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COMPARISION OF FACTS CONTROLLERS FOR IMPROVEMENT OF VOLTAGE/LINE STABILITY IN TRANSMISSION SYSTEM USING SSSC & STATCOM

[1]B.RAJANI, [2]Dr.P.SANGAMESWARA RAJU,
[1]Phd.Research Scholar,S.V.University.College of Engineering, Dept.of Electrical Engg Tirupathi ,A.P INDIA
[2] Professor, SV University, Tirupathi, Andhra Pradesh, INDIA
Email: [1]seepana__2003@yahoo.co.in , [2]Raju_ps_2000@yahoo.com

ABSTRACT

Voltage stability is concerned with the ability of a power system to maintain acceptable voltages at all nodes in the system under normal condition and after being subject to a disturbance. voltage instability becomes an increasingly serious problem . As power systems become more complex and heavily loaded, along with economical and environmental constraints, Real and Reactive power control/compensation in transmission systems improves the stability of the ac system. It also helps to maintain a substantially flat voltage profile at all levels of power transmission, and it improves performance, increases transmission efficiency, and can avoid voltage collapse. The placement of Voltage Source Converter (VSC) based FACTS controller like static synchronous compensator (STATCOM) and Static Synchronous series compensator (SSSC) have the dynamically controlling the power flow through the line .The paper, presents voltage stability L- index and three line stability indices L_{mn} ,Fast voltage stability Index (FVSI),Line stability IndexLQP have been discussed and were illustrated with the results obtained on a sample 6-bus system is incorporated in the power flow control. Line indices provide an accurate information with regards to the stability condition of the lines. The impact of these devices on voltage/line stability indices is investigated under simulated conditions on IEEE 118-bus test system, and on a real life 205-bus Indian system.
Keywords- *FACTS;STATCOM; SSSC; Voltage/Line Stability; L- index; Line Stability Index Lmn; FVSI; Line Stability Index LQP.*

1. INTRODUCTION

The paper consists of STATCOM the shunt compensator and SSSC the series compensator are incorporated in load flow algorithm to control the power flow as desired. The condition of voltage stability in a power system can be known using voltage stability indices. These indices can either reveal the critical bus of a power system or the stability of each line connected between two buses in an interconnected network or evaluate the voltage stability margins of a system. The indices used in this paper to examine the system stability. In this paper analysis of voltage behavior has been approached using static techniques, which have been widely used on voltage stability analysis. These indices provide reliable information about proximity of voltage instability in a power system. Usually, their values changes between 0 (no load) and 1 (voltage collapse). The voltage stability analysis, using different methods, is highlighted in this paper.

The paper is organized as follows: section 2 presents the detailed concepts of voltage/Line stability Indices formulation. section 3 deals with the detail study of STATCOM Newton raphson algorithm and its implementation aspects with two cases CASE I:For IEEE118-bus system the results are obtained under simulated conditions by locating STATCOM at 5 different locations and CASE II:For Real-life 205-bus system the STATCOM is placed in 3 different zones and in each zone 3 different locations are selected heuristically for studies to analyze the performance of various parameters of the system such as total generation ,real power losses, voltages, voltage stability indices are compared .In section 4 presents the detail study of SSSC as in the case of STATCOM with its simulated results. In section 5 presents the comparison of STATCOM and SSSC with the simulated results, The overall conclusions were performed on section 6.

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2. INDICES FORMULATION

L index: P Kessel [2] developed a voltage stability index based on the solution of the power flow equations. The L index is a quantitative measure for the estimation of the distance of the actual state of the system to the stability limit. The L index describes the stability of the complete system and is given by:

$$L = \max_{j \in \alpha L} \{L_j\} = \max_{j \in \alpha L} \left| 1 - \sum i \in \alpha G \frac{F_{ji} V_i}{V_j} \right| \quad (1)$$

Where αL is the set of consumer nodes and αG is the set of generator nodes L_j is a local indicator that determinates the bus bars from where collapse may originate. The L index varies in a range between 0 (no load) and 1 (voltage collapse). Line Stability Index Lmn: The line stability index, for this model, can be defined as:

$$L_{mn} = \frac{4XQ_j}{[|V_1| \sin(\theta - \delta)]^2} \quad (2)$$

Line Stability Index (FVSI) : For a typical transmission line, the stability index is calculated by:

$$FVSI = \frac{4Z^2 Q_j}{V_i^2 X} \quad (3)$$

Line Stability Index LQP: is obtained as follows:

$$LQP = 4\left(\frac{X}{V_i^2}\right)\left(\frac{X}{V_i^2} P_i^2 + Q_j\right) \quad (4)$$

X is the line reactance, V_i is the sending end voltage, θ is the line impedance angle and ,$\delta = \delta_1 - \delta_2$ is the angle difference between the supply voltage and the receiving end voltage. Z is the line impedance, Q_j is the reactive power flow at the receiving end and V_i is the sending end voltage. P_i is the active power flow at the sending bus. Based on the stability indices of lines, voltage collapse can be accurately predicted. the index should be less than 1. The line that gives index value closest to 1 will be the most critical line of the bus and may lead to the whole system instability. The line which exhibited the largest index with respect to a load increase has been determined as the most critical line. Any further increase on the load will cause the line to have an index value greater than 1.0 resulting in the entire system instability. To maintain a secure condition the values of the stability indices should be maintained well less than 1.0.To illustrate the determination of voltage/line stability indices, a 6- bus test system whose single line diagram is shown in Figure -3 is considered. This system has 2 generator buses and 4 load buses along with 7 inter connected branches. The reactive load at bus 3 is gradually increased from the base case until their maximum allowable load or maximum loadability, which is the maximum load that could be injected to a load bus before the power flow solution diverges.

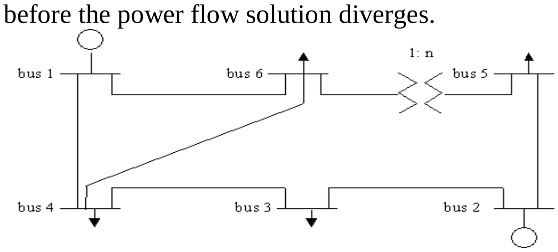

Figure1.Six bus standard test system

The values of the voltage/line stability indices for the 6-bus standard test system shown in Figure1 are obtained when the Qd at bus 3 is 65MVAR and rest of the buses are set at base case.

Table 1: Power flow results of 6-bus system

Bus No.	Name	Type	VM(p.u)	Ang - D	Generation		Load	
					MW	MVAR	MW	MVAR
1	Bus-1	Slack	1.000	0.00	74.32	68.62	0.000	0.000
2	Bus-2	PV- bus	0.950	-5.8019	40.00	74.35	0.000	0.000
3	Bus-3	PQ-Bus	0.5655	-13.0231	0.000	0.000	38.00	**65.00**
4	Bus-4	PQ-Bus	0.7701	-8.1935	-0.000	0.000	10.000	2.000
5	Bus-5	PQ-Bus	0.7901	-17.0294	0.000	0.000	20.000	2.000
6	Bus-6	PQ-Bus	0.8601	-9.7406	-0.000	0.000	30.00	3.000

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Table 2:Voltage stability L-Indices

Bus No.	Voltage stability L-Index
3	0.7506
4	0.3096
5	0.3188
6	0.2266

Table 3: Line stability indices for 6-bus system

LN	SB	EB	Lmn	FVSI	LQP
1	1	6	0.320330	0.287726	0.390429
2	1	4	0.628796	0.576016	0.644725
3	4	6	0.559319	0.551909	0.523558
4	6	5	0.174165	0.161349	0.220920
5	2	5	0.386342	0.336118	0.469789
6	2	3	0.944630	0.877305	0.936105
7	4	3	0.748013	0.715067	0.735018

From the Table -2, it is observed that the bus 3 exhibits the highest voltage stability L_j index, which indicates that it is the most vulnerable bus on the system. Table -3 shows the stressed conditions of the lines for the maximum loadability. The line that presents the largest index with respect to a bus is considering the most critical line of that bus. From the above Table -3 it is observed that the line that connects bus 2 to bus 3 is the most critical line with respect to bus 3. Based on the stability indices of lines, voltage collapse can be accurately predicted. the index should be less than 1. The line that gives index value closest to 1 will be the most critical line of the bus and may lead to the whole system instability. The line which exhibited the largest index with respect to a load increase has been determined as the most critical line. Any further increase on the load will cause the line to have an index value greater than 1.0 resulting in the entire system instability. To maintain a secure condition the values of the stability indices should be maintained well less than 1.0.

3. CONTROL FUNCTION MODEL OF STATCOM

3.1 Operating principle of statcom

A STATCOM is usually used to control transmission voltage by reactive power shunt compensation. Typically, a STATCOM consists of a coupling transformer, an inverter and a DC capacitor, which is shown in Fig.2 For such an arrangement, in ideal steady-state analysis, it can be assumed that the active power exchange between the AC system and the STATCOM can be neglected, and only the reactive power can be exchanged between them

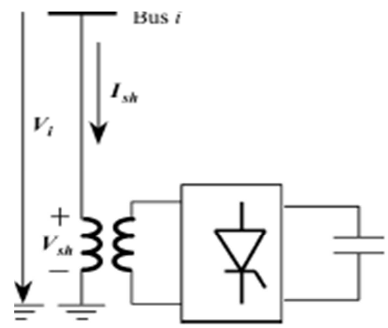

Figure 2 STATCOM

3.2 Power flow constraints of the STATCOM

$$P_{sh}=V_i^2*g_{sh}-V_i*V_{sh}(g_{sh}*\cos(\delta_i-\delta_{sh})+b_{sh}*\sin(\delta_i-\delta_{sh})) \quad (5)$$

$$Q_{sh}=-V_i^2*b_{sh}-V_i*V_{sh}(g_{sh}*\sin(\delta_i-\delta_{sh})-b_{sh}*\cos(\delta_i-\delta_{sh})) \quad (6)$$

Where $g_{sh}+jb_{sh}=1/Z_{sh}$.

Operating constraint of the STATCOM – the active power exchange via the DC link is zero, which is described by $PE = \mathrm{Re}(V_{sh} * I_{sh}^*) = 0$ (3)Where

$\mathrm{Re}(V_{sh}*I_{sh}^*)=$

$V_{sh}^2 g_{sh}-V_iV_{sh}(g_{sh}\cos(\delta_i-\delta_{sh})-b_{sh}\sin(\delta_i-\delta_{sh}))$

According to the equivalent circuit of the STATCOM $V_{sh}=V_{sh}\angle\delta_{sh}, V_i=V_i\angle\delta_i$, shown in

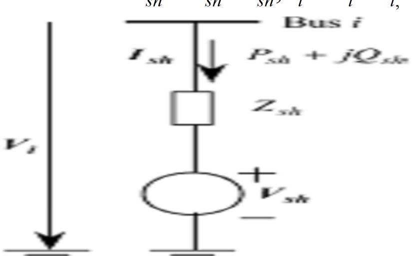

Figure 3. STATCOM equivalent circuit

3.3Voltage constraints of the STATCOM

The equivalent voltage injection V_{sh} bound constraints of STATCOM:

$$V_{sh}^{min} \le V_{sh} \le V_{sh}^{max} \quad (7)$$

$$-\pi \le \delta_{sh} \le \pi \quad (8)$$

where V_{sh}^{max} is the voltage rating of the STATCOM, while V_{sh}^{min} is the minimal voltage limit of the STATCOM.

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3.4. Implementation of statcom in Newton-Raphson algorithm

Step 1: Formation of Y bus

Step 2: calculation of injected powers

Step 3: calculation of mismatch powers

$$\Delta P_i = Pg_i - Pd_i - P_i = 0 \qquad (9)$$

$$\Delta Q_i = Qg_i - Qd_i - Q_i = 0 \qquad (10)$$

Step 4: Formation of Jacobian matrix for STATCOM

$$\begin{bmatrix} \frac{\partial P_i}{\partial \delta_i} & \frac{\partial P_i}{\partial V_i}*V_i & \frac{\partial P_i}{\partial \delta_{sh}} & \frac{\partial P_i}{\partial V_{sh}}*V_{sh} \\ \frac{\partial Q_i}{\partial \delta_i} & \frac{\partial Q_i}{\partial V_i}*V_i & \frac{\partial Q_i}{\partial \delta_{sh}} & \frac{\partial Q_i}{\partial V_{sh}}*V_{sh} \\ \frac{\partial P_{sh}}{\partial \delta_i} & \frac{\partial P_{sh}}{\partial V_i}*V_i & \frac{\partial P_{sh}}{\partial \delta_{sh}} & \frac{\partial P_{sh}}{\partial V_{sh}}*V_{sh} \\ \frac{\partial Q_{sh}}{\partial \delta_i} & \frac{\partial Q_{sh}}{\partial V_i}*V_i & \frac{\partial Q_{sh}}{\partial \delta_{sh}} & \frac{\partial Qvr}{\partial V_{sh}}*V_{sh} \end{bmatrix} \times \begin{bmatrix} \Delta\delta_i \\ \frac{\Delta V_i}{V_i} \\ \Delta\delta_{sh} \\ \frac{\Delta V_{sh}}{V_{sh}} \end{bmatrix} = \begin{bmatrix} \Delta P_i \\ \Delta Q_i \\ \Delta P_{sh} \\ \Delta Q_{sh} \end{bmatrix} \quad (8) \qquad (11)$$

Step 5: calculate the change in voltages and angles

$$\begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} = J^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \qquad (12)$$

Step 6: updating voltages and angles

$$\begin{bmatrix} \delta \\ V \end{bmatrix}_{NEW} = \begin{bmatrix} \delta \\ V \end{bmatrix}_{OLD} + \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \qquad (13)$$

Step 7:check whether a convergence criterion is satisfied or Not If yes ,stop the procedure .Else repeat the above procedure from step-2.

3.4.1 IEEE 118-Bus Test System

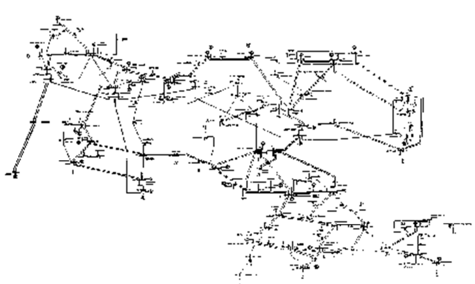

Figure 4. IEEE 118-bus test system

To determine the effectiveness of STATCOM, IEEE 118 –bus test system shown in Fig.4 is considered. The system has 54 generator buses and load is present at 64buses. It has 170 branches, 9 transformers and 14 shunts. The total load in the system is 4241 MW and 1438MVAR.The results are obtained under simulated conditions by locating STATCOM at 5 different locations i.e, at buses 93,94,95,96,and117,and are given in the Table 4.

Table 4: 118-bus system results with and without STATCOM

Parameters	Without STATCOM	STATCOM Locations				
		117	95	94	93	96
Total 'P' gen(MW)	4373.25	4359.31	4373.03	4373.09	4373.17	4373.19
Total 'Q' gen(MVAR)	754.94	746.75	753.25	753.90	754.02	754.43
Total 'P' loss (MW)	132.25	**131.02**	132.03	132.11	132.18	132.19
Vmin	0.9430	0.9430	0.9430	0.9430	0.9430	0.9430
Lmax	0.0693	0.0693	0.0693	0.0693	0.0693	0.0693
Lmn(max)	0.2219	0.2510	0.2510	0.2510	0.2510	0.2510
LQP(max)	0.2214	0.3271	0.3270	0.3270	0.3270	0.3270
FVSI(max)	0.2101	0.2509	0.2509	0.2509	0.2509	0.2509

From the Table .4 it can be observed that the STATCOM placed at the bus 117 gives best values of voltages and voltage stability indices with lower losses as compared with all the other 4 locations

3.4.2 Real life 205-bus interconnected system studies

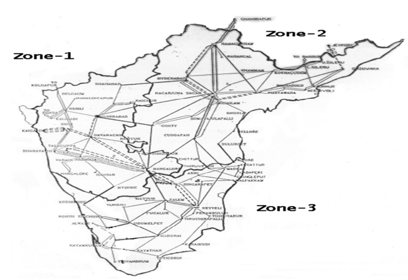

Figure 5. Zonal grid map of interconnected system

In this paper the application of FACTS device STATCOM to improve system line/voltage stability in the real-life 205-interconnected power system is explored. The zonal-wise grid map of the 205-bus interconnected system is shown in Fig.5. The system has 20 generator buses and 185 other buses. The system has 22 tap regulating transformers, 25 fixed tap transformers and 236 transmission lines. The system total peak load is

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about 7982.72 MW, 3781.02 MVAR. There are shunt reactors connected at various 400 kV buses for transient over-voltage protection.

3.4.2.1: Location of STATCOM in Zone-1

The STATCOM is placed in 3 different Zones and in each Zone 3 different locations are selected heuristically for studies. In zone-1 of 205-bus system, the STATCOM is located at buses 78, 75, 31. The results are given in the Table .5

Table.5: 205-bus results with and without STATCOM in Zone-1

Parameters	Without STATCOM	STATCOM Locations		
		78	75	31
Total 'P' gen(MW)	8182.71	8179.56	8180.00	8180.01
Total 'Q' gen(MVAR)	860.61	760.8 7	769.16	779.53
Total 'P' loss (MW)	199.99	196.84	197.28	197.29
Vmin	0.8817	0.8830	0.8831	0.8832
Lmax	0.7053	0.6983	0.6976	0.6971
Lmn(max)	0.3909	0.2471	0.2467	0.2465
LQP	0.1686	0.5297	0.5286	0.5279
FVSI	0.3481	0.2471	0.2467	0.2465

From the results given in Table .5 it can be seen that the STATCOM placed at the bus 78 gives best values of voltages and voltage stability indices with low losses as compared with all the other 2 locations in Zone-1.

3.4.2. 2: Location of STATCOM in Zone-2

In zone-2 of 205-bus system, the STATCOM is located at buses 46, 25, 47. The results are given in the Table .5

Table.6: 205-bus results with and without STATCOM in Zone-2

Parameters	Without STATCOM	STATCOM Locations		
		46	25	47
Total 'P' gen(MW)	8182.71	8182.21	8182.45	8182.48
Total 'Q' gen(MVAR)	860.61	842.34	849.34	849.59
Total 'P' loss (MW)	199.99	**199.49**	199.73	199.76
Vmin	0.8817	0.8824	0.8836	0.8834
Lmax	0.7053	0.7050	0.7052	0.7050
Lmn(max)	0.3909	0.2516	0.2517	0.2516
LQP	0.1686	0.5382	0.5391	0.5378
FVSI	0.3481	0.2499	0.2502	0.2497

The results given in Table.6 indicate that the STATCOM placed at the bus 46 gives best values of voltages and voltage stability indices with low losses as compared with all the other 2 locations at Zone-2.

3.4.2.3: Location of STATCOM in Zone-3

In zone-3 of 205-bus system, the STATCOM is located at buses 107, 140, 191. The results are given in the Table-4.The results given in Table .4 indicate that the STATCOM placed at the bus 107 gives best values of voltages and voltage stability indices with low losses as compared with all the other 2 locations at Zone-3 .The STATCOM location 107 in zone-3 is the best location among all other locations in Zone-1, 2 and 3.

Table.7: 205-bus results with and without STATCOM in Zone-3

Parameters	Without STATCOM	STATCOM Locations		
		107	140	191
Total 'P' gen(MW)	8182.71	8177.88	8178.20	8176.97
Total 'Q' gen(MVAR)	860.61	756.04	775.88	762.96
Total 'P' loss (MW)	199.99	195.16	195.89	196.35
Vmin	0.8817	0.8823	0.8824	0.8824
Lmax	0.7053	0.6055	0.6442	0.6119
Lmn(max)	0.3909	0.2505	0.2504	0.2504
LQP	0.1686	0.5336	0.5334	0.5335
FVSI	0.3481	0.2484	0.2483	0.2483

4. OPERATING PRINCIPLE OF SSSC

A SSSC usually consists of a coupling transformer, an inverter, and a capacitor. As shown in Fig-1 the SSSC is series connected with a transmission line through the coupling transformer. It is assumed here that the transmission line is series connected with the SSSC via its bus j. The active and reactive power flows of the SSSC branch i-j entering the bus j are equal to the sending end active and reactive power flows of the transmission line, respectively. In principle, the SSSC can generate and insert a series voltage, which can be regulated to change the impedance (more precisely reactance) of the transmission line. In this way, the power flow of the transmission line, which the SSSC is connected with, can be controlled.

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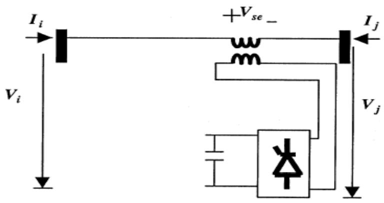

Figure 6. SSSC operation principles.

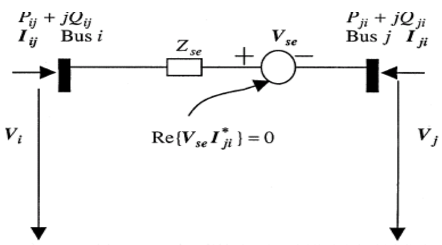

Figure 7.SSSC equivalent circuit

4.1 The power flow constraints of the sssc

An equivalent circuit of the SSSC as shown in Fig-7 can be derived based on the operation principle of the SSSC. In the equivalent, the SSSC is represented by a voltage source $\mathbf{V_{sc}}$ in series with a transformer's impedance. In the practical operation of the SSSC, $\mathbf{V_{sc}}$ can be regulated to control the power flow of line ***i-j***.

$V_{se}=V_{se}\angle\delta_{se}$, $V_i=V_i\angle\delta_i$ $V_j=V_j\angle\delta_j$

In the equivalent circuit then the power flow constraints of the SSSC are

$$P_{ij}=V_i^2g_{ii}-V_iV_j(g_{ij}\cos(\delta_i-\delta_j)+b_{ij}\sin(\delta_i-\delta_j))-V_iV_{se}(g_{ij}\cos(\delta_i-\delta_{se})+b_{ij}\sin(\delta_i-\delta_{se})) \quad (14)$$

$$Q_{ij}= -V_i^2b_{ii}-V_i V_j(g_{ij}\sin(\delta_i-\delta_j)-b_{ij}\cos(\delta_i-\delta_j))-V_iV_{se}(g_{ij}\sin(\delta_i-\delta_{se})-b_{ij}\cos(\delta_i-\delta_{se})) \quad (15)$$

$$P_{ji}=V_j^2g_{jj}-V_i V_j(g_{ij}\cos(\delta_j-\delta_i)+b_{ij}\sin(\delta_j-\delta_i))+V_jV_{se}(g_{ij}\cos(\delta_j-\delta_{se})+b_{ij}\sin(\delta_j-\delta_{se})) \quad (16)$$

$$Q_{ij}= -V_j^2b_{jj}-V_i V_j(g_{ij}\sin(\delta_j-\delta_i)-b_{ij}\cos(\delta_j-\delta_i))+V_jV_{se}(g_{ij}\sin(\delta_j-\delta_{se})-b_{ij}\cos(\delta_j-\delta_{se})) \quad (17)$$

where $g_{ij}+jb_{ij}=1/Z_{se}$; $g_{ii}=g_{ij}$; $b_{ii}=b_{ij}$; $g_{jj}=g_{ij}$;$b_{ii}=b_{ij}$.

The operating constraint of the SSSC (the active power exchange via the dc link) is

$$PE=Re(V_{se}I^*_{ji})=0 \quad (18)$$

Where $Re(V_{se}I^*_{ji})=-V_iV_{se}(g_{ij}\cos(\delta_i-\delta_{se})-b_{ij}\sin(\delta_i-\delta_{se}))+V_jV_{se}(g_{ij}\cos(\delta_j-\delta_{se})-b_{ij}\sin(\delta_j-\delta_{se}))$

4.2 Control constraints of the sssc

In the practical applications of the SSSC, it may be used for control of one of the following parameters: 1) the active power flow of the transmission line, 2) the reactive power flow of the transmission line. The SSSC active power flow control mode has been well recognized in references [3], [5], [6], [7]. The mathematical descriptions of the real and reactive power control modes of the SSSC are presented as follows. Mode 1: Active power flow cocontrolThe active power flow control constraint is as follows:

$$P_{ji}-P_{ji}^{spec}=0 \quad (19)$$

Where P_{ji}^{spec} is the specified active power flow control reference. Mode 2: Reactive power flow control The reactive power flow control constraint is as follows:

$$Q_{ji}-Q_{ji}^{spec}=0 \quad (20)$$

where Q_{ji}^{spec} is the specified reactive power flow control reference. As mentioned, P_{ji} , Q_{ji} are the SSSC branch active and reactive power flows, respectively, leaving the SSSC bus 'j' while the sending end active and reactive power flows of the transmission line are P_{ij} and Q_{ij} ,respectively.

4.3.Voltage and current constraints of the sssc

The equivalent voltage injection bound constraints are as follows:

$$0\leq V_{se}\leq V_{se}^{max} \quad (21)$$
$$-\pi\leq\delta_{se}\leq\pi \quad (22)$$

Where V_{se}^{max} is the voltage rating of, V_{se}which may be constant, or may change slightly with changes in the dc bus voltage, depending on the inverter design.

The Jacobian matrix for the SSSC

$$\begin{bmatrix}
\frac{\partial P_i}{\partial\delta_i} & \frac{\partial P_i}{\partial\delta_j} & \frac{\partial P_i}{\partial\delta_{se}} & \frac{\partial P_i}{\partial V_i} & \frac{\partial P_i}{\partial V_j} & \frac{\partial P_i}{\partial V_{se}} \\
\frac{\partial P_j}{\partial\delta_i} & \frac{\partial P_j}{\partial\delta_j} & \frac{\partial P_j}{\partial\delta_{se}} & \frac{\partial P_j}{\partial V_i} & \frac{\partial P_j}{\partial V_j} & \frac{\partial P_j}{\partial V_{se}} \\
\frac{\partial P_{ji}}{\partial\delta_i} & \frac{\partial P_{ji}}{\partial\delta_j} & \frac{\partial P_{ji}}{\partial\delta_{se}} & \frac{\partial P_{ji}}{\partial V_i} & \frac{\partial P_{ji}}{\partial V_j} & \frac{\partial P_{ji}}{\partial V_{se}} \\
\frac{\partial Q_i}{\partial\delta_i} & \frac{\partial Q_i}{\partial\delta_j} & \frac{\partial Q_i}{\partial\delta_{se}} & \frac{\partial Q_i}{\partial V_i} & \frac{\partial Q_i}{\partial V_j} & \frac{\partial Q_i}{\partial V_{se}} \\
\frac{\partial Q_j}{\partial\delta_i} & \frac{\partial Q_j}{\partial\delta_j} & \frac{\partial Q_j}{\partial\delta_{se}} & \frac{\partial Q_j}{\partial V_i} & \frac{\partial Q_j}{\partial V_j} & \frac{\partial Q_j}{\partial V_{se}} \\
\frac{\partial Q_{ji}}{\partial\delta_i} & \frac{\partial Q_{ji}}{\partial\delta_j} & \frac{\partial Q_{ji}}{\partial\delta_{se}} & \frac{\partial Q_{ji}}{\partial V_i} & \frac{\partial Q_{ji}}{\partial V_j} & \frac{\partial Q_{ji}}{\partial V_{se}}
\end{bmatrix}
\begin{bmatrix} \Delta\delta_i \\ \Delta\delta_j \\ \Delta\delta_{se} \\ \Delta V_i \\ \Delta V_j \\ \Delta V_{se} \end{bmatrix}
=
\begin{bmatrix} \Delta P_i \\ \Delta P_j \\ \Delta P_{ji} \\ \Delta Q_i \\ \Delta Q_j \\ \Delta Q_{ji} \end{bmatrix} \quad (23)$$

4.3.1 -IEEE 118-Bus Test System

To determine the effectiveness of SSSC, an IEEE 118–bus test system shown in Fig- 4 is considered

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for studies. The system has 54 generator buses and load is present at 64 buses. It has 170 branches, 9 transformers and 14 shunts. The total load in the system is 4241 MW and 1438 MVAR. The results are obtained under simulated conditions by locating SSSC at 5 different locations i.e, at the lines connected between the buses 83-82, 91-99, 59-56,65-66,and 91-89, and are given in the Table -8.

Table 8. 118-bus system results with and without SSSC

Parameters	Without SSSC	SSSC Locations				
		83-82	91-99	59-56	65-66	91-89
Line Flows	P_{mk} (pu)	1.8	0.99	1.0	0.9	0.4
	Q_{mk} (pu)	-1.6	0.75	0.5	0.45	0.3
Total 'P' gen(MW)	4373.25	4345.15	4368.89	4371.64	4371.97	4373.03
Total 'Q' gen(MVAR)	754.94	737.01	747.44	750.41	746.44	754.01
Total 'P' loss (MW)	132.25	**104.15**	127.89	130.64	130.97	132.03
Vmin	0.9430	0.8760	0.9462	0.9462	0.9462	0.9462
Lmax	0.0693	0.2791	0.1376	0.0945	0.1847	0.0913
Lmn(max)	0.2219	0.5795	0.2481	0.2219	0.2219	0.2220
LQP(max)	0.2214	0.6169	0.2451	0.2214	0.2316	0.2213
FVSI(max)	0.2101	0.6226	0.2363	0.2101	0.2101	0.2101

4.3.2-A Real life 205-bus interconnected system studies

In this paper the application of FACTS device SSSC to improve system line/voltage stability in the real-life 205-interconnected power system is explored. The zonal-wise grid map of the 205-bus interconnected system is shown in Fig.5. The system has 20 generator buses and 185 other buses. The system has 22 tap regulating transformers, 25 fixed tap transformers and 236 transmission lines. The system total peak load is about 7982MW, 4564MVAR.There are shunt reactors connected at various 400 kV buses for transient over-voltage protection.

4.3.2.1: Location of SSSC in Zone-1:

Table 9:205-bus results with and without SSSC in Zone-1.

Parameters	Without SSSC	SSSC Location		
		157-118	127-156	162-156
Line Flows	P_{mk} (pu)	1.75	3.0	3.0
	Q_{mk} (pu)	-0.725	-2.5	0.15
Total 'P' gen(MW)	8182.71	8178.71	8176.81	8182.52
Total 'Q' gen(MVAR)	860.61	849.59	980.19	833.43
Total 'P' loss (MW)	199.99	195.99	**183.57**	198.80
Vmin	0.8817	0.8818	0.7670	0.8819
Lmax	0.7053	0.7050	0.7189	0.7022
Lmn(max)	0.3909	0.3910	0.3466	0.3904
LQP(max)	0.1686	0.1683	0.2686	0.1681
FVSI	0.3481	0.3482	0.16224	0.3477

	Q_{mk} (pu)	-0.725	-2.5	0.15
Total 'P' gen(MW)	8182.71	8178.71	8176.81	8182.52
Total 'Q' gen(MVAR)	860.61	849.59	980.19	833.43
Total 'P' loss (MW)	199.99	195.99	**183.57**	198.80
Vmin	0.8817	0.8818	0.7670	0.8819
Lmax	0.7053	0.7050	0.7189	0.7022
Lmn(max)	0.3909	0.3910	0.3466	0.3904
LQP(max)	0.1686	0.1683	0.2686	0.1681
FVSI	0.3481	0.3482	0.16224	0.3477

The SSSC is placed in 3 different Zones and in each Zone 3 different locations are selected heuristically for studies. In zone-1 of 205-bus system, the SSSC is located in the lines connected between buses 127-156,157-118, and 162-156. The results are given in the Table-5 .From the results given in Table.5, it can be seen that the SSSC placed in the line connected between buses 127-156 best voltages and voltage stability indices with low real losses as compared with the other 2 locations at Zone-1.

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4.3.2.2: Location of SSSC in Zone-2:

Table-10: 205-bus results with and without SSSC in Zone-2.

Parameters		Without SSSC	SSSC Location		
			187-162	162-139	164-83
Line Flows	P_{mk} (pu)		5.0	7.5	1.3
	Q_{mk} (pu)		-1.5	-5.0	-0.08
Total 'P' gen(MW)		8182.71	8174.52	8172.93	8182.57
Total 'Q' gen(MVAR)		860.61	821.26	1068.98	855.64
Total 'P' loss (MW)		199.99	191.80	**190.21**	199.85
Vmin		0.8817	0.8830	0.8753	0.8818
Lmax		0.7053	0.7048	0.7088	0.7052
Lmn(max)		0.3909	0.3919	0.9414	0.3909
LQP(max)		0.1686	0.1704	0.5762	0.1685
FVSI		0.3481	0.3488	0.3480	0.3481

From the results given in Table-6**,** it can be seen that the SSSC placed in the line connected between 162-139 gives best values of voltages and voltage stability indices with low real losses as compared with the other 2 locations at Zone-2.

4.3.2.3: Location of SSSC in Zone-3:

Table-11: 205-bus results with and without SSSC in Zone-3.

Parameters		Without SSSC	SSSC Location		
			141-142	181-141	181-170
Line Flows	P_{mk} (pu)		10.0	12.0	10.0
	Q_{mk} (pu)		2.5	4.0	4.0
Total 'P' gen (MW)		8182.71	8151.69	8118.35	8147.57
Total 'Q'gen (MVAR)		860.61	633.78	540.47	622.57
Total 'P' loss (MW)		199.99	168.97	135.63	164.85
Vmin		0.8817	0.8825	0.8830	0.8836
Lmax		0.7053	0.5774	0.5768	0.6399
Lmn (max)		0.3909	0.3606	0.3537	0.3693
LQP (max)		0.1686	0.1677	0.1845	0.2831
FVSI		0.3481	0.3255	0.3202	0.3320

From the results given in Table-11**,** it can be seen that the SSSC placed in the line connected between the buses 181-141 gives best values of voltages and voltage stability indices with low real power losses as compared with the other 2 locations at Zone-3.

5. Comparison of System Performance with STATCOM and SSSC

5.1 Case I: IEEE 118-bus system

To analyze the performance of the 118-bus system with STATCOM and SSSC, various parameters of the system such as total generation, real power losses, voltages, voltage stability indices are compared and are given in Table .12.The results in Table.12 indicate that the SSSC placed in the line connected between buses 83-82 gives best values of voltages and voltage stability indices with low real power losses as compared with best location of STATCOM at bus 117.

Table .12: 118-bus system results with STATCOM and SSSC

Parameters	Without STATCOM/SSSC	With STATCOM at bus 117	With SSSC 83-82
Total 'P' gen(MW)	4373.25	4359.31	**4345.15**
Total 'Q' gen(MVAR)	754.94	746.75	737.01
Total 'P' loss (MW)	132.25	131.02	**104.15**
Vmin	0.9430	0.9430	0.8760
Lmax	0.0693	0.0693	0.2791
Lmn(max)	0.2219	0.2510	0.5795
LQP(max)	0.2214	0.3271	0.6169
FVSI(max)	0.2101	0.2509	0.6226

5.2 Case II: Real-life 205--bus system

To analyze the performance of the 205-bus system with STATCOM and SSSC, various parameters of the system such as total generation, real power losses, voltages, voltage stability indices are compared and are given in Table -13.

Table 13: 205-bus system results with STATCOM and SSSC in Overall best location in Zone-3

Parameters	Without STATCOM/ SSSC	With STATCOM at bus 107	With SSSC in the line 181-141
Total 'P' gen(MW)	8182.71	8177.88	8118.35
Total 'Q' gen(MVAR)	860.61	756.04	540.47
Total 'P' loss (MW)	199.99	195.16	**135.63**
Vmin	0.8817	0.8823	0.8830

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Lmax	0.7053	0.6055	0.5768
Lmn(max)	0.3909	0.2505	0.3537
LQP(max)	0.1686	0.5336	0.1845
FVSI(max)	0.3481	0.2484	0.3202

The results given in Table -13 indicate that the SSSC placed in the line 181-141 in zone-3 gives best values of voltages and voltage stability indices with low losses as compared with best location of STATCOM at bus 107 in zone-3.

6. CONCLUSIONS

In this paper STATCOM & SSSC models have been incorporated in to a Newton-Raphson load flow algorithm for large scale systems i.e for IEEE 118-bus system and 205-bus Indian system. A sample 6-bus system has been considered to illustrate the evaluation of voltage stability index and the three line stability indices to estimate the stress on the system, and is extended to 118-bus system and 205-bus system. The best locations have also been determined by comparing the real power generation losses, voltage profiles and voltage stability indices. The comparison of performance showed that the SSSC shows good improvement in active power loss reduction and improves system performance compared to STATCOM.

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