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Power Flow Solution with FACTS Devices

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Abstract—*In this paper, an approach for power flow solution of power networks with FACTS devices has been presented. The FACTS models have been incorporated in the existing Newton Raphson Load Flow Algorithm. The state variables associated with the FACTS devices have been combined with the nodal voltage magnitudes and angles of network in a single frame of reference for a unified iterative solution. Two FACTS devices, Static Var Compensator (SVC) and Thyristor controlled Series Capacitor (TCSC) have been modelled for enhancement of voltage stability and control of active power flow respectively. The results have been presented for IEEE 5-Bus system.*

1. INTRODUCTION

Advancement of power electronics in turn led to the development of Flexible AC Transmission Systems (FACTS). FACTS devices comprise of solid state switching devices like thyristors, IGBT's, GTO's, IGCT's etc to switch in or out of transmission line components like capacitors, reactors or phase shifting transformers to obtain some desirable performance of the system. FACTS technology is essentially a collection of controllers which can be used individually or in coordination with each other to control system variables [2].

Voltage regulation in a system is achieved by control of reactive power flow throughout the system. Sources and sinks of reactive power are used for this purpose such as shunt capacitors, FACTS devices like STATCOM, SVC etc. SVC, STATCOM etc fall under the category of shunt FACTS controllers. They represent injection of current in the line at the point of connection. Shunt controllers only supply or consume variable reactive power, if the voltage is in phase quadrature with the line current, otherwise for any other phase relationship it involves handling of real power as well[2].

Controllable series line compensation can be used to achieve full utilization of the transmission lines by controlling the power flow in the lines. Series FACTS devices like TCSC, TSSC, SSSC etc fall under this category. They basically control the impedance of the line and represent the injection of voltage into the line. The series controller only supplies or consumes variable reactive power, if the voltage is in phase quadrature with the line current, otherwise for any other phase relationship it involves handling of real power as well [2].

The reactive power supplied by SVC is adjusted in such a way that the voltage magnitude at the connection point remains fixed. The reactive source is usually a combination of capacitors and inductors. There are various configurations of SVC, out of which TCR-FC is used here. The model of SVC used in this paper is the firing angle model. Series compensator is functions as a controlled voltage source which is connected in series with the transmission line to control its current. The TCSC scheme is used for rapid adjustment of network impedance so as to control the power flow in the line. It consists of a series capacitor shunted by Thyristor Controlled Reactor which is connected to switching devices like thyristors. Hence an overall control of network impedance is obtained by varying the angle of thyristors[2].

Steady state modelling of power system has been done using an iterative method for load flow using the Newton Raphson Load Flow Algorithm. Various electrical variables like voltage magnitude, phase angle and power flows have been evaluated using this method. This helped in understanding the effects of inclusion of FACTS devices in the system. The variables associated with the FACTS devices SVC and TCSC are combined with the bus voltage magnitude and angles of the existing network to achieve a unified iterative solution using Newton Raphson Method [1].

2. FACTS MODELS

The models for FACTS devices used in power flow are given below [4]:

2.1 SVC Firing Angle Model

SVC is basically used in this model to maintain a particular value of the voltage by performing reactive power compensation.

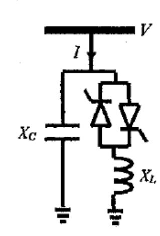


Fig. 1: SVC structure

Fig.1 represents an SVC structure comprising of a thyristor controlled reactor (TCR) and a fixed capacitor. The firing angle α of TCR is considered as a state variable. The variable TCR equivalent reactance, X_{Leq}, at fundamental frequency, is given by Equation (1) where X_L is reactance of thyristor and α is the thyristor firing angle [4].

$$X_{Leq} = X_L \frac{\pi}{2(\pi-\alpha)+\sin(2\alpha)} \qquad (1)$$

The SVC effective reactance is given by parallel combination of X_L and X_C (capacitive reactance) given by Equation (2)

$$X_{eq} = \frac{X_L X_c}{\frac{X_c}{\pi}(2(\pi-\alpha)+\sin(2\alpha))-X_L} \qquad (2)$$

The SVC equivalent susceptance as a function of firing angle is given by Equation (3)

$$B_{eq} = \frac{X_L - \frac{X_c}{\pi}(2(\pi-\alpha)+\sin(2\alpha))}{X_c X_L} \qquad (3)$$

SVC is considered as a continuously variable shunt susceptance that can be adjusted in order to achieve a specified voltage magnitude given in Fig. 2.

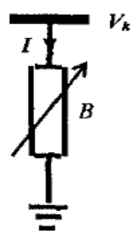


Fig. 2: Variable shunt susceptance

Reactive power ($Q_{k)}$ of variable shunt compensator is given by Equation (4)

$$Q_k = -{V_k}^2 B \qquad (4)$$

B is the shunt susceptance of the compensator connected at node k and V_k the nodal voltage.

If SVC is represented as the model given in Fig. 1 we can consider firing angle α to be a state variable. In that case the linearized equation then will be given by Equation (5) [4].

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \end{bmatrix}^i = \begin{bmatrix} 0 & 0 \\ 0 & \frac{\partial Q_k}{\partial \alpha} \end{bmatrix}^i \begin{bmatrix} \Delta\theta_k \\ \alpha \end{bmatrix}^i \qquad (5)$$

Where

$$\frac{\partial Q_k}{\partial \alpha} = \frac{2{V_k}^2}{X_L}(\cos(2\alpha)-1) \qquad (6)$$

At the end of iteration i, the firing angle α can be updated by Equation (7) and hence Beq can be calculated by Equation (3) [4].

$$\alpha^{i+1} = \alpha^i + \Delta\alpha^i \qquad (7)$$

2.2 TCSC Firing Angle Model

TCSC has often been used to increase the line power transfer as well as improve system stability [2].

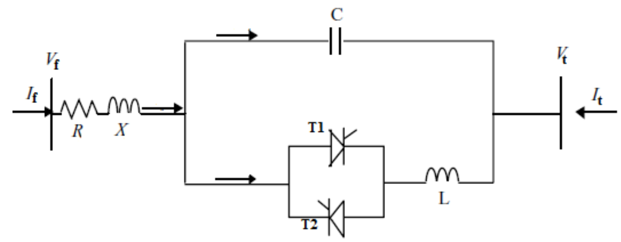
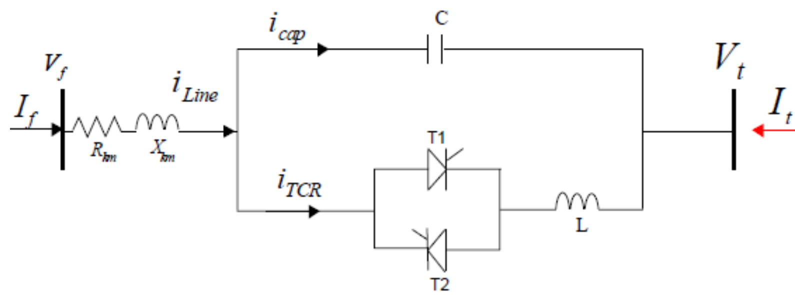


Fig. 3: Model of TCSC



The basic model of a TCSC is shown in Fig. 3. It comprises three components: capacitor banks C, bypass inductor L and bidirectional thyristors T1 and T2. The firing angles of the thyristors are controlled in order to adjust the TCSC reactance [3].

The operating principle of TCSC is that, it can control the active power flow for the line *l* (between bus- *f* and bus- *t* where the TCSC is installed).

The TCSC equivalent reactance is a function of the TCSC firing angle α is given by Equation (8) [3].

$$X_{TCSC} - X_C + K_1(2\sigma + \sin 2\sigma - \cos^2\sigma(\varpi\tan(\varpi\sigma) - \tan\sigma \qquad (8)$$

where $\sigma = \pi - \alpha$ and

$$X_{LC} = \frac{X_c X_L}{X_c - X_L}, K_1 = \frac{X_C + X_{LC}}{\pi}, K_2 = \frac{4(X_{LC})^2}{\pi X_L}, \varpi = \frac{1}{2\pi f\sqrt{LC}}$$

Where X_L, X_c, X_{LC} and X_{TCSC} are inductor reactance, capacitor reactance, combined capacitive and inductive reactance and reactance of TCSC respectively[3].

The real power P_{finj}^{TCSC} and reactive power Q_{finj}^{TCSC} injection at bus-*f* is expressed in Equations (9) and (10)

$$P_{finj}^{TCSC} = G_{ff}'' V_f^2 + (G_{ft}'' \cos\delta_{ft} + B_{ft}'' \sin\delta_{ft}) V_f V_t \qquad (9)$$

$$Q_{finj}^{TCSC} = -B_{ff}'' V_f^2 + (G_{ft}'' \sin\delta_{ft} - B_{ft}'' \cos\delta_{ft}) V_f V_t \qquad (10)$$

In the same way for bus t given by Equations (11) and (12),

$$P_{tinj}^{TCSC} = G_{tt}^{''}V_t^2 + (G_{tf}^{''}\cos\delta_{tf} + B_{tf}^{''}sin\delta_{tf})V_fV_t \quad (11)$$

$$Q_{tinj}^{TCSC} = -B_{tt}^{''}V_t^2 + \left(G_{tf}^{''}\sin\delta_{tf} - B_{tf}^{''}\cos\delta_{tf}\right)V_fV_t \quad (12)$$

where, $G_{ft}^{''} = G_{tf}^{''} = -G_{ff}^{''} = -G_{tt}^{''} = \frac{X_cR(2X+X_c)}{(R^2+X^2)(R^2+(X+X_c)^2)}$

$$B_{ft}^{''} = B_{tf}^{''} = -B_{ff}^{''} = -B_{tt}^{''} = \frac{X_c(R^2 - X(X + X_c))}{(R^2+X^2)(R^2+(X+X_c)^2)}$$

and Z(=R+jX) is the transmission line impedance, X_c is the magnitude of X_{TCSC} and $\delta_{ft} = \delta_f - \delta_t = \delta_{tf}$

Real power constraint of TCSC is given in Equation (13),

$$\Delta P_{ft} = P_{ft} - P_{ft}^{spec} = 0 \quad (13)$$

where P_{ft}^{spec} is the specified power flow of the line *l* and P_{ft} is the calculated power flow of the line *l*, and is expressed in Equation (14).

$$P_{ft} = G_{ff}^{'}V_f^2 + \left(G_{ft}^{'}\cos\delta_{ft} + B_{ft}^{'}sin\delta_{ft}\right)V_fV_t \quad (14)$$

where $G_{ff}^{'} = -G_{ft}^{'} = \frac{R}{(R^2+(X+X_c)^2)}$, $B_{ft}^{'} = \frac{(X+X_c)}{(R^2+(X+X_c)^2)}$

and $\delta_{ft} = \delta_f - \delta_t$

To implement TCSC in Newton Raphson Power Flow, we therefore assume that the TCSC is connected between bus-f and bus-t, and the real power flow in line f-t is controlled toP_{ft}^{spec}. As P_{ft}^{spec} is a constant for a particular control requirement, the real power flow in line f-t is calculated from Eq. (14**).** Consequently, in the presence of TCSC devices, the linearized power flow equations are combined with the linearized system equations related to the rest of the network. The linearized equations pertaining to TCSC are given below in Equation (15) [3].

$$F(X)^i = J^i.\Delta X^i \quad (15)$$

Where ΔX is the solution vector and J is the matrix of partial derivatives of *F(*X*)* with respect to X, that is the Jacobian matrix, and can thereby be calculated as given by the Equations (16) and(17) [3]:

$$F(X) = \begin{bmatrix}\Delta P_f\\ \Delta P_t\\ \Delta Q_f\\ \Delta Q_t\\ \Delta P_{ft}\end{bmatrix}, \Delta X = \begin{bmatrix}\Delta\delta_f\\ \Delta\delta_t\\ \Delta V_f\\ \Delta V_t\\ \Delta\alpha\end{bmatrix} \quad (16)$$

wher ΔP_f **,** ΔQ_f **,** ΔP_t , ΔQ_t are the active and reactive power mismatches at buses *f*, and *t* respectively and ΔP_{ft} is the real power flow mismatch for the line *l* (between bus-*f* and bus-*t* in which the TCSC is installed). $\Delta\alpha = \alpha_{i+1} - \alpha_i$ is the incremental change in the TCSC's firing angle (Subscript i indicates iteration number) [3].

$$J = \begin{bmatrix}\frac{\partial P_f}{\partial\delta_f} & \frac{\partial P_f}{\partial\delta_t} & \frac{\partial P_f}{\partial V_f} & \frac{\partial P_f}{\partial V_t} & \frac{\partial P_f}{\partial\alpha}\\ \frac{\partial P_t}{\partial\delta_f} & \frac{\partial P_t}{\partial\delta_t} & \frac{\partial P_t}{\partial V_f} & \frac{\partial P_t}{\partial V_t} & \frac{\partial P_t}{\partial\alpha}\\ \frac{\partial Q_f}{\partial\delta_f} & \frac{\partial Q_f}{\partial\delta_t} & \frac{\partial Q_f}{\partial V_f} & \frac{\partial Q_f}{\partial V_t} & \frac{\partial Q_f}{\partial\alpha}\\ \frac{\partial Q_t}{\partial\delta_f} & \frac{\partial Q_t}{\partial\delta_t} & \frac{\partial Q_t}{\partial V_f} & \frac{\partial Q_t}{\partial V_t} & \frac{\partial Q_t}{\partial\alpha}\\ \frac{\partial P_{ft}}{\partial\delta_f} & \frac{\partial P_{ft}}{\partial\delta_t} & \frac{\partial P_{ft}}{\partial V_f} & \frac{\partial P_{ft}}{\partial V_t} & \frac{\partial P_{ft}}{\partial\alpha}\end{bmatrix} \quad (17)$$

3. RESULTS AND DISCUSSIONS

An IEEE 5-bus system has been taken to understand power flow with FACTS devices. Data and results are based on 100 MVA base. The 5-bus system has been represented in the Fig. 4 below

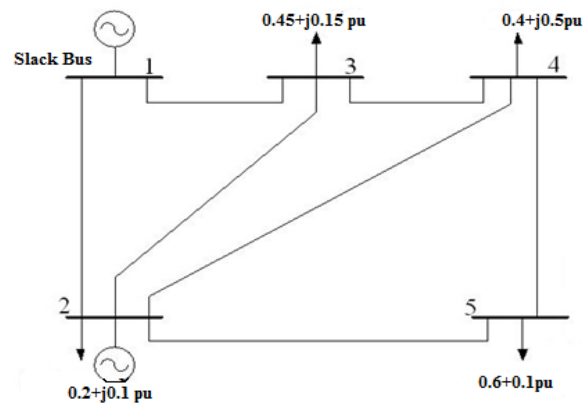


Fig. 4: IEEE 5-bus system

The result of load flow analysis for the base case has been given in the Table 1 below:

Table 1: Load Flow Analysis of a 5-Bus System

Bus	Voltage(p.u)	Angle(deg)
1	1.060	0
2	1.000	-2.062
3	0.987	-4.639
4	0.984	-4.959
5	0.971	-5.768

3.1 Results of load flow analysis with SVC

The SVC has been incorporated at bus-3 to maintain its voltage at 1p.u. SVC injects 20.47 MVar at bus -3. It is also observed that the overall voltage profile has been enhanced by the incorporation of SVC due to the reactive power compensation it has provided. The final value of firing angle of thyristors obtained is α = 148.803 degrees.

Table 2: Load Flow Analysis with SVC

Bus	Voltage(p.u)	Angle(deg)
1	1.060	0
2	1.000	-2.054

3	1.000	-4.840
4	0.994	-5.109
5	0.975	-5.800

A comparison of voltages with and without SVC has been illustrated in the Fig. 5 given below. The SVC parameters used are given in the Appendix-A.

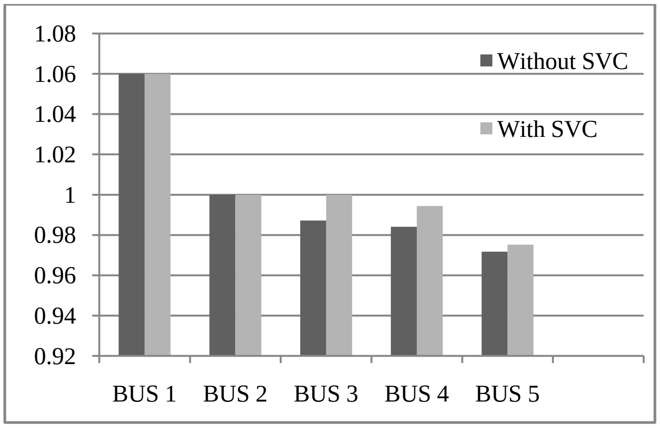


Fig. 5: Comparison of voltage levels

3.2 Results of load flow analysis with TCSC

TCSC has been incorporated between bus 3-4 to control the active power flowing between the line to 20 MW. The real power flow through the line in base case was 19.4 MW. The angle of TCSC obtained was 69.7324 deg. A redistribution of power is observed in this case as compared to the base case. The values of voltages and angles obtained in this case have been tabulated below in Table 3.The TCSC parameters have been given in Appendix-A.

Table 3: Load Flow analysis with TCSC

Bus	Voltage(p.u)	Angle(deg)
1	1.060	0
2	1.000	-2.053
3	0.987	-4.673
4	0.974	-4.905
5	0.972	-5.743

The Table 4 given below gives the real power flow(in MW) in various lines in the system in base case(case (a)) and in the case when TCSC is installed(case (b)) .

Table 4: Line Flows in case (a) and case(b)

Results	(a)	(b)
P1-2	89.4	89.1
P1-3	41.8	42.1
P2-3	24.5	24.9
P2-4	27.7	27.3
P3-4	19.4	20.0
P2-5	54.7	54.5
P4-5	6.6	6.8

4. CONCLUSION

With the help of a 5-bus system the effect of inclusion of FACTS devices has been explained in the paper and how the system parameters like voltage, power flow etc can be altered by use of FACTS devices has also been observed. Hence FACTS improves the flexibility of the system. Furthermore, it was observed with the help of the results that the SVC helped in overall improvement of the voltage profile of the system. The installation of TCSC helped in the control of active power flow in the line to a specified value. Therefore with the help of these devices a control of system parameters has been observed.

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APPENDIX-A

Data for SVC and TCSC

The values of the various parameters associated with SVC and TCSC have been given below:

SVC parameters

Capacitive Reactance X_c = 0.288 pu

Inductive Reactance X_L=1.07 pu

TCSC Parameters

Capacitive Reactance X_c = 9.372 e-3 pu

Inductive Reactance X_L=1.625 e-3 pu