Summary of C37.245 2018 "Guide for the Application of Protective Relaying for Phase-Shifting Transformers"

This paper is a product of the IEEE PSRC Committee K24 Working Group. The working group consisted of the following members: Brandon Davies, Chair; Hillmon Ladner-Garcia, Secretary; Abu Bapary, Paul Elkin, Ashley Hannigan, Charles Henville, Lubomir Sevov, Michael Thompson, and Abu Zahid

***Abstract* — This summary paper presents key concepts regarding the recently published Guide for the Application of Protective Relaying for Phase-Shifting Transformers (PST). The Guide identifies the specific issues that need to be considered when planning and designing a protection system for phase-shifting transformers. Factors considered include a brief overview of the application of PSTs, location of instrument transformers, methods of calculating short circuit current contributions through the transformers, and application of protective relaying systems.**

***Index Terms* — Phase-shifting transformer (PST), Phase angle regulating (PAR) transformer, transformer protection**

I. Introduction

This paper summarizes a new standard document (the "Guide") [1] describing methods by which PSTs may be protected. There are a variety of differences between PSTs and conventional power transformers, and these differences significantly affect the application and settings of protective relaying systems. The Guide identifies these differences and shows how effective protection can be applied. The intention of this paper is to provide an overview of the content of the Guide and help engineers who may be responsible for providing protection systems become aware of the special differences between PSTs and conventional transformers.

II. General

A. Application and theory of Phase-Shifting Transformers

PSTs are applied in the power system to control the power flow through desired paths or rated paths. PSTs are installed for many reasons including mitigation of network element overload or providing control of power though interconnection lines between different transmission networks. One possible installation is shown in Fig. 1 where a PST on one parallel transmission path is used to control power flow over one branch of the network. By controlling power flow over the branch with the PST, some level of control is also provided in the other branches.

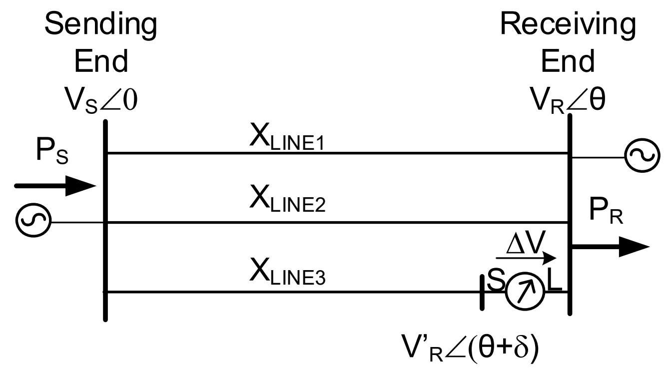

Fig. 1 – Simplified Transmission System with PST

Power flow through the PST, and therefore the line the PST is in series with, is achieved by controlling the angle between the PST's input and output voltages. The input voltage is called "source" (abbreviated as "Terminal S"), and the output voltage is called "load" (abbreviated as "Terminal L"). The PST changes the angle (δ) of the L terminal with respect to the S terminal by adding a quadrature voltage (ΔV) to the source voltage as shown in Fig. 2.

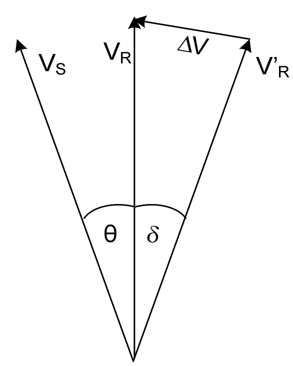

Fig. 2 – Phasor diagram with the addition of the PST

The Guide defines a positive change in angle when the voltage at terminal L leads the voltage at terminal S (i.e., the L terminal is in advanced direction with respect to the S terminal), and negative change in angle when the voltage at terminal L lags the voltage at terminal S (i.e. the voltage at L terminal is in retard direction with respect to the voltage at S terminal. Depending on the application, some PST designs support both positive and negative phase shifts, while others may allow a phase shift in only one direction. The angle of advance or retard

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controls the amount of power that is transmitted through the PST when connected to a network with parallel paths. The Guide gives an overview of several varieties of application of PST to control the power flow.

PSTs are usually installed in a transmission line or a transmission path and sometimes have a bypass path so that they can be taken out of service without taking the whole transmission path out of service. The Guide describes several possible bypass arrangements using a combination of disconnect switches and circuit breakers. The locations of circuit breakers and associated current transformers will affect the protection zones that need to be covered.

B. Types of Phase-Shifting Transformers

PSTs use a winding arrangement that injects a quadrature voltage 90 degrees out of phase from the reference voltage between the Source and Load bushings. For example, to advance the phase angle of VA, a voltage in phase with VCB is added to the VA voltage. To retard the phase angle of VA a voltage in phase with VBC is added to the VA voltage.

PSTs can be classified by the number of three-phase magnetic cores. The Guide describes three single-core designs and two two-core designs.

Further, PSTs can be classified as symmetrical and asymmetrical. A symmetrical design will not change the voltage magnitude between the source and load bushings in the process of advancing or retarding the phase angle. Two asymmetrical designs and three symmetrical designs are described in this guide, though other designs may be applied. The Guide provides several single-line and three-line diagrams showing the key differences between the various PST designs. A single-line diagram for two-core symmetrical PST is provided in Fig. 3.

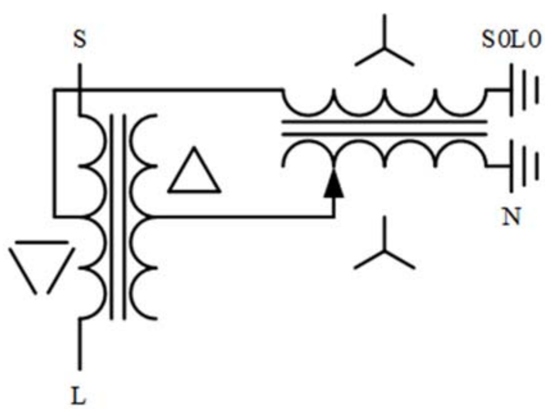

Fig. 3 – Single-line diagram for two-core symmetrical PST

C. Equivalent MVA of the PST to estimate inrush

Inrush current can affect certain transformer protection schemes. The Guide discusses how to estimate the equivalent MVA and inrush current for consideration when applying protective elements such as instantaneous overcurrent and differential protection.

PSTs are regulating transformers. While the nameplate MVA rating of a PST is associated with the power flow that it can support throughout the range of regulation from neutral to full advance and full retard, the actual MVA rating of the transformer core is associated with the range of regulation that the PST will provide. Thus, for estimating inrush for a PST, it is necessary to determine the equivalent MVA rating. Once that is done, relay protection engineers can use their own company inrush calculations based on transformer rating to determine the magnitude of inrush current to be expected.

D. PST Overload Mitigation

Operating above nameplate rating for an extended period can prematurely age the PST. In the case of severe overloads, the current switching rating of the load tap changer may be exceeded.

Unlike conventional power transformers, a PST has the unique ability to mitigate an overload condition by control action. The overload condition can be determined by a time dependent overload function that monitors current or apparent power or by monitoring temperature. If the PST is under automatic control, the control system can recognize the overload condition and automatically step to reduce the power flow until the current or apparent power is below its continuous rating allowing the PST to cool. Alternatively, if the PST is under manual control, an overload alarm may alert the operators so they can manually adjust the tap position to reduce loading to relieve the overload.

The Guide also describes the limitations of the overload mitigation under extreme overload conditions when the tap changer cannot be moved without the danger of contact damage.

III. Instrument Transformers

Depending on the PST protection schemes, both current transformers (CTs) and voltage transformers (VTs) are required for adequate PST protection.

A. Current Transformers

CTs are mainly required to determine the fault current within the PST and the application and selection of a PST protection scheme depends on the physical location of CTs. Placement of CTs depends significantly on the design of the PST. The locations for CTs and their placement need to be determined at the time the PST is specified and before it is built, because retrofit is either impractical or physically impossible. When considering CT locations, it is helpful to decide upon the design of the protection scheme so that the correct locations may be selected.

CTs can be located in the bushings of the PST or inside of the transformer tank. When CTs are located inside the tank, magnetic proximity or stray flux effects from currents in the PST windings is a concern and may cause significant error in the CTs.

Fig. 4 and Fig. 5 below show examples of CT locations for two varieties of PSTs. The Guide provides additional examples and discussion on CT considerations for various protection schemes.

B. Voltage Transformers

VTs are used for several purposes for PST protection schemes. For Permissive Overreaching Transfer Trip (POTT) schemes, VTs provide polarizing quantities for distance or directional elements. Distance or directional overcurrent elements are also used as external fault detectors to block or desensitize the differential protection to improve the security for series winding saturation. VTs may also be used for angle compensation of sequence component differential elements.

VTs are used for sync check for reclosing of Load Side Circuit Breakers in some of the PST applications as well as sensing the LTC voltage/position.

IV. Short Circuit Study

The varying phase shift across a PST will normally cause fault currents on one side to be different in magnitude and angle from fault currents on the other side. In the special case of balanced three phase faults, across a PST (with no voltage change) only the angle of the fault currents will be different. In the case of unbalanced faults, both the magnitudes and angles of the various phases will be different on each side of the PST. In addition, the impedances of the PST will combine with the other network impedances to affect the short circuit currents through the PST.

For a PST impedance model the positive and negative sequence impedance are series impedances, but the zero sequence may include shunt as well as series impedances. These impedances may differ depending on the PST's LTC position and angular regulation so modeling and fault analysis must consider the different operating modes of the PST. The factory short-circuit impedance tests required to properly model the PST in the positive, negative, and zero sequence networks across the range of regulation should be considered at the time of specifying the PST to ensure that the tests are provided by the manufacturer. For PST protection modeling and for modeling of the protection in the surrounding system, fault analysis should consider PST at Neutral tap as well as at maximum advance and retard angular regulation. The fault analysis should also include the case when the PST is bypassed.

Other factors such as excitation transformer core design (3-legged vs. 5-legged core) and winding configuration in two core PSTs also have a significant impact on the PST's response to faults. In a two core PST with grounded wye connected excitation windings and a 3-Legged core, the PST may act as a zero-sequence source during ground faults. The ability for the PST to act as a ground source or not is important as it will affect the setting selection and coordination of the PST protection and the relays in the surrounding area and needs to be modeled accurately to ensure that the system response to ground faults is fully understood.

Many steady state short circuit programs include models for PSTs which can be used to model various types of short circuits at or around the PST location. This analysis is used to determine protective settings and other criteria for protection systems, so a complete and accurate PST model is needed. The Guide provides discussion of typical PST models used by short circuit programs, considerations for modeling various PST designs, and guidance on how to check if the short circuit program model is reasonable. In addition, the Guide discusses modeling transient effects that may have an impact on PST protection systems.

V. Phase Shifting Transformer Protection

PSTs, like other important network transformers, require sensitive, fast, dependable, and secure protection for all types of faults within the PST and the bus work that makes up the zone of protection. Application of protective relaying to meet these goals varies depending on PST design (Single core vs. Two-core, Symmetrical vs. Asymmetrical) and availability and location of instrument transformers. Similar to power transformers, PST protection schemes generally consists of various differential and overcurrent protection schemes with sudden pressure and/or Buchholz protection backup; however, these schemes require different connections and considerations when applied to a PST. Depending on installation configurations, other protection may also be provided to protect against other abnormal conditions such as high levels of circulating current due to bypass switching devices being closed with the PST off neutral tap or to detect external faults that may cause saturation of a two core PST's series transformer. A high level summary of each of the commonly applied PST protection methods is provided in the following sections; however, the Guide provides detailed discussion on each scheme as well as calculation and setting examples as informative annexes to aid a protection engineer in applying and setting PST protection based on their PST configuration and installation requirements.

A. Differential Protection

There are two main types of differential protection systems. Differential schemes in which the terminals of the primary equipment within the protection zone are electrically connected, such as a bus or machine stator, operate based on Kirchhoff's Current Law (KCL) by taking the sum of currents entering and leaving the zone of protection. Differential schemes in which the primary equipment within the protection zone are magnetically linked, such as the primary and secondary windings of a transformer, operate by taking the summation of Ampere-Turns or ampere-turns balance (ATB) on a magnetic core.

Transformers typically use ATB type differential protection. Modern transformer differential relays use CT measurements at each terminal of the equipment adjusted by fixed magnitude and angle compensation settings to balance differential equations used in the ATB differential algorithm. These compensation settings are selected based on the transformer's ratings, winding configuration, CT connection and ratios.

Direct application of ATB type differential between a PST's source and load bushings is typically not possible as, by design, the phase angle between source and load vary with LTC position and phase angle regulation. Traditional differential protection for PSTs is applied as several KCL and/or ATB differential zones, each applied to protect specific windings of the PST. Multiple relays or differential elements are often required to provide complete differential coverage for all PST windings.

1) Differential Protection of Single Core PSTs

Differential protection of single core type PSTs can be provided using percent restrained KCL type or high-impedance type differential relays. A total of six single phase differential zones each protecting a single phase winding are needed with overlap at the corners of the delta winding. Relay connections for a single core with three two phase LTCs are shown in Fig. 4. Note the requirement for specification of CTs inside the delta winding in addition to the normal bushing CTs on the series windings.

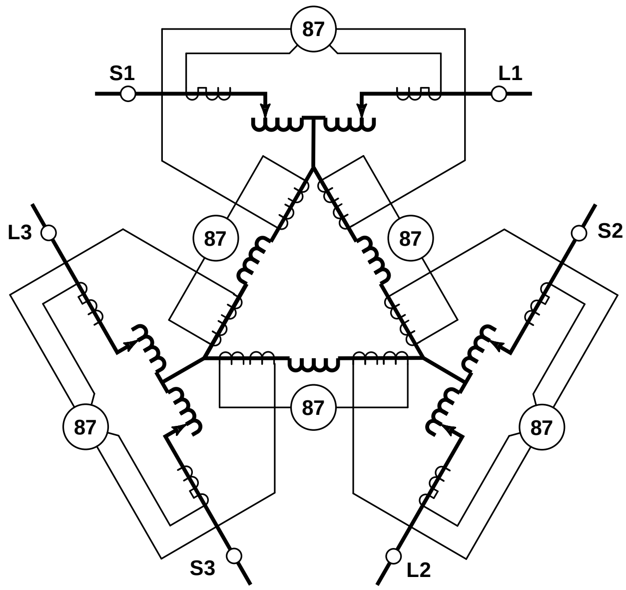

Fig. 4 - Differential Scheme for Single Core PST

It is important to note that these KCL differential elements are blind to turn-to-turn faults. Some form of protection that is responsive to turn-to-turn faults such as sudden pressure, Buchholz relays, or the sequence component differential elements mentioned in section V.A.3 below is applied.

2) Differential Protection of Two Core PSTs

Differential protection of two-core type PST is typically applied using two differential relays, one to provide protection of the primary windings of the series and excitation cores and the other to provide protection of the secondary windings of the series and excitation cores.

The primary winding differential is provided by a percent restrained or high-impedance type differential relay with a zone of protection defined by source and load bushing current transformers and CTs located in the phases at the neutral end of the exciter core primary windings as shown in Fig. 5. The primary winding differential relay is connected to satisfy Kirchhoff's law at the mid-point junction of the series and excitation core primary windings where:

$$I_{Source} + I_{Load} + I_{Excitation} = 0 \qquad (1)$$

where

I_{Source} are the source side phase currents
I_{Load} are the load side phase currents
$I_{Excitation}$ are the excitation phase currents at the neutral end of the winding

A differential relay without winding/phase angle compensation can be used because the current transformers defining the differential zone are all on the primary windings and therefore do not require compensation based on the turns ratio and winding configuration of the series or excitation transformers. Additionally, this element is not sensitive to inrush or overexcitation currents as these flow through the differential zone so harmonic restraint/blocking is not required.

The primary winding differential relay provides protection for winding to ground and winding to winding faults involving the primary windings only. The differential element will not detect turn-to-turn faults or faults on the secondary windings of the series or excitation cores. The primary winding differential relay is unaffected by series-unit winding saturation caused by overvoltages during nearby external faults.

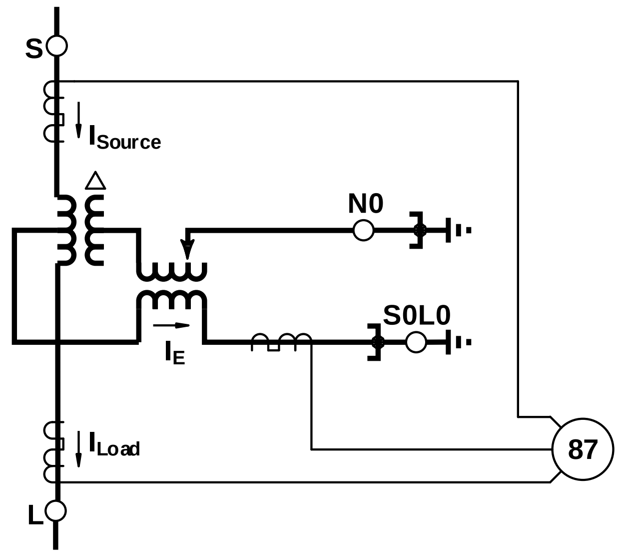

Fig. 5 - Two Core PST Primary Winding Differential

Secondary winding differential can either be applied as a KCL or ATB differential depending on the location of available current transformers. Each approach to secondary winding differential includes advantages and disadvantages that are important to consider. Because CTs are often not available within the series transformer secondary delta, ATB is more commonly applied.

The secondary winding ATB differential is provided by a percent restrained differential relay with a zone of protection defined by source and load bushing current transformers and CTs located in the phases at the neutral end of the exciter core secondary winding as shown in Fig. 6. A differential relay with winding/phase angle compensation is used to compensate for the turns ratio and winding configuration of the series unit transformer. Generally, with the Excitation transformer secondary as the reference (0°) the load and source current angular compensation of 90° or 270° is applied. Magnitude compensation calculations must consider the PST's MVA ratings, CT ratios and the turns ratio of the series transformer windings. A more detailed discussion of magnitude and angle compensation settings for the secondary winding ATB differential application is included in the Guide.

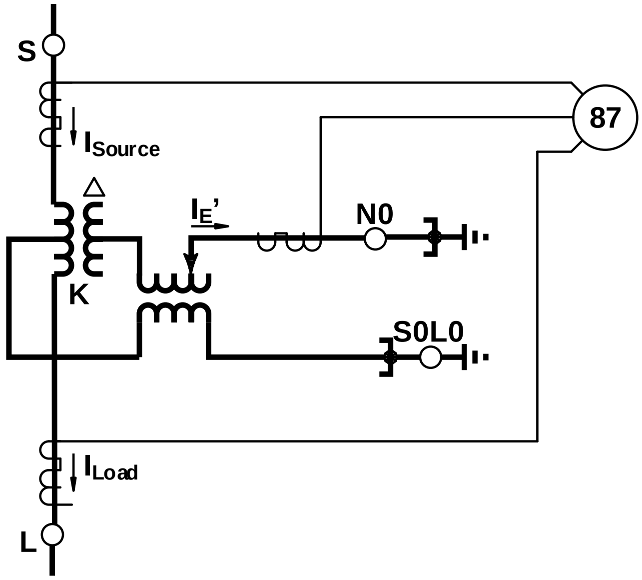

Fig. 6 - Two Core PST Secondary Winding Differential

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

Additional considerations for possible PST series transformer primary winding saturation and for the type and connection of the LTC and Advance-Retard-Switch (ARS) are discussed in the Guide.

3) Sequence Component Differential

Another differential approach to PST protection is sequence component differential with variable phase compensation. This scheme utilizes measured voltage phase angle or LTC positions to compensate for the PST's phase angle shift between source and load positive and negative sequence currents. The level of angular compensation is variable and will follow the PST's LTC position and phase angle regulation. Since the scheme will adjust the phase angle as compensation as the PST's LTC position and phase angle changes, only source and load CT's and VT's are required.

This scheme is responsive to all fault types, including turn-to-turn faults in the regulating winding. Additionally, these elements can provide protection for applications where CTs are not available in the correct locations internal to the PST to apply the other types of differential protection. For example, two-core PSTs that only include CTs in the throat between the series and excitation transformers cannot use traditional differential ATB or KCL protection methods to detect faults in the excitation transformer.

B. Overcurrent Protection

Overcurrent protection for a phase-shifting transformer is similar to that of any other power transformer, though the variable impedance of the PST and resulting range of available fault currents make it impractical to apply in some cases. Differential protection is considered primary protection while overcurrent protection is considered backup transformer protection. The primary goal of overcurrent protection is to protect the transformer from through-fault currents, overload, and ground faults. Phase time overcurrent and ground time overcurrent are the typical elements that are enabled. Application of instantaneous overcurrent protection on PST poses challenges and is often not possible. Considerations for application of instantaneous overcurrent protection are discussed in detail in the Guide.

The phase time overcurrent relay element will provide through-fault PST protection while allowing temporary overloading. Pickup settings can be selected with margin above the maximum continuous current rating. The protective relay curve shape and delay are selected based on coordination with the phase shifting transformer damage curve provided by the transformer manufacturer, and coordination with any source/line side overcurrent relay settings. Note that due to the variable impedance of a PST at different levels of regulation, direct application of transformer damage curves from IEEE C57.109 may not apply.

As with all overcurrent protection applied to networked systems, forward and reverse external faults need to be considered and directional overcurrent protection can be applied if necessary.

Application of ground or neutral overcurrent elements for a phase shifting transformer will depend on the type and design of the transformer as it may or may not be a source of ground current for external faults. Ground time overcurrent protection may be applied to the source and load terminals for any transformer configuration but will not provide complete ground fault protection. This protection will need to be coordinated with other external ground overcurrent elements in the nearby system.

In the case of two core phase shifting transformers that act as a ground source, inverse time neutral overcurrent protection can be applied on the exciting unit primary winding neutral CTs to provide backup ground fault protection. The exciting unit secondary winding generally is connected directly to the unit secondary delta winding and will not act as a ground source, so neutral overcurrent on this winding is generally not applied. Exciter primary winding neutral overcurrent element pickups can be set sensitively but should consider unbalanced magnetizing inrush currents. Overcurrent elements on the primary neutral winding need to be coordinated with external ground overcurrent elements.

C. Other Protection

Several other protection applications specific to PSTs are described in Section 11 of the Guide. Recommendations, typical practices, and considerations due to the unique characteristics of PSTs are given in more detail.

1) Circulating Current (Bypass off Neutral) Protection

PSTs often have a bypass breaker or switch to allow the network element to remain in service when the PST must be taken out of service. Transitioning into or out of the bypass state requires the PST to be in the neutral tap position to avoid very large circulating currents flowing through the transformer. The differential protection will not respond to the circulating current, so the Guide describes the application of phase overcurrent (51) and current balance (60) functions to protect for this scenario.

2) Current Balance Protection

A current balance (60) function can be used to protect the exciting winding of a two-core PST transformer. This is in addition to the main differential functions, which may not detect some faults on the exciting winding. Considerations for CT location as well as alternate solutions and typical settings are described.

3) Distance Protection

Distance relays are sometimes applied to provide backup protection for high level fault currents. Phase and ground distance relays (21) located at the source and load sides of the PST can provide this protection function. The Guide provides considerations for the user to apply distance relays in a form of pilot protection (POTT) without the need of external pilot communication. Several considerations for unique aspects of applying distance protection on a PST are described, as well as typical settings for those applications.

4) Sudden Pressure and Buchholz Relays

While the application of Sudden Pressure (63) and Buchholz relays on PSTs is more in line with the application of those functions on a traditional power transformer, there are also unique aspects and considerations that are discussed in the Guide.

5) Transmission Line Relays

PSTs are typically located on transmission lines and as such are typically incorporated into the line's zone of protection. Consideration of apparent impedance seen by the line relay for faults in the PST are discussed.

VI. Conclusions

This paper has described the contents of a new guide regarding the protection of PSTs. It has pointed how PST protection systems need to consider additional problems compared to conventional transformer protection. The issues include the following:

- The need for planning protection systems while developing the PST purchase specification. This is because of the requirement for special CTs internal to the PST.
- Factors involved in short circuit analysis, including differences in currents on each side of the transformer during unbalanced faults.
- The consideration of the difference between PST rated current, and exciter transformer rating for the purpose of estimating inrush.
- The possible need for differential protection based on Kirchhoff's current law in addition to ampere-turns balance differential protection.
- Complex connections of ampere-turns balance differential protection CTs and unusual vector group connections within the differential relay.
- Some unusual limitations of application of instantaneous overcurrent relays due to the possible zero impedance of the PST.

The Guide also includes appendices with detailed example calculations of the most common PST protection systems. It is expected that this guide will help protection engineers understand the unusual problems and solutions for the application and setting of PST protection systems.

VII. References

[1] IEEE Standard C37.245 2018 "Guide for the Application of Protective Relaying for Phase-Shifting Transformers"