Performance and Stability Analysis of Series Compensated Multi-Area Network using Facts Devices (TCSC & SSSC)

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Abstract: Now a days due to the ever increasing demand of power, the transmission line are to be operated under loaded condition and that's why there is a risk of power flow control and voltage instability. Voltage stability is an essential factor, which needs to be taken into attention during the planning and operation of electrical power systems in order to avoid voltage collapse and consequently partial or full system blackout. By the analyzing of the voltage stability, system operators need to know not only the severity of the system instability, but also the mechanisms that cause voltage instability in the system. In this paper by application of TCSC and SSSC facts devices in the transmission network, the power flow control as well as voltage stability have been studied. The TCSC and SSSC are a series compensated device to reduce the transmission line reactance in order to improve power flow as well as to improve the voltage profile also. A systematic procedure for modelling and simulation by application of facts devices using MATLAB/SIMULINK have been presented. The optimal location of TCSC and SSSC device are considered for power flow control and voltage stability limit. The proposed approach is carried out on four-area, eight-machine, and 17-bus test system in order to simulate and validate the system. The paper also compiles the results of improvement by the application of the above series compensated facts devices.

***Keywords*— FACTS devices (TCSC, SSSC), Four-area 17 bus test system model, MATLAB/SIMULINK, Power Flow, Voltage Stability.**

I. INTRODUCTION

For growing demand of electricity, traditional solution for up gradation of the existing electrical transmission system infrastructure has become essential. However due to difficulties in the process to permit, site and construct new transmission line, substation and associated equipments etc have become extremely difficult, expensive, time consuming and controversial solutions. Thus it is necessary to rely on utilizing of existing generating units and to load the existing transmission system to this thermal limit and to maintain the stability with minimum loss in the transmission line [1]. Flexible AC transmission system (FACTS) devices play an important role in controlling the power enhancing the existing usable capacity. FACTS device use to enhance controllability to increase the power transfer capability.

Presently voltage collapse is a major problem in power system which occurs due to voltage instability. FACTS controller including static synchronous series compensator (SSSC) and Thyristor controlled series capacitor (TCSC) are capable to control the network condition in a very fast way to improve voltage stability. Voltage instability occur in the power system due to instability of the system to meet reactive power demand. This reactive power imbalance may occur due to system fault or heavily loaded line and voltage fluctuation in the line. Reactive power imbalance can be removed by using FACTS devices in transmission line which can inject or absorb reactive power in the system as per requirements. Thus TCSC and SSSC are series compensated device in the power system to improve voltage stability through voltage magnitude control and at the same time regulating the active and reactive power flow [2].

II. STATIC SYNCHRONOUS SERIES COMPENSATOR (SSSC)

Static synchronous series compensator (SSSC) works like the STATCOM except that it is serially connected instead of shunt. The schematic diagram of the SSSC is shown in the fig.1 which shows three basic component.
(a) Voltage source converter (VSC): main component,
(b) Transformer: couple the SSSC to the transmission line,
(c) Energy source: provides voltage across the DC capacitor and compensate the device losses [3].

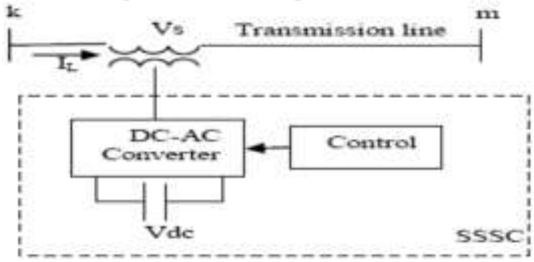

Figure 1. Simplified Diagram of SSSC

SSSC when operated with the proper energy supply it can inject a voltage component which is of the same magnitude but opposite in phase angle with the voltage developed across the line. As a result the effect of the voltage drop on power transmission is off set. The SSSC is able to transfer both active and reactive power to the system permitting it to compensable for the resistive and reactive voltage drops, maintaining high effective (X/R) ratio that is independent of the degree of series compensation.

III. THYRISTOR CONTROLLED SERIES CAPACITOR (TCSC)

The Tyristor controlled series capacitor (TCSC) is a FACTS device which comprise of a tyristor controlled reactor (TCR) in parallel with a capacitor bank. This combination provides a smooth control of the fundamental frequency capacitive reactance over a wide range. This FACTS device is used for series compensation of transmission lines. Fig.2 shows a schematic representation of a TCSC connected transmission line.

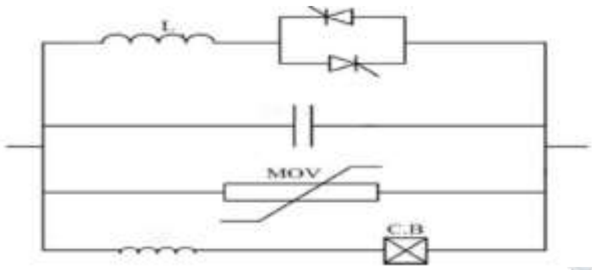

Figure 2. TCSC Circuit Configuration

The major objective in applying TCSC is to rise power transfer capacity in electrical transmission line under emergency condition as well as to improve the voltage stability over the system [3].

In an interconnected power system the actual transfer of power from one region to other might take unintended rout depending on impedance of transmission line connecting the areas. TCSC is a useful device for optimizing power flow between region of varying loads and network of different configuration. Besides this TCSC is a type of series compensator, which can be used for improvement of voltage stability of the system.

IV. VOLTAGE STABILITY

Voltage stability is essentially an aspect of stability of the load connected to a receiving end bus or a load bus. It may be noted that the receiving end voltage in a power transmission system is a function of the sending end voltage, surge impedance, line length and load along with its power factor. Figure 3 represents the profile of receiving end voltage, for a particular line, at different loading and operating power factor conditions [4].

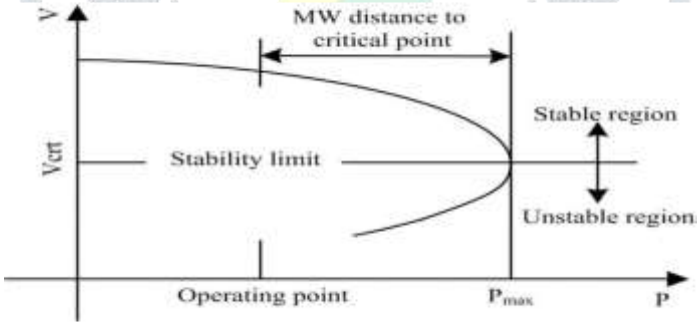

Figure 3. Sketch Map for P-V Curve

Voltage instability is caused by the mismatch of reactive power generation and absorption. The reactive power balance at any point of time is given as: $\sum Q_G + \sum Q_{TL-Net} - \sum Q_L \pm \sum Q_C = 0$.

Where Q_G is reactive power generated by the alternator, Q_L is reactive power consumed by the load, Q_{TL-Net} is the net reactive power generated by the transmission line – mostly a positive quantity for long EHV lines and Q_C is the VAR added to or subtracted from the system by compensating devices. The last term is absent if there are no compensating devices like capacitors or inductors at the terminal of the transmission lines. For the effective and reliable operation of power system the following objectives are to be fulfilled:

- Voltage at the terminals of all equipment must be within acceptable limits. Prolonged operation beyond the acceptable range is highly objectionable.
- System stability is enhanced to make the maximum utilization of the Transmission lines.
- Reactive power flow is minimized to reduce the ohomic losses and voltage drop/rise in the Transmission lines.

Fulfilling these objectives is a difficult task as there are numerous no of loads and large no of generators as well as TLs in an interconnected grid. As reactive power can not be transmitted over long distance in order to keep a good voltage profile, compensating device have to be used at vulnerable points.

V. SYTEM DESCRIPTION

A. Four Area Test System Model with SSSC

A Four Area Network with 17 bus and 8 machine test system has been developed to evaluate the operation of SSSC model. Figure_4 show the proposed single line diagram of 17 bus 8 machines power system with installed SSSC Series Fact device has been considered [5].

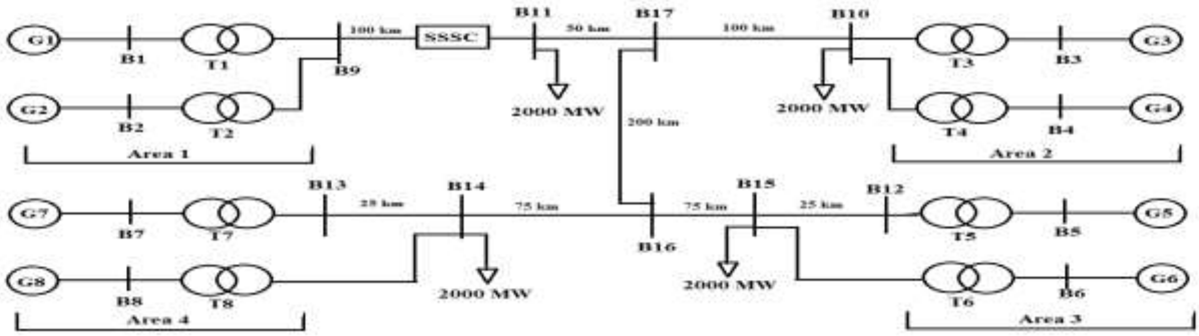

Figure 4. Four area test system single line diagram with SSSC

B. Test System Simulation Model of SSSC using Matlab Simulink

All the relevant parameters are given in Appendix. The source voltages of 13.6 kV are connected by transmission line through three-phase step-up transformers. The system consists of Four Areas with 8 Generators. Area 1 and Area 2 are connected by a 250 km Transmission line. Area 3 and Area 4 are connected by a 200km Transmission line. Area 1 and 2 and Area 3 and 4 are interconnected by a 200km Transmission line. Bus 1, 2, 3, 4, 5, 6, 7 and 8 are connected with 1200MVA, 1500MVA, 1000MVA, 1200MVA, 1000MVA, 1500 MVA, 2000MVA and 1500MVA generator respectively. Bus 1 is set as the swing bus even though the others are considered as PV buses. The rest of buses of this system are considered as PQ buses.The SSSC is connected at bus 11. The loads in each area having 2000MW are so taken that the real power flow into the transmission line over area 1 to 2 and Area 4 to Area 3 [5],[6]. The SSSC used for this model is a phasor model is shown in figure_5.

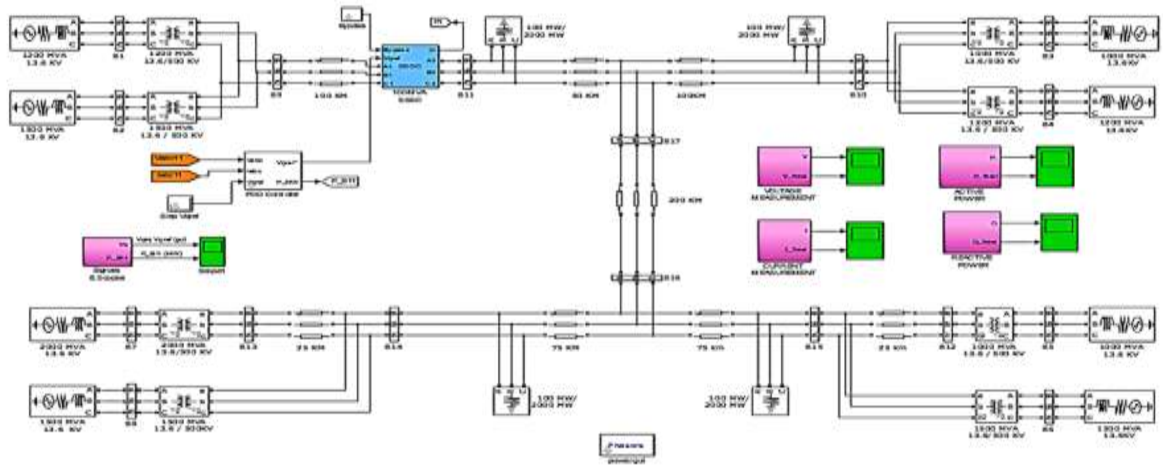

Figure.5. Simulink model of 17 bus power system with installed SSSC at bus 11.

C. Four-Area Test System Model with TCSC

A Four Area Network with 17 bus and 8 machine test system has been developed to evaluate the operation of TCSC model. Figure_6 show the proposed single line diagram of 17 bus 8 machine's power system with installed TCSC Series Fact device has been considered.The Series TCSC Fact device is connected between bus 9 and bus 11. The G1, G2, G3, G4, G5, G6, G7, G8 represent the generators and T1, T2, T3, T4, T5, T6, T7, T8 represent the transformers [7].

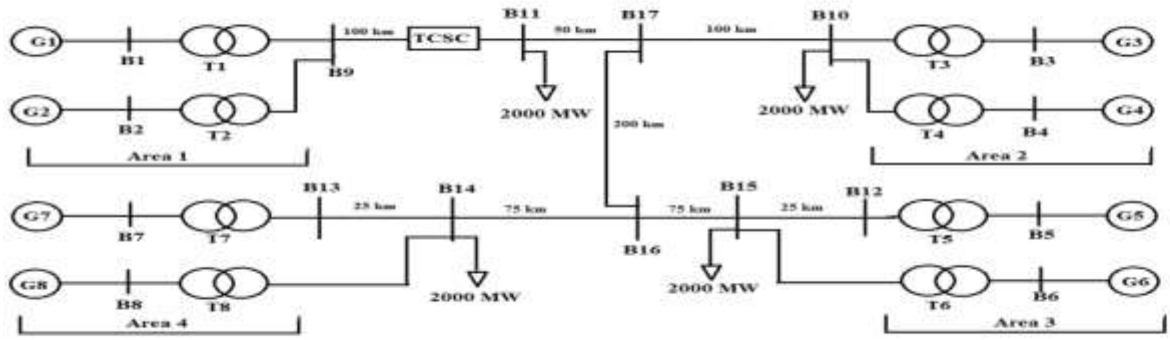

Figure 6. Four area test system single line diagram with TCSC

D. Test System Simulation Model of TCSC using Matlab Simulink

All the relevant parameters are given in Appendix. The source voltages of 13.6 kV are connected by transmission line through three-phase step-up transformers. The system consists of Four Areas with 8 Generators. Area 1 and Area 2 are connected by a 250 km Transmission line. Area 3 and Area 4 are connected by a 200km Transmission line. Area 1 and 2 and Area 3 and 4 are inter-connected by a 200km Transmission line. Bus 1, 2, 3, 4, 5, 6, 7 and 8 are connected with 1200MVA, 1500MVA, 1000MVA, 1200MVA, 1000MVA, 1500 MVA, 2000MVA and 1500MVA generator respectively. Bus 1 is set as the swing bus even though the others are considered as PV buses. The rest of buses of this system are considered as PQ buses.The TCSC is connected at bus 11. The loads in each area having 2000MW are so taken that the real power flow into the transmission line over area 1 to 2 and Area 4 to Area 3 [8],[9]. The TCSC used for this model is a phasor model is shown in figure_7.

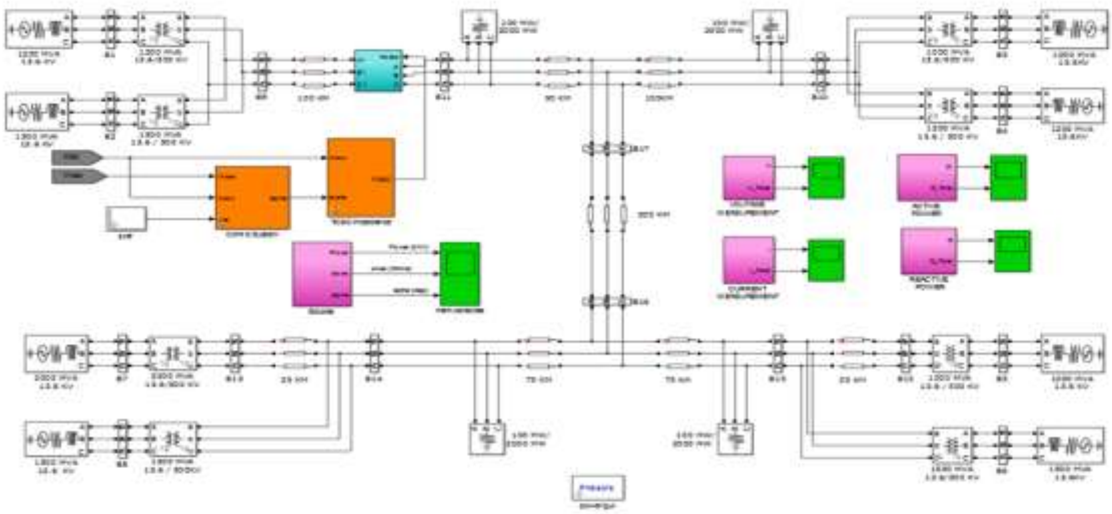

Fig.7. Simulink model of 17 bus power system with installed TCSC at bus 11. (For capacitive mode only)

VI. MEASUREMENT CIRCUIT

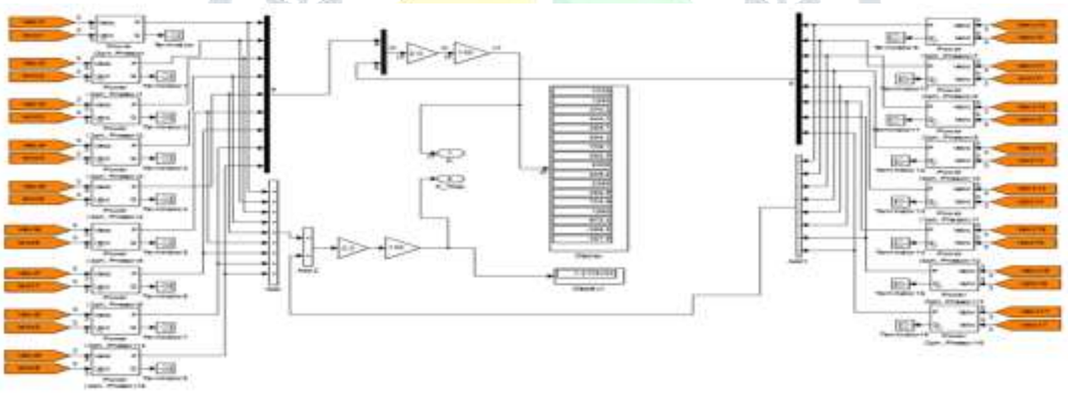

Figure 8. Block represent Active power (P) of all buses and the sum of total power at buses.

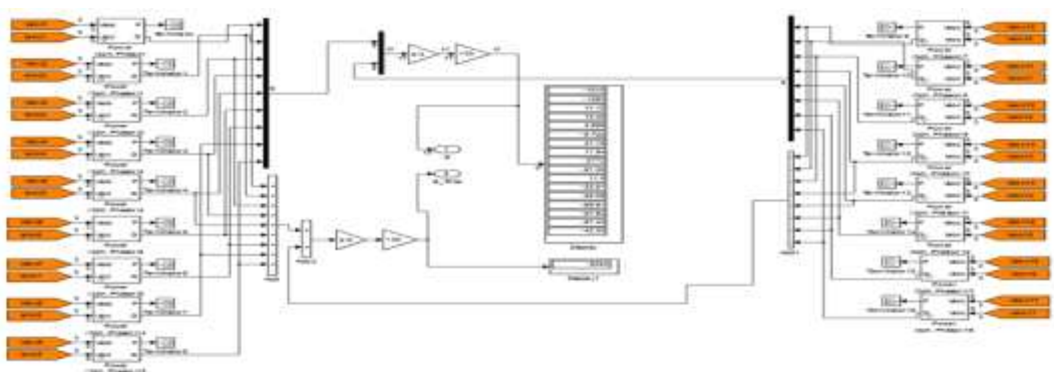

Figure 9. Block represent Reactive power (Q) of all buses and the sum of total reactive power at all buses.

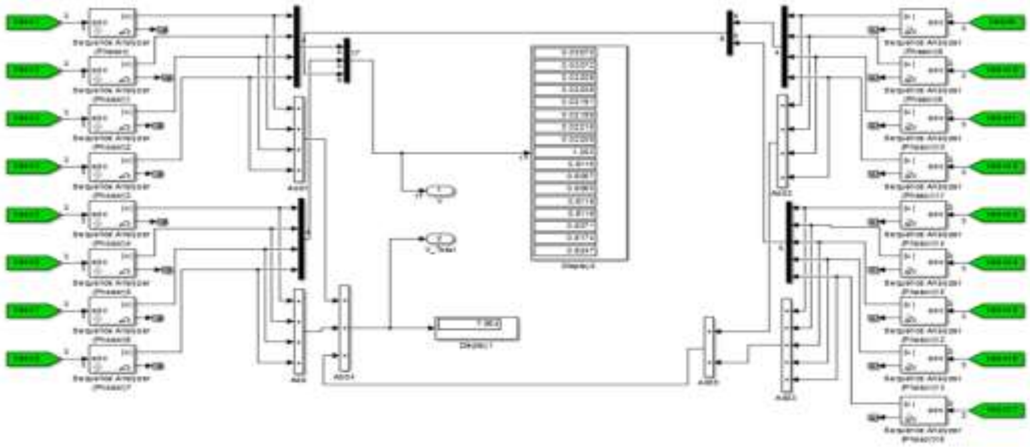

Figure10. Block representation of voltage control by Series FACT device at different buses and sum of total voltage

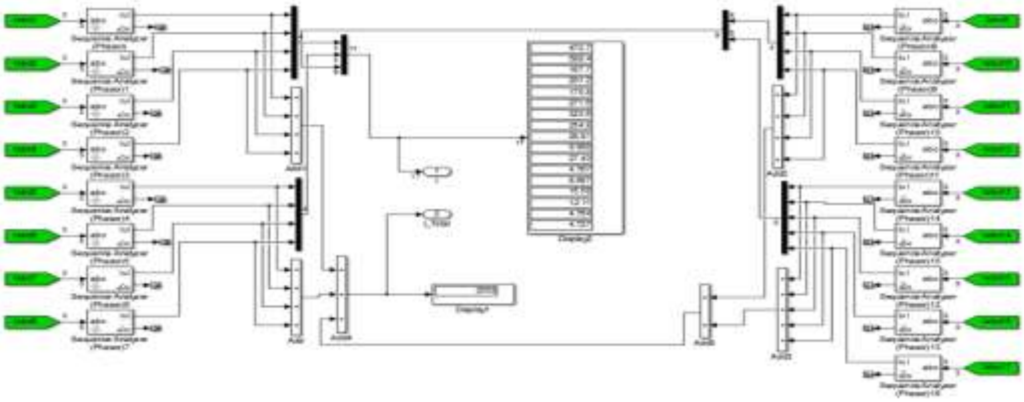

Figure11. Block representation of Currents at different buses and sum of total Current

VII. SIMULATION RESULT

A. *Simulation Results for Power Flow Control*

The simulation results are given below:

a. *Simulation Results of TCSC*

The simulation curves of TCSC blocks regarding time display the TCSC voltage, TCSC current, Active and Reactive power, TCSC impedance and firing angle are shown in figure 12. For the first 0.5s, the TCSC is bypassed and at 0.5s TCSC start to control the impedance towards 128Ω and this improves power transfer. The TCSC starts to regulate with alpha at 90^0 to enable lowest switching disturbance on the line. In this paper the TCSC work in capacitive mode only and control the firing angle 90^0 initially from 0 to 0.5 sec after that decline up to 75.6^0 from 0.56sec to 2.5sec. The capacitive mode begins at 2.5 to 5 sec and the firing angle is constant and maintain 82.35^0 at this value the impedance of TCSC is measure 121.6Ω along the reference value 121.7Ω is shown in figure_12 [10].

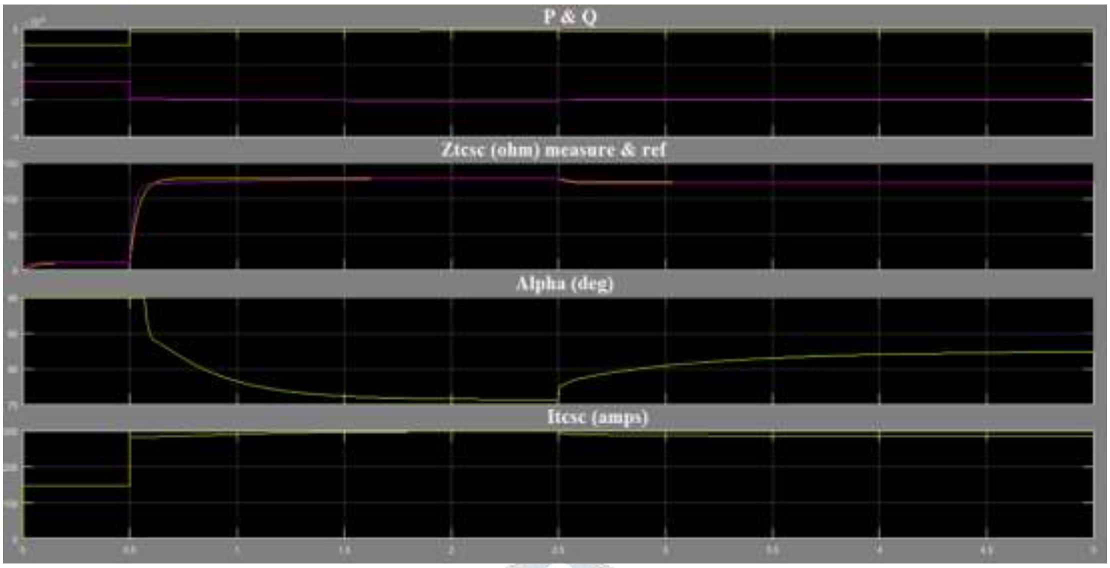

Figure 12. TCSC injected Active, Reactive Power and TCSC regulates the impedance with respect to firing angle.

The TCSC fact device set up at Bus 11 over 17 bus system to observe the active power flow in all the buses, the power at bus B1, B2, B3, B4, B5, B6, B7, B8, B9, B10, B11, B12, B13, B14, B15, B16 and B17 are detected and total power will be improved by TCSC is 14110 MW is shown in figure 13.

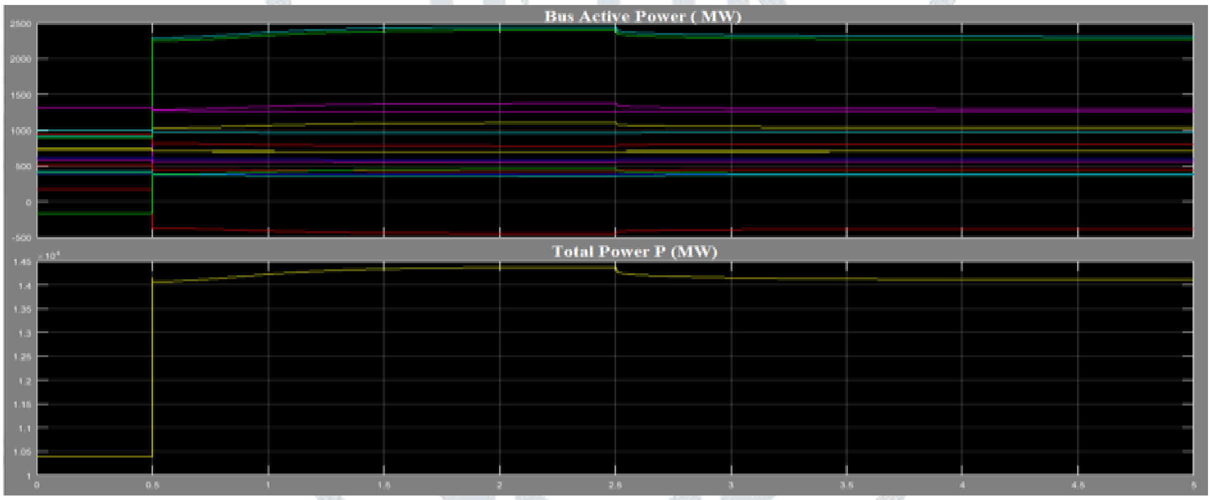

Figure 13. Active power (P) of all buses and sum of total active power at the buses.

The Reactive power flow by TCSC at different buses has been observed and evaluate that the total power will be improved by TCSC is -5324 MVAr shown in figure 14. (Block representation and graphical output)

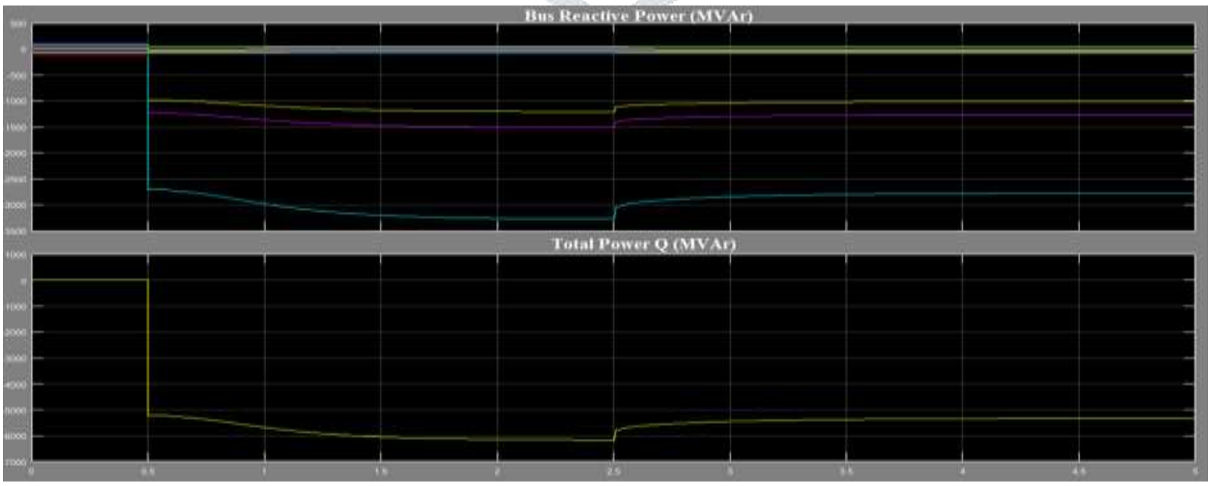

Figure 14. Reactive power (Q) of all buses and sum of total reactive power at the buses.

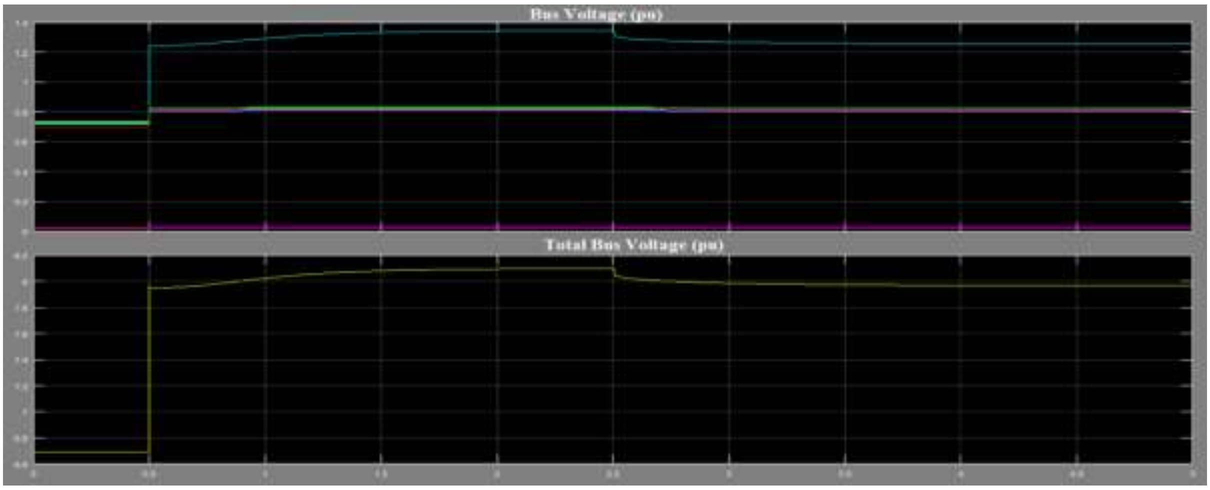

Figure 15. Graphically represent the bus voltage control by TCSC device at different buses and sum of total voltage.

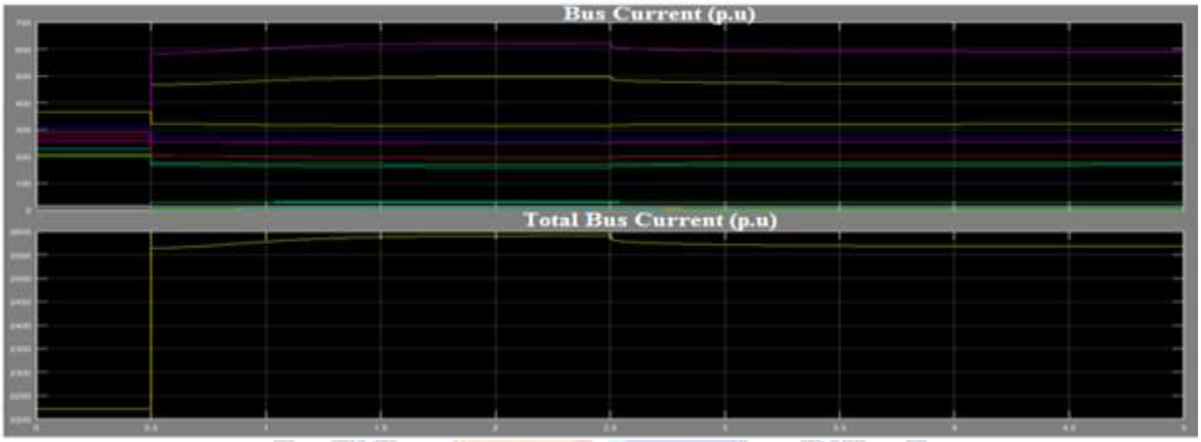

Figure 16. Graphically represent the bus current at different buses and sum of all bus current.

b. Simulation Results of SSSC

The SSSC has connected at bus B11 which is in series with 150 Km transmission line. It has a 100 MVA rating and is capable to injecting up to 10% of the nominal system voltage. This SSSC has a DC link nominal voltage of 40 kV through an equivalent capacitance of 375 uF. Its total equivalent impedance is 0.16 pu on 100 MVA on the AC side. This impedance denotes the transformer leakage reactance. The SSSC injected voltage reference is normally set by a POD (Power Oscillation Damping) controller whose output is interconnected to the Vqref input of the SSSC. An active power measurement system, a general gain, a low-pass filter, a washout high-pass filter, a lead compensator and an output limiter are comprising together in a POD controller. The inputs to the POD controller are the bus voltage at B2 and the current flowing in 50 Km line. Initially Vqref is set to 0 pu; at t=1 s, Vqref is set to -0.08 pu (SSSC inductive); then at t=3 s, Vqref is set to 0.08 pu (SSSC capacitive). The graph displays the Vqref signal along with the measured injected voltage by the SSSC and the active power flow (Bus.11) on 50 Km line, measured at bus B11. It shown that the SSSC regulator follows very well the reference signal Vqref. Depending on the injected voltage, the power flow on line varies from 805MW to 972 MW [11].

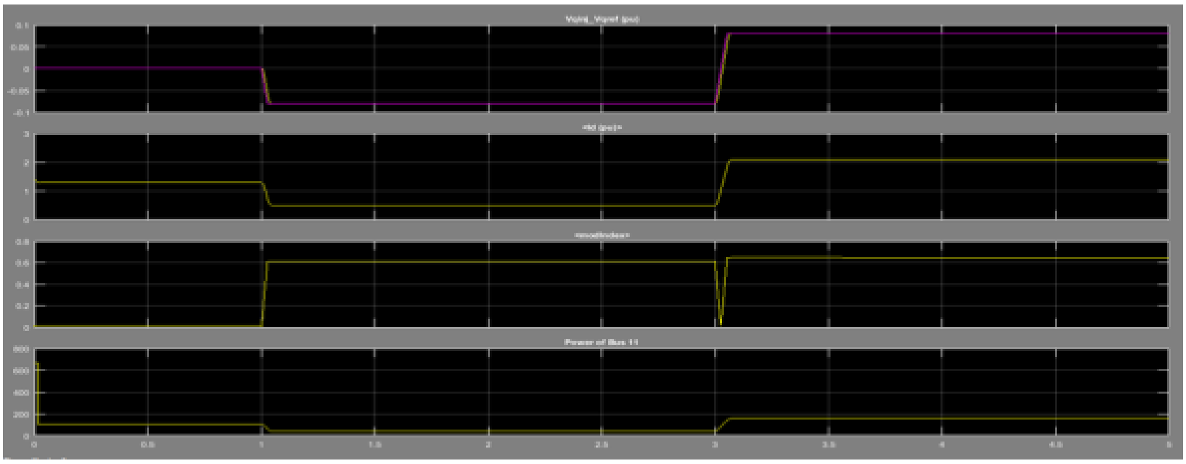

Figure17. Variation of Injected Voltage and power flow at Bus 11

The SSSC fact device connected at Bus 11 over 17 bus system to observe the active power flow in all the buses, the power at bus B1, B2, B3, B4, B5, B6, B7, B8, B9, B10, B11, B12, B13, B14, B15, B16 and B17 are observe and total power will be improved by SSSC is 10580 MW is shown in figure 18.

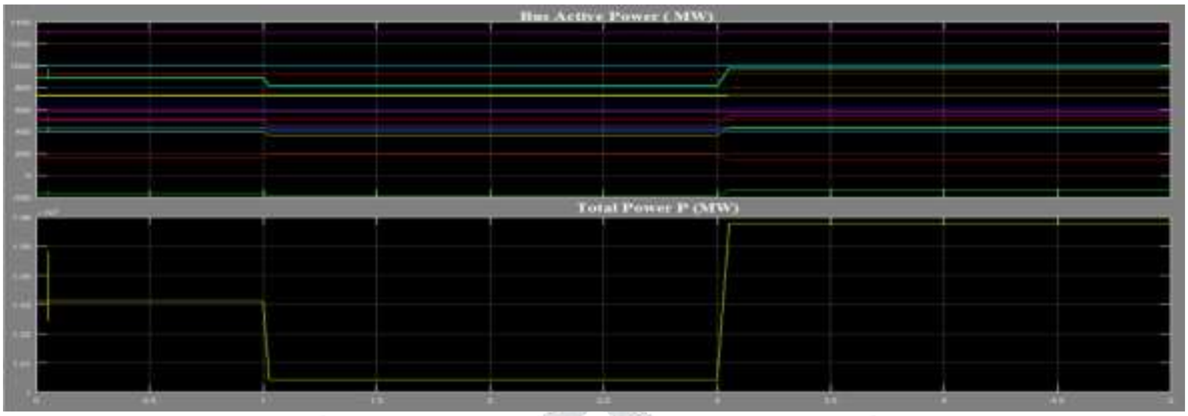

Figure 18. Active power (P) of all buses and sum of total active power at the buses.

The Reactive power flow control by SSSC at buses, the total power will be improved by SSSC is -95.9 MVAr shown in figure 19. (Block representation and graphical output)

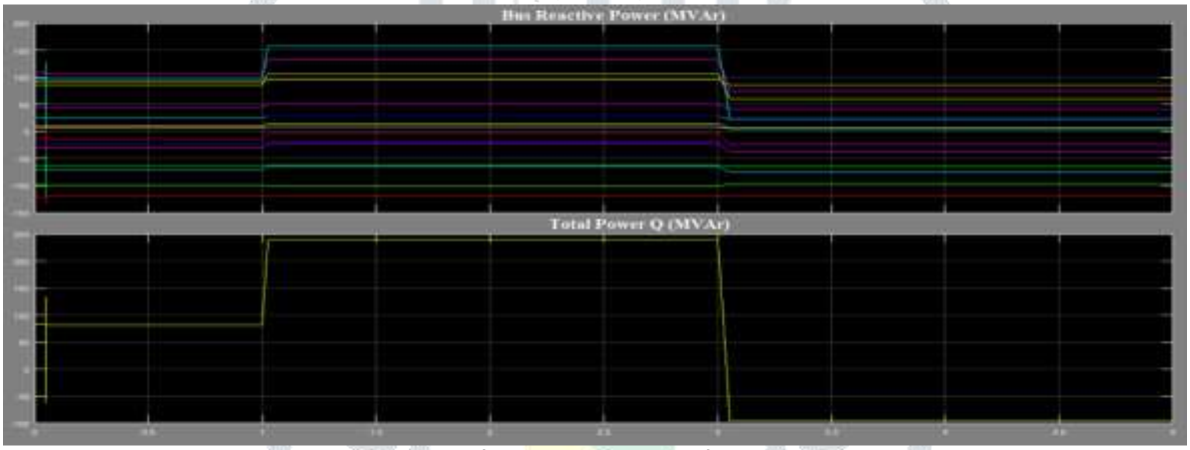

Figure 19. Reactive power (Q) of all buses and sum of total reactive power at the buses

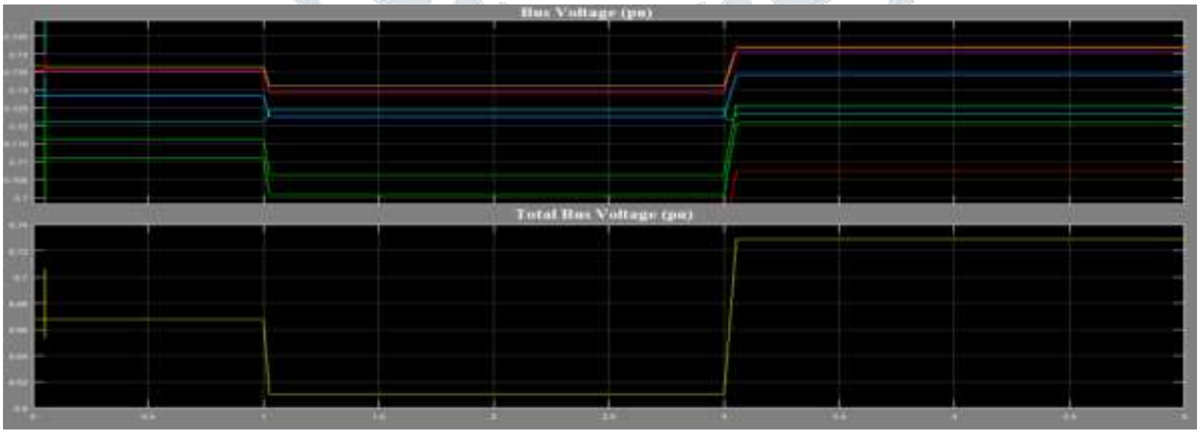

Figure.20. Graphically represent the bus voltage control by SSSC device at different buses and sum of total voltage.

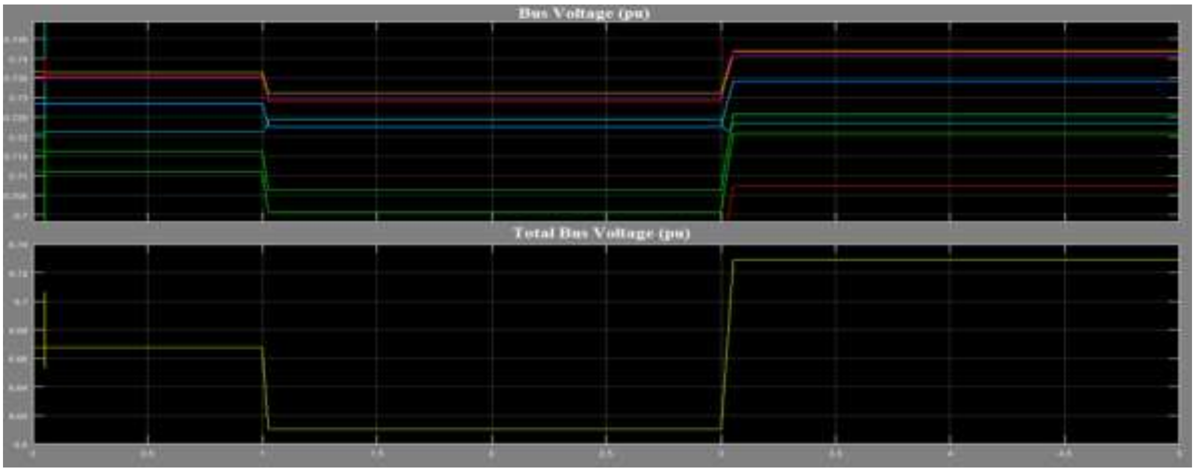

Figure 21. Graphically represent the bus current at different buses and sum of all bus current.

c. Summary of Simulated Results

The performance of the proposed model are compared and analysed with 2000MW in each area i.e. total 8000MW loading, by analysing TCSC can better improve the power flow in transmission line that is active and reactive power 14110MW, -5324MVAr as compared to SSSC 10580MW, -95.9MVAr. Also the TCSC increased the transmission line voltage 7.964 p.u as compared to SSSC is 6.729 p.u. All the TCSC data obtained for capacitive operation mode only, and SSSC data obtain for voltage regulation mode only. According to the result it was observed that in SSSC and TCSC controller, the TCSC are more effective in power flow control and voltage control in power system network and it observed that TCSC is more effective than SSSC with highly loaded condition. The bus data of SSSC and TCSC FACT device for Active, Reactive power, Voltage and current at buses for the case of 2000MW loading in each area is shown in table-1.

BUS	ACTIVE POWER (MW)		REACTIVE POWER (MVAR)		VOLTAGE (pu)		CURRENT (p.u)	
	SSSC	TCSC	SSSC	TCSC	SSSC	TCSC	SSSC	TCSC
B1	438.8	1035	60.16	-1010	0.01991	0.03072	222.5	470.7
B2	548.5	1293	75.2	-1263	0.01991	0.03072	278.1	588.4
B3	425.7	370.2	4.79	11.15	0.01915	0.02209	222.3	167.7
B4	210.8	444.3	5.748	13.38	0.01915	0.02209	266.7	201.2
B5	397.9	385.1	22.79	3.956	0.02001	0.02191	199.1	175.8
B6	613.8	594.2	20.22	-5.722	0.01996	0.02188	307.7	271.6
B7	734.4	709.1	85.74	41.18	0.02036	0.02216	363.1	320.6
B8	582.6	562.5	42.01	11.94	0.02024	0.02208	288.6	254.8
B9	981.8	2308	23	-2773	0.7235	1.252	13.57	28.81
B10	931.1	809.8	-120	-51.32	0.7074	0.8116	13.27	9.998
B11	971.4	2268	-64.49	11.9	0.7208	0.8267	13.51	27.43
B12	395.6	382.9	-25.11	-33.81	0.7339	0.8065	5.402	4.767
B13	730.3	704.9	5.745	-22.06	0.7418	0.8119	9.845	8.687
B14	1308	1263	-37.07	-69.91	0.7407	0.8119	17.67	15.58
B15	1006	973.4	-75.08	-87.94	0.7342	0.8071	13.73	12.11
B16	138	-385.2	-23.63	-57.43	0.742	0.8174	1.887	4.764
B17	-137.6	387.5	-95.91	-43.33	0.7259	0.8247	2.311	4.727
TOTAL	10580	14110	-95.9	-5324	6.729	7.964	2239	2558

Table.1. Comparison between TCSC and SSSC for P, Q, V and I at all the buses for 2000MW loading in each Area

B. Simulation Results for Voltage Stability Analysis

Conventional P-V curves of 17-bus test system are generated. P-V curves are used to predict the voltage Collapse point and the stability of the system.

a. Simulation Results of SSSC

The performance of the test system under various load power factor like unity pf and 0.8 lag and lead are analysed. P-V curves indicate the relationship between the growing load and the progressively descending bus voltages. By analysing test system, the P - V curve under various load power factor has been developed. P - V curve is supposed to be a “nose” curve that is divided by the “nose point” into two parts. The upper one is the stabale region while the corresponding lower part is the unstable region. The “nose point” stands for the voltage collapse because after this point, bus voltage will continue descending even if the loading is shedding [12]. So the P-V curve of bus 11 is shown in figure_22.

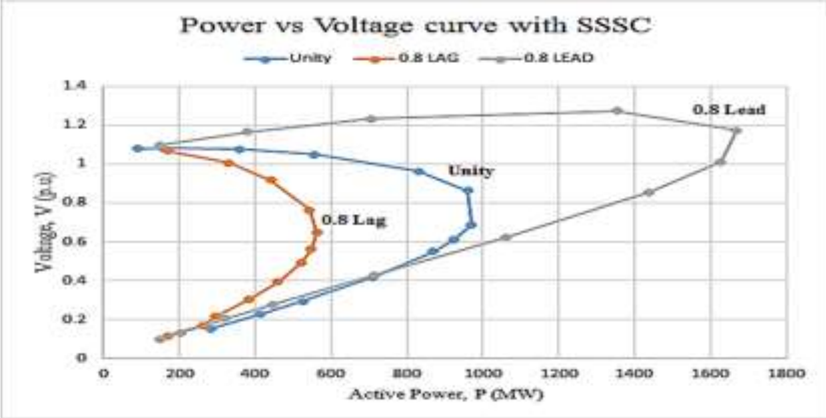

Figure 22. PV curve of bus-11 for the 17-bus test system with SSSC

b. Simulation Results of TCSC

By analysing the test system, get the P-V curve under various load power factor. So the PV curve of bus 11 is shown in figure 23.

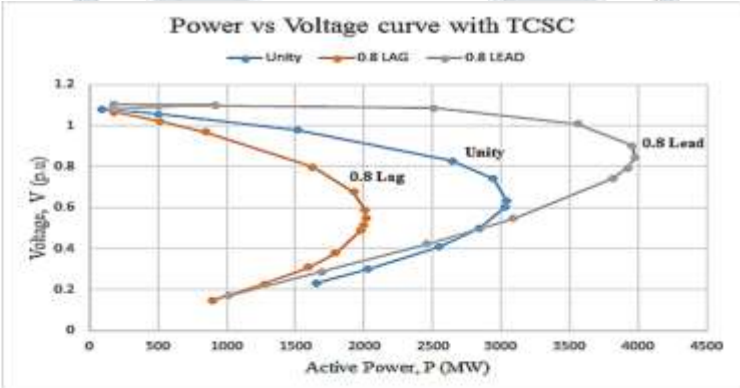

Figure 23. PV curve of bus-11 for the 17-bus test system with TCSC

c. Summary of Simulated Results

The performance of the proposed model are compared and analysed, by analysing TCSC can better improved the Voltage stability in transmission line. The result obtained from simulation shows that critical voltage of the system is lowest with TCSC. To compare the PV curve at a particular power factor we can see that the TCSC can improved the Voltage stability limit of the system as compare to SSSC [13]. Using SSSC Facts device in series with the system, the critical voltages are 0.7685 p.u, 0.648 p.u and 1.174 p.u at unity, 0.8 lagging and 0.8 leading power factor respectively. The critical voltage of TCSC connected system are 0.6321 p.u, 0.5494p.u and 0.8463 p.u at unity, 0.8 lagging and 0.8 leading power factor respectively.The P-V Curve of the system at unity, 0.8 lagging and 0.8 leading power factor are shown in the figure-24, figure-25 and figure-26 respectively [13],[14]. The bus data of SSSC and TCSC FACT device for Critical Active, Reactive power and Voltage at bus-11 is shown in table 2.

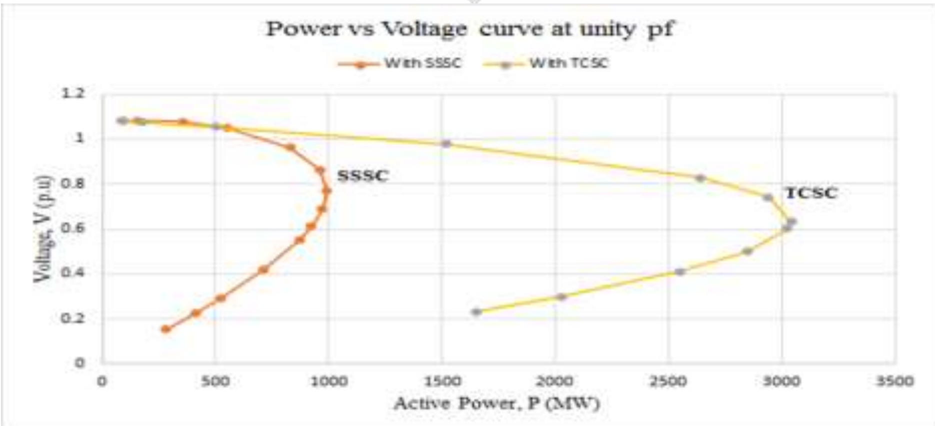

Figure 24. Compare the P-V Curve of TCSC and SSSC at unity pf

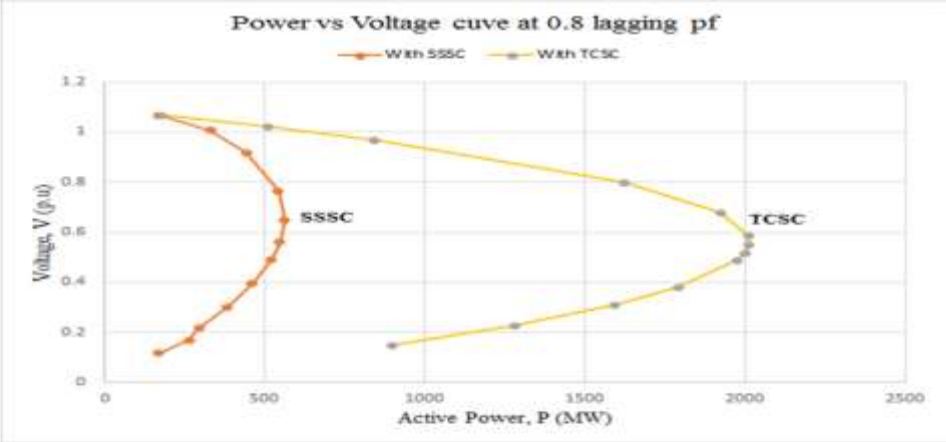

Figure 25. Compare the P-V Curve of TCSC and SSSC at 0.8 lagging pf

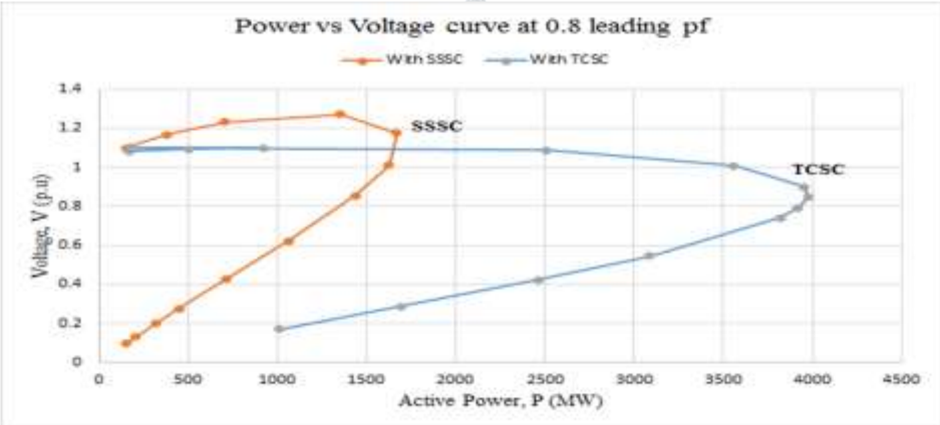

Figure 26. Compare the P-V Curve of TCSC and SSSC at 0.8 leading pf

Power Factor	Active Power, $P_{critical}$, (MW)		Reactive Power, $Q_{critical}$, (MVAr)		Critical Voltage, $V_{critical}$, (p.u)	
	SSSC	TCSC	SSSC	TCSC	SSSC	TCSC
Unity	991.5	3043	-88.53	-449.6	0.7685	0.6321
0.8 lag	561.5	2012	333.9	1082	0.648	0.5494
0.8 lead	1669	3975	-1413	-3913	1.174	0.8463

Table.2. Comparison between TCSC and SSSC for $P_{critical}$, $Q_{critical}$, and $V_{critical}$ at Bus-11 for various power factor.

VIII. CONCLUSION

This paper has compared the application of series capacitive compensative FACTS devices, TCSC and SSSC in a multi-Machine system network namely a four area, eight machine, 17-bus power system. It has been shown that the series reactance of this system network has been reduced considerably leading to an improvement in less system voltage variation at receiving end as well as better control of power flow capability. Further, power vs voltage curve teachnique have been employed to investigate the system stability.

In this contex, in evaluating the performance of both the devices under loading condition as well as the stability under diffent loading condition, TCSC is much more effective than SSSC.

IX. APPENDIX

Three Phase Transformer	Primary Voltage (KV)	Secondary Voltage KV	Nominal Power (MVA)	Fr. Hz	R1 p.u	L1 p.u	Rm p.u	Lm p.u
TR-1	13.6	500	1200	60	0.002	0.08	500	500
TR-2	13.6	500	1500	60	0.002	0.08	500	500
TR-3	13.6	500	1000	60	0.002	0.08	500	500
TR-4	13.6	500	1200	60	0.002	0.08	500	500
TR-5	13.6	500	1000	60	0.002	0.08	500	500
TR-6	13.6	500	1500	60	0.002	0.08	500	500
TR-7	13.6	500	2000	60	0.002	0.08	500	500
TR-8	13.6	500	1500	60	0.002	0.08	500	500

Table.3. Three Phase Transformer Data

From	To	Frequency Hz	Length km	Resistance ohm	Induction mH	Capacitance nF
Bus-9	Bus-11	60	100	1.273	93.37	1274
Bus-11	Bus-17	60	50	0.6365	46.685	637
Bus-10	Bus-17	60	100	1.273	93.37	1274
Bus-12	Bus-15	60	25	0.31825	23.3425	318.5
Bus-15	Bus-16	60	75	0.95475	70.0275	955.5
Bus-13	Bus-14	60	25	0.31825	23.3425	318.5
Bus-14	Bus-16	60	75	0.95475	70.0275	955.5
Bus-16	Bus-17	60	200	2.546	186.74	2548

Table.4. Transmission Line Data

TCSC Control Unit		TCSC Firing Unit			
Frequency Hz	Operating Mode	Frequency Hz	TCSC Capacitance F	TCSC reactance H	firing delay Sec
60	Capacitive	60	21.977e-6	0.043	4e-3

Table.5. TCSC Facts Control Data

Voltage V_{L-L} KV	Frequency Hz	Snom MVA	Max. injected voltage p.u	Resistance p.u	Inductance p.u	DC link nominal voltage KV	DC link total equivalent capacitance F
500	60	100	0.1	0.16/30	0.16	40	375e-6

Table.6. SSSC Facts Data

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