Variable Evaluation and Optimal Placement of STATCOM in Test Bus Systems

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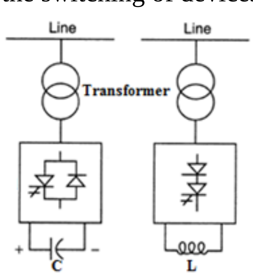
Abstract: ***This paper presents the mathematical steady-state modelling of Static Synchronous Compensator (STATCOM) for voltage control of a bus and hence the variable of the controller. MATLAB programs have been developed for implementation of a few models of STATCOM. In this regard, Newton-Raphson load flow algorithm has been modified for incorporating models of STATCOM in some standard test bus systems. IEEE 5-bus system and IEEE 14-bus system are considered. Load sensitivity factors, which are defined as the effect of load on power system variables, are evaluated for load buses of the above mentioned test bus systems by increasing load on each load bus to 140% of base case value. Since load change affects node voltage, hence node voltage load dependency factor (NVLDF) of all buses are evaluated for finding optimal location of STATCOM. Thus this paper aims at evaluation of variable of STATCOM and finding optimal location for the same.***

Keywords**: FACTS, STATCOM, NR load flow, Voltage Stability.**

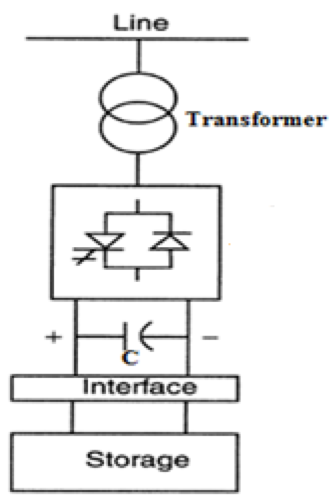
(Article History: Received 22 September 2017 and accepted 21April 2018)

1. Introduction

Static Synchronous Compensator (STATCOM) is a static synchronous generator operated as a shunt connected static var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage [1]. STATCOM is one of the key FACTS controllers. It can be based on a voltage sourced or current-sourced converter [2]. Figure:1 shows a simple one-line diagram of STATCOM based on a voltage sourced converter and a current-sourced converter. From overall cost point of view, the voltage-sourced converters are preferred. In voltage source converter, with the help of proper switching technology dc voltage of a dc capacitor is injected in ac side as ac voltage. In case of current source converter, the dc current from inductor is passed to the ac side through the switching of devices as ac current.



(a)



(b)

Figure1: Shunt-connected Controllers: (a) Static Synchronous Compensator (STATCOM) based on voltage-sourced and current-sourced converters (b) STATCOM with storage

2. Power flow model for STATCOM

The equivalent circuit diagram of STATCOM is shown in figure 2.

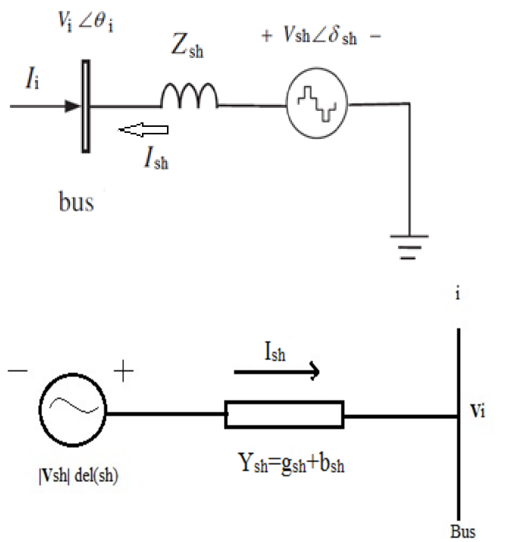


Figure 2: Equivalent circuit diagram of STATCOM

Referring to the model shown in figure 2, current flowing from the STATCOM to the bus number i in which it is connected is given by,

$$I_{sh} = Y_{sh}\,(V_{sh} - V_i) \quad \text{....................} \quad (1)$$

$$P_{sh} + j\,Q_{sh} = V_{sh}\,I_{sh}^*$$

$$= V_{sh}\,Y_{sh}^*(V_{sh}^* - V_i^*) \quad \text{....................(2)}$$

Expanding equation (2), the real and reactive power flow between STATCOM and the bus i are as follows,

$$P_{sh} = V_{sh}^2 g_{sh} - V_{sh}\,V_i\{\,g_{sh}\cos(\delta_{sh} - \delta_i) - b_{sh}\sin(\delta_{sh} - \delta_i)\} \quad \text{....................(3)}$$

$$Q_{sh} = -V_{sh}^2 b_{sh} + V_i\,V_{sh}\{\,b_{sh}\cos(\delta_{sh} - \delta_i) - g_{sh}\sin(\delta_{sh} - \delta_i)\,\} \quad \text{....................(4)}$$

Inclusion of STATCOM changes the original bus power expression and is given by,

$$P_i + j\,Q_i = \sum_{\substack{k=1 \\ k\sim=i}}^{nbus} V_i\,I_{ik}^* + V_i\,I_{ish}^*$$

$$= \sum_{\substack{k=1 \\ k\sim=i}}^{nbus} V_i\,I_{ik}^* + V_i\,Y_{sh}^*(\,V_i^* - V_{sh}^*) \quad \text{…...........(5)}$$

$$P_i = R\{\sum_{\substack{k=1 \\ k\sim=i}}^{nbus} V_i I_{ik}^*\} + V_i^2 g_{sh} - V_i V_{sh}\{g_{sh}\cos(\delta_i - \delta_{sh}) + b_{sh}\sin(\delta_i - \delta_{sh}) \quad \text{...............(6)}$$

$$Q_i = \mathrm{Im}\{\sum_{\substack{k=1 \\ k\sim=i}}^{nbus} V_i I_{ik}^*\} - V_i^2 b_{sh} + V_i V_{sh}\{b_{sh}\cos(\delta_i - \delta_{sh}) - g_{sh}\sin(\delta_i - \delta_{sh}) \quad \text{...............(7)}$$

Using these bus power equations (3), (4), (6), and (7), the linearised mismatch equation for the STATCOM model is given below, where the voltage magnitude V_{sh} and phase angle δ_{sh} are taken to be the state variables and the STATCOM is connected to the i^{th} bus.

$$\begin{bmatrix} \Delta P_2 \\ \Delta P_i \\ \Delta P_n \\ \Delta Q_2 \\ \Delta Q_i \\ \Delta Q_n \\ \Delta P_{sh} \\ \Delta V_i \end{bmatrix} = \begin{bmatrix} \frac{\partial P_2}{\partial \delta_2} & \frac{\partial P_2}{\partial \delta_i} & \frac{\partial P_2}{\partial \delta_n} & \frac{\partial P_2}{\partial V_2} & \frac{\partial P_2}{\partial V_i} & \frac{\partial P_2}{\partial V_n} & 0 & 0 \\ \frac{\partial P_i}{\partial \delta_2} & \frac{\partial P_i}{\partial \delta_i} & \frac{\partial P_i}{\partial \delta_n} & \frac{\partial P_i}{\partial V_2} & \frac{\partial P_i}{\partial V_i} & \frac{\partial P_i}{\partial V_n} & \frac{\partial P_i}{\partial V_{sh}} & \frac{\partial P_i}{\partial \delta_{sh}} \\ \frac{\partial P_n}{\partial \delta_2} & \frac{\partial P_n}{\partial \delta_i} & \frac{\partial P_n}{\partial \delta_n} & \frac{\partial P_n}{\partial V_2} & \frac{\partial P_n}{\partial V_i} & \frac{\partial P_n}{\partial V_n} & 0 & 0 \\ \frac{\partial Q_2}{\partial \delta_2} & \frac{\partial Q_2}{\partial \delta_i} & \frac{\partial Q_2}{\partial \delta_n} & \frac{\partial Q_2}{\partial V_2} & \frac{\partial Q_2}{\partial V_i} & \frac{\partial Q_2}{\partial V_n} & 0 & 0 \\ \frac{\partial Q_i}{\partial \delta_2} & \frac{\partial Q_i}{\partial \delta_i} & \frac{\partial Q_i}{\partial \delta_n} & \frac{\partial Q_i}{\partial V_2} & \frac{\partial Q_i}{\partial V_i} & \frac{\partial Q_i}{\partial V_n} & \frac{\partial Q_i}{\partial V_{sh}} & \frac{\partial Q_i}{\partial \delta_{sh}} \\ \frac{\partial Q_n}{\partial \delta_2} & \frac{\partial Q_n}{\partial \delta_i} & \frac{\partial Q_n}{\partial \delta_n} & \frac{\partial Q_n}{\partial V_2} & \frac{\partial Q_n}{\partial V_i} & \frac{\partial Q_n}{\partial V_n} & 0 & 0 \\ 0 & \frac{\partial P_{sh}}{\partial \delta_i} & 0 & 0 & \frac{\partial P_{sh}}{\partial V_i} & 0 & \frac{\partial P_{sh}}{\partial V_{sh}} & \frac{\partial P_{sh}}{\partial \delta_{sh}} \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\delta_2 \\ \Delta\delta_i \\ \Delta\delta_n \\ \Delta V_2 \\ \Delta V_i \\ \Delta V_n \\ \Delta V_{sh} \\ \Delta\delta_{sh} \end{bmatrix}$$

B=J.C

The left hand matrix **B** is the difference of specified quantities and calculated quantities. **J** is calculated by differentiating P_i, Q_i, P_{sh}, V_i with respect to δ_i, V_i, V_{sh}, δ_{sh}.

After p^{th} iteration, the variable voltage V_{sh} and variable angle δ_{sh} are upgraded as,

$$V_{sh}^{(p+1)} = V_{sh}^p + \Delta V_{sh}^p$$
$$\delta_{sh}^{(p+1)} = \delta_{sh}^p + \Delta\delta_{sh}^p$$

3. Implementation of STATCOM

IEEE 5-bus system and IEEE 14-bus system are considered for implementation of STATCOM for voltage control of a bus and hence variable of the STATCOM are evaluated.

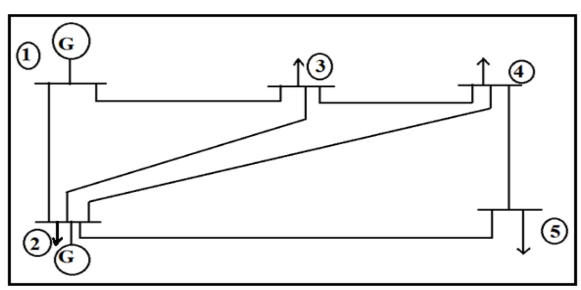


Figure 3: IEEE 5-bus Network under study

I. TABLE 1: Impedances and line charging admittances for the 5-bus network

Bus-code	Impedance	Charging Admittance
i-j	Z_{ij}	$Y_{ij}/2$
1-2	0.02 + j 0.06	0.0 + j 0.030
1-3	0.08 + j 0.24	0.0 + j 025
2-3	0.06 + j 0.18	0.0 + j 0.020
2-4	0.06 + j 0.18	0.0 + j 0.020
2-5	0.04 + j 0.03	0.0 + j 0.015
3-4	0.01 + j 0.03	0.0 + j 0.010
4-5	0.08 + j 0.24	0.0 + j 0.025

II. TABLE 2: Scheduled generation, loads and assumed bus voltages for the 5-bus network.

Bus No.	Assumed Bus Voltage	Generation		Load	
		MW	MVAR	MW	MVAR
1	1.06 + j 0.0	0	0	0	0
2	1.0 + j 0.0	40	30	20	10
3	1.0 + j 0.0	0	0	45	15
4	1.0 + j 0.0	0	0	40	5
5	1.0 + j 0.0	0	0	60	10

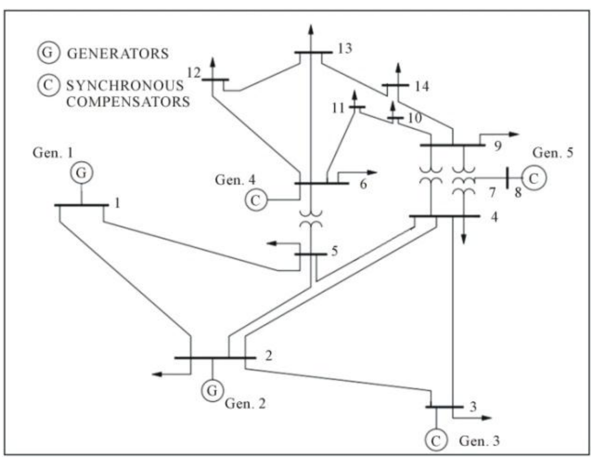


Figure 3: IEEE 14-bus Network under study

III. TABLE 3: Scheduled generation, loads and assumed bus voltages for the 14-bus network.

Bus code	Impedance	Charging admittance
i-j	Z_{ij}	$Y_{ij}/2$
1-2	0.01938 + j0.05917	0.0 + j 0.0264
1-5	0.05403 + j0.22304	0.0 + j 0.0246
2-3	0.04699 + j0.19797	0.0 + j 0.0219
2-4	0.05811 + j0.17632	0.0 + j 0.0170
2-5	0.05695 + j0.17388	0.0 + j 0.0173
3-4	0.06701 + j0.17103	0.0 + j 0.0064
4-5	0.01335 + j0.04211	0.0 + j 0.0000
4-7	0.0 + j 0.0	0.0 + j 0.0000
4-9	0.0 + j 0.0	0.0 + j 0.0000
5-6	0.0 + j 0.0	0.0 + j 0.0000
6-11	0.09498 + j0.19890	0.0 + j 0.0000
6-12	0.12291 + j0.25581	0.0 + j 0.0000
6-13	0.06615 + j0.13027	0.0 + j 0.0000
7-8	0.00000 + j0.17617	0.0 + j 0.0000
7-9	0.00000 + j0.11001	0.0 + j 0.0000
9-10	0.03181 + j0.08450	0.0 + j 0.0000
9-14	0.12711 + j0.27038	0.0 + j 0.0000
10-11	0.08205 + j0.19207	0.0 + j 0.0000
12-13	0.22092 + j0.19988	0.0 + j 0.0000
13-14	0.17093 + j0.34802	0.0 + j 0.0000

4. Simulation result

STATCOM is connected at bus number 5 in 5-bus system to fix the bus voltage at 1 p.u. and the corresponding values of STATCOM variable i.e. voltage and angle of the STATCOM are evaluated. The voltages of the buses in 5-bus system without STATCOM are shown in Table 4,

IV. TABLE 4: Bus voltages without STATCOM in 5-bus system.

Bus No	Voltage(V) p.u.	Angle Degree
1	1.0600	0
2	1.0100	-2.0623
3	0.9872	-4.6390
4	0.9841	-4.9595

5	0.9717	-5.7679

The bus voltages magnitudes and angles after inclusion of STATCOM in the 5-bus system and the corresponding values of STATCOM variables are presented in Table: 5.

V. TABLE 5: Bus voltages with STATCOM in 5-bus system.

Bus No	Voltage (V) p.u.	Angle Degree
1	1.0600	0
2	1.0000	-2.0664
3	0.9926	-4.7165
4	0.9911	-5.0614
5	1.0000	-6.2234

VI. TABLE 6: variable of the STATCOM in bus no. 5

STATCOM Bus	V_{sh} p.u.	Θ_{sh} Degree	Q_{sh} p.u.
5	1.032	-6.4070	0.3204

STATCOM is connected in bus 12 in 14-bus system to fix the bus voltage at 1 p.u. and the corresponding values of STATCOM variable i.e. voltage and angle of the STATCOM are evaluated. The bus voltages and their angles in 14-bus system without STATCOM are shown in Table: 7

VII. TABLE 7: System variables without STATCOM in 14-bus system

Bus No.	Voltage(V) p.u.	Angle Degree
1	1.0600	0
2	1.0450	4.9899
3	1.0100	-12.7489
4	1.0142	-10.2617
5	1.0172	-8.7691
6	1.0700	-14.4250
7	1.0503	-13.2586
8	1.0900	-13.2586
9	1.0337	-14.8398
10	1.0326	-15.0488
11	1.0475	-14.8553
12	1.0535	-15.2762
13	1.0471	-15.3159
14	1.0213	-16.0728

The bus voltages magnitudes and angles after inclusion of STATCOM in the 14-bus system and the corresponding values of STATCOM variables are presented in Table: 8

VIII. TABLE 8: Bus voltages with STATCOM in 14-bus system.

Bus No.	Voltage(V) p.u.	Angle Degree
1	1.0600	0
2	1.0450	-5.0240
3	1.0100	-12.8045
4	1.0135	-10.3253
5	1.0167	-8.8357
6	1.0700	-14.6183
7	1.0488	-13.3654
8	1.0900	-13.3654
9	1.0307	-14.9729
10	1.0301	-15.1922
11	1.0462	-15.0219
12	1.0000	-13.7195
13	1.0290	-15.2604
14	1.0116	-16.1447

IX. TABLE 9: variable of the STATCOM in bus no. 12

STATCOM Bus	V_{sh} p.u.	Θ_{sh} Degree	Q_{sh} p.u.
12	0.9635	-13.5104	-0.3649

From the Table:5 and Table:6, it is observed that voltage of the bus number 5 is set at 1 p.u. and the corresponding values of the STATCOM variable are V_{sh} = 1.0320 p.u, δ_{sh} = -6.4070 degree and Q_{sh} =0.3204 p.u. and from Table:8 and Table:9, it is observed that voltage of the bus number 12 is set at 1 p.u. and the corresponding values of the STATCOM variable are V_{sh} = 0.9635 p.u, δ_{sh} = -13.5104 degree and Q_{sh} = -0.3649 p.u.

5. Optimal placement of STATCOM

Voltage stability is sometimes also called load stability, because the stability problems due to lower voltages initiate at the load end. A power system at a given operating state is voltage stable if on being subjected to a certain disturbance, the voltages near loads approach the post disturbance equilibrium value [1]. Voltage instability and collapse have resulted in several major system failure or blackouts. Certain countermeasures to avoid voltage instability are: Series compensation, Shunt compensation, Generator terminal voltage increase, Increase of generator transformer tap, Strategic load shedding.

The effect of load on the power system variables is termed as load sensitivity factor. With the change in the load the node voltage also gets changed, this termed as node voltage load dependency factor (NVLDF. NVLDF is used to determine the sensitive nodes of the power system. To study the effect of these factors on performance of some test bus system, load on each load bus is increased in steps to 140% of base case value [4].

5.1. Node voltage load dependency factor (nvldf)

The calculation of NVLDF involves the following steps.

1. A load bus is selected and load on that bus is increased to 140% of its base case value and load flow is carried out.
2. The bus voltages for all the buses are calculated.
3. The process is repeated for the second load bus.
4. The number of steps for such execution is equal to the number of load buses in the system.
5. Average values of bus voltage for different load buses are calculated.
6. The NVLDF for each load bus is calculated which is the difference of the average value of bus voltage calculated in step-5 and the base case bus voltage.

6. Simulation Results

At first load flow analysis is carried out for 5-bus system using NR load flow method. Base case values for voltage, angle, real line flow, reactive line flow are obtained. Load buses are selected. Load on these buses are increased to 140% of base case values. The load sensitivity factor NVLDF is calculated. The whole process is repeated for 14-bus system.

X. TABLE10: NVLDF for 5-bus system

IEEE 5 BUS SYTEM	
Bus number	**Node Voltage Load Dependency Factor(NVLDF)**
1	0
2	0
3	0.0039
4	0.0040
5	0.0043

XI. TABLE11: NVLDF for 14-bus system

IEEE 14 BUS SYTEM	
Bus No.	**Node Voltage Load Dependency Factor(NVLDF)**
1	0
2	0
3	0
4	0.0023
5	0.0020
6	0
7	0.0022
8	0
9	0.0028
10	0.0028
11	0.0020
12	0.0016
13	0.0019
14	0.0031

For 5-bus system it is observed from Table:10 that bus number 5 have maximum value of NVLD which indicates that voltage fluctuation in bus 5 is maximum, hence bus 5 is more sensitive bus. Similarly for 14-bus system it is observed from Table:11 that bus 9,10, and14 are more sensitive. STATCOM will be preferred on those buses where node voltage load sensitivity factor i.e. NVLDF value is pretty high to limit the voltage fluctuation.

7. CONCLUSION

In this paper efforts are made to control bus voltage for stable operation of power system. MATLAB programs are developed for implementation of FACTS devices in IEEE 5-bus system and IEEE 14-bus system. A steady-state mathematical model of STATCOM is incorporated in the conventional NR power flow algorithm for voltage control of a bus of the aforesaid system. Load sensitivity analysis is done for optimal location of STATCOM. STATCOMs are preferred on those buses where the value of node voltage load dependency factor (NVLDF) is high i.e. voltage fluctuation is high with overloading to control the voltage fluctuation for stable operation of power system.

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