Power Flow Studies with Facts Devices

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Abstract - The electric power industry is undergoing the most profound technical, economic and organizational changes since, its inception some one hundred years ago. In countries like India with fast growing demand of electric power it is difficult to extend the transmission system in time by either building new lines or by introduction of a new voltage level. Power is therefore transmitted through weak system leading to unsatisfactory quality and reliability of power supply. To achieve satisfactory quality and operational reliability of power, it has become clear that more efficient utilization and control of the existing transmission system infrastructure is required. Improved utilization of the existing power system is provided through the application of advanced control technologies. Power electronics based equipment, or Flexible AC Transmission Systems (FACTS), provide proven technical solutions to address these new operating challenges which are being presented today. Considering the practical application of the FACTS devices, it is of importance to investigate the benefits as well as model these devices for power system steady state operation.

In this paper, the modeling of series FACTS devices for power flow studies and the role of that modeling in the study of FACTS devices for power flow control was discussed. A number of power flow study programs were developed in order to model various types of FACTS devices. The effectiveness of modeling and convergence was tested with various IEEE bus systems without any FACTS devices and further analyzed it with different series and shunt FACTS devices. The nonlinear load flow equations are solved using Newton-Raphson technique. Programming of the power flow studies was carried out by using MATLAB.

Keywords: ***FACTS, Power Flow Control, Thyristor Controlled Series Capacitor (TCSC), Static Synchronous Series Compensator (SSSC), Static VAR Compensator (SVC), Static Synchronous Compensator (STATCOM).***

I. INTRODUCTION

Mainly two reasons motivate the use of power flow control, one is ever increasing demand of electricity and other is deregulation of power supply industry. In order to meet the rising demand of electricity while simultaneously maintaining acceptable levels of network reliability and stability, either new power lines are added to the system or use the existing power system more efficiently. Former one is an impractical one because it is a very time consuming process and sometimes it is an impossible task due to an environmental reasons. Latter one gives an attractive solution to control the power flow. Improvement in utilization of existing power system introduces the concept of power electronic based equipment i.e., FACTS controllers. Recent development in high power electronic devices makes it possible to control the power flows in the network.

FACTS devices are introduced either in series or in shunt in transmission line to enhance its power transfer capability. FACTS devices are also used to control and utilize the flexibility and system performance by controlling the main parameters namely voltage, phase angle and impedance, which is affecting ac power transmission. In order to measure the effectiveness of these FACTS devices, we need to develop an efficient study tool. For this tool, we need to modify the existing program for load flow studies to incorporate these devices. In load flow methods, Newton Raphson (NR) method has very strong convergence characteristics. So, in this paper NR method is used to incorporate these FACTS device to control the power flow in the lines [1].

We have two methods of solution for incorporate these FACTS device in NR method, those are i) Simultaneous or unified method ii) Sequential or alternating method. In simultaneous method, the equations corresponding to the FACTS device specification and the conventional load flow equations are combined into one set of nonlinear algebraic equations and solved simultaneously. In this method significant modifications are done in existing program. In sequential method, the equations corresponding to the FACTS device specification and the conventional load flow equations are solved separately and sequentially. In this method minor modifications are done in existing program. Among these, simultaneous method has very strong convergence characteristics i.e., convergence is attained within the half number of iterations required for the sequential method. In this paper, simultaneous method is used for solving the power flow equations in NR method. This paper presents a steady state models of different FACTS devices (TCSC, SSSC, SVC, STATCOM) which can be combined in NR load flow algorithm [2,3].

II. MODELING OF POWER SYSTEM WITH TCSC

TCSC is a variable impedance type series compensator, which consist of series capacitor bank in parallel with the thyristor controlled reactor(TCR). It provides a smoothly variable series capacitive reactance to satisfy specified active power flow across the TCSC. The equivalent reactance of TCSC device is shown in Figure 1. The reactance of TCSC is a parallel combination of series capacitive reactance and TCR reactance. The fundamental frequency equivalent reactance X_{TCSC} of TCSC is [4]

$$X_{TCSC} = -X_C + C_1(2(\pi-\alpha) + \sin(2(\pi-\alpha))) - C_2 cos^2(\pi-\alpha)\,(\varpi\tan(\varpi(\pi-\alpha)) - \tan(\pi-\alpha)) \quad (1)$$

Where

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

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

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

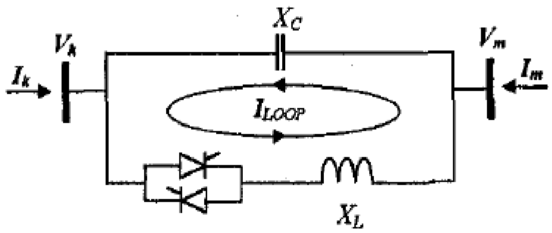

Figure 1 Equivalent circuit of TCSC

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

$$\begin{bmatrix} I_k \\ I_m \end{bmatrix} = \begin{bmatrix} jB_{kk} & jB_{km} \\ jB_{mk} & jB_{mm} \end{bmatrix} \begin{bmatrix} V_k \\ V_m \end{bmatrix} (2)$$

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

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

The active and reactive power equations of TCSC at node k are

$$P_k = -V_k V_m B_{TCSC} \sin(\theta_k - \theta_m) (3)$$

$$Q_k = -V_k^2 B_{TCSC} + V_k V_m B_{TCSC} \cos(\theta_k - \theta_m) \quad (4)$$

Exchange the subscripts k and m for power equations at node m.

The set of linearized power flow equations when the TCSC controls the real power flow from node k to m is

$$\begin{bmatrix} \Delta P_k \\ \Delta P_m \\ \Delta Q_k \\ \Delta Q_m \\ \Delta P_{km}^{\alpha} \end{bmatrix}^i = \begin{bmatrix} \frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial \theta_m} & \frac{\partial P_k}{\partial V_k} V_k & \frac{\partial P_k}{\partial V_m} V_m & \frac{\partial P_k}{\partial \alpha} \\ \frac{\partial P_m}{\partial \theta_k} & \frac{\partial P_m}{\partial \theta_m} & \frac{\partial P_m}{\partial V_k} V_k & \frac{\partial P_m}{\partial V_m} V_m & \frac{\partial P_m}{\partial \alpha} \\ \frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial \theta_m} & \frac{\partial Q_k}{\partial V_k} V_k & \frac{\partial Q_k}{\partial V_m} V_m & \frac{\partial Q_k}{\partial \alpha} \\ \frac{\partial Q_m}{\partial \theta_k} & \frac{\partial Q_m}{\partial \theta_m} & \frac{\partial Q_m}{\partial V_k} V_k & \frac{\partial Q_m}{\partial V_m} V_m & \frac{\partial Q_m}{\partial \alpha} \\ \frac{\partial P_{km}^{\alpha}}{\partial \theta_k} & \frac{\partial P_{km}^{\alpha}}{\partial \theta_m} & \frac{\partial P_{km}^{\alpha}}{\partial V_k} V_k & \frac{\partial P_{km}^{\alpha}}{\partial V_m} V_m & \frac{\partial P_{km}^{\alpha}}{\partial \alpha} \end{bmatrix}^i \begin{bmatrix} \Delta \theta_k \\ \Delta \theta_m \\ \frac{\Delta V_k}{V_k} \\ \frac{\Delta V_m}{V_m} \\ \Delta \alpha \end{bmatrix}^i \quad (5)$$

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

III. MODELING OF POWER SYSTEM WITH SSSC

SSSC is a switching converter type series compensator, consist of voltage source converter. Active power flow control is the main objective for the addition of SSSC in the line. It not only regulates the real power but also reactive power or nodal voltage magnitudes. It produces a fundamental frequency sinusoidal voltage with controllable magnitude and phase angle to satisfy specified active and reactive power flow along a compensated line. The SSSC is modeled as voltage source with variable magnitude and phase angle and the equivalent circuit of SSSC is shown in figure 2 [5].

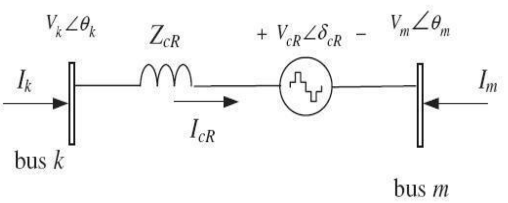

Figure 2 Equivalent circuit of SSSC

The series voltage source of SSSC

$$E_{cR} = V_{cR}(cos\delta_{cR} + j sin\delta_{cR}) \quad (6)$$

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 SSSC active and reactive power equations at node k is

$$P_k = V_k^2 G_{kk} + V_k V_m [G_{km} cos(\theta_k - \theta_m) + B_{km} sin(\theta_k - \theta_m)] + V_k V_{cR}[G_{km} cos(\theta_k - \delta_{cR}) + B_{km} sin(\theta_k - \delta_{cR})] \quad (7)$$

$$Q_k = -V_k^2 B_{kk} + V_k V_m[G_{km}sin(\theta_k - \theta_m) - B_{km}cos(\theta_k - \theta_m)] + V_k V_{cR}[G_{km}sin(\theta_k - \delta_{cR}) - B_{km}cos(\theta_k - \delta_{cR})] \quad (8)$$

And active and reactive power equations for voltage source is

$$P_{cR} = V_{cR}^2 G_{mm} + V_k V_m[G_{mm}cos(\delta_{cR} - \theta_k) + B_{km}sin(\delta_{cR} - \theta_k)] + V_m V_{cR}[G_{mm}cos(\delta_{cR} - \theta_m) + B_{mm}sin(\delta_{cR} - \theta_m)] \quad (9)$$

$$Q_{cR} = -V_{cR}^2 B_{mm} + V_k V_{cR}[G_{km}sin(\delta_{cR} - \theta_k) - B_{km}cos(\delta_{cR} - \theta_k)] + V_m V_{cR}[G_{mm}sin(\delta_{cR} - \theta_m) - B_{mm}cos(\delta_{cR} - \theta_m)] \quad (10)$$

The set of linearized power flow equations when the SSSC controls the power flow from node k to m is

$$\begin{bmatrix} \Delta P_k \\ \Delta P_m \\ \Delta Q_k \\ \Delta Q_m \\ \Delta P_{km} \\ \Delta Q_{km} \end{bmatrix}^i = \begin{bmatrix} \frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial \theta_m} & \frac{\partial P_k}{\partial V_k}V_k & \frac{\partial P_k}{\partial V_m}V_m & \frac{\partial P_k}{\partial \delta_{cR}} & \frac{\partial P_k}{\partial V_{cR}}V_{cR} \\ \frac{\partial P_m}{\partial \theta_k} & \frac{\partial P_m}{\partial \theta_m} & \frac{\partial P_m}{\partial V_k}V_k & \frac{\partial P_m}{\partial V_m}V_m & \frac{\partial P_m}{\partial \delta_{cR}} & \frac{\partial P_m}{\partial V_{cR}}V_{cR} \\ \frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial \theta_m} & \frac{\partial Q_k}{\partial V_k}V_k & \frac{\partial Q_k}{\partial V_m}V_m & \frac{\partial Q_k}{\partial \delta_{cR}} & \frac{\partial Q_k}{\partial V_{cR}}V_{cR} \\ \frac{\partial Q_m}{\partial \theta_k} & \frac{\partial Q_m}{\partial \theta_m} & \frac{\partial Q_m}{\partial V_k}V_k & \frac{\partial Q_m}{\partial V_m}V_m & \frac{\partial Q_m}{\partial \delta_{cR}} & \frac{\partial Q_m}{\partial V_{cR}}V_{cR} \\ \frac{\partial P_{km}}{\partial \theta_k} & \frac{\partial P_{km}}{\partial \theta_m} & \frac{\partial P_{km}}{\partial V_k}V_k & \frac{\partial P_{km}}{\partial V_m}V_m & \frac{\partial P_{km}}{\partial \delta_{cR}} & \frac{\partial P_{km}}{\partial V_{cR}}V_{cR} \\ \frac{\partial Q_{km}}{\partial \theta_k} & \frac{\partial Q_{km}}{\partial \theta_m} & \frac{\partial Q_{km}}{\partial V_k}V_k & \frac{\partial Q_{km}}{\partial V_m}V_m & \frac{\partial Q_{km}}{\partial \delta_{cR}} & \frac{\partial Q_{km}}{\partial V_{cR}}V_{cR} \end{bmatrix}^i \begin{bmatrix} \Delta\theta_k \\ \Delta\theta_m \\ \frac{\Delta V_k}{V_k} \\ \frac{\Delta V_m}{V_m} \\ \Delta\delta_{cR} \\ \frac{\Delta V_{cR}}{V_{cR}} \end{bmatrix}^i \quad (11)$$

IV. MODELING OF POWER SYSTEM WITH SVC

Static VAR compensators SVC's ,the most important FACTS devices, have been used for a number of years to improve transmission line economics by resolving dynamic voltage problems. Accuracy, availability and fast response enable SVC's to provide high performance steady state and transient voltage control compared with the classical shunt compensaton [6]. They are laso used to dampen power swings, improve transient stability, and reduce system losses by optimized reactive power control.

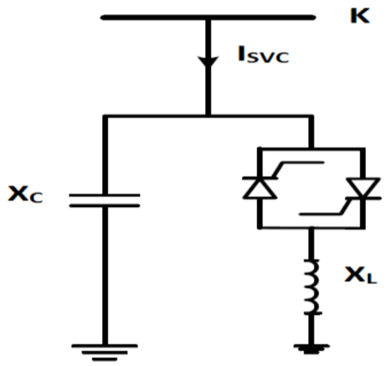

Figure 3 Firing angle model of SVC

Typically an SVC comprises a bank of individually switched capacitors in conjunction with a thyristor controlled air- or iron-cored reactor. By means of phase angle modulation switched by the thyristor, the reactor may be variably switched into the circuit, and so provide a continously variable MVAr injection (or absorption) to the electrical network. Modelling of SVC should represent the fundamental-frequency, steady-state, and balanced performance.

$$I_{SVC} = - j\, B_{SVC} V_K \quad (12)$$

The fundamental frequency TCR equivalent reactance X_{TCR}

$$X_{TCR} = (\pi X_L) / (\sigma - \text{Sin}\ \sigma) \quad (13)$$

Where $\sigma = 2(\pi - \alpha)$

SVC effective reactance X_{SVC} is determined by the parallel combination of X_C and X_{TCR}

$$X_{SVC} = (\pi X_L X_C)/(X_C[2(\pi - \alpha) + \text{Sin}\ 2\alpha] - \pi X_L) \quad (14)$$

Where $X_C = 1/wC$

$$Q_K = -V_K^2\{X_C[2(\pi - \alpha) + \text{Sin}\ 2\alpha] - \pi X_L\}/(\pi X_L X_C) \quad (15)$$

The proposed model takes firing angle as the state variable in power flow formulation. From equation (15) the SVC linearized power flow equation can be written as

$$\begin{bmatrix} \Delta P_K \\ \Delta Q_K \end{bmatrix}^{(i)} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{2V_K^2}{\pi X_L}[\text{Cos}(2\alpha - 1)] \end{bmatrix}^{(i)} \begin{bmatrix} \Delta\ \theta_K \\ \Delta\ \alpha \end{bmatrix}^{(i)} \quad (16)$$

At the end of iteration i, the variable firing angle α is updated according to

$$\alpha^{(i)} = \alpha^{(i-1)} + \Delta\ \alpha^{(i)} \quad (17)$$

V. MODELING OF POWER SYSTEM WITH STATCOM

The STATCOM is a FACTS controller based on voltage sourced convertor (VSC). As a VSC generate a synchronous voltage of fundamental frequency, controllable magnitude and phase angle [7,8]. If a VSC is shunt-connected to a system via coupling transformer resulting STATCOM can be as shown in figure5

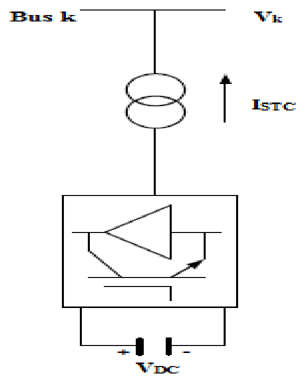

Figure 4 Equivalent circuit of STATCOM

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The active and reactive power for the STATCOM at node K respectively are:

$$P_{STC}=G_{SC}\{(e^2_{STC}+f^2_{STC})-(e_{STC}e_K+f_{STC}f_K)\}+B_{SC}(e_{STC}f_K-f_{STC}e_K) \quad (18)$$

$$Q_{STC}=G_{SC}\{(e_{STC}+e_k)+B_{SC}(-e^2_{STC}-f^2_{STC}+e_{STC}e_K-f_{STC}f_K) \quad (19)$$

The solution of the combined system of non-linear equation is carried out by iteration using the full Newton-raphson method. The jacobian used in conventional power flow is suitably extended to take account of the new element contributed by the STATCOM. The set of linearized power flow equation for the system is

$$\begin{bmatrix} \Delta P_K \\ \Delta |V_K|^2 \\ \Delta P_{STC} \\ \Delta Q_{STC} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_K}{\partial e_K} & \frac{\partial P_K}{\partial e_K} & \frac{\partial P_k}{\partial e_{STC}} & \frac{\partial P_k}{\partial f_{STC}} \\ \frac{\partial |V_K{}^2|}{\partial e_K} & \frac{\partial |V_K{}^2|}{\partial f_K} & 0 & 0 \\ \frac{\partial P_{STC}}{\partial e_K} & \frac{\partial P_{STC}}{\partial f_K} & \frac{\partial P_{STC}}{\partial e_{STC}} & \frac{\partial P_{STC}}{\partial f_{STC}} \\ \frac{\partial Q_{STC}}{\partial e_K} & \frac{\partial Q_{STC}}{\partial f_K} & \frac{\partial Q_{STC}}{\partial e_{STC}} & \frac{\partial Q_{STC}}{\partial f_{STC}} \end{bmatrix} \begin{bmatrix} \Delta e_K \\ \Delta f_K \\ \Delta e_{STC} \\ \Delta f_{STC} \end{bmatrix} \quad (20)$$

VI. Test Case And Simulation

IEEE 30-bus test network [9,10] is tested with TCSC, SSSC and separately, IEEE 24-Bus is tested with SVC and STATCOM, to investigate the behavior of the devices in the network.

Load flow program is carried out on IEEE 30 bus test system for 3 cases. The first case is the base case, without introducing any FACTS-devices. Other Cases are the same network with the addition of TCSC, SSSC respectively. The results of load flow without introducing any FACTS, with TCSC, SSSC are shown in Table 1,2.

The original 30-bus network is modified to introduce one TCSC to compensate the line connected between bus 29 and bus 30, to maintain the active power at 0.05 p.u. The extra bus is added to enable the connection of TCSC. The value of the fundamental frequency TCSC equivalent reactance required to achieve the 0.05 pu active flow through the TCSC is -0.4922. The system active and reactive power loss are 0.2102 and 0.2207 respectively. The original 30-bus network is modified to introduce one SSSC to compensate the transmission line connected between bus29 and bus 30, to maintain the active power at 0.05 p.u. and reactive power at 0.075 p.u.

The extra bus is added to enable the connection of SSSC. The power flow solution is outlined in Tables 3a and 3b. The value of the magnitude and phase angle of voltage source required to achieve the 0.05 p.u. active flow and 0.0075 p.u reactive flow through the SSSC are 0.0065 and -116.9056 respectively. The system active and reactive power loss are 0.2100 and 0.2216 respectively.

Load flow results by incorporating SVC and STATCOM in IEEE 14 bus system were presented in Table 3.

Table 1: Bus results with series compensation

Bus No.	Power Flow without FACTS		Power Flow with TCSC		Power Flow with SSSC	
	Voltage magnitude V_x in p.u	Phase angle in p.u	Voltage magnitude V_x in p.u	Phase angle in p.u	Voltage magnitude V_x in p.u	Phase angle in p.u
1	1.06	0	1.05	0	1.05	0
2	1.045	-5.0559	1.045	-6.9371	1.045	-6.9367
3	1.01	-9.8521	1.050	-15.8427	1.050	-15.8419
4	1.082	-18.3380	1.050	-16.8439	1.050	-16.8435
5	1.010	-13.6092	1.010	-15.6703	1.010	-15.6696
6	1.071	-15.0368	1.010	-13.2860	1.010	-13.2849
7	1.0348	-15.1444	1.0027	-14.3551	1.0027	-14.3542
8	1.0196	-16.0721	1.0108	-12.5455	1.0108	-12.5443
9	1.0413	-15.0368	1.0205	-15.8427	1.0205	-15.8419
10	1.0712	-15.4907	1.0113	-17.5849	1.0113	-17.5843
11	1.0080	-8.7052	1.0212	-8.9099	1.0212	-8.9092
12	0.9963	-12.0206	1.0192	-16.8439	1.0192	-16.8435
13	1.0000	-10.0109	1.0148	-10.7557	1.0148	-10.7548
14	1.0255	-15.9847	1.0043	-17.7874	1.0043	-17.7870
15	1.0200	-16.0924	1.0001	-17.8815	1.0001	-17.8810
16	1.0247	-15.7482	1.0084	-17.4543	1.0084	-17.4539
17	1.0156	-16.1897	1.0049	-17.7687	1.0049	-17.7682
18	1.0021	-16.8039	0.9915	-18.5231	0.9914	-18.5226
19	0.9948	-17.0293	0.9896	-18.6984	0.9896	-18.6979
20	1.0113	-16.8551	0.9942	-18.4815	0.9942	-18.4810
21	1.0103	-16.4859	0.9983	-18.0569	0.9983	-18.0562
22	1.0119	-16.4563	0.9987	-18.0412	0.9987	-18.0404
23	1.0141	-16.5185	0.9902	18.2722	0.9901	-18.2712
24	1.0148	-16.7285	0.9857	-18.4215	0.9856	-18.4198

25	1.0444	-16.1274	0.9822	-17.9341	0.9820	-17.9298
26	1.0272	-16.5251	0.9639	-18.3847	0.9637	-18.3806
27	1.0180	-7.2251	0.9890	-17.5535	0.9887	-17.3475
28	1.0040	-10.6714	1.0071	-13.1724	1.0071	-13.1702
29	1.0523	-16.6107	0.9688	-19.1010	0.9680	-18.6876
30	1.0414	-17.4122	0.9563	-19.0127	0.9562	-19.5847

TABLE2: Line Results with Series Compensation

S.No.	From bus/ to bus (x-y)	Power Flow without FACTS		Power Flow with TCSC		Power Flow with SSSC	
		Active Power (Pxy) in p.u	Reactive Power (Qxy) in p.u	Active Power (Pxy) in p.u	Reactive Power (Qxy) in p.u	Active Power (Pxy) in p.u	Reactive Power (Qxy) in p.u
1	1-2	1.6336	-0.2236	2.1439	-0.1539	2.1437	-0.5138
2	1-8	0.7579	0.0786	0.9004	-0.0089	0.9003	-0.0089
3	2-5	0.8044	0.0294	0.8206	0.0281	0.8205	0.0281
4	2-11	0.4182	0.0774	0.5972	0.0142	0.5971	0.0123
5	2-13	0.5479	0.0879	0.4250	0.0354	0.4249	0.0355
6	13-3	0.1252	0.2002	0.000	-0.1449	0.0000	0.1492
7	3-28	0.0748	-0.0147	0.0049	-0.0379	0.0050	-0.0381
8	7-5	0.3000	-0.2262	0.1524	-0.1315	0.1524	-0.1315
9	6-12	0.1680	-0.1917	0.0000	-0.2243	0.0000	0.2312
10	4-9	0.000	0.2210	0.2962	-0.0680	0.2961	-0.0683
11	7-8	0.1553	0.1447	0.3843	-0.0278	0.3843	-0.0279
12	10-17	0.0379	0.0331	0.0592	0.0537	0.0592	0.0537
13	10-20	0.0714	0.0088	0.0938	0.0413	0.0938	0.0413
14	10-21	0.1301	0.0662	0.1590	0.1030	0.1590	0.1032
15	10-22	0.0579	0.0241	0.0769	0.0479	0.0769	0.0480
16	12-14	0.0814	0.0256	0.0769	0.0229	0.0769	0.0229
17	12-15	0.1885	0.0756	0.1733	0.0623	0.1733	0.0624
18	12-16	0.0884	0.0455	0.0665	0.0239	0.0665	0.0240
19	10-25	0.1032	0.0833	0.0502	0.0058	0.0502	0.0055
20	10-29	0.0618	0.0165	0.0753	0.0093	0.0627	0.0166
21	27-13	0.0708	0.0164	0.0579	0.0235	0.0703	0.0171
22	11-13	0.5662	0.0344	0.8431	-0.1133	0.8431	-0.1133
23	28-27	0.7104	0.263	0.1890	0.0037	0.1888	0.0041
24	13-12	0.4010	-0.0859	0.4287	0.0056	0.4287	0.0050
25	11-12	0.1620	-0.1175	0.2853	-0.0388	0.2854	-0.0388
26	14-15	0.185	0.0078	0.0141	0.0053	0.0141	0.0053
27	15-18	0.0799	0.0446	0.0561	0.0121	0.0567	0.0121
28	15-23	0.0425	0.0089	0.0465	0.0263	0.0465	0.0264
29	16-17	0.0525	0.0257	0.0311	0.0050	0.0311	0.0050
30	18-19	0.0471	0.0338	0.0244	0.0023	0.0244	0.0023
31	20-19	0.0489	0.0008	0.0709	0.0322	0.0709	0.0322
32	22-21	0.0456	0.0474	0.0173	0.0116	0.0172	0.0115
33	22-24	0.0120	-0.0238	0.0591	0.0351	0.0591	0.0353
34	23-24	0.0103	-0.0075	0.0142	0.0097	0.0142	0.0098
35	24-25	0.0661	0.0565	0.0145	-0.0184	0.0144	-0.0188
36	25-26	0.0354	0.0236	0.0355	0.0237	0.0355	0.0237
37	29-30	0.0370	0.0060	0.0500	-0.0080	0.0500	0.0075
38	28-10	0.2282	-0.1607	0.1616	0.0061	0.1616	0.0062
39	9-10	0.4524	-0.1059	0.2853	0.8920	0.2854	0.8930
40	13-7	0.4453	-0.1474	0.1834	0.0528	0.1832	0.0534
41	13-8	0.1937	-0.0249	0.7447	-0.1073	0.7446	-0.1072

Table 3: BUS results with SVC and STATCOM

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Bus No.	Voltage magnitude V_x in p.u	Phase angle in p.u	Voltage magnitude V_x in p.u	Phase angle in p.u
1	1.0600	0	1.000	0
2	1.0000	-15.9050	1.000	-12.276
3	1.0000	-13.6634	1.000	-10.595
4	1.0000	-25.3202	1.000	-17.428
5	0.8893	-23.0520	0.870	-21.410
6	0.8559	-39.6011	0.922	-30.677
7	0.8356	-40.7832	0.891	-31.474
8	0.8310	-40.6094	0.995	-31.654
9	0.8744	-34.2418	0.949	-25.738
10	0.8921	-29.6706	0.967	-24.189
11	0.9598	-23.3898	1.036	-19.212
12	0.9419	-26.6714	1.046	-21.848
13	0.8269	-40.9429	1.000	-31.843
14	0.8610	-36.5125	1.032	-28.899
15	1.0101	-6.7827	0.974	-6.427
16	0.9368	-17.2929	0.941	-15.401
17	0.9814	-19.5541	1.022	-15.896
18	0.9027	-28.0055	1.001	-22.768
19	0.8823	-35.4519	0.970	-27.087
20	0.8688	-35.8544	0.945	-27.119
21	0.9318	-31.4633	0.985	-23.396
22	0.8568	-36.7631	1.009	-28.613
23	0.8969	-30.8204	0.993	-22.818
24	0.9624	-17.6907	0.991	-14.590

VII. CONCLUSION

This paper presented the modeling and simulation methods required for study of the steady-state operation of electrical power systems with FACTS controllers: TCSC, SSSC, SVC and STATCOM. The conventional power flow solution could systematically be modified to include multiple FACTS controllers. It was shown that the effect of FACTS controllers on power flow can be provided by adding new entries and adjusting some existing entries in the linearized Jacobean equation of the basic system with no FACTS controllers.

An existing power flow program that uses the Newton–Raphson method of solution can easily be modified through the procedure presented in this paper. This procedure was applied on the 30-bus power system and implemented using the MATLAB software package. The numerical results show the robust convergence of the presented procedure. The steady state models of TCSC, SSSC, SVC and STATCOM are evaluated in Newton-Raphson algorithm.

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