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Power Flow Control using FACTS Devices

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Abstract: In this paper, capability of various FACTS (Flexible Alternating Current Transmission System) controllers to improve power system stability and controllability is examined by developing power flow equations using power flow model and hence these linearized power flow equations are modified by a much more accurate and fast iterative technique i.e. Newton Raphson method. The simulation results are presented on IEEE-14 bus system by using MATLAB programming over a small range of power flow variation in the transmission system.

Keywords: Flexible Alternating Current Transmission system (FACTS), Static VAR Compensator (SVC), Static Synchronous Compensator (STATCOM).

I. INTRODUCTION

A. STATIC VAR COMPENSATOR (SVC)

The most commonly used load flow models of SVC are suggested by CIGRE [1] and IEEE [2]. The SVC acts as a variable susceptance when it is operating within reactive limits and otherwise it takes the form of a fixed susceptance. SVC voltage regulation characteristic is represented by SVC's reactance as shown in fig.1 [3].

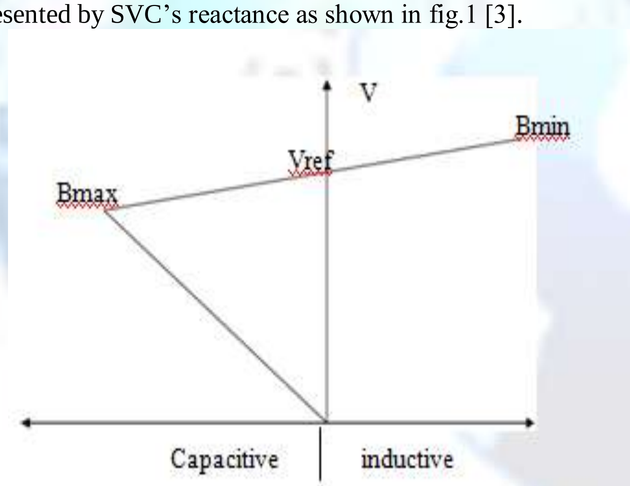

Fig. 1: VI characteristics of SVC

By connecting the SVC (act as generator) to the PV bus or Dummy bus through a step down transformer via a reactance its circuit configuration is achieved [1, 2]. High voltage node acts as PQ- type node and for connecting transformer reactance, X_t one extra node is added. If the voltage magnitude regulation is done at high voltage side of the transformer than this additional node imposes a challenge to Newton-Raphson method. Earlier methods can solve this problem in a straightforward manner [4] but Newton-Raphson method is preferred due to its strong convergence characteristics [5-9]. Within the framework of optimal and conventional power flow studies many new models of SVC have been proposed now-a-days [10]. The SVC susceptance is varied as a function of thyristor's firing angle whose value is adjusted to constrain its terminal voltage magnitude. In a Newton-Raphson load flow program this new shunt susceptance model implementation requires the use of PV bus.

SVC is connected to the transmission line through a step down transformer as shown in fig.2.

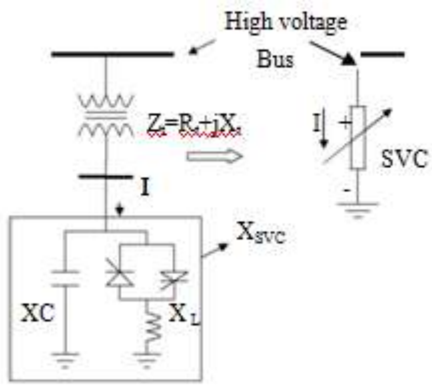

Fig. 2: SVC with step down transformer [11]

Proposed Model: As seen from the transformer's high voltage side, the total admittance of the SVC and Transformer collectively is given by the series combination of the Y_t and Ysvc i.e. the admittance of both components, respectively,

$$Y(\alpha) = \frac{Y_t\ Y_{SVC}}{Y_t + Y_{SVC}} \quad (1)$$

Or $\quad Y = G + jB \quad (2)$

Where
$$G = \frac{R_t}{R_t^2 + X_{eq}^2} \quad (3)$$

$$B = \frac{-X_{eq}}{R_t^2 + X_{eq}^2} \quad (4)$$

$$X_{eq} = X_t + X_{SVC}, X_{SVC} = \frac{X_C\, X_{tcr}}{X_C - X_{tcr}}, X_{tcr} = \frac{X_L\ \pi}{2(\pi - \alpha) + \sin(2\alpha)} \quad (5)$$

At transformer's high voltage side, the partial derivative of the power flow equation with respect to the firing angle is given as

$$\frac{\partial P}{\partial \alpha} = V_{HV}^2 \frac{\partial G}{\partial \alpha} \quad (6)$$

$$\frac{\partial Q}{\partial \alpha} = -V_{HV}^2 \frac{\partial B}{\partial \alpha} \quad (7)$$

Where
$$\frac{\partial G}{\partial \alpha} = \frac{R_t}{DT^2} \frac{\partial DT}{\partial \alpha} \quad (8)$$

$$\frac{\partial B}{\partial \alpha} = \frac{-DT \frac{\partial X_{SVC}}{\partial \alpha} + X_{eq} \frac{\partial DT}{\partial \alpha}}{DT^2} \quad (9)$$

$$\frac{\partial X_{SVC}}{\partial \alpha} = \frac{2X_{SVC}^2 (1 - \cos(2\alpha))}{\pi X_L} \quad (10)$$

$$\frac{\partial DT}{\partial \alpha} = 2X_{eq} \frac{\partial X_{SVC}}{\partial \alpha} \quad (11)$$

$$DT = R_t^2 + X_{eq}^2 \quad (12)$$

$$\begin{bmatrix} P_{HV} \\ \\ Q_{HV} \end{bmatrix}^i = \begin{bmatrix} 0 & \frac{\partial P}{\partial \alpha} \\ 0 & \frac{\partial Q}{\partial \alpha} \end{bmatrix}^i \begin{bmatrix} \Delta\theta_{HV} \\ \\ \Delta\alpha \end{bmatrix}^i$$

At the end of iteration i , the firing angle α is updated according the equation(13)

$$\alpha^{i+1} = \alpha^i + \Delta\alpha^i \quad (13)$$

B. Static Synchronous Compensator (STATCOM): STATCOM consists of a solid state Voltage Source Converter (VSC) and the corresponding shunt connected transformer connected to the transmission line/any bus. At the point of connection, STATCOM injects almost sinusoidal current of variable magnitude.This injected current is almost in quadrature with the line voltage, thereby matching a capacitive or an inductive current at the point of connection with the transmission line. When it is fed from an energy source or energy storage device at its input terminal, the STATCOM generates or absorbs controllable real and reactive power at its output terminal. A single line power circuit diagram of STATCOM where a VSC is connected to a utility bus through magnetic coupling is shown in fig.3.

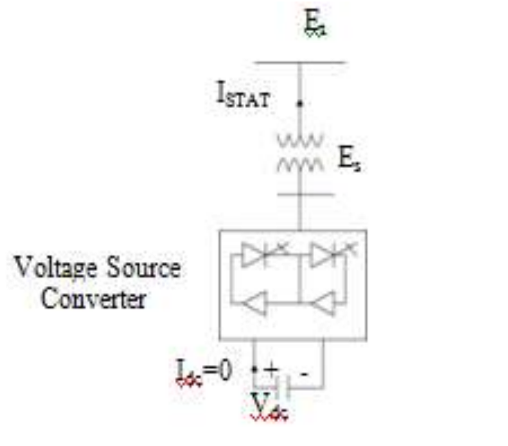

Fig 3: STATCOM Power Circuit Diagram [12]

A single line power circuit diagram of STATCOM and its equivalent circuit, which acts as adjustable voltage source behind reactance [12] is given in Fig.3and Fig.4, respectively, as shown

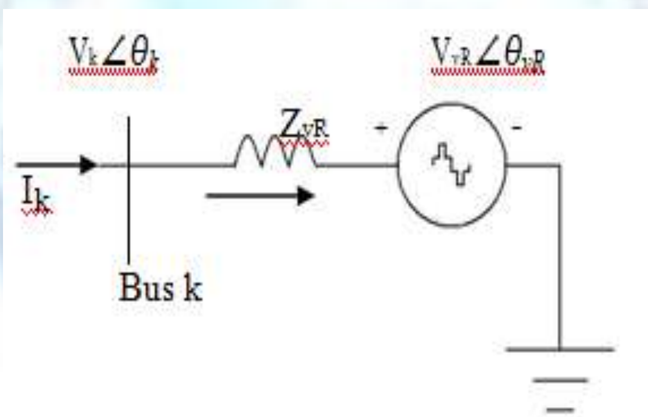

Fig. 4: STATCOM equivalent circuit.

Power Flow Model

$$S_{vR} = V_{vR} I_{VR}^* = V_{vR} Y_{vR}^* (V_{vR}^* - V_k^*) \quad (14)$$

After performing some complex operation, active and reactive power equations obtained for the converter and bus K are given as follows:

$$P_{vR} = V_{vR}^2 G_{vR} + V_{vR} V_k (G_{vR} \cos(\delta_{vR} - \theta_k) + B_{vR} \sin(\delta_{vR} - \theta_k)) \quad (15)$$

$$Q_{vR} = -V_{vR}^2 B_{vR} + V_{vR} V_k (G_{vR} \sin(\delta_{vR} - \theta_k) - B_{vR} \cos(\delta_{vR} - \theta_k)) \quad (16)$$

$$P_k = V_k^2 G_{vR} + V_k V_{vR} (G_{vR} \cos(\theta_k - \delta_{vR}) + B_{vR} \sin(\theta_k - \delta_{vR})) \quad (17)$$

$$Q_k = -V_k^2 B_{vR} + V_k V_{vR} (G_{vR} \sin(\theta_k - \delta_{vR}) - B_{vR} \cos(\theta_k - \delta_{vR})) \quad (18)$$

Using these linearized power equation alongwith the voltage magnitude V_{vR} and phase angle δ_{vR} as state variable the STATCOM model is obtained as given below:

$$\begin{pmatrix} \Delta P_k \\ \Delta Q_k \\ \Delta P_{vR} \\ \Delta Q_{vR} \end{pmatrix}^i = \begin{pmatrix} \frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial V_k} V_k & \frac{\partial P_k}{\partial \delta_{vR}} & \frac{\partial P_k}{\partial V_{vR}} V_{vR} \\ \frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial V_k} V_k & \frac{\partial Q_k}{\partial \delta_{vR}} & \frac{\partial Q_{vR}}{\partial V_{vR}} V_{vR} \\ \frac{\partial P_{vR}}{\partial \theta_k} & \frac{\partial P_{vR}}{\partial V_k} V_k & \frac{\partial P_{vR}}{\partial \delta_{vR}} & \frac{\partial P_{vR}}{\partial V_{vR}} V_{vR} \\ \frac{\partial Q_{vR}}{\partial \theta_k} & \frac{\partial Q_{vR}}{\partial V_k} V_k & \frac{\partial Q_{vR}}{\partial \delta_{vR}} & \frac{\partial Q_{vR}}{\partial V_{vR}} V_{vR} \end{pmatrix}^i \begin{pmatrix} \Delta \theta_k \\ \Delta \frac{V_k}{V_k} \\ \Delta \delta_{vR} \\ \Delta \frac{V_{vR}}{V_{vR}} \end{pmatrix}^i$$

II. ALGORITHM

Algorithm used in this paper is divided into specific steps as given below:

Step 1: The test case system is taken as IEEE 14 BUS system.

Step 2: Load flow is carried for IEEE 14 BUS system whose results are given in Table 1.1, which is considered as base case result.

Step 3: By using FACTS Devices, the voltage (power) in the bus (branch) can be increased/ decreased where it is required. In this paper the used FACTS Devices are SVC (shunt variable susceptance and firing angle model), STATCOM. The FACTS devices are incorporated into the Newton Raphson load flow algorithm.

Step 4: By connecting the SVC to the bus numbers 4, 5, 6, 7, 10, 12, 13, 14 the voltage is improved to flat voltage or improved nearer to the flat voltage which was below the flat voltage in the base case result as given in Table 1.2 & Table 1.3 and also to improve this bus voltage, the value of SVC firing angle and its reactance also given in this table.

Step 5: Like SVC, by connecting STATCOM to the different buses the voltage is improved which is given in Table 1.4.To improve this voltage, the reactive power supplied/absorbed by STATCOM and voltage magnitude and angle of STATCOM is also given in this table.

III. SIMULATION RESULTS

1.1 BASE CASE

TABLE 1.1

Bus Number	Bus Voltage Magnitude(pu)	Bus Voltage Angle(pu)	Branch From-To	PQ $_{send}$(pu)	PQ $_{rec}$(pu)
1	1.0600	0	1-2	1.5732 - 0.3287i	-1.5279 + 0.3040i
2	1.0128	-4.5715	1-5	0.7608 - 0.1130i	-0.7316 + 0.0967i
3	1.0000	-13.0732	2-3	0.7433 + 0.0997i	-0.7179 - 0.1182i
4	0.9898	-10.2542	2-4	0.5554 + 0.0579i	-0.5379 - 0.0428i
5	0.9974	-8.7373	2-5	0.4122 + 0.0654i	-0.4027 - 0.0245i
6	0.9875	-15.2057	3-4	-0.2241 - 0.1416i	0.2291 + 0.1543i
7	0.9780	-13.7583	4-5	-0.6130 - 0.0241i	0.6181 + 0.0080i
8	1.0000	-13.7583	4-7	0.2829 - 0.0647i	-0.2829 + 0.0467i

9	0.9595	-15.6592	4-9	0.1608 - 0.0616i	-0.1608 + 0.0447i
10	0.9563	-15.9144	5-6	0.4403 - 0.0641i	-0.4403 + 0.0140i
11	0.9679	-15.7048	6-11	0.0720 - 0.0630i	-0.0711 + 0.0612i
12	0.9703	-16.1963	6-12	0.0786 - 0.0289i	-0.0778 + 0.0271i
13	0.9642	-16.2518	6-13	0.1777 - 0.0871i	-0.1750 + 0.0818i
14	0.9417	-17.1206	7-8	0.0000 + 0.1224i	-0.0000 - 0.1251i
			7-9	0.2829 - 0.1691i	-0.2829 + 0.1566i
			9-10	0.0543 - 0.0158i	-0.0542 + 0.0155i
			9-14	0.0944 - 0.0196i	-0.0931 + 0.0168i
			10-11	-0.0358 + 0.0425i	0.0361 - 0.0432i
			12-13	0.0168 - 0.0111i	-0.0167 + 0.0110i
			13-14	0.0567 - 0.0348i	-0.0559 + 0.0332i

Table 1.1 shows the load flow result of IEEE 14 bus system. This result has taken as the base case result of this system and hence the new results which are given in Tables 1.2- 1.4, compared with base case result by incorporating FACTS devices in this system.

1.2 SVC

1.2.1 Variable Shunt Susceptance Model

TABLE 1.2

Bus Number	Base Case Voltage(pu)	With SVC (on base case load)			20% increased load (With SVC)			20% decreased load (With SVC)		
		Voltage (pu)	Reactive Power (pu)	SVC Susceptance (pu)	Voltage (pu)	Reactive Power (pu)	SVC Susceptance (pu)	Voltage (pu)	Reactive Power (pu)	SVC Susceptance (pu)
5	0.9974	1.0	-0.1226	0.1226	1.0	-0.2675	0.2675	1.0	0.0065	-0.0065
9	0.9595	0.99	-0.2456	0.2506	0.98	-0.2424	0.2524	0.98	-0.0713	0.0742
10	0.9563	1.0	-0.2676	0.2676	0.99	-0.2638	0.2692	1.0	-0.2033	0.2033
11	0.9679	1.0	-0.1732	0.1732	1.0	-0.2163	0.2163	1.0	-0.1322	0.1322
12	0.9703	1.0	-0.1233	0.1233	1.0	-0.1490	0.1490	1.0	-0.0962	0.0962
13	0.9642	1.0	-0.2696	0.2696	0.99	-0.2168	0.2212	1.0	-0.2112	0.2112
14	0.9417	1.0	-0.2398	0.2398	1.0	-0.2965	0.2965	1.0	-0.1853	0.1853

Here in table 1.2 the lowest base case voltage magnitude(pu) is 0.9417 at bus number 14, after connecting the SVC (variable susceptance model) to that bus, the voltage improves to 1.0 with susceptance value(pu) is 0.2398, that means the SVC works in capacitive mode and the reactive power supplied by SVC is -0.2398.Then increasing 20% load the reactive power and susceptance is -0.2965 and 0.2965 respectively with voltage at that bus improves to 1.0 and also decreasing 20% load the susceptance and reactive power supplied by SVC is 0.1853 and -0.1853. Like this bus number 14, result of other buses are given in table 1.2.

1.2.2 Firing Angle Model

TABLE 1.3

Bus Number	Base Case Voltage (pu)	With SVC (on base case load)			20%increased load (With SVC)			20% decreased load (With SVC)		
		Voltage (pu)	Reactive Power (pu)	Firing Angle (deg)	Voltage (pu)	Reactive Power (pu)	Firing Angle (deg)	Voltage (pu)	Reactive Power (pu)	Firing Angle (deg)
4	0.9898	1.0	-0.3175	135.3606	1.0	-0.4754	139.8629	1.0	-0.1742	131.8186
5	0.9974	1.0	-0.1226	130.6375	1.0	-0.2675	134.0757	1.0	0.0065	127.8475
7	0.9780	1.0	-0.2615	133.9269	1.0	-0.3417	136.0028	1.0	-0.1875	132.1198
9	0.9595	1.0	-0.3383	135.9109	1.0	-0.4265	138.3815	1.0	-0.2543	133.7476
10	0.9563	1.0	-0.2676	134.0777	1.0	-0.3349	135.8205	1.0	-0.2033	132.5051
11	0.9679	1.0	-0.1732	131.7971	1.0	-0.2163	132.8184	1.0	-0.1322	130.8537
12	0.9703	1.0	-0.1233	130.6298	1.0	-0.1490	131.2376	1.0	-0.0962	130.0478
13	0.9642	1.0	-0.2696	134.1282	1.0	-0.3297	135.6812	1.0	-0.2112	132.6944
14	0.9417	1.0	-0.2398	133.3866	1.0	-0.2965	134.8140	1.0	-0.1853	132.0789

Here in table 1.3 the lowest base case voltage magnitude(pu) is 0.9417 at bus number 14, after connecting the SVC(firing angle model) to that bus, the voltage improves to 1.0 with firing angle position of TCR is 133.3866^0 and equivalent susceptance value(pu) is 0.2398, that means the SVC works in capacitive mode and the reactive power supplied by SVC is -0.2398.Then increasing 20% load the reactive power and firing angle is -0.2965 and 134.8140^0 respectively with voltage at that bus improves to 1.0 and also decreasing 20% load, the firing angle position and reactive power supplied by SVC is 132.0789^0 and -0.1853. Like this bus, result of other buses are given in table 1.3.

1.3 STATCOM

TABLE 1.4

Bus Number	Base Case Voltage (pu)	With STATCOM (on base case load)			20%increased load (With STATCOM)			20% decreased load (With STATCOM)		
		Voltage (pu)	Reactive Power (pu)	Source Voltage magnitude& angle (pu)	Voltage (pu)	Reactive Power (pu)	Source Voltage magnitude& angle (pu)	Voltage (pu)	Reactive Power (pu)	Source Voltage magnitude& angle (pu)
4	0.9898	1.0	-0.3276	1.0318 -0.1830	1.0	-0.4980	1.0475 -0.2254	1.0	-0.1772	1.0174 -0.1416
5	0.9974	1.0	-0.1241	1.0123 -0.1548	1.0	-0.2746	1.0267 -0.1911	1.0	-0.0065	0.9993 -0.1192
7	0.9780	1.0	-0.2684	1.0262 -0.2416	1.0	-0.3534	1.0342 -0.2956	1.0	-0.1905	1.0187 -0.1887
9	0.9595	1.0	-0.3497	1.0338 -0.2759	1.0	-0.4447	1.0426 -0.3369	1.0	-0.2608	1.0254 -0.2162
10	0.9563	1.0	-0.2747	1.0268 -0.2860	1.0	-0.3461	1.0335 -0.3497	1.0	-0.2074	1.0203 -0.2238
11	0.9679	1.0	-0.1762	1.0173 -0.2836	1.0	-0.2210	1.0216 -0.3473	1.0	-0.1339	1.0132 -0.2216
12	0.9703	1.0	-0.1238	1.0122 -0.2954	1.0	-0.1513	1.0149 -0.3616	1.0	-0.0971	1.0096 -0.2310
13	0.9642	1.0	-0.2768	1.0270 -0.2971	1.0	-0.3405	1.0330 -0.3636	1.0	-0.2156	1.0211 -0.2324
14	0.9417	1.0	-0.2455	1.0240 -0.3175	1.0	-0.3053	1.0297 -0.3883	1.0	-0.1887	1.0185 -0.2485

Like SVC, STATCOM controls the bus voltage to the specified value, in table 1.4 the base case voltage at bus number-14 is 0.9417 which is lowest value, after connecting STATCOM to that bus the bus voltage improves to 1.0 having reactive power supplied by STATCOM is - 0.2445 at source voltage magnitude and phase angle is 1.024 and -0.3175 respectively. By increasing the load by 20%, the reactive power and voltage (both magnitude and phase angle) is -0.3053 and 1.029, -0.3883 respectively to make the bus voltage magnitude to 1.0. By decreasing the load by 20%, the reactive power and voltage (both magnitude and phase angle) is -0.1887 and 1.0185, -0.2485 respectively to make the bus voltage magnitude to 1.0. From this discussion it is concluded that the magnitude of STATCOM voltage is more than the bus voltage magnitude so it works in the capacitive mode and supplies reactive power to the system.

CONCLUSION

By using different FACTS devices like SVC, STATCOM load flow problems in power system are solved using the Newton Raphson Method of load flow. From the result the conclusions are:

- The voltage at specified bus is improved at base case load, 20% increasing load and 20% decreasing load by incorporating the SVC model (variable susceptance model or firing angle model) into Newton Raphson load flow model.
- The voltage magnitude at the bus is improved on base case load, 20% increasing load and 20% decreasing load by using the STATCOM model.

REFERENCES

[1]. I.A. Enrimez, Ed., “Static VAR Compensators,” Working Group 38-0, Task Force No. 2 on SVC, CIGRE, 1986.
[2]. IEEE Special Stability Controls Working Group, “Static VAR Compensator Models for Power Flow and Dynamic Performance Simulation.”, IEEE Transactions on Power Systems, Vol. 9, No.1, pp. 229-240, Feb. 1995.
[3]. P. Kundur, “Power System Stability and Control”, Mc-Graw-Hill © 1994.
[4]. E. Acha, “A Quasi-Newton Algorithm for the Load Flow Solution of Large Networks with FACTS-Controlled Branches”, 28th UPEC Conference, UK, pp.153-156, 21-23 September 1993.
[5]. C.R. Fuerte- Esquivel, E. Acha, S.G. Tang, J.J. Rico, “Efficient Object Power Systems Software for the Analysis of Large-Scale Networks Containing FACTS-Controlled Branches,” IEEE Transactions on Power Systems, Vol. 13, No. 2, pp. 464-472, May 1998.
[6]. Peterson, N.M., Scott Meyer, W., 1974, “Automatic Adjustment Of Transformer and Phase Shifter Taps in the Newton Power Flow”, IEEE Transactions Power Apparatus and Systems, PAS-90(1), pp. 103-108.
[7]. Stott, B., 1974, “Review Of Load-Flow Calculation Methods”, IEEE Proceedings 62(July), pp. 916-929.
[8]. Stott, B., Alsac, O., 1978, “Fast Decoupled Load Flow”, IEEE Transaction Power Apparatus and Systems PAS-93, pp. 859-862.
[9]. Tinney, W.F., Hart, C.E., 1967, “Power Flow Solution by Newton’s Method”, IEEE Transactions Power Apparatus and Systems PAS-86(11), pp. 1449-1460.
[10]. H. Ambriz-Perez, E. Acha, C.R. Fuerte- Esquivel, “Advanced SVC Models for the Newton-Raphson Load Flow and Newton Optimal Power Flow Studies,” PE-173-PWRD-0-11-1998, Accepted for Publication in the IEEE Trans. Power Delivery.
[11]. C.R. Fuerte-Esquivel, E. Acha , Ambriz-Perez, “Integrated SVC & Step-down Transformer Model for Newton-Raphson load flow studies”, Power Engineering Review, Vol. 20, pp. 45-46 , Feb. 2000.
[12]. Zhiping Yang, Chen Shen, M.L.Crow, Lingli Zhang, “An improved STATCOM Model for Power Flow Analysis”, Power Engineering Society Summer Meeting 2000, Vol. 2, pp. 1121-1126, July 2000.

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