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Research paper

Influence of Phase-Shifting Transformers (PSTs) on the Distance Protection of Transmission Lines and Improving the Performance of Distance Relay

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Abstract

Background and Objectives: With the ever-increasing growth of electric loads, the need for generating electric power grows correspondingly. By considering the limitations of power generation, utilizing novel technologies has gained persistent momentum, one of which is deploying Phase-Shifting Transformers (PSTs). Among the more important available relays for the transmission lines are Distance Relays. To this end, Distance Relays measure the voltage and current of the transmission line in its final installation location. On the other hand, the existence of Phase-Shifting Transformers on transmission lines alters the voltage and current signals at the relay location. This issue causes the impedance calculated by the relay to differ from its actual value at the fault location. As a result, the relay detects the fault location falsely, or in some cases does not recognize it at all.
Methods: The effect of phase shifting transformer on the relay performance of the distances has been investigated in this study. Furthermore, the digital distance relays are modeled in a software environment and its validity is investigated through analytical relationships. Next, the efficacy of the transformer on distance protection is analytically studied. Finally, a new method has been proposed to improve distance relay performance.
Results: Results from analysis and modelling shows that the effect of phase shifting transformers in relay-computed impedance has two faces, the first of which is related to the internal impedance of the transformer, while the other regards the serial voltage of the transformer. The latter face is much more influential than the former one.
Conclusion: This fact renders the mere inner Impedance of phase-shifting transformer insufficient for using it to eliminate its effect. To this end, a method has been developed in which the voltages of both ends of the phase shifting transformer are measured by the PMUs and then sent to the facility for protecting power system after synchronization. There, this voltage is reduced from the voltage calculated by the relay, which renders the effect of the phase shifting transformer in the impedance calculated by the relay completely eliminated.

Introduction

Given the recent surge of power consumption in power systems, various methods have been devised and implemented to increase transmission power, among which are capacitive compensation or the use of Flexible AC Transmission System (FACTS) devices such as phase-shifting transformers. On one hand, reviewing systems consisted of compensators and FACTS devices reveals new dynamics in power systems, necessitating the analysis, by protection engineers, of rapid changes in system parameters including line impedance, power angle, line currents and transient conductivity generated by control functions as well as harmonics injected into the AC power system [5].

Meanwhile, Distance Relays are widely used as a means to protect transmission lines, whose function is based on calculation of the line impedance from the location of the relay to the fault location [6]. To this end, and to calculate the amount of impedance, the relay continuously monitors the voltage and current of its installation location. With the emergence of fault on transmission lines, the existence of FACTS devices leads to alterations of voltage and current signals, thus altering the performance of the relay, which is dependent on such signals. Moreover, FACTS devices have variable impedance, and since they behave randomly for different errors, they would also affect computed impedance by the relay due to their existence in error loop [1], [2]. Therefore, it is necessary to consider this issue in full, and the functionality of the relay should be checked, as its faulty operation may cause serious damage to the power system [7]. In this project, one of the most widely employed FACTS devices, i.e. Phase-Shifting Transformers, is considered. Its performance, and its effect on the transmission power of the power system is analyzed. Next, the performance of distance relays is studied in the presence of such transformers. Moreover, it is necessary to review the issue considering various performance cases of Phase-Shifting Transformers and different kinds of errors. As a pioneering contribution in this literature, the effect of Phase-Shifting Transformers on Mho distance relays is studied. Also for the first time, various kinds of faults, and particularly, high-resistant faults are considered in the analyses. Distance relays of this research are all digital [8].

Various technologies have been previously used regarding the implementation of protection functions to accurately discover disruption in power grids and to activate the relevant operations for isolating erroneous components. It seemed in the late 1960s that electric relays have consolidated their status as the alternative technology for electromechanical relays [9], [10]. This shift pertained to an era where researchers were inclined to use computers as to protect power grids. Such endeavors, accompanied by the advances in the fields of compact circuit technology and software methods in the 70s, led to introduction of microprocessor-based relays as commercial devices in 1979 [11], [12]. Microprocessor- based relays have various deficiencies, among which are short life cycle, proneness to transient waves and the need for multiple configurations [4]. Parallel transmission lines are widely used in advanced power systems to increase their security margin. In order to investigate distance relay algorithm, the system considered in this study functions as a parallel transmission line [3], [5]. This algorithm is not as effective as the full-wave method in eliminating harmonics, and as previously stated, this drawback pertains to even-numbered harmonics and if harmonics are omitted from inputs with actuated harmonics, this method would become effective in removing harmonics and yield rapid response time [13], [14]. As it is evident from the algorithm, utilization of anti-parallel analog filters leads to group delay. The group delay is the time it takes for a signal to pass through the filter [15], [16]. The effects of PST on distance relay was investigated in [17]. All studies were investigated in EMTPWorks for two different types of faults, Phase to ground and phase to phase. The effects of location of faults as well as the two phase to ground fault was neglected in [17]. Also the alteration of transformer tap was not investigated in [17]. The active power based method for estimating the fault resistance is presented in [16], [17], which it is suitable for transmission lines with negligible line resistance. In [7] an independent fault resistance and communication-aided method was proposed to develop the fault detection in the presence of TCSC. In [29] an adaptive algorithm was proposed to investigate the operation of distance protection of transmission line by considering the shunt FACT device.

A simultaneous method was given in [18] to eliminate the STATCOM and fault resistance based on active power calculation of buses. Furthermore, the fault resistance in addition the PST impedance causes a mistake in operation of distance relay which was neglected in [7], [17], [19], [20].

In this study, the effects of PST as well as the resistance for three types of faults, phase to ground, phase to phase and two phase to ground faults, are investigated. Furthermore, to obtain the protection boundaries of distance relay the location of fault as well as the resistance of fault are considered. Also, The Effect of number of winding Turns of the PST that can be altered the power transmitted through the transmission line is studied. Then, a single-line circuit along with a phase shifting transformer and positive sequence networks, phase shifting transformer is modeled as a controlled voltage source , which has a momentary response to change the system conditions. Finally, a method has been developed in which the voltages of both ends of the phase shifting transformer are measured by the PMUs and then sent to the facility for protecting power system after synchronization. There, this voltage is reduced from the voltage calculated by the relay, which renders the effect of the phase shifting transformer in the impedance calculated by the relay completely eliminated. The proposed method are simulated in MATLAB software.

Investigating the Effect of Phase Shifting Transformer on Distance Protection

Analytical Investigation

The single-line circuit of the studied system, along with the phase shifting transformer and the positive, negative and zero sequence networks are shown in Fig. 1, which shows the effect of the phase shifting transformer in the middle of the transmission line 1. Two distance relays are implemented to support and protect transmission lines at bus P [21].

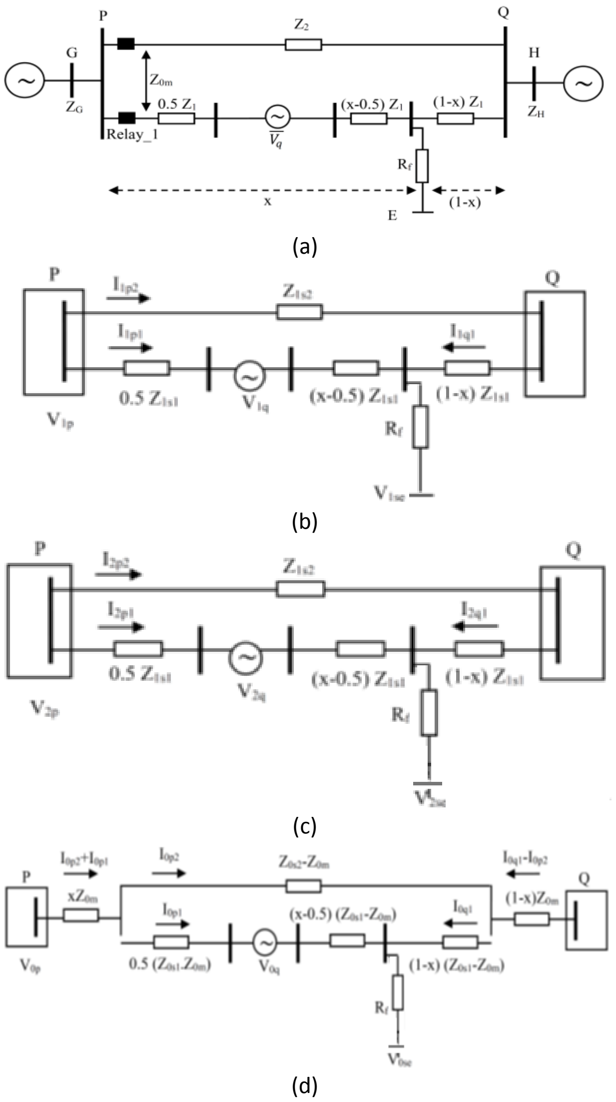

Fig. 1: (a) the single-line circuit of the studied system including (b) the positive sequence network, (c) the negative sequence network, and (d) the zero sequence network.

According to [22] the positive sequence circuit which is shown in Fig. 1 (b) for the error line and the error-free line in the P bus is given as follows:

$$V_{1p} = xZ_{1s1}I_{1p1} + V_{1q} + V_{1se} + \frac{R_f}{(1-x)}\left(I_{1p1} - k_1 I_{1p2} + \frac{V_{1q}}{Z_{1s1}}\right) \tag{1}$$

Also, the negative sequence network are explain as follows [7]:

$$V_{2p} = xZ_{1s1}I_{2p1} + V_{2q} + V_{2se} + \frac{R_f}{(1-x)}\left(I_{2p1} - k_1 I_{2p2} + \frac{V_{2q}}{Z_{1s1}}\right) \tag{2}$$

Given the zero sequence network shown in Fig. 1 (d), we arrive at the following equations [10]:

$$V_{0p} = x\left(Z_{0m}I_{0p2} + Z_{0s1}I_{0p1}\right) + R_f\left(I_{0p1} + I_{0q1}\right) + V_{0q} + V_{0se} \tag{3}$$

$$V_{0p} = xZ_{0m}\left(I_{0p2} + I_{0p1}\right) + \left(Z_{0s2} - Z_{om}\right)I_{0p2} + \left(Z_{0s1} - Z_{om}\right)(1-x)I_{0q1} + R_f\left(I_{0p1} + I_{0q1}\right) + V_{0se} \tag{4}$$

Similar to previous methods, the value of V0p equals to:

$$V_{0p} = x\left(Z_{0m}I_{0p2} + Z_{0s1}I_{0p1}\right) + V_{0q} + V_{0se} + \frac{R_f}{(1-x)}\left(I_{0p1} - k_0 I_{0p2} + \frac{V_{0q}}{(1-x)(Z_{0s1} - Z_{0m})}\right) \tag{5}$$

where k_0 is equal to:

$$k_0 = \left(Z_{0s2} - Z_{0m}\right)/\left(Z_{0s1} - Z_{0m}\right) \tag{6}$$

For transmission lines with similar parameters, k_0 is equal to k_1. In the following section, the value of the impedance calculated by the relay is obtained for different types of errors:

A. Single-phase-to-ground fault

For a Single-phase ground fault, we have:

$$V_p = xZ_{1s1}I_{p1} + x\left(Z_{0s1} - Z_{1s1}\right)I_{0p1} + xZ_{0m}I_{0p2} + \boxed{V_q} + \frac{R_f}{(1-x)}\left(I_{p1} - k_1 I_{p2} + (k_1 - k_0)I_{0p2} + \frac{V_q}{Z_{1s1}} + V_{0q}\left(\frac{1}{(Z_{0s1} - Z_{om})} - \frac{1}{Z_{1s1}}\right)\right) \tag{7}$$

For the provided system, and without the presence of Phase-Shifting Transformers, Impedance calculated by the distance relay can be obtained by the following equation [23], [24]:

$$Z = \frac{V_p}{I_{p1} + \left(\frac{Z_{0s1} - Z_{1s1}}{Z_{1s1}}\right)I_{0p1}} = \frac{V_p}{I_{Relay}} \tag{8}$$

Now, in case the phase-shifting transformer is placed in the middle of transmission line 1, Vp in (8) takes the form (7), and thus the Impedance calculated by the distance relay in the presence of the PST takes the following form:

$$Z = xZ_{1s1} + xZ_{0m}\frac{I_{0p2}}{I_{Relay}} + \boxed{\frac{V_q}{I_{Relay}}} + \frac{R_f}{(1-x)I_{Relay}}\Big(I_{p1} - k_1 I_{p2} + (k_1 - k_0)I_{op2} + \frac{V_q}{Z_{1s1}} + V_{0q}\big(\frac{1}{(Z_{0s1}-Z_{om})} - \frac{1}{Z_{1s1}}\big)\Big) \quad (9)$$

By considering (9), and by the virtue of the highlighted part, it is evident that the existence of phase-shifting transformer in the fault loop causes the impedance calculated by the relay to increase, an issue which is discussed with more details in Simulation Results.

B. Two-phase fault

Under a two-phase fault (a-b), with resistance Rf, we arrive to the following relation [25]:

$$V_{1p} - aV_{2p} = xZ_{1s1}(I_{1p1} - aI_{2p1}) + (V_{1q} - aV_{2q}) + \frac{R_f}{(1-x)}\Big((I_{1p1} - aI_{2p1}) + k_1(aI_{2p2} - I_{1p2}) + \frac{(V_{1q}-aV_{2q})}{Z_{1s1}}\Big) \quad (10)$$

In the absence of PST for two-phased fault, impedance may be calculated using the following relation [20]:

$$Z = \frac{V_{1p}-aV_{2p}}{I_{1p1}-aI_{2p1}} = \frac{V_{1p}-aV_{2p}}{I_{Relay}} \quad (11)$$

As a result, with the presence of the phase shifting transformer in the fault loop, impedance can be obtained through the following formula [26]:

$$Z = xZ_{1s1} + \boxed{\frac{(V_{1q}-aV_{2q})}{I_{Relay}}} + \frac{R_f}{(1-x)I_{Relay}}\Big((I_{1p1} - aI_{2p1}) + k_1(aI_{2p2} - I_{1p2}) + \frac{(V_{1q}-aV_{2q})}{Z_{1s1}}\Big) \quad (12)$$

Given the aforementioned relation, it is evident that the effect of phase shifting transformer on the relay impedance is originated from the difference in vectors of the voltage between positive and negative sequences, which is described in the simulation results section [27].

C. Two-phase-to-ground fault

Under a Two-phase-to-ground fault (a-b-g), impedance calculated by agents A-B, B-G, and A-G in the relay are subject to change. Using the impedance relation for the B-G agent, the following relation is obtained:

$$a^2V_{1p} + aV_{2p} + V_{0p} = xZ_{1s1}\Big(a^2I_{1p1} + aI_{2p1} + \frac{Z_{0s1}}{Z_{1s1}}I_{0p1}\Big) + (a^2V_{1q} + aV_{2q} + V_{0q}) + xZ_{0m}I_{0p2} + \frac{R_f}{(1-x)}\Big((a^2I_{1p1} + aI_{2p1} + I_{0p1}) - k_1(a^2I_{1p2} + aI_{2p1} + \frac{k_0}{k_1}I_{0p1}) + \frac{(a^2V_{1q}+aV_{2q})}{Z_{1s1}} + \frac{V_{0q}}{(Z_{0s1}-Z_{om})}\Big) \quad (13)$$

In the absence of the PST, impedance calculated by B-G agent is calculated from the following equation:

$$Z = \frac{a^2V_{1p}+aV_{2p}+V_{0p}}{a^2I_{1p1}+aI_{2p1}+\frac{Z_{0s1}}{Z_{1s1}}I_{0p1}} = \frac{a^2V_{1p}+aV_{2p}+V_{0p}}{I_{Relay}}, \quad (14)$$

Thus, (14) takes the following form when the phase-shifting transformer is introduced in the fault loop:

$$Z = xZ_{1s1} + \boxed{\frac{(a^2V_{1q}+aV_{2q}+V_{0q})}{I_{Relay}}} + \frac{R_f}{(1-x)I_{Relay}}\Big((a^2I_{1p1} + aI_{2p1} + I_{0p1}) - k_1\Big(a^2I_{1p2} + aI_{2p1} + \frac{k_0}{k_1}I_{0p1}\Big) + \frac{(a^2V_{1q}+aV_{2q})}{Z_{1s1}} + \frac{V_{0q}}{(Z_{0s1}-Z_{om})}\Big) + \frac{I_{op2}}{I_{Relay}} \quad (15)$$

where,

I_{ap2}, I_{bp2}, I_{cp2} are phase currents through transmission line 2 at relay location of bus P without fault.

V_{0p}, V_{1p}, V_{2p} are sequence phase voltages (Zero, positive and negative) at relay location

I_{0p1}, I_{1p1}, I_{2p1} are sequence current phase at relay location through transmission line 1

I_{0p2}, I_{1p2}, I_{2p2} are sequence current phase at relay location through transmission line 2 under fault

I_{0q1}, I_{1q1}, I_{2q1} are sequence current phase at relay location through transmission line 1 under fault

V_{0se}, V_{1se}, V_{2se} are sequence phase voltages (Zero, positive and negative) at fault location E

R_f is Fault resistance

V_{0q}, V_{1q}, V_{2q} are sequence phase voltages injected by PST

Z_{0s1}, Z_{1s1}, Z_{2s1} are sequence impedance through transmission line 1 with fault

Z_{0s2}, Z_{1s2}, Z_{2s2} are sequence impedance through transmission line 2 without fault

Z_{0m} is coupling zero sequence between transmission line 1 and 2

Z_{0G}, Z_{1G}, Z_{2G}, Z_{0H}, Z_{1H}, Z_{2H} are sequence impedances of generators G and H

Simulation of Problem statement

A. The Effects of PST on the location of phase to ground fault

The studied power system is depicted in Fig. 2. Here, three transmission lines are situated in series [28]. At the beginning of every transmission line, a distance relay is considered.

This power system is strictly selected as to show the effect phase-shifting transformers on the supportive protection of relays. For this purpose, 3 protection areas are considered for every distance relay.

In Fig. 2, these three areas are shown for transmission line 1. Area 1 contains 80% of transmission line 1, while Area 2 covers the entire transmission line 1 and half of the transmission line 2.

Finally, Area 3 covers the entire transmission lines 1 and 2, and 20% of the transmission line 3. Function delays are used to configure this area, so that Area 1 has no delay, Area 2 presents 0.5 seconds of delay, and Area 3 introduces 1 second of function delay. In this power system, the PST is placed in the middle of transmission line 2. The transmission lines are equal in distance, each being 200 kilometers. The impedance calculated by the relay of transmission line 1 (RA) for a fault occurring 100 kilometers of RA relay is shown in Fig. 3. It can be seen from the figure that, in the absence of a phase shifting transformer, the relay detects the fault correctly at 100 km of the RA and in Area 1. It is also seen that the phase shifting transformer has no effect on the relay function, which is normal, as for the fault occurred on the transmission line 1, the phase shifting transformer is not situated in the fault loop of RA relay, and thus bears no effect on its performance.

The impedance calculated by the RA relay for fault occurring 350 kilometers away is shown in Fig. 4. According to the results shown in Fig. 4, it is evident that in the absence of a phase shifting transformer, the RA relay can correctly detect the faults in its area 3. The impedance calculated by the RB relay is also shown in Fig. 5. As can be seen, this relay also correctly detects faults at a distance of 150 kilometers in Area 1 in the absence of a transformer.

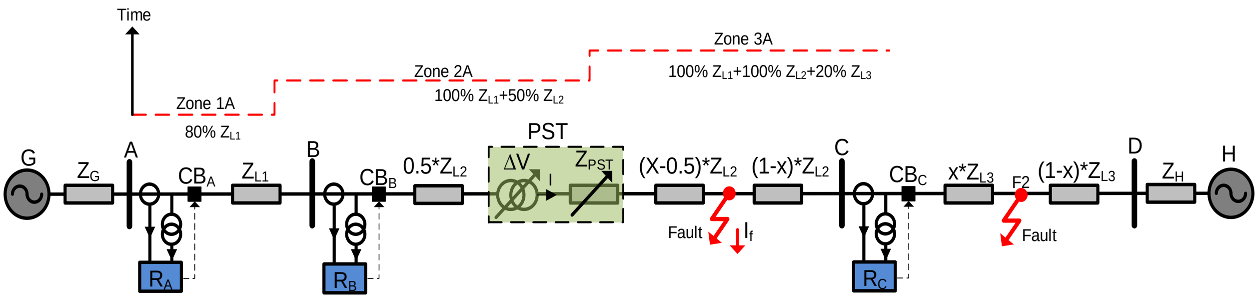

Fig. 2: Modeled power system with phase shifting transformer at middle of transmission line 2 and distance relays.

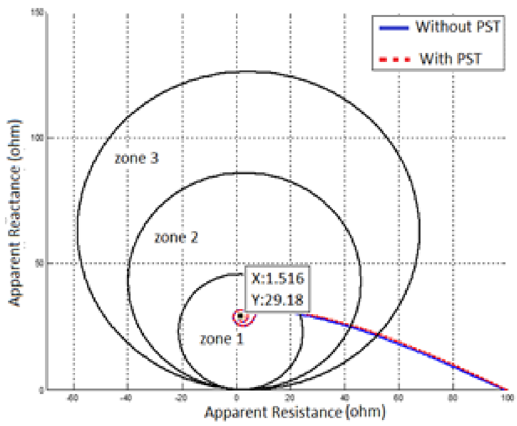

Fig. 3: Impedance calculated by RA relay for A-G fault in 100 km of RA.

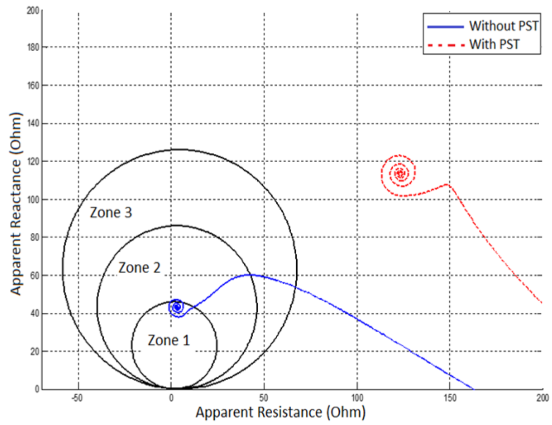

Fig. 5: Impedance calculated by RB relay for A-G fault in 150 km of RB.

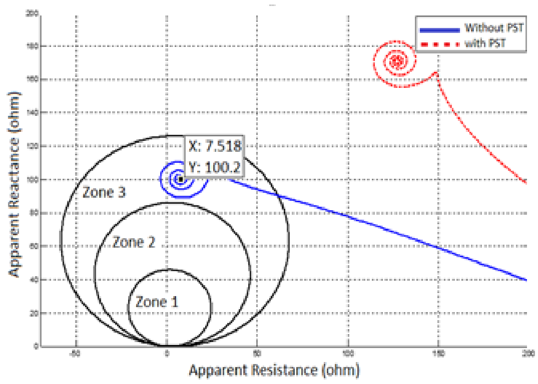

Fig. 4: Impedance calculated by RA relay for A-G fault in 350 km of RA.

It can be seen from the results that existence of PST renders the relays unable to detect faults, a deficiency which may incur severe damages to the power system. The impedances of Relays RA, RB and RC for fault A-G in transmission line 3 are respectively depicted in Fig. 6, Fig. 7 and Fig. 8. The location of this fault in Fig. 8 is marked with F2. This fault occurs at 10 Kilometers of RC Relay, i.e. in its Area 1, Area 2 of RB Relay, and in Area 3 of Relay RC. As can be seen for cases where phase-shifting transformers are missing, all three relays detect the fault accurately. Yet in the presence of a PST, Relays RA and RB are subject to severe range loss, to the extent that they are now unable to detect any fault whatsoever. Relay RC, however, is still able to detect the fault correctly, as the PST is situated outside its fault loop. This causes the RC relay to lack supporting protection, and thus in case of failure, Relays RA and RB are also ineffective in detecting the faults.

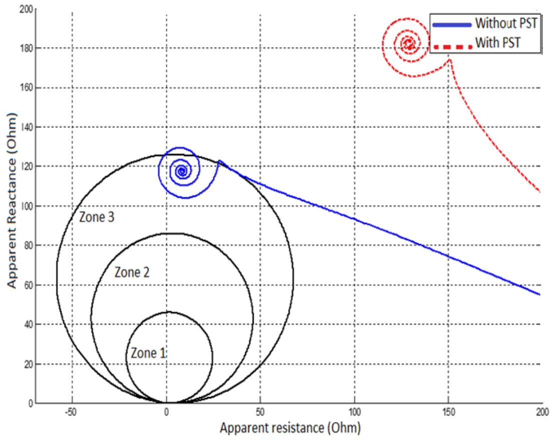

Fig. 6: Impedance calculated by RA relay for A-G fault at 410 km of RA.

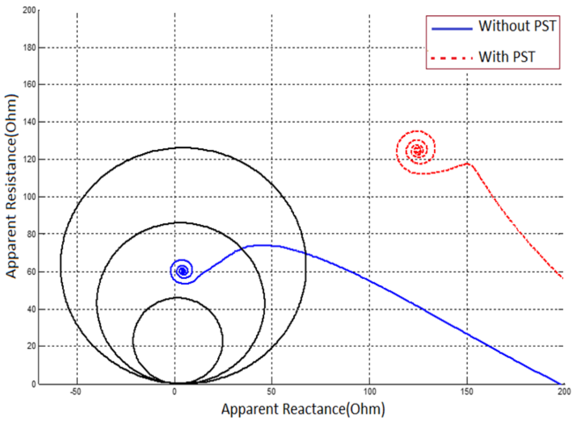

Fig. 7: Impedance calculated by RB relay for A-G fault at 210 km of RB.

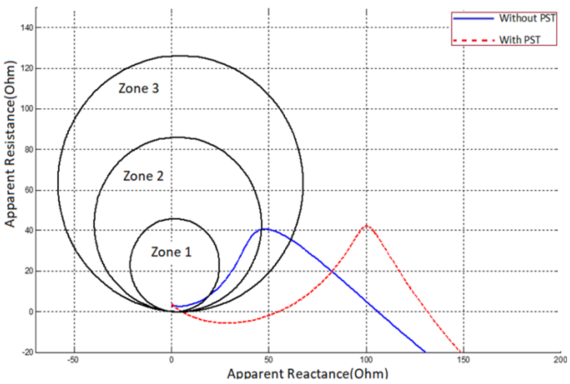

Fig. 8: Impedance calculated by RC relay for A-G fault at 10 km of RC.

B. The Effect of number of winding Turns of the Transformer

The power transmitted through the transmission line can be altered by varying the Tap of the PST [30].

There have been various cases where the extent phase-shifting depended on the alterations of the Tap. Prior modellings have considered the transformer tap to be 1 in the direction of increasing transmission power, i.e. Tap=-1.

Results from modelling an A-G fault at 350 kilometers of RA Relay for various Taps are depicted in Fig. 9 and Fig. 10.

Figure 9 illustrates results for negative tap, in which it is evident that for cases involving negative taps, the range of relay is greatly reduced.

Results for positive taps are shown in Fig. 10, according to which, it is evident that for higher Taps, the presence of PST has caused negative resistance as per the calculations of the relay. In positive taps, the phase-shifting transformer causes the transmission to drop, to the extent that after certain taps, the transformer negates the transmitted power and hence the direction of the power is reserved.

Here, the direction of power transmission is reversed for Tap=5, 10, and thus the impedance calculated by the relay has a negative resistance.

It can be concluded from the comparison of the results that the effect of the transformer in positive taps is greater than that of negative taps.

Figure 11 demonstrates a case where Tap is altered at 0.05 s, with a fault occurring at t=0.2 s. in case of Tap=1, the transmission power remains positive after the fault, while for the other values, power remains negative after the fault, and hence the impedance calculated by the relay retains a positive resistance for Tap=1, yet in Tap=5, 10, the corresponding value is negative.

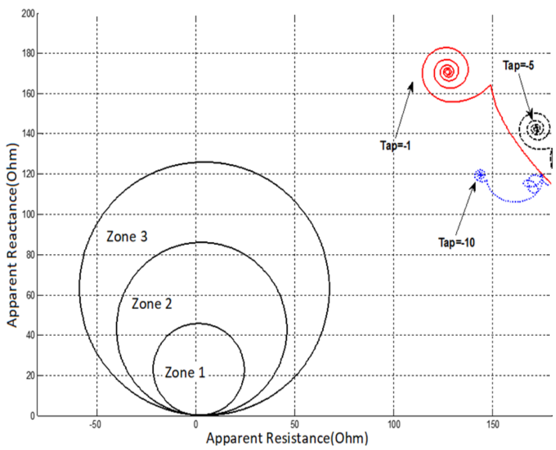

Fig. 9: impedance calculated by RA relay for A-G at 350 kilometers of RA for negative Taps of the PST.

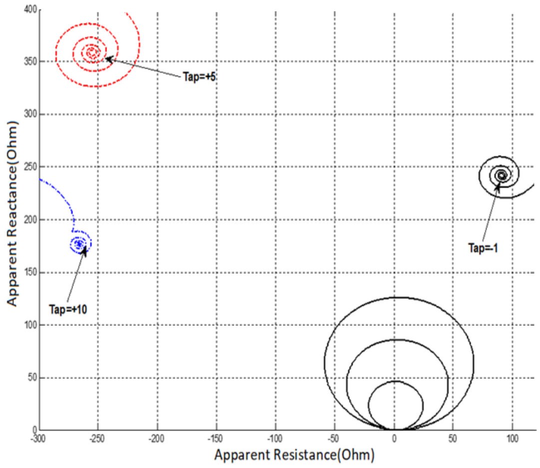

Fig. 10: impedance calculated by RA relay for A-G at 350 kilometers of RA for positive Taps of the PST.

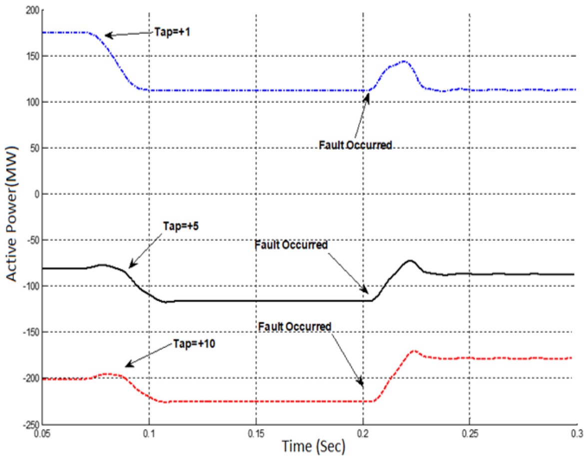

Fig. 11: transmitted active power in transmission line 1 with the presence of PST, for various Tap values and A-G fault occurred at t=0.2 s.

C. *The Effect of Internal Impedance of Phase-Shifting Transformer*

Impedances calculated by RA and RB relays for an A-G fault at 410 kilometers of RA for various values of positive and negative sequence impedance of the PST are shown in Fig. 12 and Fig. 13, respectively, from which it is evident that the Internal Impedance of Phase-Shifting Transformer influences the impedance variations of the relay.

Moreover, one can observe that the effect of zero sequence impedance of the phase-shifting transformer is greater than that of the positive sequence impedance. From Fig. 13, it can be concluded that with the increased zero sequence impedance of the PST, the impedance calculated by the relay is also greater, hence revealing a direct relation.

The comparison of results from this section to those of the previous section arrives us to the fact that the effect of Tap numbers in the PST, i.e. injected voltage of the transformer, on the performance of the relay is greater than the internal impedance, as it was observed in the previous section the variation of Tap even led to a negative resistance for the impedance.

One of the rather traditional ways of neutralizing the effect PST on the relay-calculated impedance was to add the internal Impedance of the transformer to line impedance and to introduce the results in the calculations made by relay.

Nonetheless, this procedure was only able to eliminate the effect of the internal impedance of the PST on the performance of the relay, while as observed, the greatest effect pertained to the main transformer voltage, and hence this method proved ineffective.

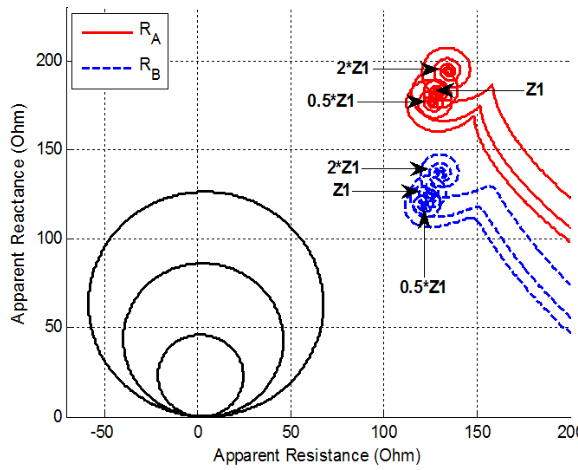

Fig. 12: impedance calculated by RA and RB relays for an A-G fault at 410 kilometers of RA for various values of positive sequence impedance of the PST.

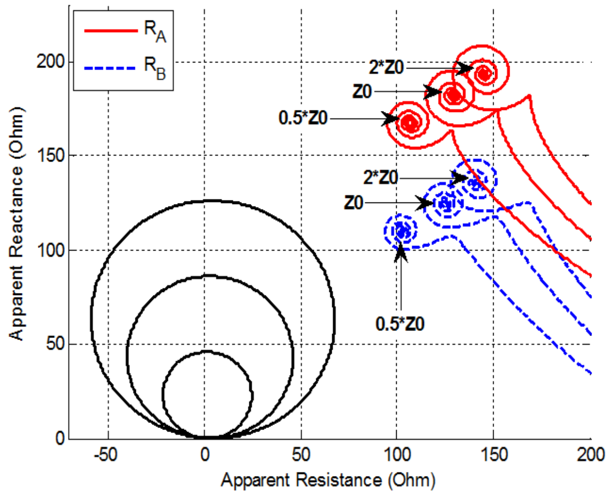

Fig. 13: impedance calculated by RA and RB relays for an A-G fault at 410 kilometers of RA for various values of negative sequence impedance of the PST.

D. Studying the Effect of Phase-Shifting Transformers at Protection Boundaries

To acquire the protection boundaries, two parameters of location of the fault and resistance of the fault are considered. First, the value of the fault resistance is set zero and the location is varied along the path. In this study, this process was performed with 20 kilometer steps. This process resulted in the formation of the AB section in Fig. 14.

In the next step, the location of the fault is considered constant, and the resistance is varied from 0 to 300 ohms, a process which is done with 30-hms steps, yielding the BC section. In the third step, the resistance is preserved at 300 ohms while the location is decreased from the end of the line to its beginning, the result of which is CD. In the fourth and final step, the location of the fault is kept at the beginning of the line, while the resistance of the fault is decreased from 300 ohms to zero.

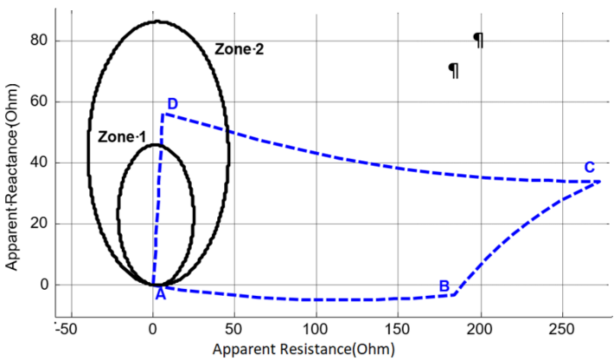

Fig. 14: protection boundaries of distance relay for A-G fault.

This issue causes the formation of DA section. Thus, every fault occurring anywhere along the transmission line with a resistance range of 0-300 ohm situated well within ABCDA protection boundary, and hence the effect of fault resistance is nullified. The protection boundary for A-G fault is depicted in Fig. 14.

As the transmission lines are similar, such protection area are similar for all relays as well. The effect of phase shifting transformers on these boundaries are investigated in the following section. Results from Fig. 15 pertain to condition where Tap=-5 and the operation mode is to increase the transmission power, while Fig. 16 demonstrates the results for Tap=+5 and power reduction mode. Considering the results from both cases, the presence of phase-shifting transformers has divided the protection boundaries in two sections. The section where the effect is more pronounced (C1D1E1F1) pertains to the right-hand side faults of the PST, in which the transformer is situated in the fault loop. For faults occurred at the left-hand side of phase-shifting transformer, the presence of transformer on protection boundaries is only effective when the resistance is non-zero. It is also evident from the results that A1F1 has remained unchanged, as the resistance is zero along this path. It can also be seen from the results that for Tap=+5, the effect of transformer is greater on protection boundaries, and this effect is pronounced on both the resistance and the reactance of the Impedance, to such extent that the value of resistance has increased to 500 Ohms at E1, while for Tap=-5, the corresponding value is 360 ohms. Reactance varies similar to resistance.

Parameters of case study are described in Table 1 [7], [23], [31]:

Table 1: Case study and distance relay parameters

Parameters	Value
Positive sequence impedance of transmission line	0.0201+j0.2868 Ω/km
Negative sequence of transmission line	0.1064+j0.8670 Ω/km
Zero sequence impedance of transmission line	0.1718+j0.6930 Ω/km
Positive sequence impedance of source P	1.7431+j19.424 Ω
Zero sequence impedance of source P	2.6147+j4.886 Ω
Positive sequence impedance of source Q	0.8716+j9.7120 Ω
Zero sequence impedance of source Q	1.3074+j2.4430 Ω
Voltages of P&Q	Vp=Vq=500kv
Load angle between 2 sources	30
Anti-aliasing filter parameters	Cut-off frequency=250Hz Damping factor Zeta Q=1/(2*Zeta)=0.707

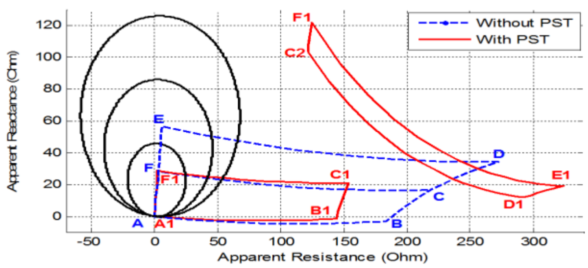

Fig. 15: protection boundaries for distance relay for A-G fault with presence of Phase Shifting Transformer in increased transmission power mode.

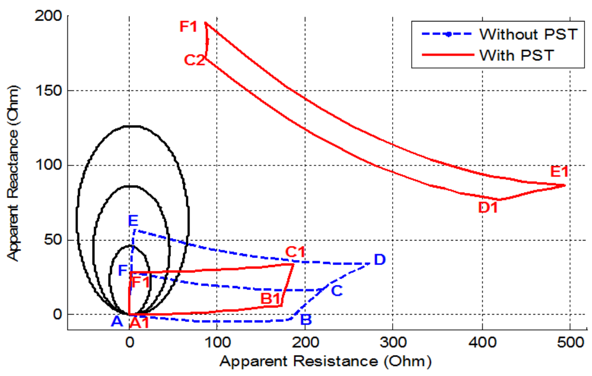

Fig. 16: protection boundaries for distance relay for A-G fault with presence of Phase Shifting Transformer in reduced transmission power mode.

Proposed Method to Improve Distance Relay Performance

It may be observed from the results that the voltage difference across the phase-shifting transformer causes the relays to operate faulty. So if the voltage can be involved in the calculations, the effect of the phase shifting transformer can be eliminated with ease.

For this purpose, the voltage across the phase shifting transformer can be measured by the phasor measurement units (PMU) in the smart grid and have sent to the Protection Center. There, reducing the acquired voltage from the relay's local voltage is sufficient to eliminate its effect in the relay computation. The corresponding power system in this situation is shown in Fig. 17. In this figure, the transformer and bus data are sent to the System Protection Center (SPC) by the virtue communication channels. Further details on PMUs are provided in Fig. 18.

In this figure, similar to what happens in the digital distances relay, the voltage and current signals in the bus are measured by VT and CT, and then passed through the corresponding filters to remove the harmonics, and next they are sampled. From the samples obtained by the full wave Fourier method, the phasor of the signals is obtained. In this way, because the signals received in the SPC are obtained from different locations in the power system, different delays are yielded. As a result, they must be first synchronized before use, for which GPS is used, and the signals are next time-stamped to be used in calculations.

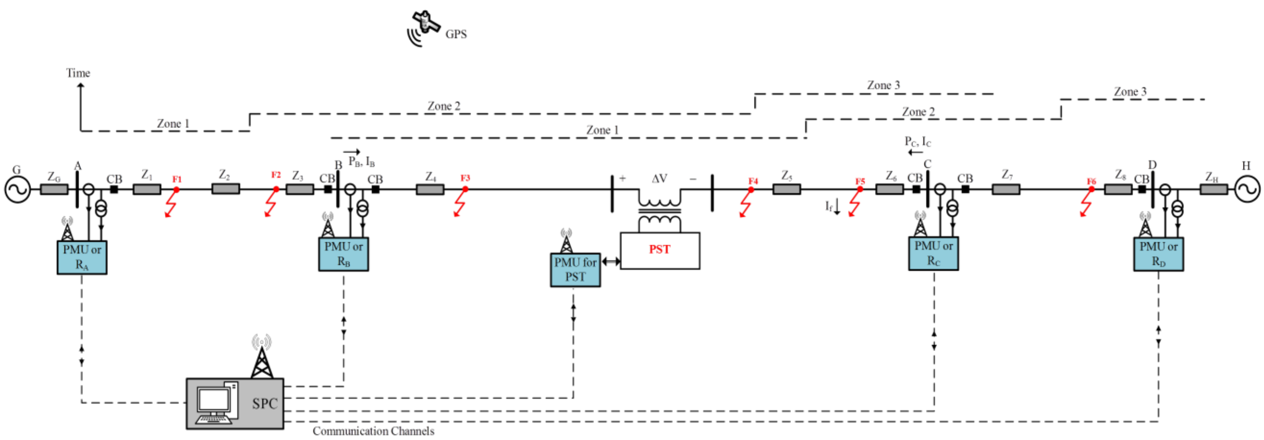

Fig. 17: Smart grid in the presence of phase shifting transformers.

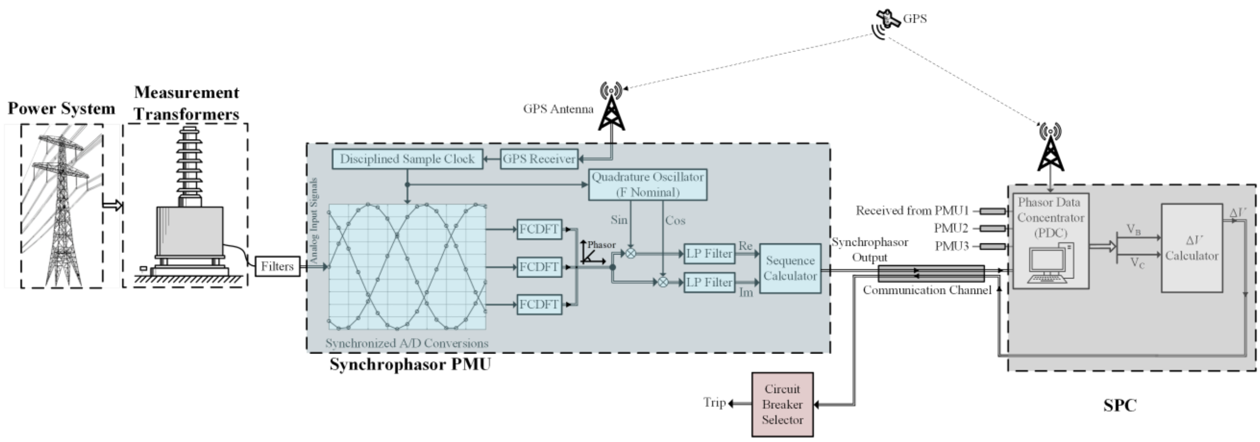

Fig. 18: Details of the PMUs.

Results and Discussion

The results from modelling based on the proposed model are presented in the following. The result for the single-phase-to-ground fault (A-G) occurring at 410 km of relay RA are shown in Fig. 19.

In this figure, the impedance computed by both RA and RB relays is provided. The results pertain to the state where the transformer is not situated in the transmission line and the relays are therefore working properly. The impedance calculated by the relays for the two-phase fault (A-B) is also shown in Fig. 20. For this type of faults, the relay has also been capable of correctly identify the fault, and thus the proposed method can neutralize the effect of the transformer properly. Finally, based on the results, it is safe to say that proposed method can neutralize the detrimental effect of the transformer for both types of fault, and no complex algorithm is needed for this end, yet a smart grid is required in which PMUs are employed to analyze the performance and to control the network as the power system is expanded and PSTs are introduced.

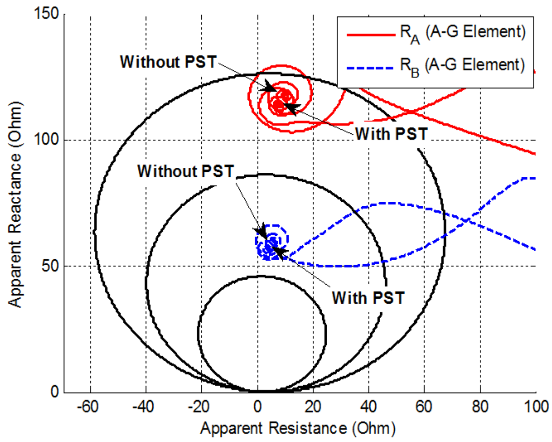

Fig. 19: Impedance calculated by Relays RA and RB for A-B fault at 410 Kilometers of RA.

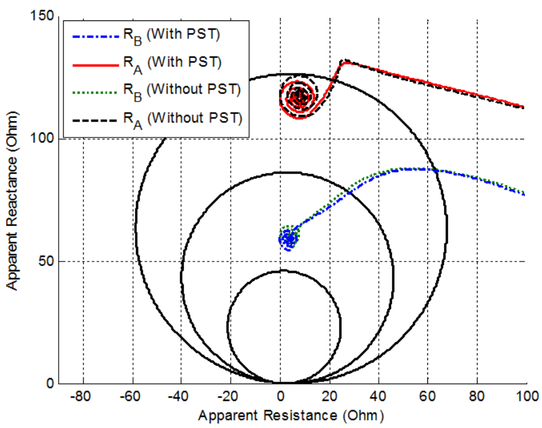

Fig. 20: Impedance calculated by Relays RA and RB for A-B fault at 410 Kilometers of RA.

Conclusion

In this study, the effect of phase shifting transformer on the performance of digital distance relay on a transmission line was investigated. The analytical and modeling results show that the presence of the phase shifting transformer in the fault loop causes the faulty operation of the relay. This disorder is mostly manifested in the form increase impedance. In other words, in all studied cases, the phase shifting transformer reduces the range of distance relays. This means that in spite of the fault occurring in the functional range of the relay, the presence of the phase shifting transformer renders the relay unable to identify the fault. During the fault, the presence of the phase shifting transformer disrupts and the voltage measured by the relay, thus interrupting the function of the relay. The effect of phase shifting transformers on phase-to-ground faults is more heavily pronounced than phase-to-phase faults. Moreover, the effect of the phase shifting transformer in operating mode where the transmission power of the line is reduced is greater than where the transmission power is increased, to such extent that if the phase shifting transformer changes the direction of transmission power, the impedance calculated by the relay will have a negative resistance. It was also observed in high-resistance faults that the presence of a phase shifting transformer causes a two-fold separation of the protective boundaries. To the extent that the parts pertaining to the right-hand side of the PST are more affected, meaning that the phase shifting transformer is in their fault loop. The aforementioned change in the protective boundary is far more severe in the cases where the phase shifting transformers is in the operational mode of reducing transmission power. Results from analysis and modelling shows that the effect of phase shifting transformers in relay-computed impedance has two faces, the first of which is related to the internal impedance of the transformer, while the other regards the voltage of the transformer. The latter face is much more influential than the former one. This fact renders the mere inner Impedance of phase-shifting transformer insufficient for using it to eliminate its effect. To this end, a method has been developed in which the voltages of both ends of the phase shifting transformer are measured by the PMUs and then sent to the facility for protecting power system after synchronization. There, this voltage is reduced from the voltage calculated by the relay, which renders the effect of the phase shifting transformer in the impedance calculated by the relay completely eliminated.

Author Contributions

Dr. Mohammad Tolou Askari supervised and proposed the main problem. Hosein Sahraei simulated the problem. Results has been interpreted and then the manuscript has been written the by Dr. Mohammad tolou Akasri and Hosein Sahraei.

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Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

Abbreviations

PST	Phase Shifting Transformer
FACTS	Flexible AC Transmission Systems
EMTP	Electromagnetic Transients Program
SPC	System Protection Center
VT	Voltage Transformer
CT	Current Transformer
A-G	Phase A to Ground
A-B	Phase A to Phase B

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