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Protection of standard-delta phase shifting transformer using terminal currents and voltages

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ABSTRACT

This paper presents a new standard-delta phase shifting transformer (PST) protection technique based on the normal operating voltage–current (v–i) relationships of the PST equivalent circuit. These voltage–current relations are used to define the v–i differential equations, which are further used to detect and discriminate the internal and external faults. Using the v–i differential relationships, the proposed protection relay computes small or zero (ideally) differential quantity during normal and external fault conditions. However, in the event of an internal fault, the v–i relationships become invalid and the proposed differential relay therefore computes significantly large differential quantity. A comparative performance analysis of the proposed protection technique and the former methods, that make use of the current differential principle, suggest that the proposed technique offers a more secure protection solution of the standard-delta PST. It successfully detects and discriminates the internal/external faults, while remaining stable during a magnetizing inrush current and the saturation of the series winding, and offers a high degree of tolerance against external faults with current transformer saturation. A real representation of a standard-delta PST has been modeled in PSCAD/EMTDC to simulate various normal and faulted conditions to test and validate the performance of the proposed protection technique. Implementation of the proposed protection algorithm requires currents, voltages and tracking of the tap-changer position.

1. Introduction

Phase shifting transformers are available in single- or two-core designs and constructions. Depending on the application, they can be categorized as symmetrical or asymmetrical [1,2]. A symmetrical design alters the phase-shift angle with equal magnitudes of source- and load-side voltages, whereas an asymmetrical design alters the phase shift and voltage magnitude, which can cause changes in the reactive power flow [2]. The advantage of a symmetrical design over an asymmetrical is that the phase-shift angle is the only parameter that influences the power flow [3]. However, it employs two single-phase on-load tap changers (OLTC) per phase, and therefore it is more expensive than the asymmetrical design. The standard-delta PST belongs to the symmetrical single-core PST type.

Conventionally, current differential protection has been widely used for the protection of standard and non-standard transformers [4]. Because of the distinguished features like speed and selectivity, the differential protection has been serving as a major transformer protection for decades. However, it is also associated with un-faulted conditions such as magnetizing inrush current and saturation of the series winding that can result in a false differential current and leads to an instability of the system.

Moreover, the phase shift across the PST is not fixed, it is an increment of the non-standard phase angle, and changes online as a function of the tap-changer position, e.g., the maximum phase shift across the two ends of the PST is 30 deg with 32 steps, i.e., phase-shift of ~0.94 deg/step. Thus, the phase compensation algorithms used in the standard differential protection cannot be applied for the compensation of the phase-shift across the PST.

Due to various PST designs, the differential current measuring principle applied to one type of PST cannot be applied to another type. The literature survey suggests that the various current differential-based techniques have been proposed by [5–8] for various types of PSTs. Ref. [5] proposes the differential protection for two-core symmetrical and delta-hexagonal PSTs. Refs. [6,7] propose a technique that can be applied to any type of PST. These techniques propose the phase/magnitude compensation algorithms to solve the dilemma of non-standard phase-shift between two ends (source and load sides) by tracking the tap position of the PST. However, both lack in demonstrating the performance when applied to a standard-delta PST. Ref. [8] proposes

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linear and non-linear current differential measuring principles for the protection of a delta-hexagonal PST. Ref. [9], in brief, discusses the differential current measuring principle that reflects the ampere-turn relation of the magnetically coupled series and exciting windings of a standard-delta PST.

This paper presents a new protection technique based on the monitoring of normal operating v–i relationships of the equivalent circuit of magnetically coupled series and exciting windings of a standard-delta PST. These v–i relations not only express the magnetically coupled windings but also the electrically connected exciting winding of one phase to the series windings of the other two phases. The proposed technique exploits the validity of the current and voltage relations to detect and discriminate internal and external faults by proposing the v–i differential equations. During normal and external fault conditions, the v–i relations remain valid; however, in the event of an internal fault these relations become invalid. The proposed v–i differential relay remains stable and secure in the event of various un-faulted conditions, such as inrush current and saturation of the series winding, which makes it a unique protection solution from the conventional current differential protection.

For the purpose of a performance comparison, the existing current differential-based techniques are reviewed first in Section 2, followed by the development of the proposed v–i relationships in Section 3. Section 4 addresses various issues and their solutions related to the application of the proposed v–i relations for the protection of the PST. The proposed method is tested and analyzed for various system conditions in Section 5. Discussions and conclusions in Section 6 suggest that the proposed method provides a more secure protection solution for the protection of a standard-delta phase shifting transformer.

2. A review of the current differential based approaches

Traditionally, differential protection is used as a main protection element for the protection of phase shifting transformers. As mentioned before, there is no fully developed techniques reported in the literature. However, Refs. [7,9] suggest differential based approaches that can be distinguished based on the differential current measuring principle. The detail review of these two approaches is as follows:

2.1. Differential current measuring principle 1 (87PST-1)

Ref. [9] briefly discusses the differential current measuring principle that reflects the ampere-turn relation of the magnetically coupled series and exciting windings. Computation of the differential and restraining current requires source and load sides currents, I_S and I_L, respectively, along with the tracking of the tap-changer position (D). The differential current measuring principle as a function of tap position can be expressed as

$$\mathrm{IDIFF}_{A[App.1]} = \left| n_S \frac{D}{2}(I_{SA} - I_{SC} + I_{LC} - I_{LA}) + n_E(I_{SB} + I_{LB}) \right|$$

$$\mathrm{IDIFF}_{B[App.1]} = \left| n_S \frac{D}{2}(I_{SB} - I_{SA} + I_{LA} - I_{LB}) + n_E(I_{SC} + I_{LC}) \right|$$

$$\mathrm{IDIFF}_{C[App.1]} = \left| n_S \frac{D}{2}(I_{SC} - I_{SB} + I_{LB} - I_{LC}) + n_E(I_{SA} + I_{LA}) \right|$$

where I_{SA}, I_{SB}, I_{SC} and I_{LA}, I_{LB}, I_{LC} are the source and load sides currents and n_s and n_e are the series and exciting windings' number of turns, respectively.

2.2. Differential current measuring principle 2 (87PST-2)

The differential current measuring principle proposed by [7] uses the source- and load-side currents. However, prior to the computation of the differential current, both sides currents are processed through the phase and magnitude compensation algorithm. The differential current is measured by taking the vector sum of the source-side (reference) and load-side (compensated) currents. In additions to the tracking of the tap-changer position, the algorithm also requires values of the base current for each tap position in order to compute the differential current. The general expression of the differential current measuring principle for a symmetrical PST can be expressed as

$$\begin{bmatrix} \mathrm{IDIFF}_{A[App.2]} \\ \mathrm{IDIFF}_{B[App.2]} \\ \mathrm{IDIFF}_{C[App.2]} \end{bmatrix} = \frac{1}{I_{base}} M(0^\circ) \begin{bmatrix} I_{SA} \\ I_{SB} \\ I_{SC} \end{bmatrix} + \frac{1}{I_{base}} M(\delta^\circ) \begin{bmatrix} I_{LA} \\ I_{LB} \\ I_{LC} \end{bmatrix}$$

where

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

I_{base} is the base current of source- or load-side and δ is the phase shift between source- and load-side.

3. Development of the proposed technique

Transformer protection technique based on the relationship of windings currents and voltages are known from [10–14]. The voltage–current relationship of the winding expresses the electromagnetic equation. A mathematical representation of the two magnetically coupled windings can be developed based on the assumption that the flux linkage, λ, between magnetically coupled winding 1 and winding 2 are equal, i.e., $\lambda_{12} = \lambda_{21}$ [15]. By exploiting this assumption, the electromagnetic equations are then combined to derive the v–i differential equations. During normal and external fault conditions, the v–i differential relation remains valid and therefore, computes zero or small differential quantity |DIFF|, however, v–i differential relay computes a significantly large differential quantity |DIFF| in the event of an internal fault. This criterion is used to detect and discriminate an internal/external fault in a standard-delta PST.

As shown in Fig. 1(a), the tap winding with which the source (S) and load (L) sides are connected is called the series winding, whereas the excitation winding is connected to the other two phases of the series winding, making delta connections. Hence, the quadrature voltage ΔV is developed; this, when added to the nominal voltage V_n will generate the phase shift between the source and the load sides [2].

As shown in Fig. 1(b), the following current, voltage and impedance notations are used in this section to develop the voltage–current relationships:

- Current: source-side ($I_{SA}/I_{SB}/I_{SC}$), load-side ($I_{LA}/I_{LB}/I_{LC}$) and exciting-winding ($I_a/I_b/I_c$) currents.
- Voltage: source-side ($V_{SA}/V_{SB}/V_{SC}$), load-side ($V_{LA}/V_{LB}/V_{LC}$), exciting-winding ($V_a/V_b/V_c$) and nominal voltages ($V_{na}/V_{nb}/V_{nc}$).
- $Z_{A1/B1/C1}$, $Z_{A2/B2/C2}$, $Z_{a/b/c}$ are the impedances of windings Wdg A1/B1/C1, Wdg A2/B2/C2 and Wdg a/b/c, respectively.

The turn ratio of the series and exciting winding at a particular tap position (D) is as follows:

$$\frac{\Delta V_A}{\Delta V_a} = D\frac{n_s}{n_e} = DN \tag{1}$$