Performance analysis of FACTS devices in steady state power flow

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Abstract: - This paper focuses on the performance analysis of FACTS devices namely SVC and TCSC in steady state power flow control. Application of Flexible AC Transmission Systems (FACTS) devices in a power system network is an efficient way for the control and transfer of bulk amount of power for long distances. The performance of SVC and TCSC for reactive power injection, real power flow, power loss and voltage improvement are analyzed. The effective utilization of the existing transmission line for the transfer of bulk power is demonstrated. The performance of FACTS devices during single line contingency is also analysed. The modes of operation of SVC and TCSC with respect to bus voltage and power flows are discussed. The ability of FACTS devices to control power flows with various loading conditions is also demonstrated. SVC and TCSC are modelled using Variable Reactance modelling and are then incorporated into the existing Newton Raphson load flow algorithm. Numerical results on a benchmark 5 bus test system and an IEEE 30 bus test system with incorporation of SVC and TCSC are presented.

Key-Words: - Load flow, FACTS, SVC, TCSC

1 Introduction

Available Transmission capacity shall often be limited by disbursement of transmission lines and losses, as well as problems occurring in building new lines. The number of transmission corridors are increased only to handle the active power transfer, ending up always, not being optimally utilize these facilities as built. One of the major reasons is the inability to push more active power in the given transmission line due to frequent line over loading and voltage related issues that are attributed to lack of reactive power management. In a deregulated electricity market an efficient electric grid is important for reliable supply of power [1]. In most of the today's power systems, the failure rate is increasing due to unexpected power growth. Congestion in transmission network is created with the unscheduled power flows and losses in the lines are increased [2]. Every 1% reduction in the reactive power brings down reactive support by 2% , which further reduces voltage till the stabilized value of system operation. when the transmission losses are predominant, weakening of reactive power support to the system is large, brings voltage further down. The electrical power system experiences voltage collapse where the system reaches unstable operating point with very low voltages across the system striving for the reactive support. Flexible AC Transmission Systems (FACTS) technology is necessary to mitigate some of the difficulties, by allowing the utilities to get the maximum service from their transmission facilities and improve grid reliability[3].

Reactive power control is required to improve the quality of power supply in ac power systems to have better utilization of existing equipment resulting in the deferment of new investment for equipments and transmission lines. Reactive power consumed by the load is fairly easy to understand, but the reactive power generated or consumed within the network is difficult to comprehend and is of major concern. FACTS Controllers helps to control voltages and power flows at required magnitude and locations of the network. The main objective of these controllers is to enhance transmission capability by allowing safer loading of the transmission lines up to their thermal limits[4]. These controllers have the ability to control the interrelated parameters of the transmission network like impedance, voltage, phase angle and current[2]. Various types of controllers have been developed based on the type of compensation. They are distinguished as series controllers, shunt controllers and combined series – shunt controllers[1]. Several FACTS Controllers exist and each one has its own proprieties. The choice of a controller is always based on the objectives to be achieved.

The power flow problem is solved to determine the steady state complex voltages at all buses of the network, from which active and reactive power flows in every transmission line and transformer are calculated in [5]. Power flow analysis, involves solving a set of nonlinear algebraic equations whose results are ambiguous. These equations are solved using iterative techniques such as gauss seidel method, gauss elimination method, Fast Decoupled method and Newton Raphson (NR) method in [6]. NR method due to its quick convergence is widely used for power flow problem [5]. With the prior information in regard to the power flows in the lines, it is possible to invoke efficient operation and control of present systems and also planning for new systems [6].

FACTS controllers are incorporated in the existing NR power flow algorithm and simulations are performed [6]. Two different controllers are chosen in this paper for comparison. The first one is Static VAR Compensator (SVC), which is used to generate or absorb reactive power at the bus, thus providing voltage support at the installed bus. Second one is Thyristor Controlled Series Compensator (TCSC), used to control active power flow as desired in a transmission network.

In this paper SVC and TCSC are incorporated in the test system and the following case studies are carried out standard 5 bus and IEEE 30 bus test systems.

(a) Load flow without FACTS devices

(b) Load flow incorporating SVC and TCSC

(c) Voltage profile improvement with SVC

(d) Analysis of active power flow improvement with TCSC

(e) Analysis on operating modes of SVC and TCSC

(f) Performance of SVC and TCSC at various loading conditions

(g) Performance of TCSC under single line contingency

2 Modelling of FACTS devices

2.1 Modelling of SVC

SVC acts as a shunt connected variable reactance, which either injects or absorbs reactive power in order to regulate the voltage magnitude at the point of connection[6]. It provides instantaneous reactive power and voltage support. The SVC has two regions: Capacitive and Inductive. In capacitive mode the SVC injects reactive power and in inductive mode it absorbs reactive power. The SVC is modelled as a variable susceptance and its value depends up on the requirement at the particular node. The equivalent circuit is shown in fig(1).

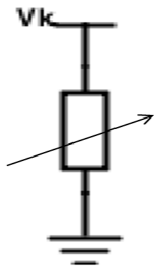


Fig 1: Static Var Compensator (Variable susceptance model)

2.1.1 Power flow equations of SVC:

Let us consider that an SVC is connected at bus k.

The reactive power absorbed or injected at bus K is given by[6], $Q_{SVC} = Q_k = -V_k^2 B_{SVC}$ (1)

From fig(1) the linearised equation taking B_{SVC} as state variable is given by[6]

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \end{bmatrix}^{(i)} = \begin{pmatrix} 0 & 0 \\ 0 & Q_K \end{pmatrix}^{(i)} \begin{bmatrix} \Delta Q_K \\ \Delta B_{SVC} / B_{SVC} \end{bmatrix}^{(i)} \quad (2)$$

The susceptance B_{SVC}, is updated in every iteration is given by[3]

$$B_{SVC}{}^{(i)} = B_{SVC}{}^{(i-1)} + \left[\Delta B_{SVC} / B_{SVC} \right]^{(i)} B_{SVC}{}^{(i-1)} \quad (3)$$

The final value of susceptance represents the total susceptance required to maintain specified nodal voltage.

2.2 Modelling of TCSC:

The impact of TCSC on a power network may be interpreted by a controllable reactance embedded in series to the related transmission line. Active power flow through the compensated transmission line may be kept up at a predefined level under extensive variety of working conditions[10]. A basic TCSC consists of Thyristor controlled reactor (TCR) in parallel with a fixed capacitor. The model of the network with TCSC connected between buses i and j is shown in Fig 2 and the equivalent circuit used for modelling is shown in Fig 3.

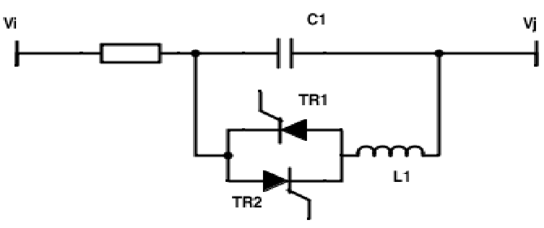


Fig 2: TCSC connected in a transmission lines between buses i and j

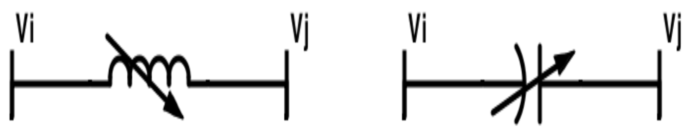


Fig 3: Equivalent circuit of TCSC

2.2.1 Power flow equations of TCSC

The power flow equations of the branch with TCSC are given by (4) and (5)

$$P_{ij} = V_i^2 G_{ij} - V_i V_j G_{ij} \cos(\delta_i - \delta_j) - V_i V_j \sin(\delta_i - \delta_j) \quad (4)$$

$$Q_{ij} = -V_i^2 B_{ij} - V_i V_j G_{ij} \sin(\delta_i - \delta_j) + V_i V_j B_{ij} \cos(\delta_i - \delta_j) \quad (5)$$

Similarly the power flows from j-th to i-th bus are given by (6) and (7)

$$P_{ji} = V_j^2 G_{ji} - V_j V_i G_{ji} \cos(\delta_i - \delta_j) + V_j V_i \sin(\delta_i - \delta_j) \quad (6)$$

$$Q_{ji} = -V_j^2 B_{ji} + V_j V_i G_{ji} \sin(\delta_i - \delta_j) + V_i V_j B_{ij} \cos(\delta_i - \delta_j) \quad (7)$$

3 Results and Discussion:

Load flow analysis is carried out on standard 5 bus system and an IEEE 30 bus system under normal and over loaded conditions without and with FACTS devices. FACTS devices are modelled as given in section 2 and incorporated in to Newton Raphson load flow algorithm with a tolerance level of $1e^{-12}$. SVC and TCSC are placed at various locations in the test systems and their performance is analysed. The parameters considered here are voltage magnitude, power flows, real & reactive power generation and power loss in the transmission lines. The standard 5 bus system is shown in appendix1.

3.1 Standard 5 bus system:

3.1.1 Analysis without FACTS devices:

In this case, load flow analysis is carried out without incorporating any FACTS devices. The results obtained for standard 5 bus system are furnished in table 1. Here voltage magnitudes and their phase angles at all buses total real and reactive power loss, the power generations are

given. The obtained voltages, power loss and power generations are considered as the base case results of 5 bus system.

Table 1
Base case results for 5 bus test system

Parameter	Magnitude
Voltage V_1	1.06
V_2	1.00
V_3	0.987
V_4	0.984
V_5	0.971
Phase Angle θ_1	0
θ_2	-2.06
θ_3	-4.63
θ_4	-4.95
θ_5	-5.76
Active Power Loss P_L	6.122 MW
Reactive Power Loss Q_L	-10.77 MVAr
Active Power Generation P_{G1}	131.12 MW
Active Power Generation P_{G2}	40 MW
Reactive Power Generation Q_{G1}	90.81 MVAr
Reactive Power Generation Q_{G2}	-61.59 MVAr

3.1.2 Load flow analysis incorporating SVC:

In this case, the shunt connected FACTS device SVC is placed at various locations in the test system and its ability to improve the bus voltage is analysed. The results are furnished in table 2. For instance, when SVC is placed in bus 3 to improve the bus voltage to 1.00 p.u. , it injects a reactive power of 20.47 MVAr to maintain specified voltage level. Even though SVC is placed at bus 3 the voltage magnitudes of bus 4 and 5 are also improved by 0.7% and 0.4% respectively (Table 2). This shows the capability of SVC to improve the voltage profile of the nearby buses also. Similarly SVC is placed in buses 4 & 5 and the voltage profiles in various buses are furnished in Table 2. In most of the cases it is observe that SVC improves the voltage profile of the bus in which it is placed as well as the other buses also. The percentage improvement depends on the location. This is because the reactive power injected by the SVC improves the reactive power flow in the nearby transmission lines also

Table 2

Voltage Profile without and with SVC at various locations

Bus No	Voltage Magnitude			
	Base case	SVC at Bus 3	SVC at Bus 4	SVC at Bus 5
1	1.06	1.06	1.06	1.06
2	1.00	1.00	1.00	1.00
3	0.987	1.00 (1.31%)	0.999 (1.2%)	0.992 (0.5%)
4	0.984	0.994 (0.7%)	1.00(1.6%)	0.991 (0.7%)
5	0.971	0.975 (0.4%)	0.977(0.6 %)	1.00(2.98 %)

3.1.3 Modes of operation of SVC

The quantity of reactive power to be injected by SVC depends on required voltage magnitude and desired location in the test system. SVC is placed at bus 3 and the voltage magnitude is varied to determine the reactive power injected and susceptance value of SVC. Positive sign indicates SVC absorbs reactive power from the system and negative sign indicates injection of reactive power in to the system. Table 3 gives the values of reactive power injected and susceptance value of SVC for various voltage magnitude specified. If the SVC has to maintain a voltage 1.00 p.u which is greater than base case (0.987 p.u.) then SVC injects 20.47 MVAr in to the system. Here the susceptance B_{SVC} is 0.2047 p.u. which shows the SVC is operating in capacitive mode. If the SVC has to maintain voltage 0.96 p.u. which is less than the base case then the SVC absorbs 41.86 MVAr from the system. Here the susceptance Bsvc is -0.45 which indicates that the SVC is operating in inductive mode. If the SVC has to maintain voltage which is equal to base case voltage it neither absorbs nor injects reactive power from the system. But here it absorbs a very small value of reactive power from the system almost equal to zero indicates that SVC is not operating. Same analysis is carried out at buses 4, 5 and the corresponding graphs (V_{spec} vs Q_{SVC} and V_{spec} vs B_{SVC}) are shown in Fig 4 and

5. From Fig 4 it is inferred that the reactive power injected/ absorbed depends up on voltage. The plot between V_{spec} and B_{SVC} shown in Fig 5 indicates that SVC can operate either in capacitive mode or inductive mode.

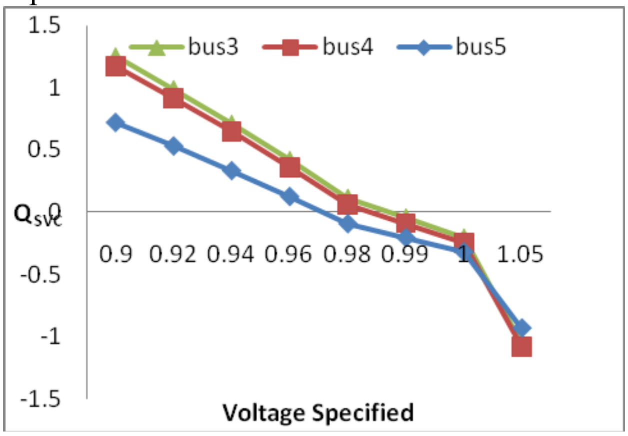


Fig 4: Q_{SVC} vs. V_{spec} with SVC at various buses

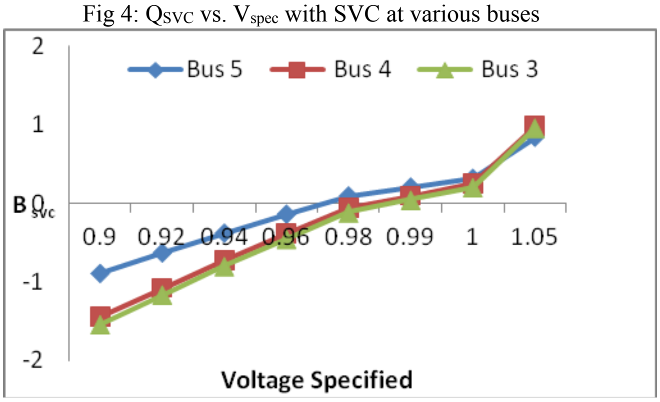


Fig 5: B_{SVC} vs. V_{spec} with SVC at various buses

Table 3
SVC operating modes for specified voltage in standard 5 bus system

Specified Voltage	Q_{svc} (MVAr)	B_{SVC}	Mode
0.9	125.0	-1.544	Inductive
0.92	98.6	-1.166	Inductive
0.94	70.9	-0.8031	Inductive
0.96	41.86	-0.4542	Inductive
0.98	11.3	-0.1185	Inductive
0.987 (base case)	0.01	0.0001	In operative
0.99	-4.37	0.0446	Capacitive
1.0	-20.47	0.2047	Capacitive
1.05	-106.16	0.9629	Capacitive

3.1.4 Analysis of pow er flows with SVC at various locations

The active and reactive power flows in various lines when SVC is placed in different locations is given in Table 4. From the Table it is inferred that the real and reactive power flows in the transmission line has improved when SVC is incorporated in the test system. For example when SVC is placed at bus 3 the incoming lines 1-3 and 2-3 carry less reactive power and the outgoing line 3-4 carry more reactive power compared to base case significantly. This is because the SVC injects the reactive power required by the load and reduces reactive power burden on the generators. Similar case study is carried out at buses 4,5 and the results are given in Table 4.

The active and reactive power loss when SVC is placed at different locations is given in Table 5. From the Table it is observed that the active power loss is reduced by 1.07% when SVC is placed at bus 3. Conversely, the real power loss has increased by 0.96% when SVC is placed in bus 5. This shows that the performance of FACTS devices depends upon the location in which they are placed. Reactive power loss has reduced significantly in all the cases with SVC as given in Table 5.

The active and reactive power generations at the buses are presented without and with SVC in Table 6. When SVC is placed at the load buses it is observed that there is a very minute change in real power generation, but there is a significant change in reactive power generation. The generator at slack bus reduces it generation and the generator at bus 2 absorbs more reactive power compared to base case. This shows that SVC can inject reactive power into the bus which in turn reduces the reactive power burden on the generators.

Table 4
Power Flows of standard 5 bus system without and with SVC at various locations

TL NO	Flow Type	Base case			SVC at 3rd bus			SVC at 4th bus			SVC at 5th bus		
		Sending end	Receiving end	Loss	Sending end	Receiving end	Loss	Sending end	Receiving end	Loss	Sending end	Receiving end	Loss
1-2	Active	89.331	-86.845	2.485	89.109	-86.629	2.480	89.164	-86.682	2.481	89.389	-86.902	2.487
	Reactive	73.995	-72.908	1.086	74.060	-72.989	1.071	74.044	-72.969	1.074	73.978	-72.887	1.090
1-3	Active	41.790	-40.273	1.517	41.946	-40.552	1.394	41.923	-40.562	1.396	41.792	-40.335	1.456
	Reactive	16.820	-17.512	-0.692	11.282	-12.409	-1.126	11.469	-12.586	-1.117	14.497	-15.399	-0.901
2-3	Active	24.472	-24.113	0.359	24.487	-24.093	0.393	24.449	-24.059	0.390	24.351	-23.988	0.362
	Reactive	-2.518	-0.352	-2.870	-9.506	6.687	-2.819	-9.266	6.438	-2.827	-5.433	2.551	-2.882
2-4	Active	27.713	-27.252	0.460	27.659	-27.183	0.476	27.774	-27.269	0.55	27.601	-27.136	0.464
	Reactive	-1.723	-0.830	-2.554	-7.317	4.768	-2.549	-10.415	7.932	-2.483	-5.478	2.907	-2.571
2-5	Active	54.659	-53.444	1.215	54.482	-53.288	1.194	54.458	-53.269	1.189	54.950	-53.638	1.311
	Reactive	5.557	-4.829	0.728	2.746	-2.089	0.657	-1.193	-0.557	0.635	-17.630	18.565	0.935
3-4	Active	19.386	-19.346	0.040	19.645	-19.592	0.053	19.585	-19.541	0.044	19.323	-19.285	0.038
	Reactive	2.864	-4.687	-1.822	11.192	-13.020	-1.828	-8.852	6.986	-1.865	-2.151	0.298	-1.853
4-5	Active	6.598	-6.555	0.043	6.775	-6.711	0.063	6.810	-6.730	0.079	6.422	-6.361	0.060
	Reactive	0.518	-5.170	-4.652	3.252	-7.910	-4.658	4.794	-9.442	-4.647	-8.206	3.432	-4.773

Table 5
Power loss of standard 5 bus system without and with SVC at different locations

Power Loss	Base case	SVC at Bus 3	SVC at Bus 4	SVC at Bus 5
P_{loss} (MW)	6.122	6.056 (-1.07%)	6.087 (-0.57%)	6.181 (0.96%)
Q_{loss} (MVAr)	-10.77	-11.254 (-4.49%)	-11.231 (-4.28%)	-10.955 (-1.71%)

Table 6
Active and Reactive power generations when SVC is incorporated at various buses

Active/ Reactive Power	Generator Outputs			
	Base case	SVC at Bus 3	SVC at Bus 4	SVC at Bus 5
P_{G1} (MW)	131.12	131.06 (-0.05%)	131.08 (-0.04%)	131.18 (0.05%)
Q_{G1} (MVAr)	90.82	85.34 (-6.03%)	85.51 (-5.84%)	88.47 (-2.59%)
P_{G2} (MW)	40	40	40	40
Q_{G2} (MVAr)	-61.59	-77.07 (25.13%)	-81.45 (32.25%)	-91.42 (48.43%)

3.1.5 Analysis with increased Load demand

Here the system is loaded from base to 150% of load at each bus, the voltage magnitudes and power generations at the buses and the power losses in transmission lines are observed without and with SVC.

The base case voltage profile without SVC is compared with increased 150% load without and with SVC at all the load buses in Table 7. When the load is increased from base case to 150% of base, the voltage magnitudes at the load buses are decreased. Now SVC is incorporated at the bus in which load is increased and the performance is observed. Even at 150% of base loading, with SVC the voltage profile at all the buses is increased and are within the desired limits. Here the reactive power injected by SVC to maintain the voltage profile is increased compared to the base case.

The active and reactive power loss at the base case are compared with increase in 150% load without and with SVC. The results are given in Table 8. With the increase in load at the bus the overall active power loss is also increased. From the Table it is summarised that if SVC is placed at the bus 3, the loss is reduced by 2.5% of the loss with increased load. Conversely the real power loss is increased by 0.73% when SVC is placed in bus 5. This shows that the location of FACTS device plays an important role in the reduction of losses in a line. The reactive power loss is reduced significantly in all the cases with SVC is shown in Table 8.

Table 7

Voltage Profile of standard 5 bus system without and with SVC at different locations

Bus No	Voltage Magnitude						
	Base case	Without SVC at Bus 3	With SVC at Bus 3	Without SVC at Bus 4	With SVC at Bus 4	Without SVC at Bus 5	With SVC at Bus 5
B1	1.06	1.06	1.06	1.06	1.06	1.06	1.06
B2	1.00	1.00	1.00	1.00	1.00	1.00	1.00
B3	0.987	0.981	1.00	0.981	0.999 (1.83%)	0.983	0.991 (0.81%)
B4	0.984	0.977	0.994 (1.74%)	0.977	1.00	0.979	0.990 (1.12%)
B5	0.971	0.969	0.975 (0.61%)	0.969	0.976 (0.72%)	0.955	1.00

Table 8

Power loss without and with SVC at various locations

Power Loss	Base case	Without SVC at Bus 3	With SVC at Bus 3	Without SVC at Bus 4	With SVC at Bus 4	Without SVC at Bus 5	With SVC at Bus 5
P_{loss} (MW)	6.122	7.698	7.540 (-2.5%)	7.541	7.495 (-0.6%)	8.865	8.930(0.73%)
Q_{loss} (MVAr)	-10.77	-5.821	-6.799(-16.8%)	-6.366	-7.004(-10.02%)	-2.334	-2.695 (-15.47 %)

Table 9

Real and reactive generations at the buses when SVC is placed at different buses

Power Generation	Base case	Without SVC at Bus 3	With SVC at Bus 3	Without SVC at Bus 4	With SVC at Bus 4	Without SVC at Bus 5	With SVC at Bus 5
P_{G1} (MW)	131.12	155.19	155.04(-0.06%)	152.54	152.49(-0.03%)	163.86	163.93(0.04%)
Q_{G1} (MVAr)	90.81	88.85	78.94(11.15%)	87.39	79.83(8.65%)	83.414	79.79(4.33%)
P_{G2} (MW)	40	40	40	40	40	40	40
Q_{G2} (MVAr)	-61.59	-47.17	-75.29(59.61%)	-51.25	-79.64(55.39%)	-40.74	-87.19(114%)

The real power generation is increased with increase in load at the a bus and there is no major change even when SVC is placed at that bus. The generator at the slack bus generates less reactive power compared to base case and the other generator at bus 2 absorbs more reactive power compared to base case. It is also observed that SVC supplies the desired reactive power with increased load and reduces the reactive power burden on the generators. The above discussed analysis is given in Table 9.

3.2 IEEE30 bus system:

3.2.1 Analysis without FACTS devices:

Load flow analysis using Newton Raphson method is carried out on IEEE 30 bus system without any FACTS devices. The voltage magnitudes obtained at each bus are shown in Fig 6. From the fig it is observed that the voltage magnitudes of many buses are not in desired limits. The active power loss obtained in this case is 18.313MW and the reactive power loss obtained is 59.398 MVAr.

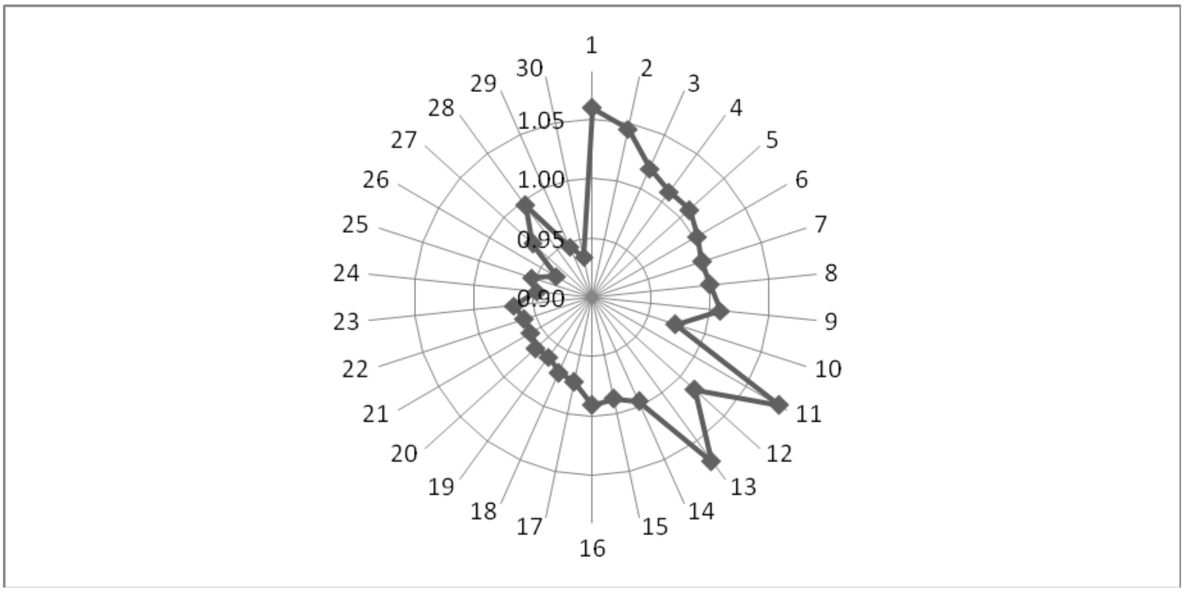


Fig 6: Voltages Magnitudes at the buses for IEEE 30 bus system

3.2.2 Load flow analysis with SVC:

A similar case study is done on IEEE 30 bus system by placing SVC at buses 21, 22, and 24. For instance, when SVC is placed in bus 21, it improves the voltage to 1.00 p.u. from base case voltage of 0.960 p.u. The voltages at the other buses are also improved significantly. This shows the ability of SVC in improving the voltage profile of the test system. Results with SVC placed at buses 21, 22 and 24 are given in Table 10. In Fig 7 the voltage profile of IEEE 30 bus system without and with SVC is given.

In IEEE 30 bus system SVC is placed at bus 21 and the characteristics of specified voltage (V_{spec}) vs reactive power (Q_{svc}) and susceptance (B_{svc}) are given in Table 11. Here the performance of SVC operating in inductive and capacitive modes is clearly observed. By placing SVC at buses 21, 22 and 24 the characteristics of specified voltage (V_{spec}) vs reactive power (Qsvc) are plotted in Fig 8.

Table 10

Voltage Profile without and with SVC at various locations

Bus No	Voltage Magnitude			
	Base Case	SVC at Bus 21	SVC at Bus 22	SVC at Bus 24
1	1.060	1.060	1.060	1.060
2	1.045	1.045	1.045	1.045
3	1.019	1.021	1.021	1.021
4	1.010	1.013	1.013	1.013
5	1.010	1.010	1.010	1.010
6	1.002	1.005	1.005	1.005
7	0.997	0.999	0.999	0.999
8	1.000	1.000	1.000	1.000
9	1.008	1.022	1.022	1.019
10	0.974	1.001	1.000	0.993
11	1.082	1.082	1.082	1.082
12	1.016	1.025	1.025	1.026
13	1.071	1.071	1.071	1.071
14	0.996	1.008	1.008	1.010
15	0.987	1.002	1.002	1.005
16	0.991	1.008	1.007	1.005
17	0.973	0.998	0.997	0.991
18	0.970	0.989	0.989	0.988
19	0.962	0.985	0.984	0.982
20	0.964	0.988	0.987	0.984
21	**0.960**	**1.000**	0.997	0.986
22	**0.961**	0.998	**1.000**	0.988
23	0.966	0.986	0.987	0.999
24	**0.947**	0.975	0.976	**1.000**
25	0.954	0.973	0.974	0.990
26	0.935	0.955	0.956	0.972
27	0.968	0.981	0.982	0.993
28	0.996	1.000	1.000	1.001
29	0.947	0.960	0.961	0.972
30	0.935	0.948	0.949	0.960

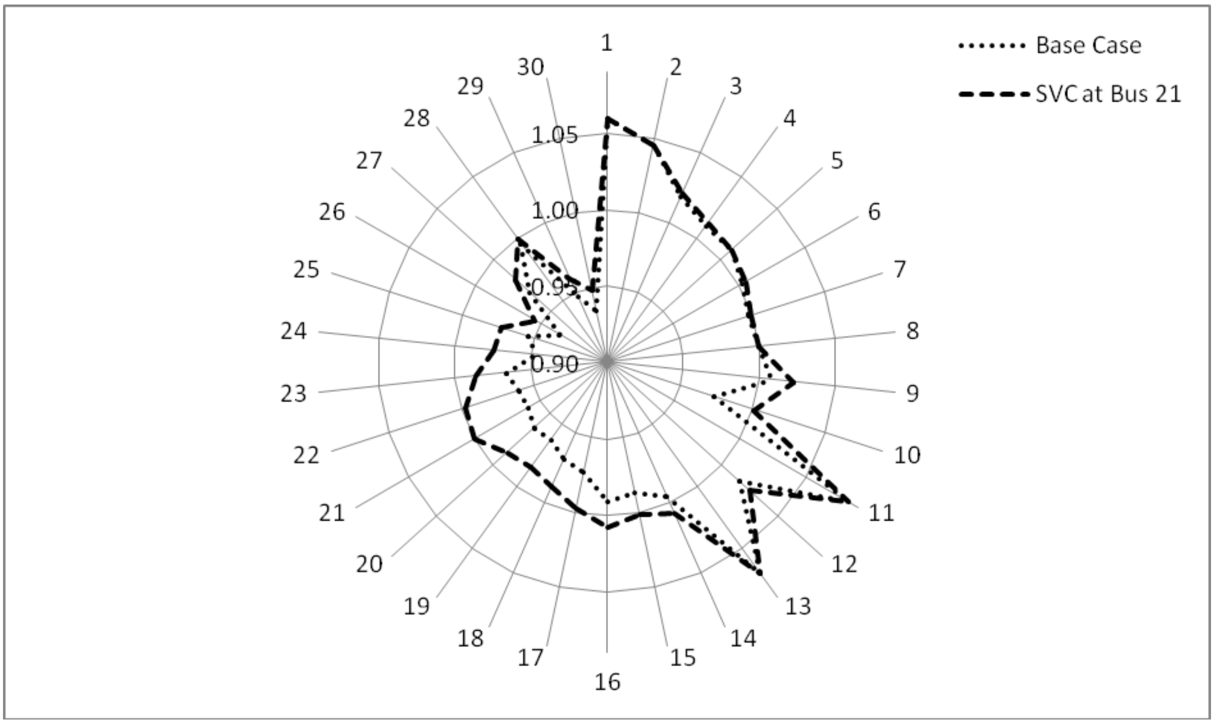


Fig 7: Comparison of voltage profile without and with SVC at bus 21

Table 11
SVC operating modes for specified voltage in IEEE 30 bus system

Specified Voltage	Qsvc (Bus 21)	B_{SVC} (Bus 21)	Mode
0.9	0.3653	-0.451	Inductive
0.92	0.2494	-0.2946	Inductive
0.94	0.1276	-0.1444	Inductive
0.96 (base case)	0.0001	0.0001	In operative
0.98	-0.1334	0.1389	Capacitive
0.99	-0.2023	0.2017	Capacitive
1.0	-0.2727	0.2675	Capacitive
1.05	-0.6467	0.5795	Capacitive

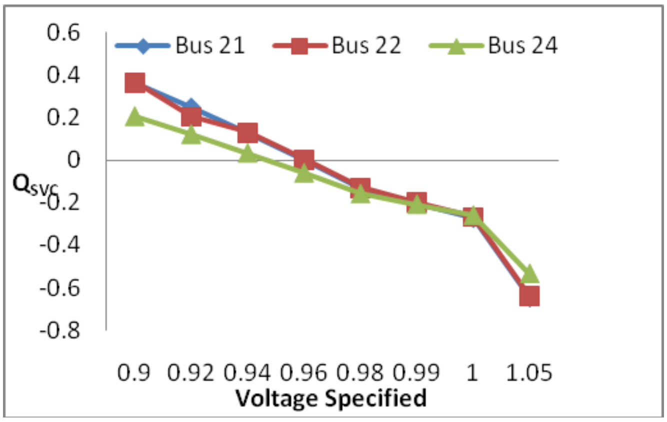


Fig 8: Variation : Q_{SVC} vs. V_{spec} with SVC at various buses in IEEE 30 bus system

The active and reactive power losses while placing SVC at buses 21, 22 and 24 are given in Table 12. From the table it is inferred that the losses are different at each location and found to be very less compared to base case when SVC is placed at bus 21.

Table 12
Power loss of IEEE 30 bus system without and with SVC at various locations

Power Loss	Base case	SVC at Bus 21	SVC at Bus 22	SVC at Bus 24
P_{loss} (MW)	18.313	17.945	17.962	17.946
Q_{loss} (MVAr)	59.398	55.852	55.936	56.105

3.3 Load flow analysis with TCSC

3.3.1 Modes of operation of TCSC and power loss in standard 5 bus system

The modes of operation of TCSC for active power flow is discussed in Table 13. TCSC is placed in line 3-4 in standard 5 bus system and the performance is analysed. The base case power flow in line 3-4 is 19.38 MW. For instance if the power flow is increased by 50% (29.16 MW) then the TCSC reactance is -0.0958 which shows that it is in capacitive mode. We can also observe the power flows in certain lines are increased and in some lines it is decreased. Now if the power flow in line 3-4 is decreased by 50% (9.70 MW) then the TCSC reactance is 0.2581 which shows it is in Inductive mode. So we observe that TCSC not only helps in improving Power flow in a line, it also helps in reducing the power flow if required.

Table 13
Mode of TCSC with Change in Power flow

Line/ reactance	Actual Power Flow (MW)	Rise 50% (MW) in Line 3-4	Decrease 50 % (MW) in Line 3-4
1--2	89.33	85.43	93.27
1--3	41.79	45.79	37.88
2--3	24.47	30.68	18.28
2--4	27.71	21.02	34.36
2--5	54.65	51.32	58.04
3--4	**19.38**	**29.16**	**9.70**
4--5	6.59	9.83	3.34
Reactance	--	-0.0958	0.2581
Mode	--	Capacitive	Inductive

Table 14
Power flow in Standard 5 bus system without and with TCSC when Line 2-4 is removed

Line/ Power Loss	Actual Power Flow (MW)	Power Flow with Contingency in Line 2-4	Power Flow with Contingency in Line 2-4 and TCSC in Line 3-4.
1--2	89.33	82.10	79.61
1--3	41.79	49.92	52.49
2--3	24.47	37.04	41.01
2--4	27.71	--	--
2--5	54.65	62.73	56.32
3--4	19.38	39.03	45.21
4--5	6.59	-1.127	5.00
Active Power Loss	6.12	7.03	7.10

The performance of TCSC for single line contingency is shown in Table 14. Line 2-4 of standard 5 bus system is taken as line with contingency. It was observed that the power flow other lines is increased and the line 2-5 has highest power flow of 62.73MW. Now TCSC is placed in line 3-4 and the power flow in that line is increased from 39.03MW to 45.21MW. With this the over loading of the line 2-5 is reduced to 56.32MW which is an acceptable value. The power flows in remaining lines are also in desirable limits. With contingency the losses in the lines are increased but they were in acceptable limits. The power flows of all the lines before and after contingency with placing TCSC in line 3-4 are given in Table 14.

3.3.2 Analysis with single line con tingency in IEEE 30 bus test system:

Single line Contingency analysis in IEEE 30 bus system with and without TCSC is shown in Table 15. Line 4-12 is considered as the line with contingency and is removed.

Table 15
Power flows without and with TCSC when line 4-12 is removed

SNo	Line	Power Flow with Line 4--12 removed	Power Flow with Line 4--12 removed and TCSC in 4--6	Power Flow with Line 4--12 removed and TCSC in 2--5	Flow Limit (MW)
1	1--2	183.707	191.974	195.982	130
2	1--3	81.490	73.972	73.607	130
3	2--4	42.152	30.369	28.918	65
4	3--4	76.390	69.340	68.988	130
5	2--5	86.279	92.316	**128.774**	130
6	2--6	**67.709**	**81.176**	49.903	65
7	4--6	**109.242**	**90.965**	89.189	90
8	5--7	-11.148	-5.575	25.800	70
9	6--7	34.465	28.715	-2.293	130
10	6--8	31.505	31.460	31.520	32
11	6--9	51.953	52.245	52.302	65
12	6--10	28.922	29.115	29.128	32
13	9--11	0.000	0.000	0.000	65
14	9--10	51.953	52.245	52.302	65
15	4--12	--	--	--	-
16	12--13	0.000	0.000	0.000	65
17	12--14	3.524	3.677	3.688	32
18	12--15	-1.179	-1.159	-1.155	32
19	12--16	-13.546	-13.717	-13.733	32
20	14--15	-2.733	-2.591	-2.581	16
21	16--17	-17.387	-17.638	-17.661	16

22	15--18	-5.079	-5.096	-5.100	16
23	18--19	-8.366	-8.410	-8.417	16
24	19--20	-17.940	-17.999	-18.007	32
25	10--20	20.694	20.751	20.763	32
26	10--17	27.002	27.321	27.353	32
27	10--21	18.189	18.255	18.271	32
28	10--22	9.190	9.232	9.242	32
29	21--22	0.522	0.594	0.609	32
30	15--23	-7.277	-7.177	-7.165	16
31	22--24	9.626	9.743	9.769	16
32	23--24	-10.658	-10.597	-10.589	16
33	24--25	-10.151	-10.008	-9.979	16
34	25--26	3.552	3.551	3.551	16
35	25--27	-13.931	-13.784	-13.756	16
36	28--27	27.487	27.326	27.299	65
37	27--29	6.206	6.204	6.205	16
38	27--30	7.112	7.110	7.111	16
39	29--30	3.709	3.708	3.708	16
40	8--28	1.373	1.330	1.363	32
41	6--28	26.241	26.119	26.065	32
Active Power Loss		21.790	23.510	26.180	-

Then the lines 4-6 and 2-6 carries 109.242MW and 67.709MW which indicates overloading. Now TCSC is incorporated in the overloaded line 4-6 to limit the power flow below the flow limit. The power flow in the line is brought down to specified value but the other line 2-6 is even more overloaded compared to base case. When TCSC is placed in line 2-5 and the power flow is raised up to the its maximum flow limit of 128.77MW then the two lines 4-6 and 2-6 carries power below the flow limit. Even though the losses in the lines are increased slightly, continuity in power flow under the flow limit is achieved. From the above discussed two cases it is observed that choice of location of TCSC plays a key role in contingency analysis.

4 Conclusion

This paper investigates the effects of installing SVC and TCSC in the power system network in terms of voltage profile, power flows and losses in transmission lines. The load flow solution with SVC and TCSC are conducted on standard 5 bus system and IEEE 30 bus system. By installing the FACTS devices the voltage profile at the buses are improved and power losses in the lines are reduced. The transmission lines can be loaded above or below the base value with incorporation of TCSC to meet the required load demand. TCSC helps in controlling power flows in lines to an acceptable value in case of contingency is shown. This analysis shows that proper choice and location of FACTS devices improves the performance of existing power transmission network.

References:

[1] Hingorani, Narain G., and Laszlo Gyugyi. *Understanding FACTS: concepts and technology of flexible AC transmission systems*. Ed. Mohamed El-Hawary. Vol. 1. New York: IEEE press, 2000.

[2] Rao, B. Venkateswara, and GV Nagesh Kumar. "Optimal power flow by BAT search algorithm for generation reallocation with unified power flow controller."*International Journal of Electrical Power & Energy Systems* 68 (2015): 81-88.

[3] Bhattacharyya, Biplab, Vikash Kumar Gupta, and Sanjay Kumar. "UPFC with series and shunt FACTS controllers for the economic operation of a power system." *Ain Shams Engineering Journal* 5.3 (2014): 775-787.

[4] Gasperic, Samo, and Rafael Mihalic. "The impact of serial controllable FACTS devices on voltage stability." *International Journal of Electrical Power & Energy Systems* 64 (2015): 1040-1048.

[5] Saadat, Hadi. *Power system analysis*. McGraw-Hill Primis Custom, 2002.

[6] Acha, Enrique, et al. *FACTS: modelling and simulation in power networks*. John Wiley & Sons, 2004.

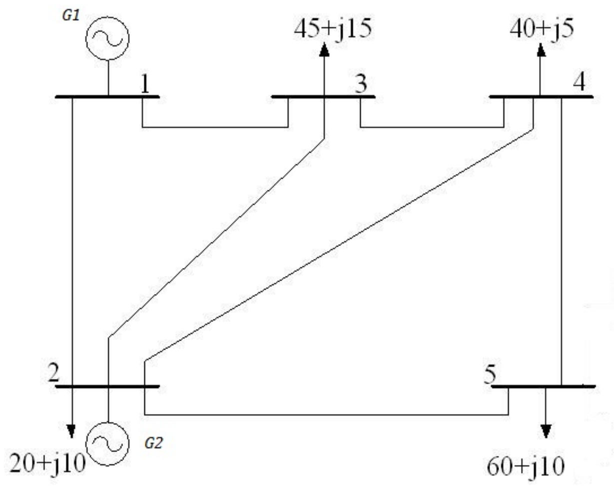
[7] Arboleya, P., C. Gonzalez-Moran, and M. Coto. "Modeling FACTS for power flow purposes: A common framework." *International Journal of Electrical Power & Energy Systems* 63 (2014): 293-301.

[8] Kothari, D. P., and I. J. Nagrath. *Modern power system analysis*. Tata McGraw-Hill Education, 2003.

[9] Singh, S. N., and A. K. David. "Optimal location of FACTS devices for congestion management." *Electric Power Systems Research* 58.2 (2001): 71-79.

[10] Singh, Rudra Pratap, V. Mukherjee, and S. P. Ghoshal. "Particle swarm optimization with an aging leader and challengers algorithm for optimal power flow problem with FACTS devices." *International Journal of Electrical Power & Energy Systems* 64 (2015): 1185-1196.

Appendix 1:



Single line diagram of standard five bus system