Phase shifting transformer to reduce power congestions and to redistribute power in interconnected systems

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ABSTRACT

The increased penetration of wind and solar power, as well as the liberalized electricity market, makes the power system network interconnected and complex. As the power demand is increasing daily, the complexity of operating large power systems is also increasing. Congestion in the transmission network may become more common than previously, making power flow management a problem that becomes increasingly important. Unexpected power flows (also known as loop flows) are becoming a bigger issue in today's linked power networks. These flows have a detrimental impact on the safe functioning of integrated power networks, which hinders their ability to conduct cross-border trade. Phase shifting transformers (PSTs) allow real power flow to be controlled by changing the phase shift across the device. This study deals with two interconnected parallel power system networks and the power flow controlled through a PST in between. The simulation results emphasize the importance of the PST in facilitating the transfer of energy throughout the regional transmission interconnection.

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1. INTRODUCTION

It has become increasingly difficult to find solutions for power flow problems because power networks have become more complicated owing to increased load penetration and intermittent renewable energy sources. Transformers are extensively employed in electrical systems to manage power flow across different voltage levels. The phase angle between the main (source) and secondary (load) sides can also be adjusted with transformers. Phase shifting transformers (phase angle regulating transformers) or, more simply, phase-shifters are the names given to these transformers [1]. Although interconnected power grids improve the reliability of a power system, the regulation of steady-state power flow over particular portions of the system can be complicated. Due to transmission network capacity restrictions and the need to maintain a continuous balance between demand and supply, complexity continues to rise. Transmission congestion is an issue caused by increasing demand and inadequate capacity of transmission networks. The impedance of lines in the electrical grid, fluctuation in power generating output, variation of loads, and load center phase angles are all variables that contribute to power transfer capability and controllability in power systems [2]. Phase shifting transformers (PSTs) play an important role in liberalizing the electricity sector. A PST can be used to manage power flows as part of a coordinated system, enabling the system to run at maximum efficiency. The employment of PSTs in power systems can help solve key issues that arise as a result of deregulation of the electric sector, such as power transit and uneven loading [3]–[10].

The principal objective of a phase shifting transformer is to regulate the level of active power flow in the transmission line by adjusting the phase displacement between the input and output voltages of the line. Under versatile flexible alternating current transmission systems (FACTS), PST or phase angle regulator (PAR) are important devices. A phase shifting ttransformer controls the active power flow along the lines within an interconnected power transmission network. PSTs with on-load tap changers, were introduced to address power flow issues and to enhance transmission line usage. The PSTs control and alters power flows, mitigate line over-burdens, adjust parallel line load sharing, minimize curtailments, and promote power transfer through regional transmission interconnections [11]–[13]. The main contributions of this study include i) the effectiveness of PST in a typical 33 kV parallel feeder line connecting two networks and ii) obtain the desired distribution of power flow. Only real power flow management is discussed here in this study. Reactive power control is not addressed here.

2. PHASE SHIFTING TRANSFORMER

Based on impedances of the network lines linking the regions, the power transfer between one region and the other could result in unintended paths in an interconnected power system. Real power control can be achieved by placing capacitors in series with a transmission line to compensate for the line inductance. There are certain FACTS devices that can change the overall line impedance [14]–[17]. When the power angle across such a section is small, a phase-shifting transformer can become a cost-effective solution. A PST produces a phase shift between the two zones in the power system network zone1 and zone 2, as shown in Figure 1. The normal current distribution is subject to the impedance of the lines. This characteristic circulation might be wasteful, for instance if X_{L1} and X_{L2} are very unique. With the presentation of an extra voltage source, a circulating current can be created, which balances the flows [18]–[20]. It is critical to consider, that as a result of the principally inductive line impedance, embedding a voltage in phase with or opposite to the line voltage (changing the extent of the voltage) will affect the reactive power flow, while a lift voltage with a phase angle opposite to the line voltage (making a phase shift) really impacts the real power flow. Accordingly, the power flow in a transmission line can be viably controlled.

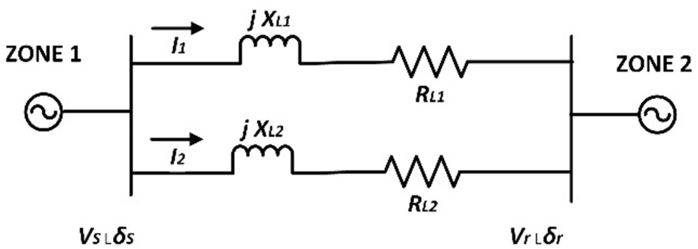


Figure 1. Current distribution in parallel lines between two zones

A new variety of 3-phase controlling transformer is created by integrating a transformer in series with a line to a voltage transformer equipped with a tap changer. The voltage transformer windings are so coupled that phase-quadrature voltages are created on its secondary side and are fed into the series transformer's secondary windings. Adding small, phase-quadrature voltage components to the line's phase voltages thus produces phase-shifted output voltages without any significant magnitude change [21]–[24]. The resulting angular shift is nearly proportional to the applied voltage for relatively small angular changes, although the voltage amplitude remains nearly constant. Even then, for higher angular changes, the magnitude of the system voltage would then increase significantly and is sometimes regarded as the quadrature booster transformer (QBT) for this reason. Figure 2, shows a single-line schematic. Where I_s the current entering at sending end bus s; i_s the outgoing current at bus s; i_r is the current entering at receiving end bus r; I_r is the outgoing current at bus r; V_s is the sending end bus voltage at bus s; V_r is the receiving end bus voltage at bus r; T is the off-nominal turns ratio of the PST; E_s represents the transmission line voltage and y is the line admittance in series with the PST [25].

2.1. Working of phase shifting transformer

The basic concept of power flow control by PST or PAR, illustrated in Figure 3(a), is represented in terms of the usual two-machine model in which a phase shifting transformer is placed between the transmission line and the sending end point (bus). In principle, the phase shifting transformer could be viewed as a source of sinusoidal (fundamental frequency) AC voltage with an adjustable magnitude and angle of phase [26]–[28]. Consequently, the available sending end voltage V_{seff} becomes the total of the succeeding sending end bus voltage V_s and PST generated voltage V_σ, as shown in the phasor diagram in Figure 3(b). The correlations involving real power P with phase angle δ and σ are shown plotted in Figure 3(c). It is clear to see that, the maximum power reached at a generator angle less than π/2 (that is, at $\delta = \pi/2 - \sigma$).

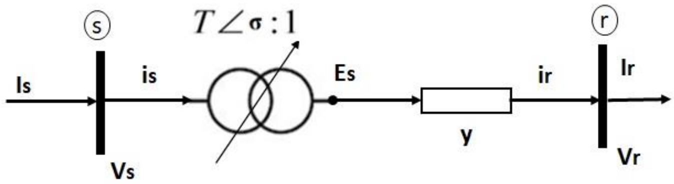


Figure 2. Single-line schematic representation of phase shifting transformer

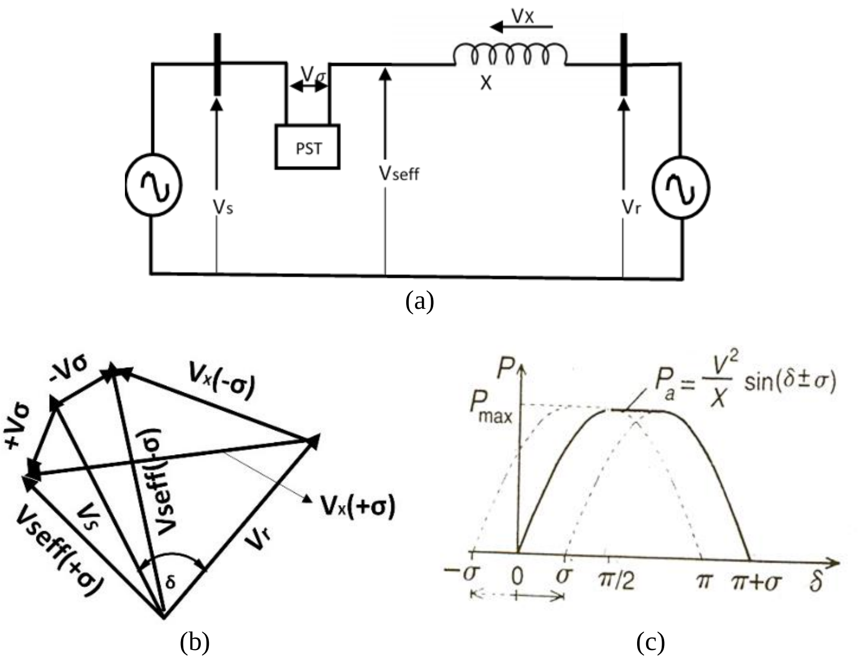


Figure 3. As phase shiting transformer (a) model of two machine with PST, (b) corresponding phasor diagram, and (c) transmitted power vs. angle characteristic

The angle of phasor V_σ corresponding to phasor V_s is provided to diverge with σ such that the angular change will not result in a much change of magnitude, that is,

$$V_{seff} = V_s + V_\sigma \text{ and } |V_{seff}| = |V_{seff}\ | = V_{seff} = V_{seff} = V \quad (1)$$

The fundamental principle behind independent angle control is to keep the transmitted power within a fixed operating range, regardless of the dominant transmission angle δ. For example, after angle exceeds π/2 (peak power angle), the power is being kept at its limit value by regulating the magnitude of quadrature voltage V_σ such that the effective phase angle (δ-σ) remains constant. Even if the phase angle regulator does not raise the steady-state power transmission cap, the real transmitted power can be raised considerably in this manner. The phase angle that exists between transmitting end and receiving end voltages becoming (δ-σ) with the phase-angle control scheme specified by (1), and the transmission power P and reactive power Q requirements at the line's ends can be simply written as:

$$P = \frac{V^2}{X}\, Sin\,(\delta - \sigma), \text{ and} \quad (2)$$

$$Q = \frac{V^2}{X}\{1 - Cos\,(\delta - \sigma)\} \quad (3)$$

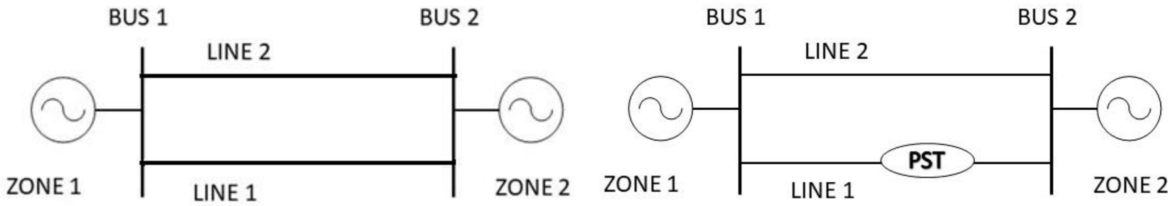
In most cases, phase angle regulators must deal with both true and reactive powers. The angle regulator's total VA throughput (as a voltage source) is:

$$VA = |V_{seff} - V_s|\,|I| = |V_\sigma|\,|I| = V_\sigma\, I \quad (4)$$

The maximum infused voltage and the full load line current are multiplied together to get the angle regulator's rating.

3. SIMULATION RESULTS AND DISCUSSION

Modeling and simulations were performed using the power systems computer aided design/ electromagnetic transient direct current (PSCAD/EMTDC) simulation package of the Manitoba HVDC research centre. PSCAD is an efficient and versatile graphical user interface for EMTDC solution engine, which is widely used [29]. Figure 4(a) shows sinle line schematic of the studied system without a PST and with the inclusion of PST in Figure 4(b).



(a) (b)

Figure 4. Single line schematic of the studied system (a) system without PST and (b) system with PST

The above defined system with two power systems “ZONE 1” and “ZONE 2” connected with two parallel transmission lines with reactances X_{L1}, X_{L2} and resistances R_{L1}, R_{L2}. The transmission of power from “ZONE 1” to “ZONE 2” results in a difference in magnitude between the bus terminal voltages V1 and V2 and also a shift in the phase angle between V1 and V2. PST is modeled with two transformers: the regulating (or magnetizing) transformer, linked in shunt and the Boosting transformer connected in series. Single phase two winding transformers are used to do this. Shunt transformer secondary is having tap changer. Tap positions are varied though slider control. A transition in tap setting is represented by a change in the transformer's turns ratio. To measure admittance for the new voltage rating referring to the tap configuration, the p.u. leakage reactance as well as magnetizing currents defined for 100 percent tap are used.

With transformer winding voltages rated at 19.05 kV primary and 1.5 kV secondary and a tap changer is placed on the secondary winding. The turns ratio for this transformer is 1: 0.0787. A 100 percent tap equates to an on-line tap input of 1.0. (i.e., no tap adjustment). The secondary of shunt transformer with tap is fed to the secondary of series transformer. This connection is of two types as A-B-C sequence and A-C-B sequence so as to get both advance and retard phase shift respectively. Transmission lines line1 and line2 are modeled with Bergeron type. Circuit breakers remain closed throughout the simulation.

When the simulation case is made to run on PSCAD it will go through several stages of processing. This will generate the outputs of the simulation, which can be obtained through output channels and meters. First the system studied, is run without PST. The same system, which is used to study the power flow controllability of PST, is used for simulation of system with PST. Then the system with PST is run for two types of transformer connection, which are for A-B-C sequence connected PST and for A-C-B connected PST.

By varying the tap position through slider in steps simulation is run and different values are noted. The tap shifter is placed on the secondary winding of shunt transformer. The tap changer modelled with the slider control is having 8 tap positions, i.e., the secondary winding voltage of 1.5 kV is divided into 8 step variation. Simulation is made run with each step variation in the tap through slider control and the noted values are tabulated as in Table 1. In actual practice the variation of tap position is done through mechanical or power electronics-based switches.

By looking into the power flow in line1 and line2 columns of the Table 1, we can see that the power flow is altered in the network. Also, the line1 current and line2 currents are varied with the variation in phase shift angle of PST readdressing the line flow. The increased power demand can be met by making use of line1 to its capacity. Initially, the power flow was from zone 1 to zone 2. Through the variation of phase shift by the PST, the power flow direction can be altered and also the magnitude of power can be varied. The negative power indicates that the power flow is from zone 2 to zone 1. Because a phase angle regulation may be utilised to reroute active power flows and regulate the loading of transmission pathways line1 and line2, PSTs play an important role in parallel line load sharing and also the congested line load management.

Table 1. Simulation results of PST system studied

Line 1 power P1 in MW	Line 2 power P2 in MW	Line 1 current in kA	Line 2 current in kA	Phase Shift in Degrees
With A-B-C sequence connection for advanced phase shift				
2.673	3.317	0.07	0.085	0
1.703	3.465	0.065	0.086	0.945
0.714	3.616	0.074	0.087	1.845
0.233	3.689	0.084	0.087	2.702
-0.239	3.76	0.094	0.089	3.558
-1.158	3.899	0.121	0.092	5.36
-2.042	4.033	0.148	0.095	6.217
With A-C-B sequence connection for advanced phase shift				
2.777	3.301	0.071	0.085	0
3.781	3.147	0.089	0.085	-0.944
4.867	2.979	0.114	0.086	-1.889
5.422	2.892	0.127	0.087	-2.832
5.984	2.804	0.142	0.087	-3.776
7.128	2.623	0.172	0.089	-4.719
8.297	2.436	0.202	0.092	-6.606

4. CONCLUSION

The contribution of environmentally friendly power source infiltration and cross line exchange leads to the issue of unscheduled power flows, messing blockage on interconnectors, and a genuine danger to the operational security of inter linked power systems. Based on simulation studies on phase shifting transformer, it is demonstrated and concluded that the PST control and alters power flows, alleviate line overloads, change parallel line sharing and facilitate transfer of energy throughout regional transmission interconnections. The desired distribution of power in the interconnected network can be achieved through PST.

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