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

Abstract — Phase shifting transformers (PSTs) are used to control active power flow over the parallel transmission network. PSTs are available in different designs and types. Today, for the protection of PST conventional power transformer differential and/or busbar differential protection are applied. The standard current differential protection method established based on the ampere-turn balance of magnetically coupled windings may not be fully applied to a PST. As a standalone device, transformer protection relays today lack the ability to provide a single-box protection solution that can be applied to all PST types. This paper takes relaying technology into perspective and revisits various issues and challenges related to existing solutions used for the protection of PSTs. It discusses the limitations of conventional differential protection when applied to PST and answers questions like:

- Why is a conventional power transformer differential principal established based on the ampere-turn relation not fully applicable to PST?
- What are the hardware limitations of today's transformer protection relay?
- Can a universal protection philosophy be established that can be applied to conventional and special transformers, including PSTs?

I. INTRODUCTION

With the expansion of the transmission system network and greater penetration of distributed generation, the need for optimal power flow becomes necessary to achieve maximum efficiency. It becomes essential to control and manage power flow through the transmission network; thus, the installation of advanced flexible AC transmission system (FACTS) devices [1] or phase shifting transformers [2] become necessary.

The active power flow between two systems can be represented by the following relation:

$$P = \frac{|V1||V2|}{Z_L} sin\alpha \tag{1}$$

where V1 and V2 are the voltages of two systems, α is the phase angle shift between V1 and V2, and ZL is the reactance of the path or transmission line connecting two systems.

By examining (1), power flow between two independent systems can be controlled in three ways: (1) by adjusting the relative phase shift between the voltages of the two systems; (2) by regulating the voltages; or (3) by varying the reactance of the system using capacitance in series.

As compared to the FACTS devices, phase shifting transformers, also known as phase-angle regulating transformers, provide an economical solution to control power flow and also used in renewable energy systems to integrate distributed resources such as wind and solar power into the grid.

Within the power transformer family, PSTs are the most expensive types of transformers and are also vulnerable to abnormal fault conditions. Ensuring proper and effective protection becomes essential to protect them from abnormal conditions and maintain system reliability. Current differential protection is used as a primary protection to detect internal faults, along with other protection and monitoring devices such as overcurrent and overvoltage protection, temperature monitoring, arcing protection, and advanced monitoring and diagnostic devices.

Differential protection is particularly effective in detecting internal faults within the transformer, ensuring prompt isolation, and minimizing damage. While differential protection is generally effective in detecting internal faults, additional overcurrent protection is essential for preventing excessive current flow through the transformer, which can lead to overheating and damage. Overvoltage protection protects the transformer from voltage spikes or surges that could cause insulation breakdowns or other electrical failures. In this paper, the authors maintain their focus on differential protection, thus excluding other protection methods from the scope of this paper.

This paper discusses various differential protection methods [2], [3]-[8] used for the protection of PSTs. The primary goal of this paper is to highlight critical aspects that need to be considered when applying the available differential protection solutions for the protection of PSTs. An attempt has been made to introduce gaps between the available differential protection methods and the protection requirements of the phase shifting transformers. This paper takes relaying technology into perspective and revisits various issues and challenges related to existing solutions used for the protection of PSTs.

II. PHASE SHIFTING TRANSFORMERS

Phase Shift Transformers are available in different designs, each utilizing the principle of introducing varying quadrature voltage to vary phase shift between the source and load sides. The PSTs come in two-core and single-core designs, which can be either symmetrical or asymmetrical. Both the source (S) and load (L) sides are linked to the series winding. A symmetrical design changes the phase angle with equal magnitudes of source- and load-side voltages (VS, VL), while an asymmetrical design changes both the phase shift and voltage magnitude, potentially affecting the reactive power flow. In symmetrical design, the power flow is influenced solely by the phase shift angle, unlike in asymmetrical design. It utilizes two single-phase on-load tap changers (OLTCs) per phase, making it more expensive than the asymmetrical design. Fig. 1 shows an example of a two-core symmetrical PST design.

III. STANDARD CURRENT DIFFERENTIAL PROTECTION (87T)

Current differential protection operates by continuously monitoring the imbalance between the currents entering and leaving the protected zone [3]. A zone is defined by the location of the two-end current transformers (CTs). The current differential protection zone can be a magnetically coupled circuit, i.e., a transformer, or an electrically connected circuit, i.e., a busbar or a line. A power transformer current differential is established based on the ampere-turn balance of the magnetically coupled windings. A fault that occurs within this zone causes an ampere-turn imbalance, and the protective relay detects the fault and initiates a trip signal to isolate the faulty zone. Fig. 2 illustrates the concept of standard differential protection arrangements and typical two slope differential characteristics.

IV. CURRENT DIFFERENTIAL PROTECTION OF PHASE SHIFTING TRANSFORMERS

PST's unique design and construction present extra challenges in addition to the typical issues associated with standard transformer differential protection. PST differential protection faces challenges such as non-standard phase shift, winding saturation due to high voltages, detecting turn-turn faults, and determining the location of current transformers.

Unlike PSTs, the standard transformer design relies entirely on magnetic coupling, so the principle of determining differential current reflects the ampere-turn balance of the magnetically coupled transformer windings. However, the design and construction of the PST incorporate both magnetic coupling and electrically connected circuits. For example, the exciting unit primary winding is connected directly to the midpoint of series winding, as illustrated in Fig. 1. PST differential protection can be represented by magnetically coupled and/or electrically connected windings

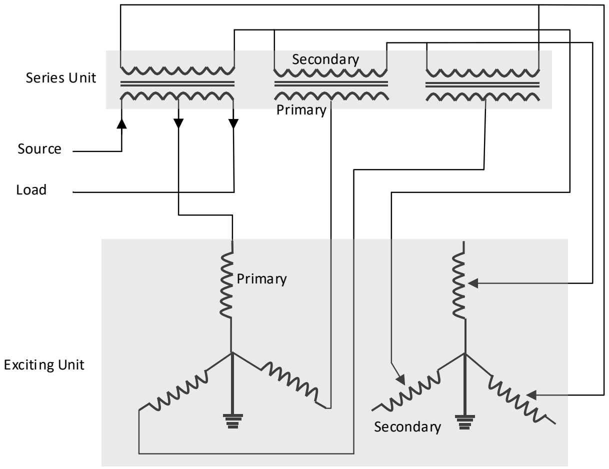

Fig. 1. Example of two-core symmetrical PST

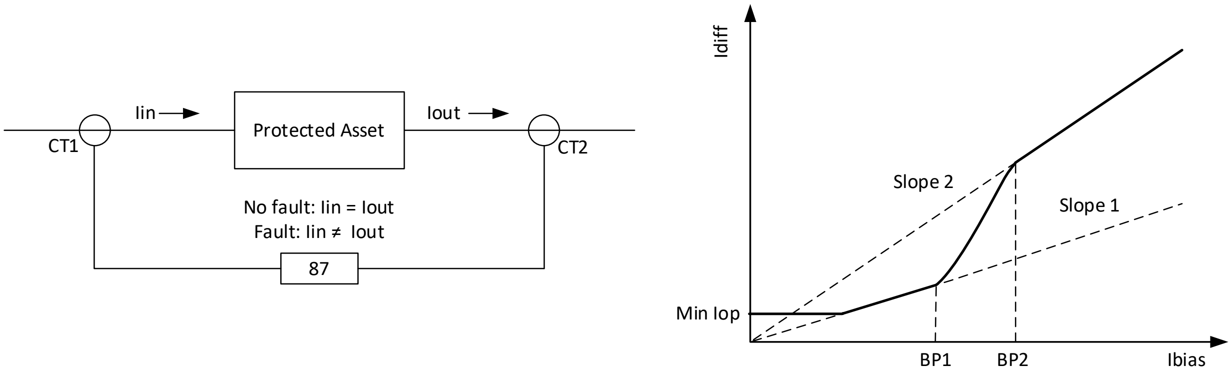

Fig. 2. Standard Differential Protection

[2] [4], or by the vector sum of the compensated currents entering and leaving the two ends of the PST, regardless of the PST design and construction [8].

This paper presents various differential protection methods in the remaining section and the limitations of those methods in section V.

Reference [2] suggests two zones based differential current measuring principles for a two-core symmetrical PST due to its complex design, as shown in Fig. 3. The differential protection zones comprise of a magnetically coupled zone (87T, T→transformer) and an electrically connected zone (87B, B→busbar). Equation (2) specifies the differential current based on the ampere-turn balance of the series unit, whereas (3) specifies the differential current relations for the electrically connected primary of series unit and exciting unit windings.

$$\begin{bmatrix} IdA \\ IdB \\ IdC \end{bmatrix}_{87T[2]} = \begin{bmatrix} 0 & -\frac{1}{Ns} & \frac{1}{Ns} \\ \frac{1}{Ns} & 0 & -\frac{1}{Ns} \\ -\frac{1}{Ns} & \frac{1}{Ns} & 0 \end{bmatrix} \begin{bmatrix} ISA + ILA \\ ISB + ILB \\ ISC + ILC \end{bmatrix} - \begin{bmatrix} IeA \\ IeB \\ IeC \end{bmatrix} \tag{2}$$

$$\begin{aligned} IdA_{87B[2]} &= |I_{SA} - I_{LA} - I_{EA}| \\ IdB_{87B[2]} &= |I_{SB} - I_{LB} - I_{EB}| \\ IdC_{87B[2]} &= |I_{SC} - I_{LC} - I_{EC}| \end{aligned} \tag{3}$$

where *IS* is the source side current, *IL* is the load side current, *Ie* is the exciting unit secondary side current, and IE is the exciting unit primary winding current.

Reference [2] also suggests two electrically connected zones (87B_S, 87B_E) of delta-hexagonal type PST differential protection, each protecting the series and exciting windings, as shown in Fig. 4. Equation (4) specifies the differential current relations for the series winding differential protection, and (5) specifies the relation for the exciting winding differential protection.

$$\begin{aligned} IdA_{87B\_S[2]} &= |I_{SA} - I_{LA} + I_c - I_b| \\ IdB_{87B\_S[2]} &= |I_{SB} - I_{LB} + I_a - I_c| \\ IdC_{87B\_S[2]} &= |I_{SC} - I_{LC} + I_b - I_a| \end{aligned} \tag{4}$$

$$\begin{aligned} IdA_{87B\_E[2]} &= |I_{ea} + I_{ea'}| \\ IdB_{87B\_E[2]} &= |I_{eb} + I_{eb'}| \\ IdC_{87B\_E[2]} &= |I_{ec} + I_{ec'}| \end{aligned} \tag{5}$$

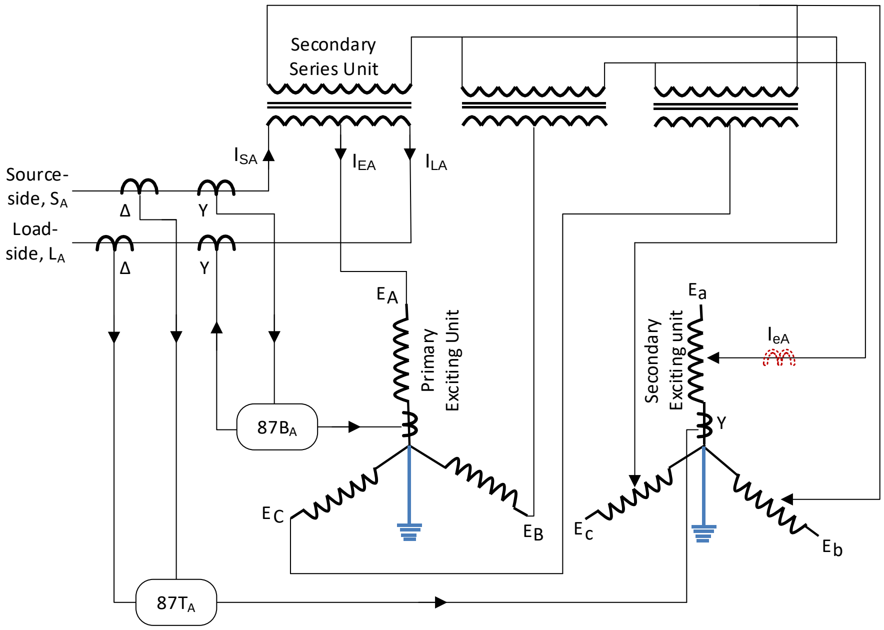

Fig. 3. Two-core symmetrical PSTs differential protection

where I_a, I_b, and I_c are the currents in the exciting windings.

Reference [8] proposes a universal differential protection (87X) that can be applicable to any type of PST. Differential current is computed using the source and load side currents and requires tap position input to properly compensate phase and magnitude due to phase shift between two ends. Instead of defining the differential current relation that reflects either an ampere-turn relation (87T) or an electrically connected circuit (87T), or both, it simply considers PST as a black box and uses source- and load-side currents to establish the differential current relations (6), thus named "87X" for reference within the paper.

$$\begin{bmatrix} IdA \\ IdB \\ IdC \end{bmatrix}_{87X[8]} = \frac{1}{I_{base}} M(0^o) \begin{bmatrix} I_{SA} \\ I_{SB} \\ I_{SC} \end{bmatrix} + \frac{1}{I_{base}} M(\delta^o) \begin{bmatrix} I_{LA} \\ I_{LB} \\ I_{LC} \end{bmatrix} \tag{6}$$

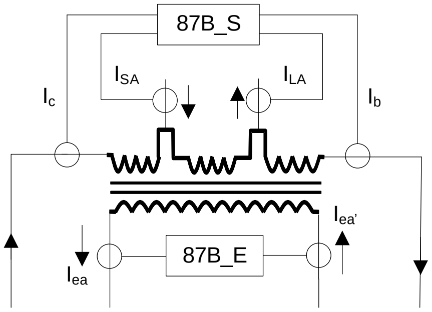

Fig. 4. Phase A differential protection of single-core delta-hexagonal PST

$$M(\delta^{o}) = \frac{1}{3}\begin{bmatrix} 1+2\,cos(\,\delta) & 1+2\,cos(\,\delta+120) & 1+2\,cos(\,\delta-120) \\ 1+2\,cos(\,\delta-120) & 1+2\,cos(\,\delta) & 1+2\,cos(\,\delta+120) \\ 1+2\,cos(\,\delta+120) & 1+2\,cos(\,\delta-120) & 1+2\,cos(\,\delta) \end{bmatrix} \quad (7)$$

where I_{base} is the base current and δ is the phase shift between source and load sides.

Reference [4] proposes the relation to compute the differential current of delta-hexagonal PST that reflects the ampere-turn relation (87T) between the magnetically coupled windings but requires reading of the actual tap position. The differential currents are defined as:

$$\begin{aligned} IdA_{87T[4]} &= \left(\frac{D+1}{2}+\frac{1}{N}\right)(I_{LC}+I_{SC})+D(I_{LA}+I_{SB}) \\ IdB_{87T[4]} &= \left(\frac{D+1}{2}+\frac{1}{N}\right)(I_{LA}+I_{SA})+D(I_{LB}+I_{SC}) \\ IdC_{87T[4]} &= \left(\frac{D+1}{2}+\frac{1}{N}\right)(I_{LB}+I_{SB})+D(I_{LC}+I_{SA}) \end{aligned} \quad (8)$$

where D and N are the tap position and series-to-exciting winding turn ratio, respectively.

References [5] and [7] propose electromagnetic differential protection methods for a single-core delta-hexagonal and a standard-delta phase shifting transformers. The principle combines equations for mutually coupled windings to detect faults and maintain stability during magnetization inrush current and series winding saturation. Equation (9) shows electromagnetic differential relations for single-delta standard delta PST:

$$\begin{aligned} IdA &= VSA - VLA - ZA.(ISA + ILA) - D.N.(VnB - VnC + Za.Ia) \\ IdB &= VSB - VLB - ZB.(ISB + ILB) - D.N.(VnC - VnA + Zb.Ib) \\ IdC &= VSC - VLC - ZC.(ISC + ILC) - D.N.(VnA - VnB + Zc.Ic) \end{aligned} \quad (9)$$

Reference [6] proposes a universal method for protecting any type of phase shifting transformer. The proposed technique is based on the directional comparison method. The fault detection criterion is based on the fault's direction, as determined by two directional comparison elements (RS, RL) installed on the transformer's source and load sides. According to the directional comparison principle, the loci of the superimposed positive- and negative-sequence impedances for forward faults are in the third quadrant of the impedance plane, while for reverse faults, the loci are in the first quadrant.

V. DISCUSSION ON PHASE SHIFTING TRANSFORMER DIFFERENTIAL PROTECTION

In this section, the authors intend to discuss several important aspects of designing a PST differential protection solution. These aspects include relaying technological aspects, traditional differential protection challenges, and non-traditional challenges associated with PSTs differential protection methods. The authors emphasize the need to consider relaying technology in perspective when designing differential protection solutions for PSTs.

A. Relaying Technology Perspectives

1) Need for a Single Box Solution

The differential protection methods suggested in [2] are designed to protect all windings of two-core symmetrical and delta-hexagonal PSTs. The differential protection method for a two-core PST involves utilizing two separate differential protection elements. One element monitors the ampere-turn balance of the magnetically coupled series unit windings, while the second element detects any imbalance in the electrically connected circuit. Currently, there

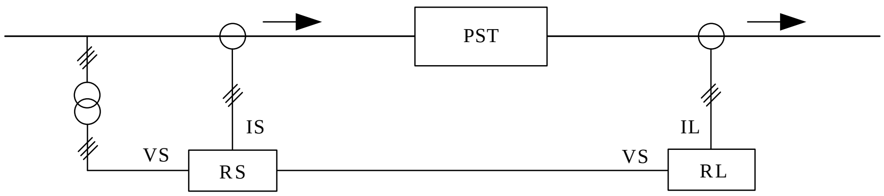

Fig. 5. Arrangement of Directional Comparison based PST protection [6]

is no transformer protection relay available that provides dual differential protection elements capable of detecting ampere-turn imbalances and imbalances in electrically connected circuits. To achieve dual functionality, a two-box solution is required. The first box provides the differential protection element that detects ampere-turn imbalances in magnetically coupled windings. Meanwhile, the second box provides the differential criterion based on the protection of the electrically connected circuit, which is commonly protected by a busbar protection relay.

Presently, there is a notable gap in PST protection, as no existing relay integrates dual differential protection elements capable of detecting both ampere-turn imbalances and imbalances in electrically connected circuits. This gap can be filled using today's microprocessor relays, which allow a single-box solution that could potentially handle both types of differential protection criteria simultaneously, assuming no hardware constraints. This advancement not only simplifies installation but also reduces the costs associated with dual box solutions.

2) Tap Position Reading

The differential protection methods 87X [8] and 87T [4] require onload tap changer position information to calculate the differential current. However, obtaining tap position data, which is typically encoded in binary coded decimal (BCD), can present difficulties in converting to the required format. Moreover, the reliance on tap-changer information is perceived as a drawback by certain users. In contrast, the differential methods proposed by [2] and [6] calculate the differential current independent of the tap position input requirement.

3) Currents Input Requirements

Standard transformer differential relays normally offer a limited number of current transformer (CT) inputs, typically fewer than required for phase shifting transformers, which often demand more than three CT inputs. For instance, when protecting two-core PSTs, 87T [2] requires four current transformers (CTs) per phase for the computation of differential and restraint current quantities. Conversely, [6] and [8] require two CTs per phase, positioned on the source and load sides, minimizing hardware challenges associated with replacement or maintenance. Consequently, instead of relying on standard transformer differential relays, the deployment of bus bar differential relays becomes necessary to adequately address the needs of phase shifting transformers. By using the bus bar differential relays, the requisite number of CT inputs can be accommodated, overcoming the hardware limitations inherent in standard transformer differential relays.

However, applying the traditional busbar protection relay and even standard differential protection relay lack the differential characteristics and built-in computational algorithms necessary to accurately compute the differential and restrain equations tailored to the unique magnetically and/or electrically coupled criteria of various PST configurations.

B. Performance Analysis of PST Differential Protection Methods

Differential protection provides speed and selectivity but can encounter numerous challenges in ensuring reliable and secure operation. Prior to calculating the differential and restraining currents, it is essential to compensate the phase angle shift introduced by the winding connections, mismatch in CT ratios and zero-sequence current compensation. In the standard transformer differential protection, typically phase and magnitude compensations can be achieved externally by installing interposing current transformers or internally in modern microprocessor-based relays by using compensation algorithm. Modern differential relay can be applied to various transformer winding configurations, regardless of how the primary current transformers are linked to the windings. This eliminates the need for extra space and cost associated with interposing current transformers.

Moreover, magnetizing inrush current, current transformer saturation, core saturation, and other factors can also jeopardize the differential protection reliability. Differential protection has always relied on a complementary restraining or blocking methods to enhance its security in situations where false differential currents occur. Furthermore, it may not be sensitive to minor current faults, so transformer protection must include multiple protection components to guarantee the full protection of the power transformer.

In the context of PSTs, the authors attempted to discuss both traditional and non-traditional challenges associated with PST differential protection methods, discussed in section IV.

1) Compensation of Varying Phase Shift

The phase angle shift between the primary and secondary windings of a standard transformer is normally a multiple of 30 degrees. Therefore, magnitude and phase angle compensation are required before applying the current to differential protection. In contrast, the phase angle shift between the two ends of the phase shifting transformer is not fixed and varies online. The conventional phase-shift compensation methods are not applicable to PST differential

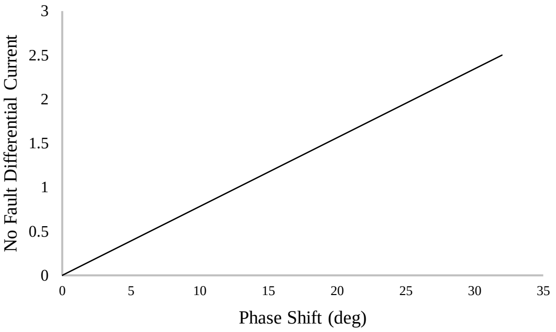

Fig. 6. Influence of phase angle shift on no fault differential current sensing

protection. Therefore, the standard differential protection, when applied to a PST, results in a false differential current that varies with phase angle shift. If the minimum pickup is increased to the point where the false differential current is less than the operating characteristic, the relay's sensitivity suffers.

The differential protection methods, 87T [4] and 87X [8], require tap position to compensate phase angle, therefore the differential current ideally remains very small and constant as the phase angle shifts from minimum to maximum allowed limit. On the contrary, as shown in Fig. 6, 87T [2] measures differential current under normal system conditions that increases as the phase angle shift increases. A higher slope differential characteristic may resolve the issue, but differential protection may not remain sensitive to low fault current.

2) Measurement of winding currents

The differential methods, for instance 87T [2], that rely on ampere-turn balance of the magnetically coupled windings are more effective in detecting internal faults than the methods that use differential relation representing electrically connected zone, for instance 87B [2]. The various designs and constructions of phase-shifting transformers pose challenges when it comes to measure all the windings terminal currents in order to establish the ampere-turn based differential current measuring principle. The differential protection 87T [2] is based on the ampere-turn balance of the series unit windings and utilizes current measurements obtained from the neutral point of the secondary of the exciting unit windings. However, since there are no measurements available for the secondary terminals of the exciting unit, it is not possible to use the ampere-turn based differential current measuring principle to effectively protect the exciting unit. Figure 3 displays the intended position of the current transformer (CT) with a red marker on the secondary side of the exciting unit.

3) Saturation of series-winding

The series winding that connects the source and load sides has voltage rating less than the system voltage rating. This winding is prone to saturation when the voltage across its terminals exceeds the max voltage limit. This can result in the differential protection not working properly, as depicted in Fig. 7 from the previous publication by this paper

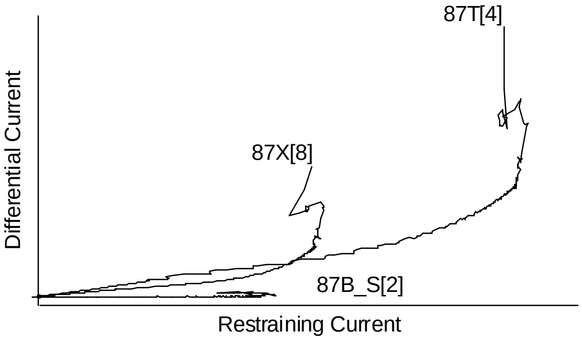

Fig. 7. False Differential Current due to series winding saturation [9]

Table I. Turn to Turn Fault

Case	Tap	Fault Location	Shorted Turns (% of total winding turns)	87B [2]	87T [2]	87X [8]
1	1	Secondary winding of Series Unit	10		✓	✓
2			4		✓	
3		Primary winding of Exciting Unit	4			✓
4	0.2	Secondary winding of Series Unit	25		✓	
5			10		✓	
6			5		✓	
7		Primary winding of Exciting Unit	25			✓
8			10			✓
9			5			✓

author [9]. As shown in Fig. 7, saturation of the series winding of hexagonal PST results in the large false differential current measured by 87T [4] and 87X [8]. However, 87B_S [2], which represents an electrically connected zone, measures a very small differential current during the saturation of the series winding.

4) *Turn-Turn Fault Detection*

Table I shows the test results on the detection of turn-turn faults in a two-core power system transformer (PST) using differential protection techniques 87T [2], 87B [2], and 87X [8]. The result shows how sensitive these differential methods are to turn-turn faults with respect to tap position, fault location at different points on the windings, and shorted turns as percentage of total winding turns.

It can be seen from the test results that 87B, which protects the electrically connected zone of primaries of the exciting and series units, failed to detect a turn-turn fault on the exciting unit primary windings. 87T, which protects the magnetically coupled zone, successfully detects a turn-turn fault on the secondary of the series unit. And it does not detect turn-turn faults on the exciting unit primary winding due to fact that it is out of the protection zone of 87T. On the other hand, 87X, which neither represents a magnetically coupled circuit nor an electrically connected circuit, fails to detect turn-turn faults on the secondary of the series unit at low tap positions and turn-turn faults with shorted turns of 4% of the winding at maximum tap position. When the PST is running at its maximum tap position, 87X detects turn-turn faults with a large number of shorted turns.

VI. CONCLUSIONS

A review of the different current differential protection methods frequently used for protecting PSTs is presented. The authors attempted to emphasize key factors to consider when applying differential protection solutions for protecting PSTs. Various research gaps have been highlighted between the existing differential protection methods and the needs of phase shifting transformer protection. The paper emphasized the need to consider relaying technology in perspective when designing differential protection solutions for the PSTs. And discussed various traditional and non-traditional challenges to existing differential protection methods. PST protection demands a single-box solution that can be applied to any type of PST and provides a complete, reliable protection solution with or without the need for tap position reading.

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VIII. BIOGRAPHIES

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