zone



Example of Two-Core Symmetrical PST Diff (1)

Method 1 – two zone-based solution

Zone 1 (87S) protection series unit and extends to secondary of Exciting Unit

$$\begin{bmatrix} IdA\_87S \\ IdB\_87S \\ IdC\_87S \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{Ns} & \frac{1}{Ns} \\ \frac{1}{Ns} & 0 & -\frac{1}{Ns} \\ -\frac{1}{Ns} & \frac{1}{Ns} & 0 \end{bmatrix} \begin{bmatrix} ISA + ILA \\ ISB + ILB \\ ISC + ILC \end{bmatrix} - \begin{bmatrix} IeA \\ IeB \\ IeC \end{bmatrix}$$

Based on Ampere-turn Balance

Zone 2 (87P) protects primaries of Series and Exciting Units

$$IdA\_87P = |I_{SA} - I_{LA} - I_{EA}|$$
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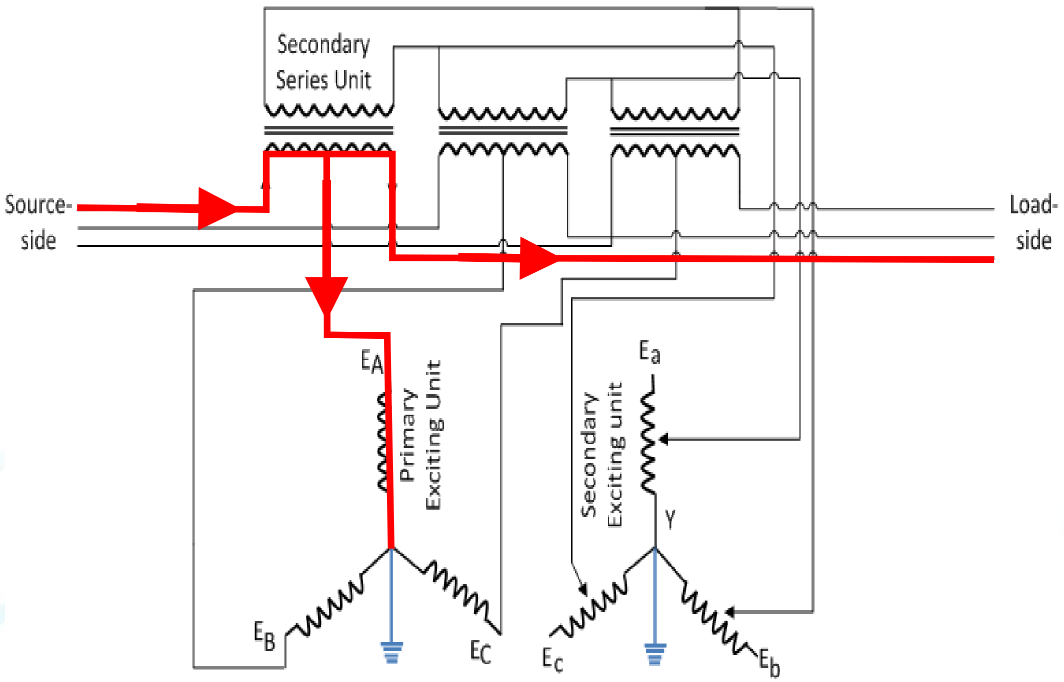
$$IdC\_87P = |I_{SC} - I_{LC} - I_{EC}|$$

Based on Electrically Connected Circuit – like in busbar

Electrically Connected Zone



Example of Two-Core Symmetrical PST Diff (1)

Method 1 – two zone-based solution

Zone 1 (87S) protects series winding

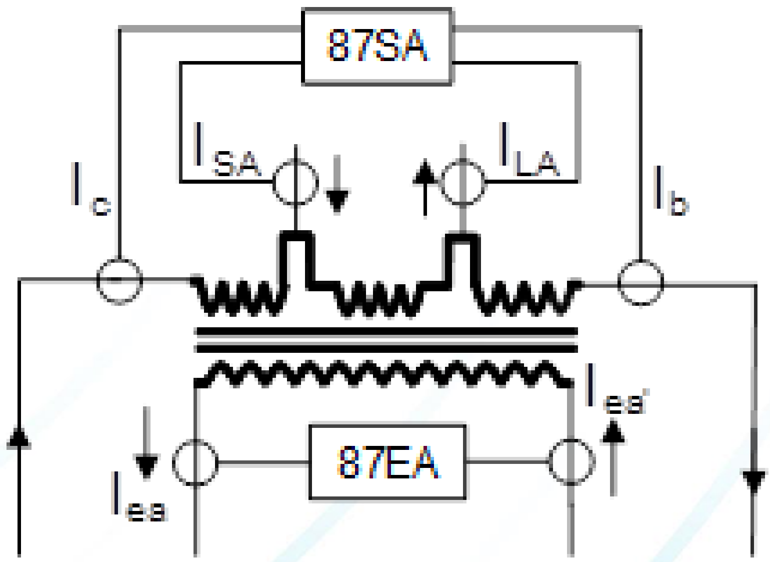
$$IdA\_87SA = |I_{SA} - I_{LA} + I_c - I_b|$$
$$IdB\_87SB = |I_{SB} - I_{LB} + I_a - I_c|$$
$$IdC\_87SC = |I_{SC} - I_{LC} + I_b - I_a|$$

Based on Electrically Connected Circuit – like in busbar

Zone 2 (87P) protects exciting winding

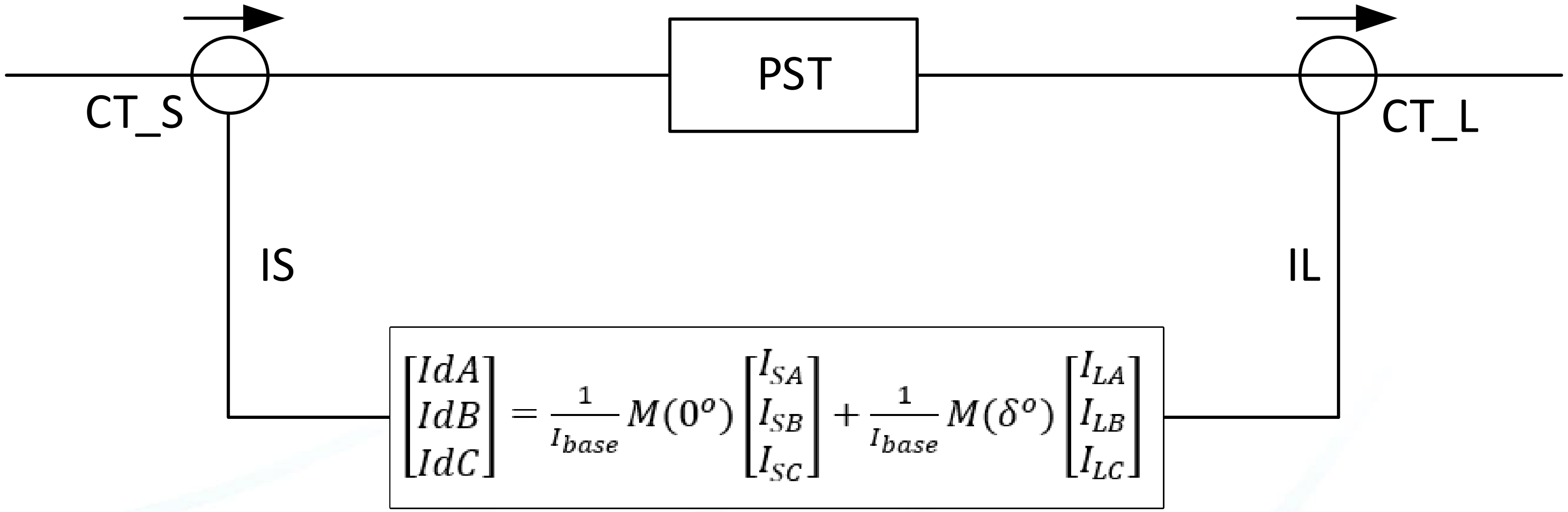
$$IdA\_87EA = |I_{ea} + I_{ea'}|$$
$$IdB\_87EB = |I_{eb} + I_{eb'}|$$
$$IdC\_87EC = |I_{ec} + I_{ec'}|$$

Based on Electrically Connected Circuit – like in busbar



Example of Two-Core Symmetrical PST Diff (2)

Method 2 – Two ends currents-based method that can be applied to Any PST Type



$$\begin{bmatrix} IdA \\ IdB \\ IdC \end{bmatrix} = \frac{1}{I_{base}} M(0^o) \begin{bmatrix} I_{SA} \\ I_{SB} \\ I_{SC} \end{bmatrix} + \frac{1}{I_{base}} M(\delta^o) \begin{bmatrix} I_{LA} \\ I_{LB} \\ I_{LC} \end{bmatrix}$$

- ❑ Requires Tap Position information to apply phase and magnitude compensation
- ❑ Considers PST as a black box.
- ❑ Uses two ends' currents to define differential current relations.
- ❑ Differential Current neither reflect ampere-turn relation or electrically connected circuit

PST Differential Protection Aspects

We aim to discuss few important aspects of designing a differential protection

- ❑ Relaying technological aspects
  - ✓ Need of single box solution
  - ✓ Requirement of tap position reading
  - ✓ Current inputs requirements
  - ✓ Non-standard online varying phase shift
- ❑ Traditional differential protection challenges
- ❑ Non-traditional differential protection challenges associated with PSTs

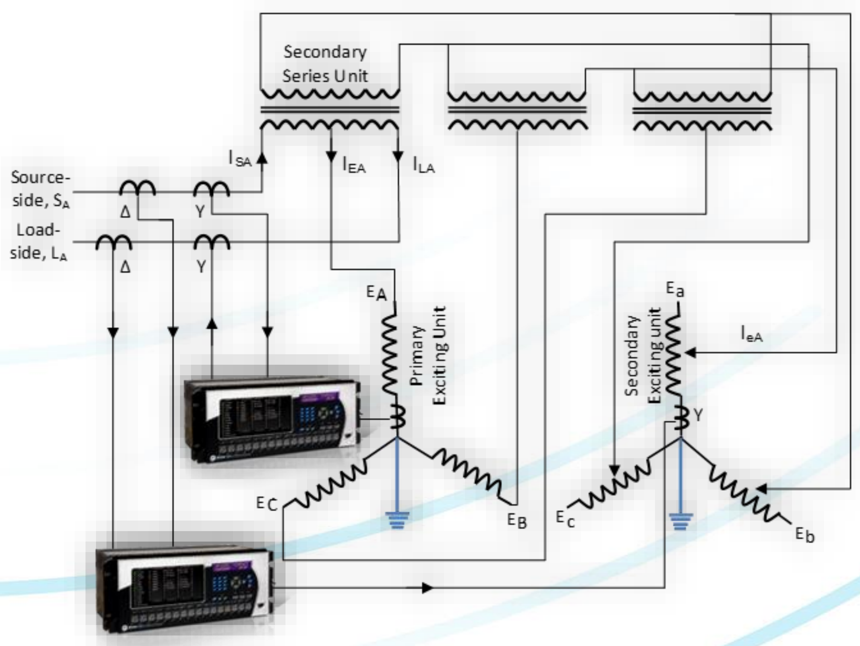
Relaying Technology Aspects

Need of Single Box Solution

Method 1 requires two box solution

Relay 87S -> represents magnetically-coupled zone

Relay 87P -> represents electrically-connected zone

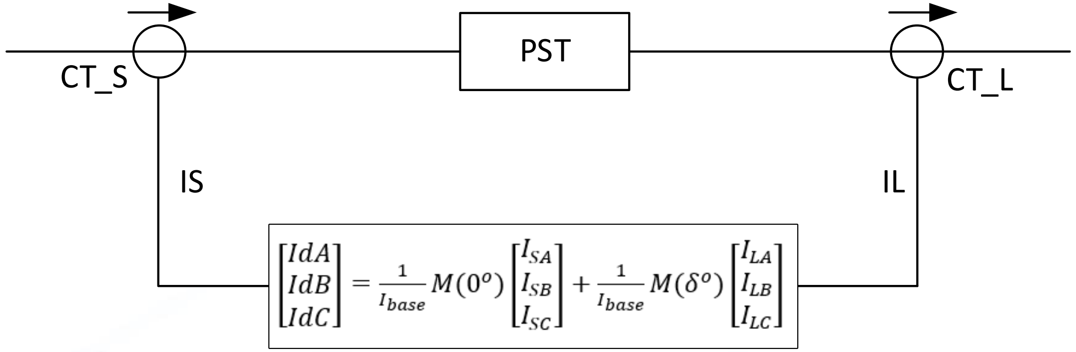


- To the best of author's knowledge, no signal box offers dual differential protection that uses both ampere-turn balance and electrically connected balance
- Need for a two-box solution: one for detecting ampere-turn imbalances in windings and the other for evaluating circuit protection

Relaying Technology Aspects

Requirement of tap position reading

Method 2 fills the gap of Need of Single Box Solution, but it requires reading of the Tap Changer Position



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- ❑ Converting tap-position data to required format can be challenging.
- ❑ Dependence on tap-changer information is perceived as a drawback.
- ❑ Differential principle calculates differential current independently of tap position input requirement.

Non-Traditional Relaying Technology Aspects

Other Aspects

Transformer Differential Relays and Phase Shifting Transformers

- Method 1 - Standard transformer differential relays have limited current transformer inputs, compared to phase shifting transformers' need for more than three CT inputs.
- Method 1 - Bus bar differential relays are needed to provide than 4 currents
- Method 2 - Two CTs per phase are required for phase shifting transformers, minimizing hardware challenges.

Standard Differential Relays used for PST protection

- Do not provide special designed functions that reflect differential characteristics of the PST

Differential Protection Challenges with PSTs

Problems associated with differential protection can be categorized as

- ❑ **Traditional**
- ❑ Non-traditional

Traditional Problems
Category I
❑ Phase shift due to winding connections across the transformer
❑ Magnitude mismatch between the currents due to CT ratio mismatch
❑ Zero-sequence current
Category II
❑ Magnetizing inrush current
❑ External fault with current transformer saturation
❑ Over-excitation

Differential Protection Challenges with PSTs

Problems associated with differential protection can be categorized as

- ❑ Traditional
- ❑ Non-traditional

Measurement of false differential current

Various conditions result in measurement of false differential current that can jeopardize the security of the relay. These condition includes

- Magnetizing Inrush Current
- Series-winding saturation
- Mismatch between current transformers
- Current transformer saturation during external fault

Therefore, differential protection is always dependent on the restraining or blocking unit in complementary

Differential Protection Challenges with PSTs

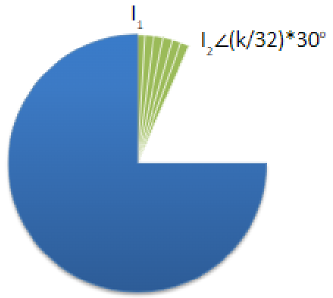
Problems associated with differential protection can be categorized as

- ❑ Traditional
- ❑ Non-traditional

Non-standard phase shift between source and load sides

In PST, phase shift (δ)depends on the step size; e.g. maximum 300 phase shift in 32 steps ∠(I1-I2)={k/32}*30 deg   where k = 1 to 32

Therefore, standard phase compensation techniques can't be applied in PST differential protection



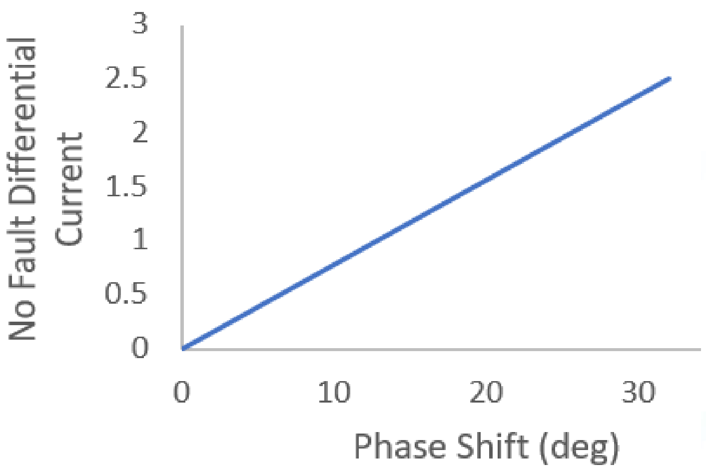
Differential Protection Challenges with PSTs

Problems associated with differential protection can be categorized as

- ❑ Traditional
- ❑ **Non-traditional**

False Differential Current

- ❑ Method 1 87S – no fault imbalance of ampere-turn relation – resulting into high false differential measurement as the function of varying phase shift
- ❑ Method 2 requires tap position to compensate phase angle, the differential current ideally remains zero with varying phase shifts



Method 1 – 87S presents magnetically-coupled circuits
Method 1 – 87P presents electrically-connected circuits
Method 2 uses two ends compensated currents

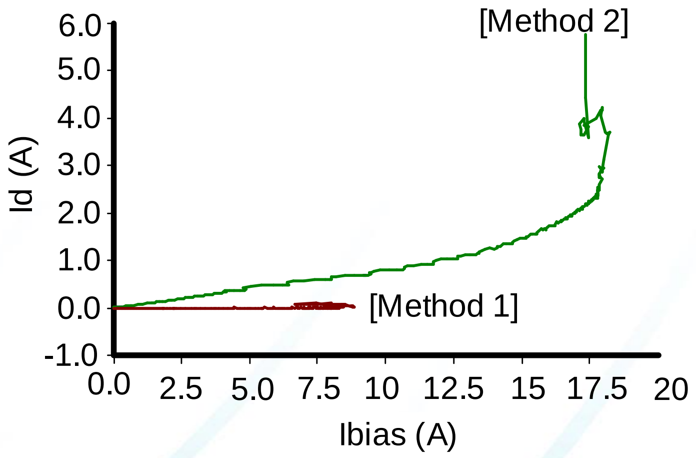
Differential Protection Challenges with PSTs

Problems associated with differential protection can be categorized as

- ❑ Traditional
- ❑ **Non-traditional**

Saturation of Series Winding

- ❑ Method 1 – no significant increase in the false differential current because the differential current is based on the electrically connected circuit
- ❑ Method 2 – measures large differential current due to saturation of series winding



Test Run on Delta Hexagonal PST

Method 1 – 87S presents magnetically-coupled circuits
Method 1 – 87P presents electrically-connected circuits
Method 2 uses two ends compensated currents

Differential Protection Challenges with PSTs

Problems associated with differential protection can be categorized as

- ❑ Traditional
- ❑ Non-traditional

Case	Tap	Fault Location	Shorted Turns (% of winding turns)	Method [1-87P]	Method [1-87S]	Method [2]
1	1	Secondary winding of Series Unit	10	No Trip	Trip	Trip
2			4	No Trip	Trip	No Trip
3		Primary winding of Exciting Unit	4	No Trip	No Trip	Trip
4	0.2	Secondary winding of Series Unit	25	No Trip	Trip	No Trip
5			10	No Trip	Trip	No Trip
6			5	No Trip	Trip	No Trip
7		Primary winding of Exciting Unit	25	No Trip	No Trip	Trip
8			10	No Trip	No Trip	Trip
9			5	No Trip	No Trip	Trip

Method 1 – 87S presents magnetically-coupled circuits
Method 1 – 87P presents electrically-connected circuits
Method 2 uses two ends compensated currents

Conclusion

- Various differential protection methods used for PSTs are discussed from the relaying technological perspectives and performance perspectives.
- Comparative analysis are discussed to show the performance of these methods under Traditional and Non-traditional challenges
- All the methods discussed have some pros and cons
- Significant scope of research still exists for the development of new protection techniques with built-in immunity to false differential current conditions and sensitivity to all kinds of low current internal faults

Thank You

Questions?