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Analysis of Phase-Shifting Transformer (PST), on Congestion management and Voltage Profile in Power System by MATLAB/Simulink Toolbox

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Abstract: This study presents a scheme to solve the congestion problem and improvement of voltage profile using control with Phase-Shifting Transformer (PST). An efficient design of PST can improve Total Transfer Capability (TTC) in interconnected systems. This paper deals with an application of optimization technique such as Linear Programming (LP) for TTC calculation. The Phase-Shifting Transformer (PST),is used to increase power flow of tie line subject to security constraints such as voltage magnitude and real power flow. In order to show the effectiveness of the implementation of PST, it has been tested on simple power system, and its results are presented and discussed. The MATLAB/SIMULINK program is used to investigate the effect of PST on power flow in power system.

Key words: Congestion management, hybrid control, Phase-Shifting Transformer (PST), total transfer capability

INTRODUCTION

Today's flexible alternative transmission lines are one of most important devices that used in power system to enhance the characterization of power system (Noroozian *et al*., 1997; Taranto *et al*., 1992; Enrique *et al*., 2004).

Because of development of Flexible AC Transmission Systems (FACTS) technology, Phase-Shifting Transformer (PST), power flow is controlled by Thyristor Controlled Phase-Shifting Transformer (TCPST) and Interline power flow controller (IPFC) (Mihalic, 2005; Teerathana *et al*., 2005). Most of the electric power in Iran's power system flows from the southern area to Kerman, the capital city in the north. Electrical loads demands nearly 40% are consumed in the capital area and generation plants are mainly located in the southern portion of the country. Because of this characteristic, transmission congestion is a significant research issue. Transferring power from the south to the north is anticipated to be increased more and more in the future. Due to the increase in this flow pattern, the congestion of transmission has the potential to cause a serious voltage stability problem in the power system (Peng *et al*., 2004). During transmission system planning, basic consideration involves securing the power systems for electric power demand levels, various operating points of generation outputs, contingencies and so on. Sufficient transmission capacities are needed to meet the operation condition within the limits in the event of unplanned outages. However, it is not easy to support sufficient transmission capacities to overcome engineering constraints including thermal capacity limits of transmission lines, disturbances and faults in power systems, and social and economical constraints such as cost, environmental and social problems (Venkataraman, 2002). Therefore, the possibility of transmission line congestion is ever present. In previous, many works were studied for the application of FACTS devices and many researches were developed including power flow control based on FACTS devices (Zhang, 2003; Zhang and Handschin, 2001).Especially, many studies for the application of phase-shifting transformer have emerged to solve Total Transfer Capability (TTC). The modeling of phase shift transformer for the fast-decoupled load flow method is presented. It is also discussed the possibility of improving the transient stability of power systems by installing phase-shifting transformer and not implemented practically. This article presented a pattern to analyze and solve power system congestion problems by managing power flow of system in emergency states. The scheme for controlling line flow congestion is phase-shifting transformer (PST) in power systems.

MODELING PHASE-SHIFTING TRANSFORMER (PST)

Consider a phase-shifting transformer connected between nodes i and j with an ideal turns ratio $T = 1.0 < \Psi^t$ in series with transformer admittance $y^t = |y^t| < \alpha^t$ as shown in Fig. 1 (Handschin and Lehmkoster, 1999; Narain and Laszlo, 2000).

$$\frac{V_i}{E_i} = T = \frac{i_j^{*t}}{i_i^{*t}}, E_i = T^* V_i \qquad (1)$$
$$T^{-1} = T^*, i_j^t = T^* i^t$$

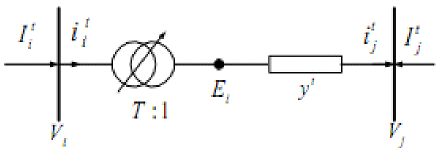


Fig. 1: Phase-shifting transformer

$$\begin{aligned} i_i^t &= T i_j^t = y^t T\left(T^* V_i - V_j\right) \\ i_i^t &= y^t\left(V_i - T V_j\right) \end{aligned} \tag{2}$$

Using above equations, $I_i^t = i_i^t$, $I_j^t = i_j^t$

$$\begin{bmatrix} I_i^t \\ I_j^t \end{bmatrix} = y^t \begin{bmatrix} 1 & -T \\ -T^* & 1 \end{bmatrix} \begin{bmatrix} V_i \\ V_j \end{bmatrix}$$

The off-diagonal elements of the admittance matrix Y for a phase-shifting transformer are not symmetrical, i.e.,

$$\begin{aligned} Y_{ij} = -yT = &\left(b^t \sin\psi^t - g^t \cos\psi^t\right) \\ &- j\left(g^t \sin\psi^t + b^t \cos\psi^t\right) \end{aligned} \tag{4}$$

$$\begin{aligned} Y_{ij} = -y^t T^* = &-\left(b^t \sin\psi^t + g^t \cos\psi^t\right) \\ &+ j\left(g^t \sin\psi^t - b^t \cos\psi^t\right) \end{aligned} \tag{5}$$

At the end of the phase-shifting transformer the Apparent MVA S_i is showed by using Eq. (6) as follows:

$$\begin{aligned} S_i &= P_i + jQ_i = V_i I_i \\ &= y^{t*}\left(V_i^2 - V_i V_j^* T^*\right) \end{aligned} \tag{6}$$

where

$$V_i = |V_i| \angle \theta_i, V_j = |V_j| \angle \theta_j$$

Hence the real power flow P_i and P_j of bus i and j can be calculated as follows (Jun and Akihiko, 2006).

$$P_i = gV_i^2 - V_i V_j y^t \cos\left(\beta_{ij}\right) \tag{7}$$

$$P_j = gV_j^2 - V_i V_j y^t \cos\left(-\beta_{ij}\right) \tag{8}$$

where $\beta_{ij} = \theta_i - \theta_j - \Psi^t - \alpha^t$ the partial derivatives of the real power with respect to the transformer shifting angle for node i and j are as follows respectively (Zhang *et al*., 2001):

$$\frac{\partial P_i}{\partial \psi^t} = -V_i V_j y^t \sin\left(\beta_{ij}\right) \tag{9}$$

$$\Delta\psi^t = \frac{-\Delta P_i}{V_i V_j y^t \sin\left(\beta_{ij}\right)} \tag{10}$$

$$\frac{\partial P_j}{\partial \psi^t} = -\frac{\partial P_i}{\partial \psi^t} \tag{11}$$

$$\Delta\psi^t = \frac{\Delta P_j}{V_i V_j y^t \sin\left(\beta_{ij}\right)} \tag{12}$$

Eq. (8) and (9) are used for adjusting the shifting angle of transformer for either the specified power P_i of the sending end or the specified power P_j of the receiving end.

SIMULATION AND RESULTS

The power system that is implemented for analyzing the effects of PST is shown in Fig. 2. This test power system is included in (Carsten, 2002).

A PST is used to control the power flow in a 500 kV/230 kV transmission system. The system, connected in a loop configuration, consists essentially of five buses (B1 to B5) interconnected through three transmission lines (L1, L2, L3) and two 500 kV/230 kV transformer banks Tr1 and Tr2. Two power plants located on the 230 kV system generate a total of 1500 MW which is transmitted to a 500 kV, 15000 MVA equivalent and to a 200 MW load connected at bus B3. Each plant model includes a speed regulator, an excitation system as well as a Power System Stabilizer (PSS). In normal operation, most of the 1200 MW generation capacity of power plant # 2 is exported to the 500 kV equivalents through two 400 MVA transformers connected between buses B4 and B5. For this demo we are considering a contingency case where only two transformers out of three are available (Tr2= 2*400 MVA = 800 MVA). The load flow shows that most of the power generated by plant # 2 is transmitted through the 800 MVA transformer bank (899 MW out of 1000 MW) and that 96 MW is circulating in

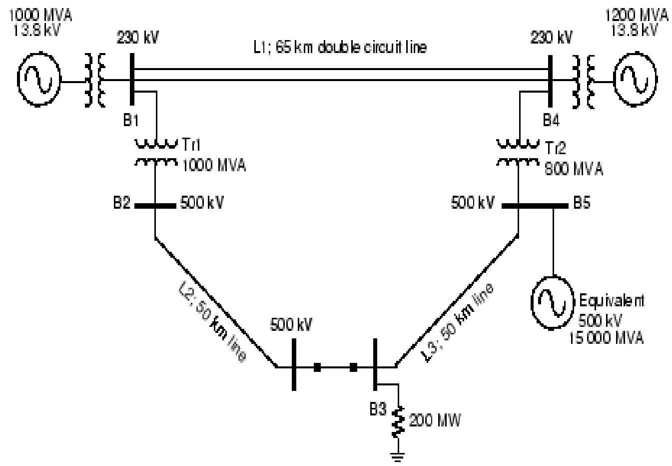
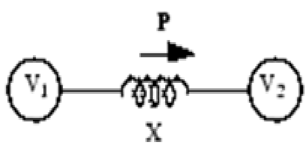


Fig. 2: The test power system single line diagram



$$P = \frac{V_1 V_2 \sin\delta}{X}$$

Where

P = Active power transmitted

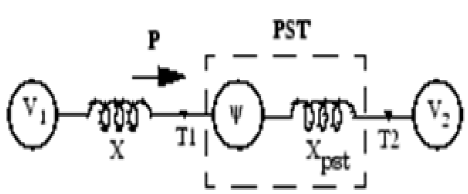
V_1 = Line to line voltage of source V_1

V_2 = Line to line voltage V_2

X = Reactance of interconnection

Δ = Angle of V_1 with respect to V_2

Fig. 3a: Power flow diagram in power system without PST



$$P = \frac{V_1 V_2 \sin(\delta + \psi)}{X + X_{pst}}$$

X_{pst} = PST leakage reactance

Ψ = PST phase shift = Angle of T2 voltages with respect to T1

Fig. 3b: Power flow diagram in power system with PST

the loop. Transformer Tr2 is therefore overloaded by 99 MVA. The paper illustrates how a PST can relief this power congestion. The PST located at the right end of line L2 is used to control the active and reactive powers at the 500 kV bus B3, as well as the voltage at bus B_PST.

The Phase Shifting Transformer (PST) is nevertheless a very efficient means to control power flow because it acts directly on the phase angle δ, as shown Fig. 3a and b (Gyugyi, 1994). The PST is the most commonly used device to control power flow on power grids.

The simulation is performed with MATLAB/ Simulink program. Figure 4 and 5 shows the MATLAB modeling test power system in presence and in absence of PST. Pulse generation in PST configuration is shown in Fig. 6 in MATLAB/Simulink program.

The nominal power is set to 800 MVA (maximum expected power transfer through the PST). The number of taps is set to 20, so that the phase shift resolution is approximately 60/20 = 3 degrees per step.

In the power system, the natural power flow (without PST) from B_PST to B3 is P=+587 MW. If V1and V2 in Fig. 3 represents the internal voltages of systems connected respectively to B_PST and B3, it means that the angle δ of Eq. (1) is positive. Therefore, according to Eq. (2), to increase power flow from B_PST to B3, the PST phase shift Ψ of abc terminals with respect to ABC terminals must be also positive. For this type of PST the taps must be moved in the negative direction. This is achieved by sending pulses to the Down input of the PST tap changer. The tap position is controlled by sending pulses to either the Up input or the Down input. In this simulation c, as it is needed to increase phase shift from zero toward positive values, it has to send pulses to the Down input.

Therefore, every 5 sec the taps will be moved by one step in the negative direction and the phase shift will increase by approximately 3^o. The variation of tap position, PST phase shift Ψ and active power transfer

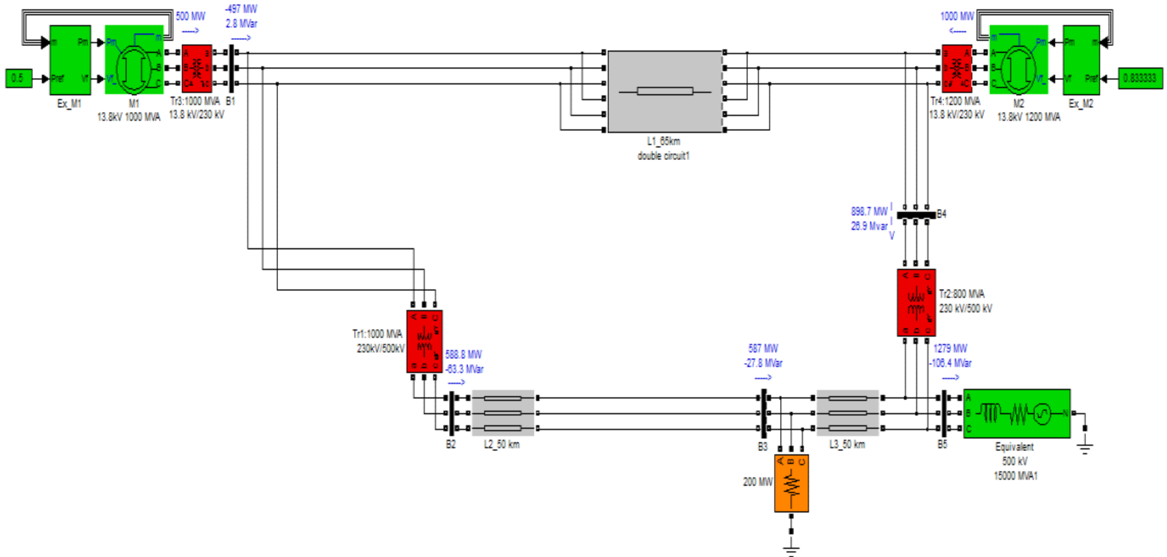


Fig. 4: MATLAB modeling of test power system without PST

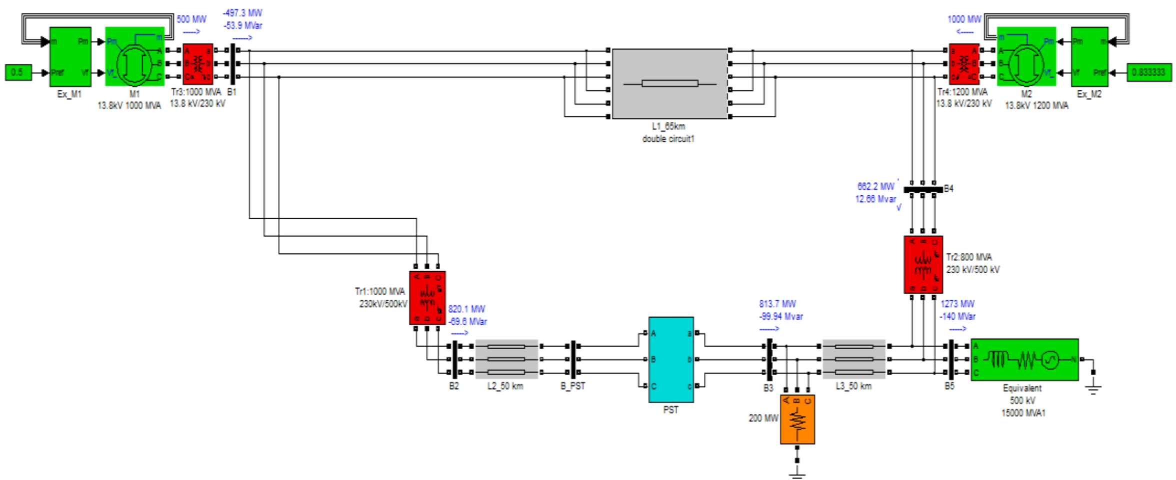


Fig. 5: MATLAB modeling of test power system with PST between buses B_PST and B3

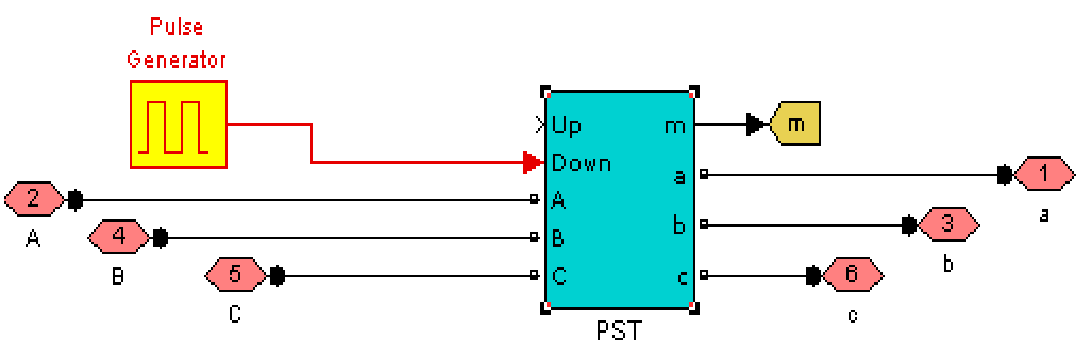


Fig. 6: Pulse generation in PST configuration

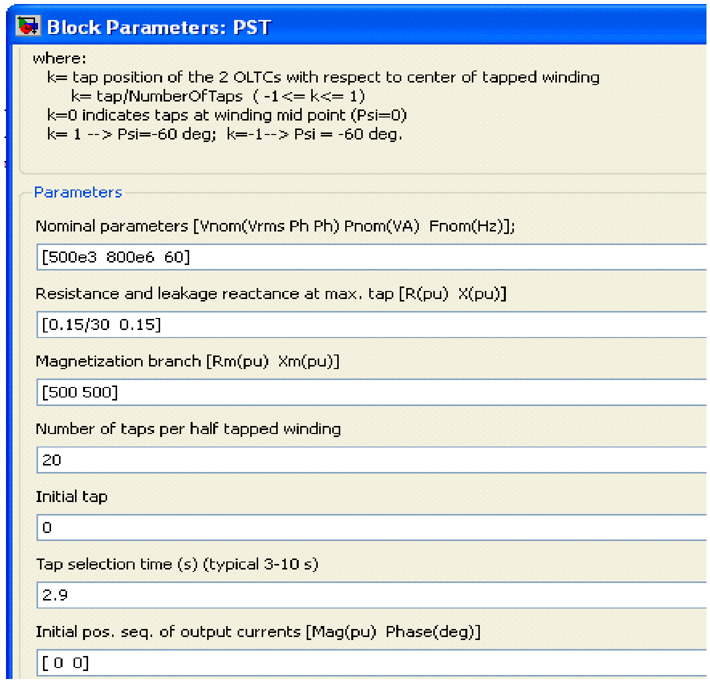


Fig. 7: Setting parameters of PST in SIMULINK program

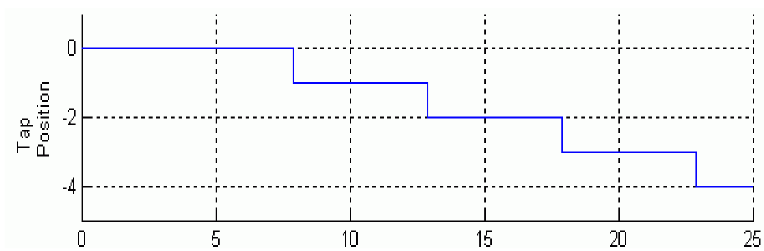


Fig. 8: The variation of tap position

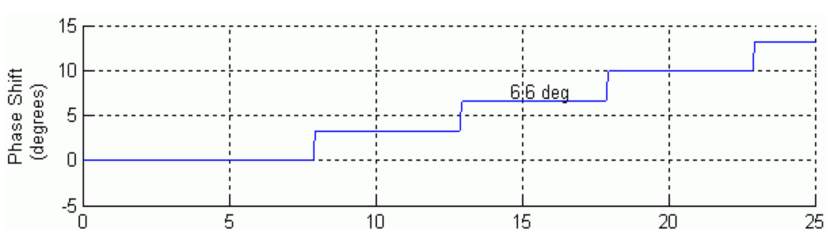


Fig. 9: The variation of PST phase shift Ψ

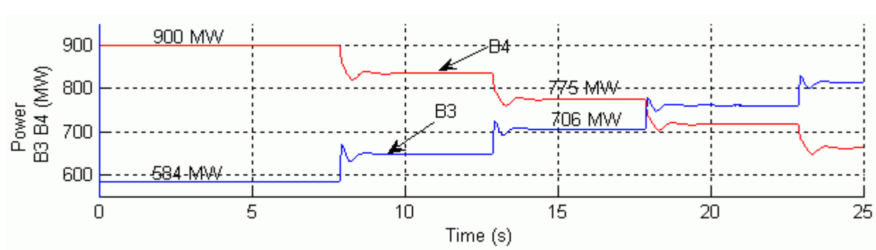


Fig. 10: Power active power transfer through bus B3 (power through PST) and B4 (power through transformer Tr2)

Table 1: The variations magnitudes and phase angles of power system buses before and after PST installing

	Magnitude of voltage (p.u)		Angle of voltage (rad)	
Bus	Without PST	With PST	Without PST	With PST
B1	0.9965	0.9914	0.2265	0.1360
B2	0.9993	0.9925	0.1553	0.0420
B3	0.9995	0.9947	0.1136	0.1265
B4	0.9925	0.9932	0.2569	0.2222
B5	0.9977	0.9963	0.0863	0.0863

Table 2: Active and reactive power flow in transmission lines of power system before and after installing PST

	Reactive power		Active power	
Line	Without PST	With PST	Without PST	With PST
L1(circuit 1)	- 0.81685	- 16.277	47.5777	136.9573
L1(circuit 2)	- 8.1685	- 16.277	47.5777	136.9573
2	- 63.2672	- 70.517	4588.7694	766.8544
L3	27.7881	80.5257	- 387.2092	- 563.4736

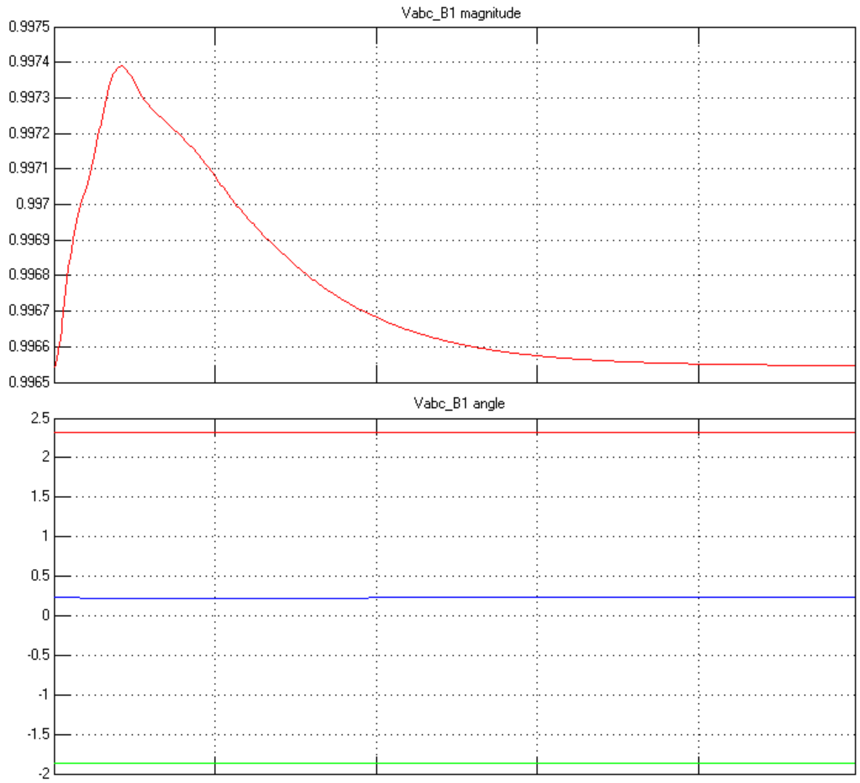
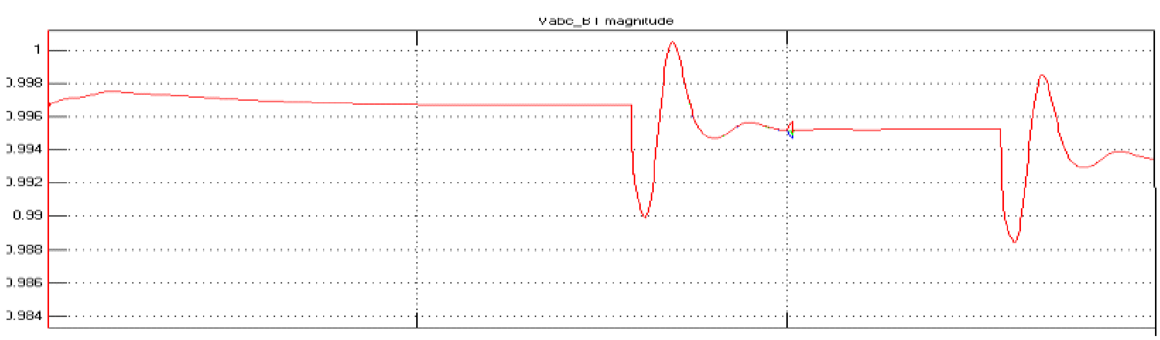


Fig. 11: Voltage magnitude and angle of Bus 5 before installing PST



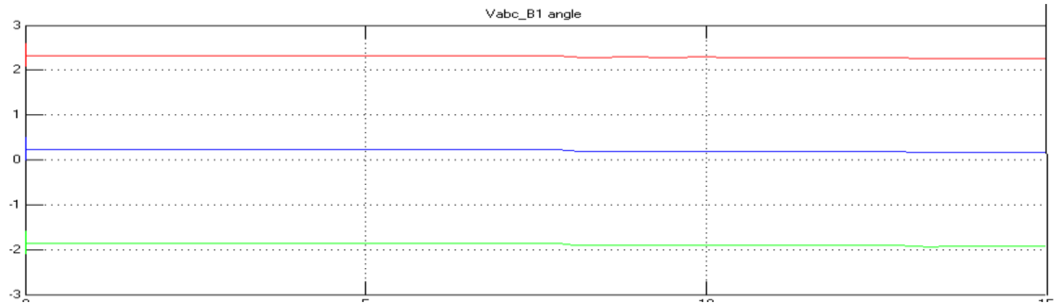


Fig. 12: Voltage magnitude and angle of Bus 5 after installing PST

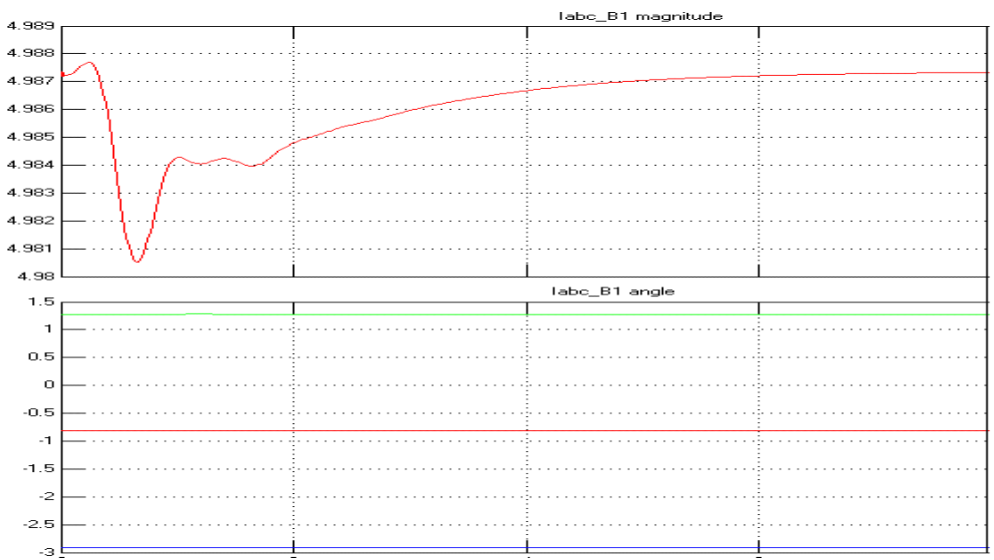


Fig. 13: Current magnitude and angle of Bus 5 before installing PST

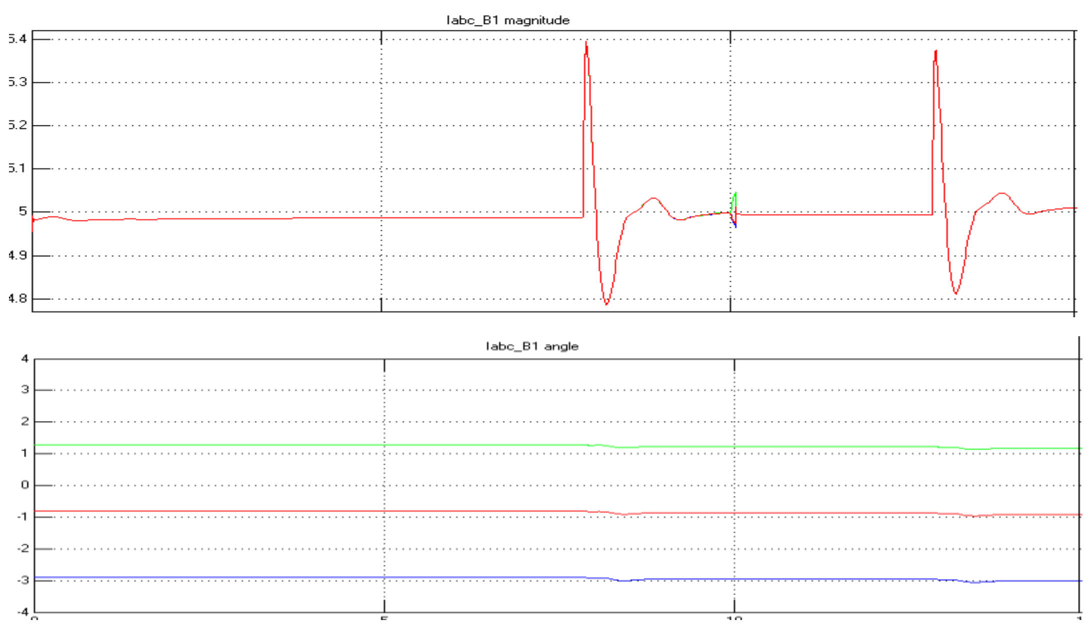


Fig. 14: Current magnitude and angle of Bus 5 after installing PST

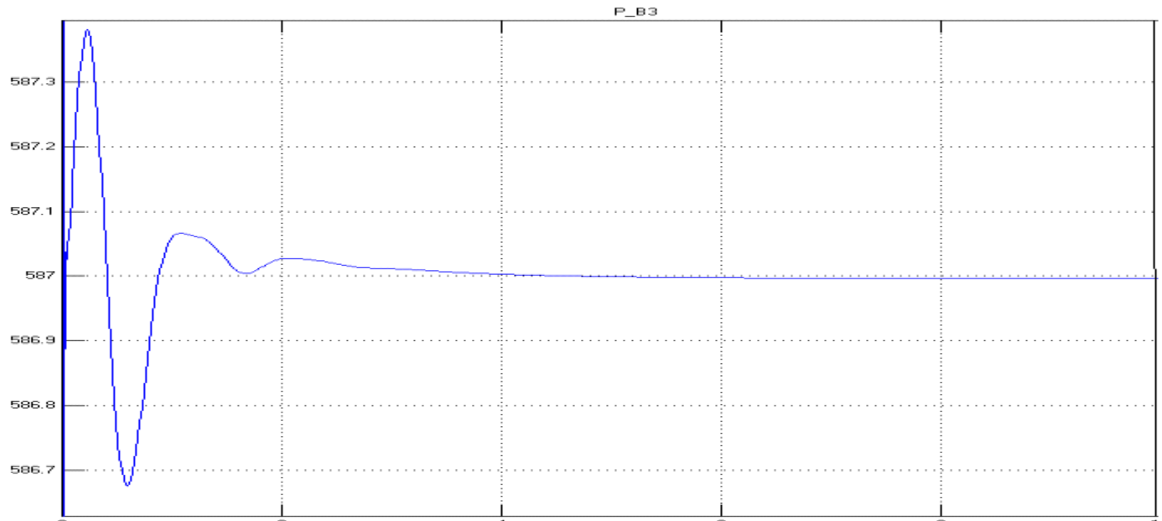


Fig. 15: Real power of Bus 3 before installing PST

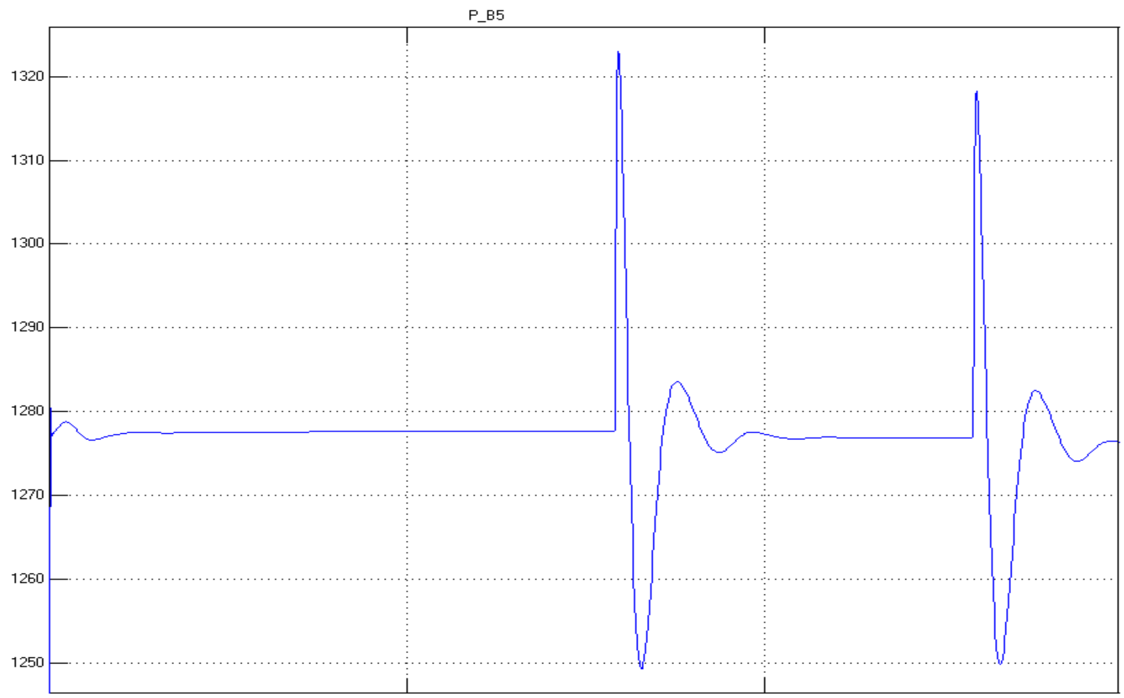


Fig. 16: Real power of Bus 5 after installing PST

through bus B3 (power through PST) and B4 (power through transformer Tr2) are reproduced on the Fig. 8-10. Each tap change produces a phase angle variation of approximately 3º, resulting in a 60 MW power increase through B3. At tap position -2, the power through transformer Tr2 as decreased from 900 MW to 775 MW.

The variations magnitudes and phase angles of power system buses before and after PST installing is shown in Table 1. Active and reactive power flow in transmission lines of power system before and after installing PST is shown in Table 2. The figures of voltage and current magnitude and phase angle variations of Bus 5 during simulation times are shown in Fig. 11-14. It is obvious that the steady states of these figures are same results that listed in Table 1 and 2. The figures of active power and reactive power of Bus 5 (differences of injection and demanded power) are shown in Fig. 15-18. It notable, that setting parameters of PST is shown in Fig. 7.

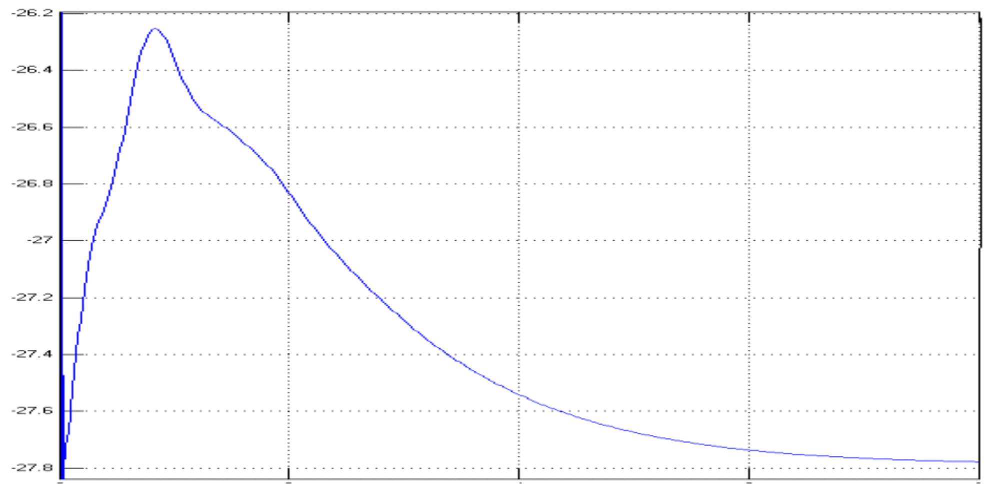


Fig. 17: Reactive power of Bus 5 before installing PST

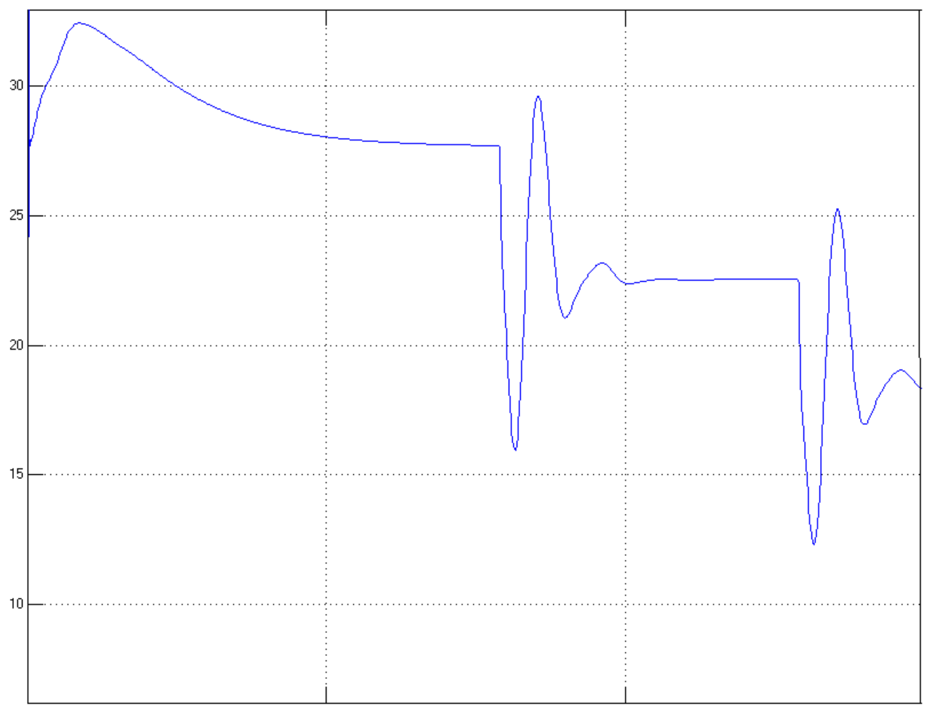


Fig. 18: Reactive power of Bus 5 after installing PST

CONCLUSION

The power injection models of PST is reviewed and implemented in an OPF problem. With the proper selection of initial conditions, the proposed OPF problem, which optimizes the overall generating cost and is subject to the branch flow constraints of either the PST subject to the branch power flow constraints of the PST, can be solved by the SQP algorithm. Some techniques to select initial values of the PST are presented as a supplement to the analytical solution. It is shown that PST is powerful tools for power flow regulation, by which the transfer capability of the transmission line can be increased significantly. Combined with the generating bus voltage adjustment, the OPF incorporating either FACTS device can effectively minimize the overall generating cost without active power generation redispatching. When PST is incorporated to control the active and reactive power flows in a chosen transmission line, the effectiveness varies with the location of the PST without the branch power flow constraints. The results show that by PST the profile of voltage and real and reactive power flow in transmission lines can be improved.

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