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An adaptive distance protection scheme in the presence of phase shifting transformer

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ABSTRACT

Distance relays detect transmission line faults and their locations by measuring the voltage and the current signals. Also, phase shifting transformers (PSTs) are used to control the power flow in electrical power systems. PSTs protect transmission lines from thermal overloading, improve the stability of transmission system and control the power flow between different networks. Unfortunately, existence of PST in a transmission line vitiates the operation of protection relays by altering the voltage and current signals. In this paper, the effects of the delta–hexagonal PST on the operation of distance relays are investigated by both analytical and computational methods under different fault types and locations. Results of investigations reveal that the PST causes the distance relays to under-reach. Finally, a feasible method for eliminating the PST detrimental effects on the operation of the distance relays is presented. This method uses the voltage difference between the PST terminals to modify the operation of the distance relays. The phasor measurement units (PMUs) are used to calculate this voltage and remote signal systems are used to transfer it to the system protection center (SPC). All the simulations are conducted with electro-magnetic transient program (EMTPWorks).

1. Introduction

The phase shifting transformer is a device for controlling the power flow through specific lines in a complex power transmission network. When power flows between two systems, there is a voltage drop and a phase-angle shift between the source and the load depending upon the magnitude and power factor of the load current [1]. When a PST is connected to a transmission line, it changes not only the impedance of the line but also the voltage and the current signals by shifting the phases. This change in the signals vitiates the operation of distance relays since they operate based on the measured line impedance by the voltage and the current signals.

Recently, there have been valuable efforts devoted to solve this problem. In [2–8], the effects of various flexible ac transmission system (FACTS) controllers on transmission line distance protection have been investigated. In [2–4], effects of shunt-FACTS controllers like static synchronous compensator (STATCOM) and static Var compensator (SVC) on the distance protection have been presented. Investigations in [5,6] have been aimed to study the effects of series-FACTS controllers like static synchronous series compensator (SSSC) and thyristor controlled series capacitor (TCSC) on the distance protection. Also, the effects of series-shunt FACTS controllers like unified power-flow controller (UPFC) and generalized interline power-flow controller (GIPFC) on the distance protection have been presented in [7,8]. The following results are the common conclusion of all these investigations:

(1) FACTS controllers alter the impedance which is measured by the distance relay.
(2) They usually make the distance relay to under-reach.
(3) Series-shunt FACTS controllers have more severe effects on the relays because of series convertors injected zero sequence voltage.
(4) FACTS controllers manipulate the tripping boundaries of the distance relays.

Another set of papers deal with the effects of FACTS controllers on the loss of excitation (LOE) protection of synchronous generator. In [9,10], effects of shunt-FACTS on the LOE relay of synchronous generator are investigated. Results of investigations show that the presence of shunt-FACTS controllers impedes the decline of the voltage of the generator and consequently causes a substantial delay in the relay operation. Also, in the presence of shunt-FACTS controllers and partial LOE, the LOE relay cannot detect partial LOEs.

The PMUs provide a measurement system to protect, monitor and control a power system. The high reliability and accuracy of the

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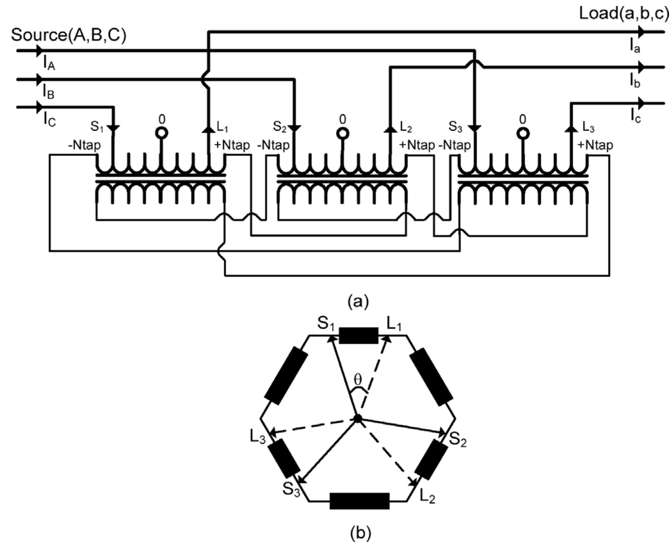

Fig. 1. A delta–hexagonal PST (a) windings connections diagram and (b) phasor diagram.

data provided by PMUs make them to be widely used in industrial applications, especially if the fast data transportation systems like optical-fiber networks are available. In [11,12] transmission lines protection has been modified by means of PMUs and measuring the positive sequence voltage of bus-bars. In [13] this method has been used to minimize the negative effects of UPFC on the distance relays. Also, in [14] synchronous PMUs have been used to coordinate the synchronous generators, STATCOM and wind farm to increase the transient frequency support and inter-area oscillations damping.

In this paper, the PST effects on the operation of transmission lines distance protection are studied. Transmission line distance relays accompanied with a PST are considered in a system and various faults in the transmission line under different operation conditions of the power system and the PST are investigated. Results of analytical studies and EMTPWorks simulations reveal that the presence of PST vitiates the operation of the distance relays; it causes the relays to encounter a severe under-reach condition so that the calculated impedance roughly transcends the actual value. Finally, a simple and feasible method is presented to eliminate the detrimental effects of the PST on the measured impedance of the distance relays. This method uses the equivalent circuit of the PST to modify the distance relays. PMUs are used to calculate the voltage across the equivalent circuit of the PST and a remote signal system is used to transfer them to the SPC.

2. Modeling of system with PST

The windings connections diagram (a) and phasor diagram (b) of the delta–hexagonal PST as its general structure are shown in Fig. 1 [1,15,16]. Each phase consists of two coupled windings; one tapped winding with two on-load tap changers (OLTCs) and one winding without taps. All the windings have the same number of turns. The two OLTCs change the phase shift by moving transformer input terminals (A, B, C) and output terminals (a, b, c) symmetrically with respect to center tap 0. This delta–hexagonal connection has the advantage of keeping a 1:1 voltage ratio while the phase shift is changed. When the two OLTCs move taps from the center position (0) to the winding end (position N_{tap}), the phase shift between inputs (ABC) and outputs (abc) varies from 0 to 60 deg. When (ABC) and (abc) are respectively at positions $-N_{\text{tap}}$ and $+N_{\text{tap}}$, the output voltages (abc) are lagging the input voltages (ABC) by 60 deg and vice versa. For intermediate positions the phase shift θ is given by the following equation:

$$\theta = 2 \times \tan\left(\frac{-k}{\sqrt{3}}\right)^{-1} \tag{1}$$

where $k = N/N_{\text{tap}}$ and N = tap position. The single-line diagram of the power system used for this study is shown in Fig. 2(a). In this figure, the PST is connected to the beginning of the transmission line-2. The characteristics of the PST and the power system are presented in Appendix A. Herein, the results of PST simulation are presented. The transferred active power at bus-A is shown in Fig. 3. If the PST is not connected to the system, transferred active power is equal to 175 MW; the power increases to about 370 MW at the $N = -10$ by applying the controlling signal to the PST and increasing its tap. In this simulation it is assumed that $N_{\text{tap}} = 10$ so that regarding (1), by increasing each tap, the phase angle is shifted by 6.6 degrees. $|N| = 1$ shows the minimum tap; $|N| = 5$, the middle tap; and $|N| = 10$ shows the maximum tap. The positive taps mean that the transmitted power with the PST decreases and vice versa. As it is shown in Fig. 3, for positive N values, the power flow decreases and the PST even flips the power flow direction after $N = 3$.

2.1. Modeling of distance relay

Distance relay is one of the most important protection relays of power systems, which is used to detect the faults of transmission line by measuring the impedance of the line. It detects the faults by measuring the voltage and current of its own location. Locations of the distance relays in the system under study are shown in Fig. 2(a). Following procedure is applied for modeling of the distance relays: (1) samples are taken from the outputs of current-transformers (CTs) and voltage-transformers (VTs) after passing the low-pass filters; (2) phasors of signals are calculated from the samples using full cycle discrete Fourier transform (FCDFT) method. Six elements related to different faults are modeled in the distance relay modeling. These elements are titled as A-G, B-G, C-G, A-B, A-C and B-C. For instance, the following equations are used for the elements A-G and A-B.

$$Z_{\text{A-G}} = \frac{V_R}{I_R + \left[(Z_{0L} - Z_{1L})/Z_{1L}\right] \cdot I_{0R}} \tag{2}$$

$$Z_{\text{A-B}} = \frac{V_{1R} - a \cdot V_{2R}}{I_{1R} - a \cdot I_{2R}} \tag{3}$$

where $I_R = I_{1R} + I_{2R} + I_{0R}$ and I_{1R}, I_{2R}, I_{0R} are sequence (positive, negative, zero) phase currents through transmission line at relay location. Also $V_R = V_{1R} + V_{2R} + V_{0R}$ and V_{1R}, V_{2R}, V_{0R} are sequence phase voltages at relay location and $a = -0.5 + j0.886$. The distance relay has three zones. These zones for R_A relay are shown in Fig. 2(a). The zones for other relays are also similar to this figure. Zone-1 responses instantaneously; while, zones-2 and 3 has some delay in their response. In the following sections, the effects of PST on the operation of distance relay are investigated by analytical methods.

3. Impact of PST on distance protection

The positive, zero and negative sequence networks of the power system from the viewpoint of a R_A distance relay are shown in Fig. 2(b–d). These networks are considered regarding the R_A. The equivalent circuit of the PST is presented as the variable impedance in series with a voltage source (under phase shift form). The PST has two separate effects on power flow. First, the no-load phase angle creates an additional voltage that drives additional current through the line. Second, the PST's additional impedance is added to the transmission line impedance.