Investigation of Power Flow Effect of Serial and Parallel FACTS Devices

H.Bakir, A.Ozturk, and S.Tosun

Abstract— **It is difficult to increase the capacity of the transmission system by establishing new lines or switching to a new voltage level to meet the rapidly rising electricity demand. Thus, there is an increased need for power flow controllers that can increase the capacity of the existing transmission line and control power flows in predetermined transmission corridors. For this reason, in recent years a new class of controllers has emerged called Flexible AC Transmission System (FACTS). It is very important to investigate the advantages of FACTS devices and to model these devices so that power systems can be operated in steady state. In this study, a comprehensive modeling of the most popular FACTS devices for power flow operation was performed. Power flow studies were first performed using the Newton Raphson method for an IEEE 5-bus power system without any FACTS devices. Then, different FACTS controllers were added to the system to perform power flow studies. As a result of the power flow studies performed, it was observed that the FACTS controllers increased the capacity of the existing transmission line and contributed to the voltage stability.**

Index Terms— **FACTS devices, newton-raphson, power flow, voltage stability.**

I. INTRODUCTION

THE ENERGY industry is undergoing a profound transformation around the world. Decreases in natural resources and increasing demand for electricity are some of the reasons for this change. Many studies have been done to maximize the capacity of existing transmission systems with high reliability and stability. The work carried out has pointed to the need for a power electronic based controller because of the slow response times of the controllers based on electromechanical technology and high maintenance costs [1]. Until recently, active and reactive power control in Alternating Current (AC) transmission networks was done by carefully adjusting the transmission line impedances to adjusting the generator excitation control and transformer step changes and terminal voltage.

FACTS technology has a critical role in transmission line planning. Because it creates new opportunities to control the power and increase the available capacity [2, 3].

Due to the increase in population and economy, there is a need to increase the flexibility, reliability and capacity of existing transmission systems. Due to changing market conditions, electrical utilities are looking for various ways to operate existing transmission lines at maximum limits. To achieve these goals, FACTS devices are used that can control the power flow and increase the transmission capacity [4]. FACTS devices commonly used in power systems are Static Var Compensator (SVC), Static Synchronous Compensator (STATCOM), Thyristor Controlled Series Compensator (TCSC), Static Synchronous Series Compensator (SSSC) and Unified Power Flow Controller (UPFC) [6].

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Manuscript received September 13, 2017; accepted January 08, 2018.
DOI: 10.17694/bajece.410204

II. POWER FLOW ANALYSIS

It is necessary to plan the operation of the power systems under the existing conditions and to carry out the load flow for the future situation. With load flow studies, voltage magnitudes and angles at each bar of the steady-state system can be obtained. Active and reactive power capacities are obtained in each line when the bus voltages and angles are calculated. Also losses in the lines can be calculated depending on the difference in the sender and receiver ends. The most preferred power flow method is the Newton-Raphson method because of its reliability in terms of convergence [7, 8].

A. Newton-Raphson Method

The Newton-Raphson method is one of the most common power flow solution methods that operate iteratively. This method is a classic method based on the Taylor series expansion and approaching well in a short time [5].

In Eq. (1) bus variables; n total number of bara i and j bara numbers [2].

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \quad (1)$$

In large scale power flow studies, the Newton Raphson power flow is the most successful because of its strong convergence feature. The Newton-Raphson power flow algorithm is expressed by Eq. (2) [10, 11].

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} - \begin{bmatrix}\Delta P/\Delta\theta & \Delta P/(\Delta V/V)\\ \Delta Q/\Delta\theta & \Delta Q/(\Delta V/V)\end{bmatrix}\begin{bmatrix}\Delta\theta\\ (\Delta V/V)\end{bmatrix} \quad (2)$$

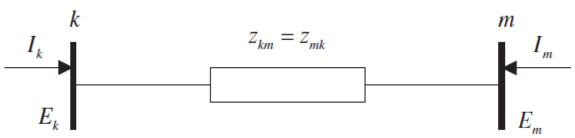

Fig. 1. Equivalent impedance

For the system in Fig. 1, the Jacobian matrix elements are constructed according to the following equations [8].

For k ≠ m;

$$\frac{\partial P_{k,1}}{\partial Q_{m,1}} = V_k V_m\,[G_{km}\sin(\theta_k - \theta_m) - B_{km}\cos(\theta_k - \theta_m)] \quad (3)$$

$$\frac{\partial P_{k,1}}{\frac{\partial V_{m,1}}{V_{m,1}}} = V_k V_m\,[G_{km}\cos(\theta_k - \theta_m) + B_{km}\sin(\theta_m - \theta_m)] \quad (4)$$

$$\frac{\partial Q_{k,1}}{\partial \theta_{m,1}} = -\frac{\partial P_{k,1}}{\frac{\partial V_{m,1}}{V_{m,1}}} \quad (5)$$

$$\frac{\partial Q_{k,1}}{\frac{\partial V_{m,1}}{V_{m,1}}} = \frac{\partial P_{k,1}}{\partial \theta_{m,1}} \quad (6)$$

For k=m;

$$\frac{\partial P_{k,1}}{\partial \theta_{k,1}} = -Q_k^{cal} - V_k^{2}B_{kk} \quad (7)$$

$$\frac{\partial Q_{k,1}}{\frac{\partial V_{k,1}}{V_{k,1}}} = P_k^{cal} + V_k^{2}G_{kk} \quad (8)$$

$$\frac{\partial P_{k,1}}{\partial \theta_{k,1}} = -Q_k^{cal} - V_k^{2}B_{kk} \quad (9)$$

$$\frac{\partial Q_{k,1}}{\frac{\partial V_{m,1}}{V_{m,1}}} = Q_k^{cal} - V_k^{2}B_{kk} \quad (10)$$

B. Test System Data

The IEEE-5 bus power system constructed using the Power System Analysis Toolbox (PSAT) program was shown in Fig 2. The base values of the system were set at 100 MVA and 100 KV.

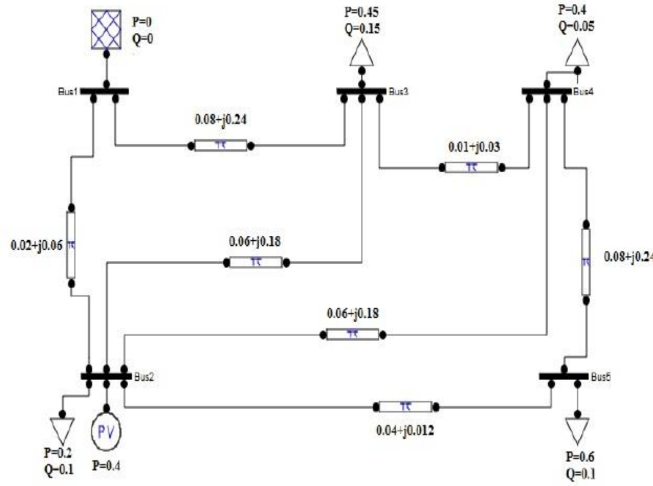

Fig. 2. IEEE-5 bus power system generated by PSAT

The generator and load data of the power system were shown in Table 1. The voltage and angle values obtained from the power flow for the IEEE 5-bus power system without FACTS were shown in Table 2.

TABLE I
GENERATOR AND LOAD DATA

Bus Type	Bus No	Voltage (p.u)	Active Power (p.u)	Reactive Power (p.u)
Slack	1	1.06	-	-
P-V	2	1.00	0.4	-
P-Q	3	-	0.45	0.15
P-Q	4	-	0.4	0.05
P-Q	5	-	0.6	0.1

TABLE II
VOLTAGE AND ANGLE VALUES WİTHOUT FACTS

Parameters	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5
VM (p.u.)	1.06	1	0.987	0.984	0.972
VA (degree)	0.00	-2.06	-4.640	-4.96	-5.770

III. POWER FLOW MODEL OF FACTS DEVİCES

A. Static Var Compensator (SVC) Power Flow Model

Two alternative power flow models are commonly used to assess the effect of the SVC controller on power system applications. These are the variable shunt susceptance model and the trigger angle model.

Variable shunt susceptance SVC model was shown in Fig. 3. The equivalent circuit shown in Fig. 3 is used to derive nonlinear power equations. In the equivalent circuit shown in Fig. 3, the SVC current equation was shown in Eq. (11). The reactive power equation of the SVC was shown in Eq. (12) [12].

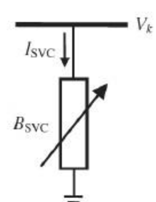

Fig. 3. Variable shunt susceptance SVC model

$$I_{SVC} = j\,B_{SVC}\,V_k \tag{11}$$

$$Q_{SVC} = -{V_k}^2\,B_{SVC} \tag{12}$$

At the end of each iteration, the variable shunt susceptance is updated according to Eq. (13) [8].

$$ {B_{SVC}}^{i} = {B_{SVC}}^{(i-1)} + \left\{\frac{\Delta B_{SVC}}{B_{SVC}}\right\} {B_{SVC}}^{(i-1)} \tag{13}$$

Another SVC model is the trigger angle model. An alternative SVC model, which circumvents the additional iterative process, consists in handling the thyristor controlled reactor trigger angle α as a state variable in the power flow formulation. The SVC susceptance is obtained by Eq. (14) [8].

$$Q_k = \frac{-{V_k}^2}{X_C X_L}\left\{ X_L - \frac{X_C}{\pi}\ [\,2(\pi - \alpha_{SVC}) + \sin(2\,\alpha_{SVC})\,]\right\} \tag{14}$$

Using the above equation, the linearized SVC equation is expressed by Eq. (15) [12].

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \end{bmatrix}(i) = \begin{bmatrix} 0 & 0 \\ 0 & \dfrac{2{V_k}^2}{\pi X_L}[\cos(2\alpha_{SVC}) - 1] \end{bmatrix}(i) \begin{bmatrix} \Delta Q_k \\ \Delta \alpha_{SVC} \end{bmatrix}(i) \tag{15}$$

The trigger angle is updated according to equation (16) at the end of each iteration [12].

$$ {\alpha_{SVC}}^{(i)} = {\alpha_{SVC}}^{(i-1)} + \Delta {\alpha_{SVC}}^{(i)} \tag{16}$$

B. Thyristor Controlled Series Compensator (TCSC) Power Flow Model

Two alternative power flow models have been introduced to assess the effect of the TCSC controller in power system applications. The simple TCSC model uses the concept of variable series reactance. In this model, the series reactance is automatically adjusted to provide active power flow within the specified limits. The advanced model uses a nonlinear reactance trigger angle graph. In this model, the TCSC trigger angle is selected as the state variable in the Newton Raphson power flow solution [13].

The TCSC power flow model presented in this section is based on the simple concept of variable series reactance. The value is automatically set to limit the power flow to a certain value. The amount of reactance is determined effectively using Newton's method. Thyristor controlled series compensator equivalent circuit was shown in Fig. 4 [8].

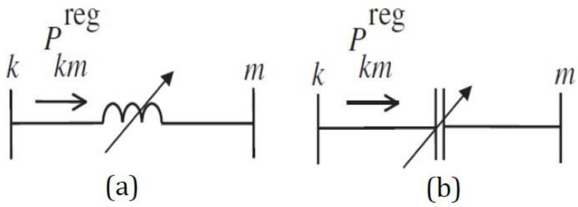

Fig. 4. Thyristor controlled series compensator equivalent circuit (a) inductive and (b) capacitive regions

The transfer matrix of the variable series compensator was shown in Eq. (17) [14].

$$\begin{bmatrix} I_k \\ I_m \end{bmatrix} = \begin{bmatrix} jB_{kk} & jB_{km} \\ jB_{mk} & jB_{mm} \end{bmatrix}\begin{bmatrix} V_k \\ V_m \end{bmatrix} \tag{17}$$

The equations for inductive operation were shown in Eq. (18) and (19). For capacitive operation, the signals are inverted [14].

$$B_{kk} = B_{mm} = -\frac{1}{X_{TCSC}} \tag{18}$$

$$B_{km} = B_{mk} = \frac{1}{X_{TCSC}} \tag{19}$$

The active and reactive power equations were shown in equations (20) and (21) [8].

$$P_k = V_k V_m\,B_{km} \sin(\theta_k - \theta_m) \tag{20}$$

$$Q_k = -{V_k}^2 B_{kk} - V_k V_m B_{km} \cos(\theta_k - \theta_m) \tag{21}$$

The state variable X_{TCSC} is updated at the end of each iterative step as in Eq. (22) [8].

$$ {X_{TCSC}}^{(i)} = {X_{TCSC}}^{(i-1)} + \ \{\Delta X_{TCSC}/X_{TCSC}\}(i)\ {X_{TCSC}}^{(i-1)} \tag{22}$$

The trigger angle model presented in this section uses the concept of equivalent series reactance to represent TCSC. After the reactance value is determined using the Newton method, the angle can be calculated. However, this calculation requires an iterative solution since the TCSC reactance value and the trigger angle $\alpha_{\ TCSC}$ are nonlinearly related [15].

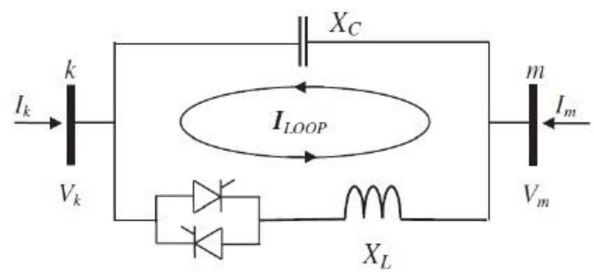

Fig. 5. TCSC Equivalent Circuit

The equivalent reactance of TCSC shown in Fig. 5 is calculated according to Eq. (23) [8].

$$\begin{aligned} X_{TCSC} = {} & -X_C + C_1\{2\,(\pi - \alpha) + \sin[\,2\,(\pi - \alpha)]\} \\ & -C_2 \cos^2(\pi - \alpha)\{\omega \tan[\omega(\pi - \alpha)] - \tan(\pi - \alpha)\} \end{aligned} \tag{23}$$

$$C_1 = \frac{X_C + X_{LC}}{\pi} \tag{24}$$

$$C_2 = \frac{4{X_{LC}}^2}{X_L \pi} \tag{25}$$

$$X_{LC} = \frac{X_C X_L}{X_C - X_L} \tag{26}$$

 ISSN: 2147-284X

The active and reactive power equations of TCSC are as follows [14].

$$P_k = V_k V_m B_{km} sin(\theta_k - \theta_m) \quad (28)$$

$$Q_k = -V_k^2 B_{kk} - V_k V_m B_{km} cos(\theta_k - \theta_m) \quad (29)$$

$$B_{kk} = -B_{km} = B_{TCSC} \quad (30)$$

C. Static Synchronous Compensator (STATCOM) Power Flow Model

The static synchronous compensator (STATCOM) is represented by a synchronous voltage source with minimum and maximum voltage magnitude limits. The synchronous voltage source represents the fundamental fourier series component of the switched voltage waveform at the AC converter terminal of STATCOM [9]. The STATCOM equivalent circuit shown in Figure 6 is used to obtain the mathematical model of the controller to be included in power flow algorithms [16].

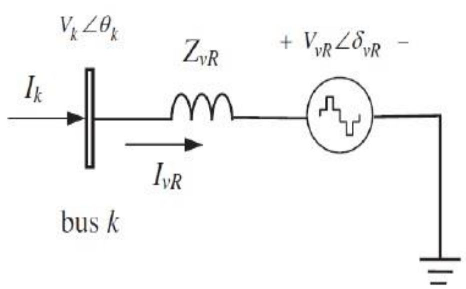

Fig. 6. STATCOM Equivalent Circuit

Based on the shunt connection shown in Figure 6, power flow equations for STATCOM can be written following.

$$E_{vR} = V_{vR}(cos\,\delta_{vR} + j\;sin\,\delta_{vR}) \quad (31)$$

$$S_{vR} = V_{vR} I_{vR}^* = V_{vR}\, Y_{vR}^* \,(V_{vR}^* - V_k^*) \quad (32)$$

The active and reactive power equations for the converter and k bus are obtained as follows.

$$P_{vR} = V_{vR}^2 G_{vR} + V_{vR} V_k \,[\, G_{vR} \cos(\delta_{vR} - \theta_k) + B_{vR}\, \sin(\delta_{vR} - \theta_k)\,] \quad (33)$$

$$Q_{vR} = -V_{vR}^2 B_{vR} + V_{vR} V_k \,[\, G_{vR} - B_{vR}\, cos(\delta_{vR} - \theta_k)] \quad (34)$$

$$P_k = V_k^2 G_{vR} + V_k V_{vR} \,[\, G_{vR} \cos(\theta_k - \delta_{vR}) + B_{vR}\, \sin(\theta_k - \delta_{vR})] \quad (35)$$

$$Q_k = -V_k^2 B_{vR} + V_k V_{vR} \,[\, G_{vR} \sin(\theta_k - \delta_{vR}) - B_{vR}\, \cos(\theta_k - \delta_{vR})] \quad (36)$$

IV. SIMULATION RESULTS

A. Power Flow With SVC

SVC was added to the IEEE-5 bus power system to examine the voltage control capability of the SVC controller. The power system with SVC controller was shown in Fig. 7. Before running the simulation, the amplitude value of the slack bus was set to 1.06 p.u and the amplitude of the PV bus was set to 1 p.u. SVC was placed in the Bus-3 to hold the bus voltage at 1 p.u. The inductive reactance value of the SVC was 0.288 p.u, and the capacitive reactance value was 1.07 p.u. The SVC trigger angle was initially set to 140 degrees. This value allows the SVC to operate in the capacitive region. The voltage magnitude and phase angle values obtained as a result of the power flow was shown in Table 3.

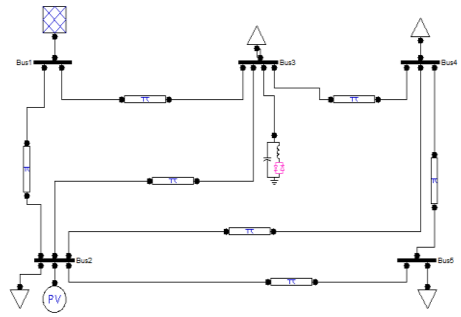

Fig. 7. IEEE-5 bus power system with SVC

TABLE III
VOLTAGE AND ANGLE VALUES OBTAINED FROM LOAD FLOW OF SYSTEM INCLUDING SVC

Parameters	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5
VM (p.u.)	1.06	1	1	0.994	0.9752
VA (degree)	0.00	-2.053	-4.837	-5.107	-5.797

B. Power Flow With TCSC

As shown in Fig. 8, the IEEE-5 bus power system was modified to include the TCSC to compensate the transmission line between Bus 3 and Bus 4. The TCSC was added to the transmission line to control the active power flowing from Bus 3 to Bus 4. The initial value of the TCSC was set to be equal to % 50 of the inductive reactance value of the transmission line. The TCSC initial capacitive reactance value was 0.015 p.u and the triggering angle was 145 degrees.

As a result of the power flow, it was observed that the TCSC sets the active power value of the transmission line 3-4 to 21 MW. The voltage magnitude and phase angle values obtained from the power flow result for the system in Fig. 8 were shown in Table 4.

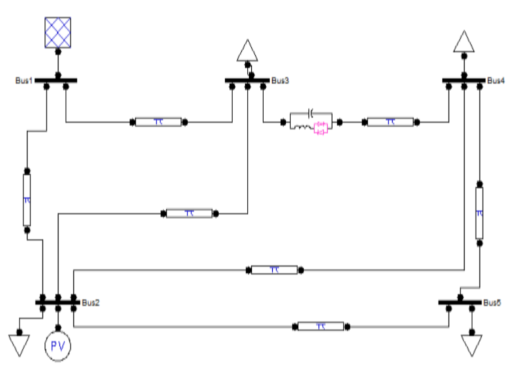

Fig. 8. IEEE-5 bus power system with TCSC

TABLE IV
VOLTAGE AND ANGLE VALUES OBTAINED FROM LOAD FLOW OF SYSTEM INCLUDING TCSC

Parameters	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5
VM (p.u.)	1.06	1	0.987	0.988	0.984
VA (degree)	0	-2.04	-4.72	-4.46	-4.81

C. Power Flow With STATCOM

STATCOM was added to Bus 3 of the IEEE-5 bus power system in order to maintain the node voltage at 1 p.u. The initial source voltage of STATCOM was 1 p.u, the phase angle was 0 degree and the transformer reactivity was 10 p.u.

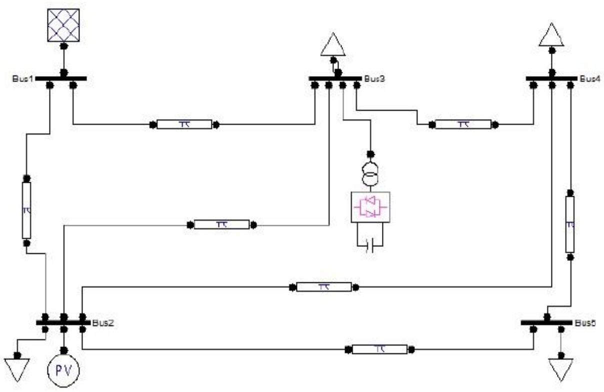

Fig. 9. IEEE-5 bus power system with STATCOM

It was observed from the power flow results that STATCOM produced 20.5 MVAR of power to hold the voltage at 1 p.u in Bus 3. The results in Table 5 showed that the use of STATCOM could improve the voltage profile.

TABLE V
VOLTAGE AND ANGLE VALUES OBTAINED FROM LOAD FLOW OF SYSTEM INCLUDING STATCOM

Parameters	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5
VM (p.u.)	1.06	1	1	0.994	0.974
VA (degree)	0	-2.05	-4.82	-5.11	-5.81

V. CONCLUSION

In this study, the power flow of the IEEE-5 bus power system using the Newton-Raphson method was performed for situations with and without FACTS devices. Serial and parallel FACTS devices were added to the power system and serial and parallel compensation was performed. STATCOM and SVC from the parallel FACTS controllers were added to the system. In addition, TCSC is added to the system from serial FACTS controllers.

From the simulation results it is observed that parallel FACTS devices have an important role in voltage control and serial FACTS devices have an important role in increasing transmission line capacity. In series compensation, the line impedance is changed, which means that the net impedance is reduced and thus the transmittable active power is increased. In shunt compensation, it has been observed that even reactive current is injected to adjust the voltage at the connection point.

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