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A Study of Series FACTS Devices for the Control of Power Flow in Electrical Power Networks

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ABSTRACT: This paper concentrates on controlling of power flow in power lines with the help of series Flexible Alternating Current Transmission Systems (FACTS) device. The power flow control deals with the task of taking remedial measures against overloads and nonlinear loads in the system due to the occurrence of contingencies. The series FACTS devices considered in this paper are Thyristor Controlled Series Capacitor (TCSC), Thyristor Controlled Phase Shifter (TCPS) and Static Synchronous Series Compensator (SSSC). This paper presents the modelling of these series FACTS devices suitable for incorporation in load flow program for the study of steady state operation of power system. A systematic foundation on the theory and practice of positive sequence power flow is presented here. An efficient Newton-Rapshon (NR) method is used for solving the nonlinear algebraic load flow equations in the load flow problem. A step by step procedure for incorporation of series FACTS devices within the NR load flow algorithm is described. The effectiveness of the proposed models and convergence of the proposed load flow algorithm is tested on standard IEEE 30 bus test network without and with these series FACTS devices. Programming for the solution of series controllable branches with these proposed models is done by using MATLAB software. Results are reported and studies are presented to demonstrate and compare the efficiency of TCPS, TCSC and SSSC.

KEYWORDS: Flexible AC Transmission Systems (FACTS), Newton-Raphson method, Thyristor Controlled Series Capacitor (TCSC), Static Synchronous Series Compensator (SSSC), Thyristor Controlled Phase Shifter (TCPS).

1 INTRODUCTION

Mainly two bases encourage the control of power flow, first one is improvement in high power electronic devices and the second one is deregulation of power market and continually increasing demand of electric power. In order to meet the growing demand of electricity while maintaining economic and secure operation, either utilize the existing network high proficiently or construct the new power lines and power generators. Due to right of way issues and environmental problems the latter one is very difficult. Implementation of former one is easy and provides a smart solution to control the power flow. The idea of utilize the existing power system efficiently has pointed in the forward direction of power electronics based equipment i.e., Flexible AC Transmission Systems (FACTS) controllers [1]. Recent development in high power electronic devices makes it possible to control the power flows in the network.

The concept of FACTS devices is implemented in power lines, to increase the power transfer capability, either in series or in shunt with the power lines. FACTS device introduced in series with the line is the most efficient one to control the power flow and to enhance the power transfer capability of the line. Series compensation [1] enhances the line power transfer capability, damping sub-synchronous oscillations and power oscillations, improves the voltage profile and system stability and also reduces losses. The efficient tool is needed to be developed to determine the effectiveness of the series FACTS devices. Hence, existing program of load flow studies is required to be modified for include the series devices in the power

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system. Newton-Raphson (NR) method has very strong convergence characteristics for the solution of load flow. This paper presents the solution of series controllable branches through the NR method to rule the power flow in the transmission lines.

Two methods of load flow solution [2] exist for include the series FACTS device in NR algorithm, those are 1) Simultaneous or Unified method [3], 2) Sequential or Alternating method [4]. In former method, the equations related to the FACTS device specification and the conventional load flow equations are pooled into set of nonlinear equations and solved simultaneously. In this method, major modifications are made in existing program. In latter method, the equations related to the FACTS device specification and the conventional load flow equations are solved sequentially and separately. In this method insignificant modifications are made in existing program. Among these, unified method has very strong convergence characteristics i.e., convergence is attained within the half number of iterations requisite for the alternating method. This paper presents the unified method for solving the load flow equations with series FACTS devices. Standard IEEE 30 bus system is used for testing the effectiveness of the proposed method by using MATLAB.

In this paper, section 2 presents a steady state modeling of TCSC[3], [5], [6], [7], [8], [9], SSSC[9], [10], [11] and TCPS[12], [13] that can pooled in NR power flow algorithm. Section 3 summarizes the step by step procedure for incorporating the series FACTS device in the NR method. Section 4 presents a test case and simulation results and section 5 presents a conclusion.

2 SERIES FACTS DEVICE MODELLING

The power flow through the transmission line connected between the nodes x and y depends on sending and receiving buses voltage magnitudes V_x and V_y, voltage phase angle difference between the sending and receiving buses $\delta_x - \delta_y$ and the branch reactance X_{xy} is expressed in (1). A simple power line connecting the buses x and y is shown in Fig. 1.

$$P_{xy} = \frac{V_x V_y}{X_{xy}} \sin(\delta_x - \delta_y) \tag{1}$$

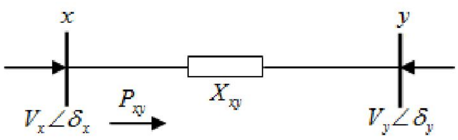

Fig. 1. The representation of transmission line between nodes x and y

TCSC device controls branch reactance and TCPS device controls voltage phase angle difference so as to control power flow across controlled line at specified value. SSSC is the most versatile member of FACTS family and control phase angles, bus voltage and line impedance. Power flow can be controlled and optimized by changing power system parameters using FACTS devices.

2.1 TCSC DEVICE MODELLING

The main objective of TCSC is to enhance the power transfer capability and to control the power flow by increasing or decreasing the series transmission reactance. The modeling of this device is based on the idea of varying reactance. The reactance value of the TCSC is changed automatically to restrict the branch power at pre-defined value. With the help of NR method, the reactance of the TCSC is gritty efficiently. The TCSC equivalent circuit is shown in Fig. 2. The equivalent reactance of TCSC device is X_{TCSC} given by

$$X_{TCSC} = -X_C + C_1(2(\pi - \alpha) + \sin(2(\pi - \alpha))) - C_2 \cos^2(\pi - \alpha)(\varpi \tan(\varpi(\pi - \alpha)) - \tan(\pi - \alpha)) \tag{2}$$

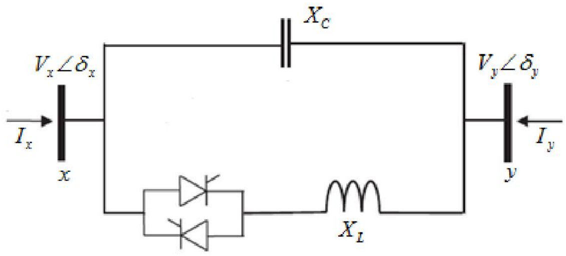

Fig. 2. Equivalent Circuit of TCSC

Where X_C is the capacitive reactance and X_L is the reactance of the thyristor controlled reactance and:

$$X_{LC} = \frac{X_C X_L}{X_C - X_L}$$

$$C_1 = \frac{X_C + X_{LC}}{\pi}$$

$$C_2 = \frac{4X_{LC}^2}{X_L \pi}$$

From the equivalent circuit of TCSC, the current equations at node x and y represented in the form of matrix is

$$\begin{bmatrix} I_x \\ I_y \end{bmatrix} = \begin{bmatrix} jB_{xx} & jB_{xy} \\ jB_{yx} & jB_{yy} \end{bmatrix} \begin{bmatrix} V_x \\ V_y \end{bmatrix} \tag{3}$$

Where $$B_{xx} = B_{yy} = B_{TCSC} = -\frac{1}{X_{TCSC}}$$

$$B_{xy} = B_{yx} = -B_{TCSC} = \frac{1}{X_{TCSC}}$$

The active and reactive power equations at node x are

$$P_x = -V_x V_y B_{TCSC} \sin(\delta_x - \delta_y) \tag{4}$$

$$Q_x = -V_x^2 B_{TCSC} + V_x V_y B_{TCSC} \cos(\delta_x - \delta_y) \tag{5}$$

Exchange the subscripts x and y for power equations at node y. The set of linearized power flow equations when the TCSC controls the real power flow from node x to y is

$$\begin{bmatrix} \Delta P_x \\ \Delta P_y \\ \Delta Q_x \\ \Delta Q_y \\ \Delta P_{xy}^{X_{TCSC}} \end{bmatrix}^k = \begin{bmatrix} \frac{\partial P_x}{\partial \delta_x} & \frac{\partial P_x}{\partial \delta_y} & \frac{\partial P_x}{\partial V_x}V_x & \frac{\partial P_x}{\partial V_y}V_y & \frac{\partial P_x}{\partial X_{TCSC}}X_{TCSC} \\ \frac{\partial P_y}{\partial \delta_x} & \frac{\partial P_y}{\partial \delta_y} & \frac{\partial P_y}{\partial V_x}V_x & \frac{\partial P_y}{\partial V_y}V_y & \frac{\partial P_y}{\partial X_{TCSC}}X_{TCSC} \\ \frac{\partial Q_x}{\partial \delta_x} & \frac{\partial Q_x}{\partial \delta_y} & \frac{\partial Q_x}{\partial V_x}V_x & \frac{\partial Q_x}{\partial V_y}V_y & \frac{\partial Q_x}{\partial X_{TCSC}}X_{TCSC} \\ \frac{\partial Q_y}{\partial \delta_x} & \frac{\partial Q_y}{\partial \delta_y} & \frac{\partial Q_y}{\partial V_x}V_x & \frac{\partial Q_y}{\partial V_y}V_y & \frac{\partial Q_y}{\partial X_{TCSC}}X_{TCSC} \\ \frac{\partial P_{xy}^{X_{TCSC}}}{\partial \delta_x} & \frac{\partial P_{xy}^{X_{TCSC}}}{\partial \delta_y} & \frac{\partial P_{xy}^{X_{TCSC}}}{\partial V_x}V_x & \frac{\partial P_{xy}^{X_{TCSC}}}{\partial V_y}V_y & \frac{\partial P_{xy}^{X_{TCSC}}}{\partial X_{TCSC}}X_{TCSC} \end{bmatrix}^k \begin{bmatrix} \Delta \delta_x \\ \Delta \delta_y \\ \frac{\Delta V_x}{V_x} \\ \frac{\Delta V_y}{V_y} \\ \frac{\Delta X_{TCSC}}{X_{TCSC}} \end{bmatrix}^k \quad (6)$$

Where $\Delta P_{xy}^{X_{TCSC}} = p_{xy}^{reg} - P_{xy}^{X_{TCSC},cal}$, is the mismatch equation for active power flow across TCSC and $\Delta X_{TCSC} = X_{TCSC}^{(k+1)} - X_{TCSC}^{(k)}$, is the incremental change in the TCSC firing angle α . Superscript k indicates the iteration value.

2.2 SSSC DEVICE MODELLING

The SSSC is a static, synchronous generator which can generates a sinusoidal ac voltage at fundamental frequency of changing and controllable phase angle and magnitude. The output voltage of this converter is in quadrature with the line current. It can absorb or generate the reactive power from the line thus it can be used as power flow controller for the transmission line. The line injected voltage emulates an inductive or a capacitive reactance in series with a transmission line; hence it provides variable transmission line reactance. This changing reactance affects the power flow in the line. The SSSC equivalent circuit is shown in Fig. 3. The SSSC output terminal voltage is changed automatically to control the branch power flow at a pre-defined value.

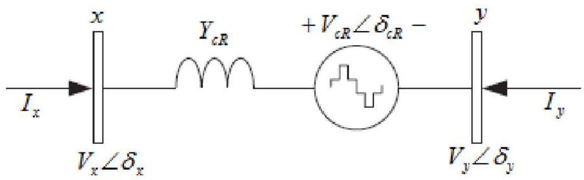

Fig. 3. Equivalent Circuit of SSSC

The series voltage source of SSSC

$$E_{cR} = V_{cR}(\cos\delta_{cR} + j\sin\delta_{cR}) \quad (7)$$

where V_{cR} and δ_{cR} are the magnitude and phase angle of the voltage source representing series compensator. The voltage source introduces two new state variables V_{cR} and δ_{cR} to the load flow problem. so, we need two new equations for the load flow solution.

The active and reactive power equations at node x is

$$P_x = V_x^2 G_{xx} + V_x V_y[G_{xy}\cos(\delta_x - \delta_y) + B_{xy}\sin(\delta_x - \delta_y)] + V_x V_{cR}[G_{xy}\cos(\delta_x - \delta_{cR}) + B_{xy}\sin(\delta_x - \delta_{cR})] \quad (8)$$

$$Q_x = -V_x^2 B_{xx} + V_x V_y[G_{xy}\sin(\delta_x - \delta_y) - B_{xy}\cos(\delta_x - \delta_y)] + V_x V_{cR}[G_{xy}\sin(\delta_x - \delta_{cR}) - B_{xy}\cos(\delta_x - \delta_{cR})] \quad (9)$$

And active and reactive power equations for voltage source is

$$P_{cR} = V_{cR}^2 G_{yy} + V_x V_{cR}[G_{xy}\cos(\delta_{cR}-\delta_x) + B_{xy}\sin(\delta_{cR}-\delta_x)] + V_y V_{cR}[G_{yy}\cos(\delta_{cR}-\delta_y) + B_{yy}\sin(\delta_{cR}-\delta_y)] \quad (10)$$

$$Q_{cR} = -V_{cR}^2 B_{yy} + V_x V_{cR}[G_{xy}\sin(\delta_{cR}-\delta_x) - B_{xy}\cos(\delta_{cR}-\delta_x)] + V_y V_{cR}[G_{yy}\sin(\delta_{cR}-\delta_y) - B_{yy}\cos(\delta_{cR}-\delta_y)] \quad (11)$$

The set of linearized power flow equations when the SSSC controls the power flow from node x to y is

$$\begin{bmatrix} \Delta P_x \\ \Delta P_y \\ \Delta Q_x \\ \Delta Q_y \\ \Delta P_{xy} \\ \Delta Q_{xy} \end{bmatrix}^k = \begin{bmatrix} \frac{\partial P_x}{\partial \delta_x} & \frac{\partial P_x}{\partial \delta_y} & \frac{\partial P_x}{\partial V_x}V_x & \frac{\partial P_x}{\partial V_y}V_y & \frac{\partial P_x}{\partial \delta_{cR}} & \frac{\partial P_x}{\partial V_{cR}}V_{cR} \\ \frac{\partial P_y}{\partial \delta_x} & \frac{\partial P_y}{\partial \delta_y} & \frac{\partial P_y}{\partial V_x}V_x & \frac{\partial P_y}{\partial V_y}V_y & \frac{\partial P_y}{\partial \delta_{cR}} & \frac{\partial P_y}{\partial V_{cR}}V_{cR} \\ \frac{\partial Q_x}{\partial \delta_x} & \frac{\partial Q_x}{\partial \delta_y} & \frac{\partial Q_x}{\partial V_x}V_x & \frac{\partial Q_x}{\partial V_y}V_y & \frac{\partial Q_x}{\partial \delta_{cR}} & \frac{\partial Q_x}{\partial V_{cR}}V_{cR} \\ \frac{\partial Q_y}{\partial \delta_x} & \frac{\partial Q_y}{\partial \delta_y} & \frac{\partial Q_y}{\partial V_x}V_x & \frac{\partial Q_y}{\partial V_y}V_y & \frac{\partial Q_y}{\partial \delta_{cR}} & \frac{\partial Q_y}{\partial V_{cR}}V_{cR} \\ \frac{\partial P_{xy}}{\partial \delta_x} & \frac{\partial P_{xy}}{\partial \delta_y} & \frac{\partial P_{xy}}{\partial V_x}V_x & \frac{\partial P_{xy}}{\partial V_y}V_y & \frac{\partial P_{xy}}{\partial \delta_{cR}} & \frac{\partial P_{xy}}{\partial V_{cR}}V_{cR} \\ \frac{\partial Q_{xy}}{\partial \delta_x} & \frac{\partial Q_{xy}}{\partial \delta_y} & \frac{\partial Q_{xy}}{\partial V_x}V_x & \frac{\partial Q_{xy}}{\partial V_y}V_y & \frac{\partial Q_{xy}}{\partial \delta_{cR}} & \frac{\partial Q_{xy}}{\partial V_{cR}}V_{cR} \end{bmatrix}^k \begin{bmatrix} \Delta \delta_x \\ \Delta \delta_y \\ \frac{\Delta V_x}{V_x} \\ \frac{\Delta V_y}{V_y} \\ \Delta \delta_x \\ \frac{\Delta V_{cR}}{V_{cR}} \end{bmatrix}^k \quad (12)$$

2.3 TCPS DEVICE MODELLING

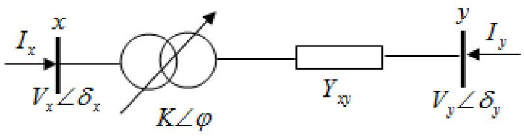

Fig. 4. Equivalent Circuit of TCPS

Thyristor Controlled Phase shifter with quadrature voltage injection controls the active power via phase adjustment, φ. The modeling of this device is based on the idea of varying phase angle. The phase angle value of the TCPS is changed automatically to restrict the branch power at pre-defined value. With the help of NR method, the phase angle of the TCPS is gritty efficiently. The TCPS equivalent circuit is shown in Fig. 4. From the equivalent circuit of TCPS, the current equations at node k and m represented in the form of matrix is

$$\begin{bmatrix} I_x \\ I_y \end{bmatrix} = \begin{bmatrix} Y & -Y(\cos\varphi + j\sin\varphi) \\ -Y(\cos\varphi - j\sin\varphi) & Y \end{bmatrix} \begin{bmatrix} V_x \\ V_y \end{bmatrix} \quad (13)$$

The active and reactive power equations at node x is

$$P_x = V_x^2 G_{xx} + V_x V_y [G_{xy}\cos(\delta_x-\delta_y) + B_{xy}\sin(\delta_x-\delta_y)] \quad (14)$$

$$Q_x = -V_x^2 G_{xx} + V_x V_y [G_{xy}\sin(\delta_x-\delta_y) - B_{xy}\cos(\delta_x-\delta_y)] \quad (15)$$

Exchange the subscripts x and y for power equations at node y.

From the (13),

$$\left.\begin{aligned} Y_{xx} &= Y_{yy} = Y \\ Y_{xy} &= -Y(\cos\varphi + j\sin\varphi) \\ Y_{yx} &= -Y(\cos\varphi - j\sin\varphi) \end{aligned}\right\} \tag{16}$$

Substitute (16) in to (14) and (15) gives the following more explicit expressions

$$P_x = V_x^2 G - V_x V_y [G\cos(\delta_x - \delta_y - \varphi) + B\sin(\delta_x - \delta_y - \varphi)] \tag{17}$$

$$Q_x = -V_x^2 B - V_x V_y [G\sin(\delta_x - \delta_y - \varphi) - B\cos(\delta_x - \delta_y - \varphi)] \tag{18}$$

The set of linearized power flow equations when the TCPS controls the power flow from node x to y is

$$\begin{bmatrix} \Delta P_x \\ \Delta P_y \\ \Delta Q_x \\ \Delta Q_y \\ \Delta P_{xy}^{\varphi^{ps}} \end{bmatrix}^k = \begin{bmatrix} \frac{\partial P_x}{\partial \delta_x} & \frac{\partial P_x}{\partial \delta_y} & \frac{\partial P_x}{\partial V_x}V_x & \frac{\partial P_x}{\partial V_y}V_y & \frac{\partial P_x}{\partial \varphi} \\ \frac{\partial P_y}{\partial \delta_x} & \frac{\partial P_y}{\partial \delta_y} & \frac{\partial P_y}{\partial V_x}V_x & \frac{\partial P_y}{\partial V_y}V_y & \frac{\partial P_y}{\partial \varphi} \\ \frac{\partial Q_x}{\partial \delta_x} & \frac{\partial Q_x}{\partial \delta_y} & \frac{\partial Q_x}{\partial V_x}V_x & \frac{\partial Q_x}{\partial V_y}V_y & \frac{\partial Q_x}{\partial \varphi} \\ \frac{\partial Q_y}{\partial \delta_x} & \frac{\partial Q_y}{\partial \delta_y} & \frac{\partial Q_y}{\partial V_x}V_x & \frac{\partial Q_y}{\partial V_y}V_y & \frac{\partial Q_y}{\partial \varphi} \\ \frac{\partial P_{xy}^{\varphi}}{\partial \delta_x} & \frac{\partial P_{xy}^{\varphi}}{\partial \delta_y} & \frac{\partial P_{xy}^{\varphi}}{\partial V_x}V_x & \frac{\partial P_{xy}^{\varphi}}{\partial V_y}V_y & \frac{\partial P_{xy}^{\varphi}}{\partial \varphi} \end{bmatrix}^k \begin{bmatrix} \Delta\delta_x \\ \Delta\delta_y \\ \frac{\Delta V_x}{V_x} \\ \frac{\Delta V_y}{V_y} \\ \Delta\varphi^{ps} \end{bmatrix}^k \tag{19}$$

Where $\Delta P_{xy}^{\varphi^{ps}} = P_{xy}^{\varphi,reg} - P_{xy}^{\varphi^{ps}}$, is the mismatch equation for active power flow across TCPS and $\Delta\varphi^{ps} = \varphi^{(k+1)} - \varphi^{(k)}$, is the thyristor controlled phase shifter angle incremental change. Superscript k indicates the iteration value.

3 PROCEDURE FOR LOAD FLOW SOLUTION WITH SERIES FACTS DEVICES

The load flow solution procedure with series FACTS devices is summarized as follows.

i) Each series FACTS device is assumed as an individual branch in the present network.
ii) One bus is assigned as a slack bus, and the remaining buses as either (P, V) or (P, Q) buses.
iii) Series FACTS device branches are assigned as (P, Q or V), or (P, I) branches.
iv) Because of the voltage magnitude at (P, V) bus is specified, it is no more addressed as a state variable and in the solution of equations, the shunt reactive power equation for that bus is not counted.
v) Similarly, because of the current magnitude in (P, *I*) branch is specified, it is no more addressed as a state variable and in the solution of equations, the series reactive power (or V) equation for that branch is not counted.
vi) The total number of equations to be solved = 2 × (no. of buses – 1) – (no. of (P, V) buses) + 2 × (no. of series FACTS device branches) – (no. of (P, I) series FACTS device branches). This gives the number of unknown state variables.
vii) The unknown state variables are initialized to supposed values.
viii) Solve the appropriate Jacobian.
ix) In order to find out the correction values of state variables, calculate mismatches and evaluate the linear equation. Based on this correction values, modify the values of the state variables.

x) Check for limit violation if any limit is violated then change the specifications[2] otherwise go to next step.

xi) Check convergence by comparing maximum mismatch with the tolerance (ε). If convergence is achieved then stop the process; otherwise, go to step viii.

4 TEST CASE AND SIMULATION

IEEE 30-bus test network is tested with TCSC, SSSC and TCPS separately, to examine the behavior of these devices in the network. The network necessary data is taken from [14].

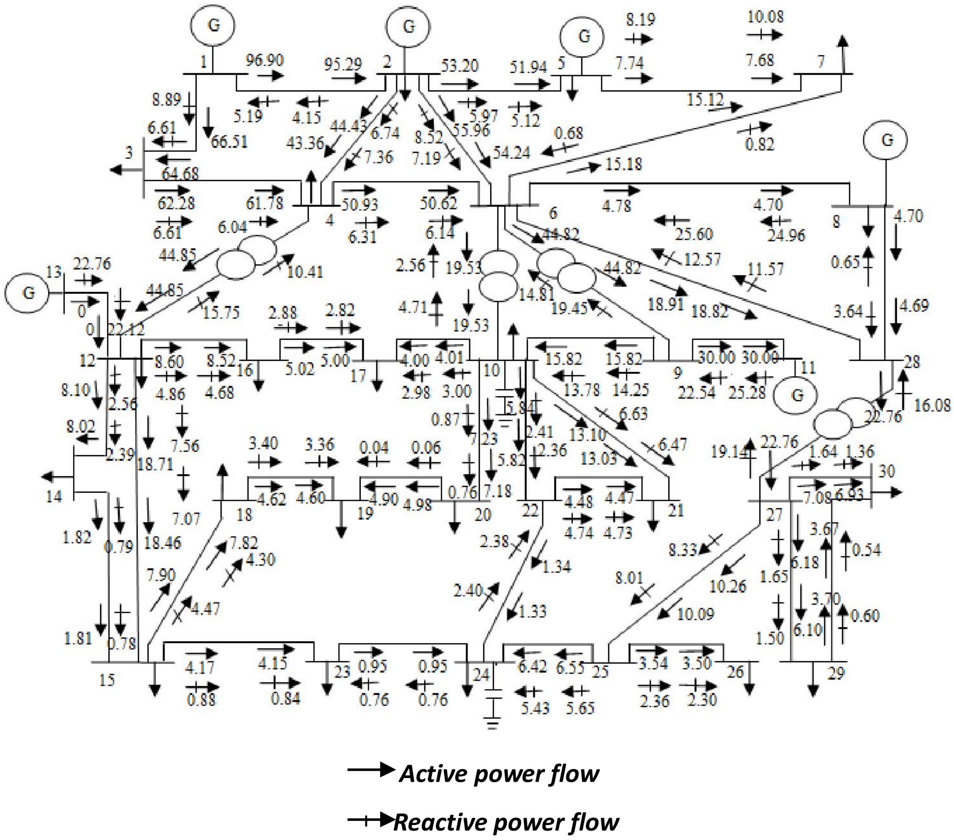

Fig. 5. Line Flow Results under Case 1

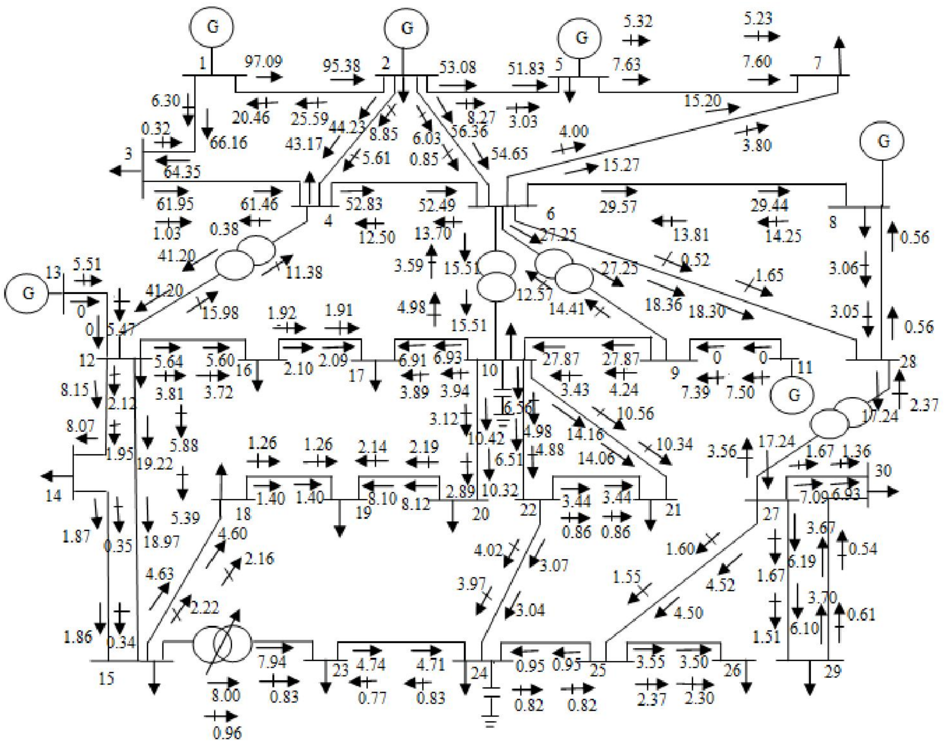

Fig. 6. Line Flow Results under Case 2

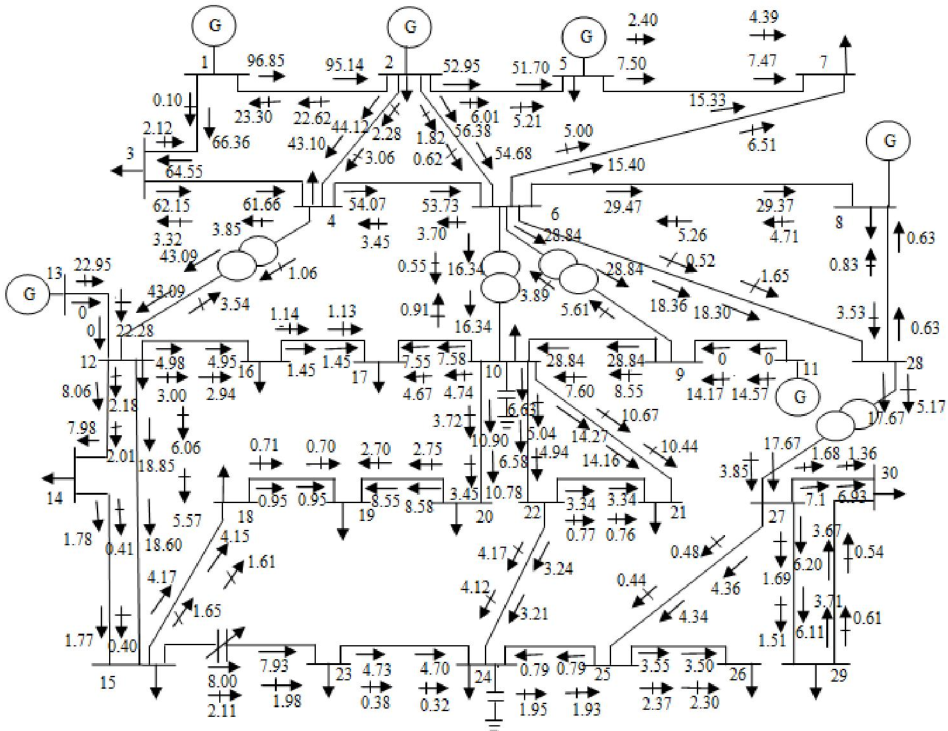

Fig. 7. Line Flow Results under Case 3

Load flow program is carried out on IEEE 30 bus test system for 4 cases. The first case is the conventional load flow case without introducing any FACTS-devices, while the others are modified load flow with FACTS device. In case 2, 3 and 4, transmission line connecting the buses 15 and 23 is installed with TCPS, TCSC and SSSC respectively to achieve the active power flow at specified value in that line. The extra bus is added to enable the connection of these devices. These devices are used to preserve the real power flow at 8 MW in the line 15-23. Without installing these devices, the power flowing in that line is 4.17 MW, with these the power flow amplifies to 8 MW. The tolerance value is fixed at 0.0001.

In case 1, the convergence is attained within the 19 iterations and the active and reactive power losses are 0.1001 p.u and -0.1178 p.u respectively. The results of line flows are shown in Fig. 5.

In case 2, the voltage phase angle difference between the buses 15 and 23 is increased from -0.4178 to -1.2010 to enhance the active power from 4.17 MW to 8 MW. The result of the phase shifter angle required to achieve the specified active flow through the TCPS is -2.4809. The convergence is attained within the 7 iterations and the active and reactive power losses are 0.0986 p.u and -0.1749 p.u respectively. The results of line flows are shown in Fig. 6.

In case 3, the equivalent reactance of TCSC which is necessary to attain the specified active flow through the TCSC is -0.4430. The convergence is attained within the 8 iterations and the active and reactive power losses are 0.0981 p.u and -0.1639 p.u respectively. The results of line flows are shown in Fig. 7.

In case 4, voltage magnitude and angle of series converter required to achieve the active and reactive power flow at 8 MW and 5 MVAR respectively through the SSSC are 0.0134 p.u and -136.1871 deg respectively. The convergence is attained within the 4 iterations and the active and reactive power losses are 0.0976 p.u and -0.1625 p.u respectively. The results of line flows are shown in Fig. 8.

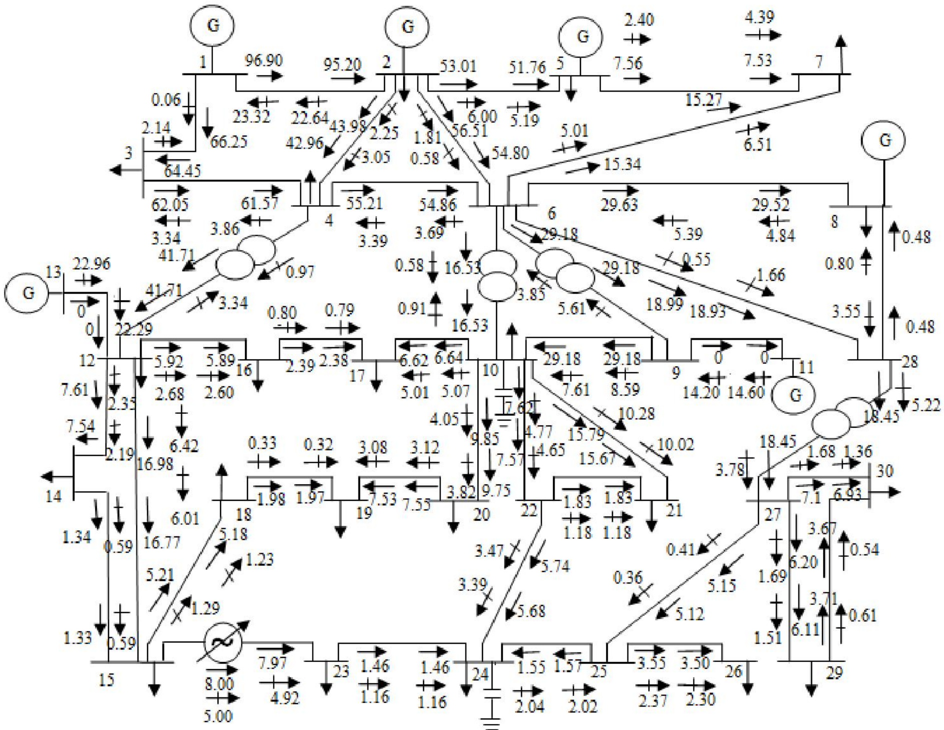

Fig. 8. Line Flow Results under Case 4

The variation of active power losses during each iteration under cases 2, 3 and 4 is shown in Fig. 9. From this figure, it can observe that active power losses in the presence of SSSC is less compared to TCSC and TCPS and also observe that SSSC convergent time is less compared to TCSC, TCPS and base case.

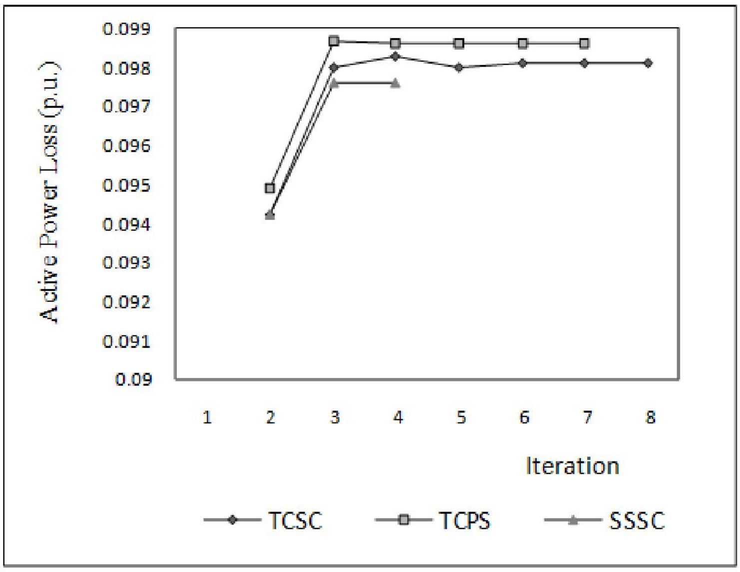

Fig. 9. Active power loss during each iteration under case 2, 3 and 4

5 CONCLUSION

This paper presents the modeling of series FACTS device: TCSC, SSSC, and TCPS suitable for the study of steady state operation of power system. To include FACTS devices: TCSC, SSSC, and TCPS, the base load flow solution is methodically changed. It is revealed that the effect of FACTS controllers on power flow can be provided by adjusting some existing entries and adding new entries in the conventional load flow linearized equation.

The conventional load flow program can simply be altered by using the proposed model in this paper. This proposed model is applied on the standard IEEE 30 bus test system and carried out by using the MATLAB software. The obtained results illustrate the strong convergence of the proposed models. The modeling of TCSC, SSSC, and TCPS are incorporated in NR algorithm and the result demonstrates that SSSC gives better performance compared to both TCSC and TCPS.

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