Analysis of Static Synchronous Series Compensators (SSSC), on Congestion Management and Voltage Profile in Power System by PSAT Toolbox

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Abstract: The maintenance and availability of the power system can be considerd a major aspect of investigation. The encouragement to the planning of HV lines, the valuet of power that transfer per km on HV line and the amount of power transaction as seen from economic side is much responsible for concern towards congestion phenomena in power system. The idea for solving this problem is the use of FACTS devices especially the use of Synchronous Series Compensators (SSSC). In this paper the study of SSSC with its various modes of operation is investigated. Finally by help of modeling of a power system in MATLAB/PSAT toolbox, and by installing SSSC in transmission link, its use as power flow controller and voltage injection is seen. Conclusion is made on different results to see the benefit of SSSC in power system.

INTRODUCTION

Today's, energy, environment, restrurcherd of power utilities have delayed the planning of both generation facilities and new transmission lines (Xiao *et al*., 2002). These problems have needed to be a changed in the traditional concepts and practices of power systems. There are updating techniques available, which can help electric companies to deal with above problems. One of these technologies is FACTS (Flexible AC Transmission System) that is a family of power electronic products including Static Synchronous Compensator (STATCOM) (Muwaffaq, 2003), Static Synchronous Series Compensator (SSSC) and Unified Power Flow Controller (UPFC), etc. These components are called FACTS controllers that are based on converter (Noroozian *et al*., 1997). Better utilization of existing power system capabilities by emerging new power electronic controllers such as Flexible AC Transmission System (FACTS) has become imperative. FACTS devices are responsible to change, in a fast and effective way, the power system parameters in order to obtain a better system operation (Teerathana *et al*., 2005). FACTS devices, such as Phase Shifter Transformer (PST), shunt or series compensation and the most recent developed converter- based power electronic controllers, make it controllable for circuit impedance, voltage magnitude and voltage angle and real and reactive power flow for optimal operation of power systems, facilitate the development of competitive electric energy markets, and stipulate the unbundling the power generation from transmission and mandate open access to transmission services, etc. However, against the practical applications of the STATCOM, SSSC, PST, GUPFC, GUIPFC, DUPFC and UPFC in power systems, very few publications have been focused on the mathematical modeling of these converters based FACTS controllers in optimal power flow analysis (Zhang, 2003a, b). In other references a UPFC model has been presented, and the model has been used in a Successive QP. In another reference mathematical model for TCSC, IPC and UPFC have been established, and the OPF problem with these FACTS controllers has been solved by Newton's approach (Saadat, 2002; Gyugyi *et al*., 1999). Modeling of STATCOM and SSSC in OPF has not been reported yet. In this paper, general mathematical model for the converter based FACTS controller such as SSSC suitable for optimal power flow study are described. There is various solution approach for OPF available, which include interior point methods. In this paper the optimal power flow problem with SSSC is solved by Newton Method.

Static Synchronous Series Compensators (SSSC):
Characteristics of SSSC: Outage of transmission lines, congestion, cascading line tripping, and power system stability loss are the major ideas where capability and utilization of FACTS are considered. It is known that one of the last and new generations of FACTS devices is Static Synchronous Series Compensators (SSSC). The SSSC is a device which can control simultaneously all three parameters of line power flow (line impedance, voltage and phase angle).This device is Voltage Source Inverters (VSI's) connected in series with the transmission line through a series transformer, in practice, that is connected to each other by a common dc link including storage capacitor (Fuerte-Esquivel *et al*., 2000). The series inverter can be applied to control the real and reactive line power flow and voltage with controllable
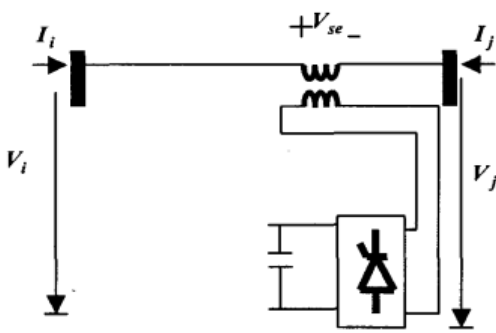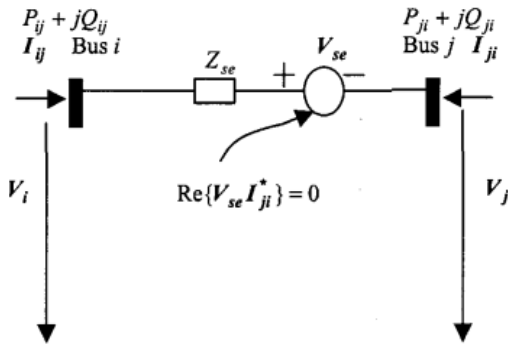
Fig. 1: SSSC link in transmission line

Fig. 2: Equivalent circuit of SSSC

magnitude and phase in series with the transmission line. Therefore, the SSSC can do responsibility of, active and reactive series compensation and phase shifting. In addition to, the SSSC has a secondary function but important that is used to stability control for standing power system oscillations and therefore improving the transient stability of power system. Because of needing for flexible and fast power flow controllers, such as the SSSC, is expected to grow in the future due to the changes in the electricity markets, there is a corresponding need for available and realistic models of this controller to study the impact of it on the performance and operation of the power system (Carsten, 2002). In this study emphasis is laid to project the use of SSSC in transmission link to increase the power flow and to get better the voltage profile of the system with MATLAB/PSAT toolbox.

Operation of SSSC: A SSSC usually is comprised of a coupling transformer, an inverter and a capacitor. However, it is series connected with a transmission line through the coupling transformer. Operation concept of a SSSC is shown in Fig. 1. In principle, the inserted series voltage V with SSSC can be regulated such a way that change the impedance (more precisely reactance) of the transmission line. Therefore the real and reactive power flow of transmission line can be controlled.

Mathematical equations of SSSC: An equivalent circuit of the SSSC is depicted in Fig. 2 that can be derived based on the operation principle of the SSSC (Muwaffaq, 2003).

According to the equivalent circuit, suppose $V_{se} \angle \theta_{se}$, $V_{sk} \angle \theta_{sh}$, $V_i \angle \theta_i$ and $V_j \angle \theta_j$. Then the real and reactive power flow of the SSSC are (Jun and Akihiko, 2006):

$$P_{ij} = V_i^2 g_{ii} - V_i V_j \left(g_{ij} \cos\theta_{ij} + b_{ij} \sin\theta_{ij} \right)$$
$$- V_i V_{se} \left(g_{ij} \cos\left(\theta_i - \theta_{se}\right) + b_{ij} \sin\left(\theta_i - \theta_{se}\right) \right) \quad (1)$$

$$Q_{ij} = V_i^2 b_{ii} - V_i V_j \left(g_{ij} \sin\theta_{ij} - b_{ij} \cos\theta_{ij} \right)$$
$$- V_i V_{se} \left(g_{ij} \sin\left(\theta_i - \theta_{se}\right) - b_{ij} \cos\left(\theta_i - \theta_{se}\right) \right) \quad (2)$$

$$P_{ji} = V_j^2 g_{jj} - V_i V_j \left(g_{ij} \cos\theta_{ji} + b_{ij} \cos\theta_{ji} \right)$$
$$+ V_i V_{se} \left(g_{ij} \cos\left(\theta_j - \theta_{se}\right) + b_{ij} \sin\left(\theta_j - \theta_{se}\right) \right) \quad (3)$$

$$Q_{ji} = V_j^2 b_{jj} - V_i V_j \left(g_{ij} \sin\theta_{ji} - b_{ij} \cos\theta_{ji} \right)$$
$$+ V_i V_{se} \left(g_{ij} \sin\left(\theta_j - \theta_{se}\right) - b_{ij} \cos\left(\theta_j - \theta_{se}\right) \right) \quad (4)$$

where;

$$g_{se} + jb_{se} = 1/z_{se},$$
$$g_{ii} = g_{ij} + g_{sh}, b_{ii} = b_{ij} + b_{sh},$$
$$g_{jj} = g_{ii}, b_{jj} = b_{ii}$$

Operating constraint of the UPFC (active power exchange between two inverters via the DC link) is:

$$PE = \text{Re}\left(V_{se} I_{ji}^*\right) = 0$$

or

$$- V_i V_{se} \left(g_{ij} \cos\left(\theta_i - \theta_{se}\right) \right.$$
$$- b_{ij} \sin\left(\theta_i - \theta_{se}\right) \right)$$
$$+ V_j V_{se} \left(g_{ij} \cos\left(\theta_j - \theta_{se}\right) \right.$$
$$- b_{ij} \sin\left(\theta_j - \theta_{se}\right) \right) = 0 \quad (5)$$

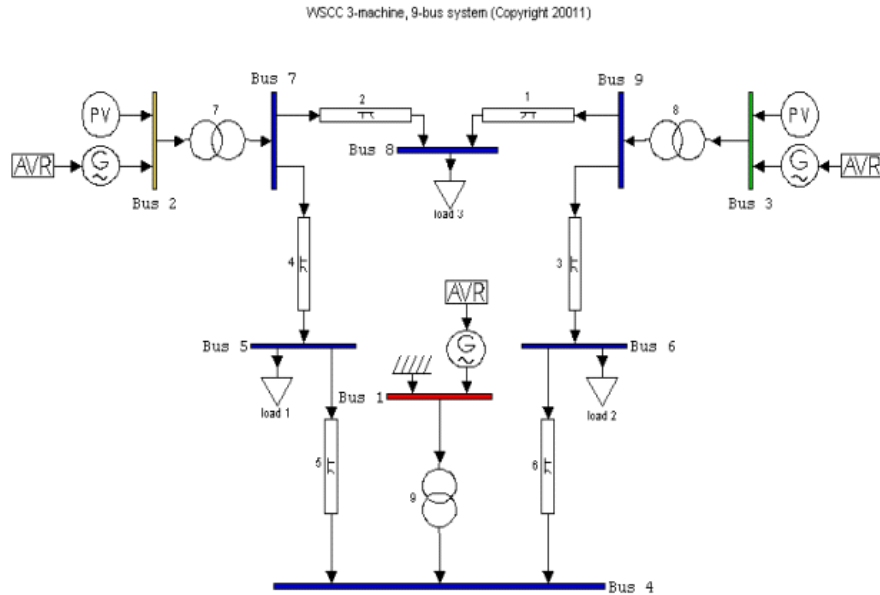WSCC 3-machine, 9-bus system (Copyright 20011)

Fig. 3: Test power system for analyzing effect of SSSC

The active power flow control constraint is as follows:

$$P_{ji} - P_{ji}^{specified} = 0 \qquad (6)$$

where $P_{ji}^{specified}$ is the specified active power flow?

The two equivalent voltage injections $V_{se} \angle \theta_{se}$, bounds constraints:

$$V_{se}^{min} \leq V_{se} \leq V_{se}^{max} \qquad (7)$$

$$\theta_{se}^{min} \leq \theta_{se} \leq \theta_{se}^{max} \qquad (8)$$

MODELING AND SIMULATION OF SSSC ON AT TRANSMISSION SYSTEM

Model block of single line diagram: Using the concept of the control system a power system is taken to implement the application of SSSC. The two modes i.e. the power flow control and the voltage injection mode are simulated in PSAT toolbox to see the effect of SSSC on a power system. Investigation is carried out to verify the utility of FACT device. Figure 3 illustrates application study the steady-state and dynamic performance of a SSSC used to relieve power congestion and improve power flow in a transmission system. The load flow analysis and the single line diagram simulation are done on power flow simulator. This software helps to calculate the power flow, the voltage magnitude and voltage angle at each bus and the each transmission lines of the system. A SSSC is used to control the power flow in a test power transmission system. The system, connected in a loop configuration, consists essentially of nine buses (B1 to B9) interconnected through three transmission lines (L1, L2, L3,L4,L5,L6) and three 18 kV/230 kV transformer banks with power rated equals to 100 MVA. Three Specifications of synchronous machines connected to buses 1,2,3 on the 16.5,18,13.8 kV buses respectively that generate a total loads of 1500 MW (Fig. 3) which their data are presented in Table 3. Each plant model includes a speed regulator, an excitation system as well as a Power System Stabilizer (PSS). In normal operation, most of the 1200 MW generation capacity of power plant#2 is exported to the 18 kV equivalents through transformers connected between buses. For this illustration we consider a contingency case where only two transformers out of three are available (Tr2 = 2*100 MVA = 200 MVA). The load flow shows that most of the power generated by plant #3 is transmitted through the 200 MVA transformer bank (140 MW out of 200 MW) and that rest of power is circulating in the loop. Transformer Tr2 is therefore overloaded by 99 MVA. This will now illustrate how a UPFC can relieve this power congestion. The UPFC located at the right end of line L2 is used to control the active and reactive powers at the 18 kV buse B3, as well as the voltage at bus B6. The SSSC consists of two 100 MVA, IGBT-based, converters (one shunt converter and one series converter interconnected through a DC bus).
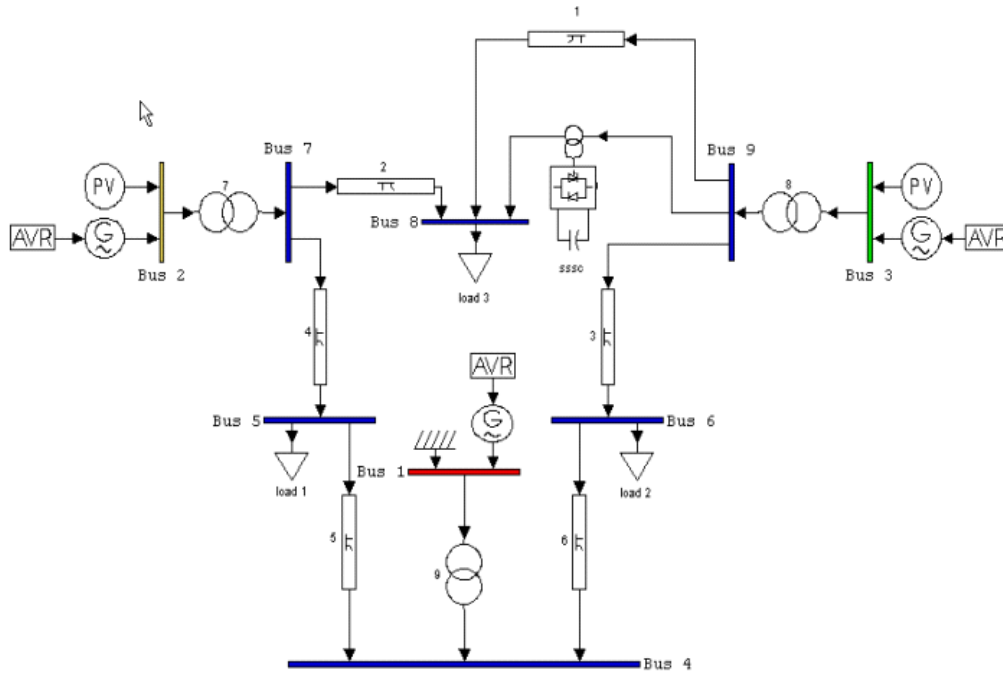
Fig. 4: Installing SSSC on test power system

The series converter can inject a maximum of 10% of nominal line-to-ground voltage (28.87 kV) in series with line L2.

The single line diagram illustrated in Fig. 3 is implemented on MATLAB/PSAT toolbox to check the validity of the SSSC controller. This system with SSSC is shown in Fig. 4. The Model of SSSC will generate two kinds of results. First is based upon the simulations at power flow control mode and another on voltage injection Mode. The important keys to note in the block diagram are:

- Use of Bypass breaker: Used to connect or disconnect SSSC Block from power system
- The reference power inputs [P Qref]: Reference for power flow control
- The reference voltage Vdref: Reference for voltage injection
- Power flow analysis at load flow indicated by arrows: Comparison with and without SSSC

Power flow control with the SSSC: Parameters of the SSSC are given in the dialog box. In the Power data parameters that the series converter is rated 100 MVA with a maximum voltage injection of 0.1 pu. The shunt converter is also rated 100 MVA. Also, in the control parameters, that the shunt converter is in Voltage regulation mode and that the series converter is in Power

flow control mode. The SSSC reference active and reactive powers are set in the magenta blocks labeled Pref(pu) and Qref(pu). Initially the Bypass breaker is closed and the resulting natural power flow at bus B3 is 157 MW and -47 Mvar. The Pref block is programmed with an initial active power of 5.87 pu corresponding to the natural power flow. Then, at t = 10s, Pref is increased by 1 pu (100 MW), from 5.17 pu to 3.27 pu, while Qref is kept constant at -0.17 pu.

Operation mode of SSSC:
Power flow control mode: The results are in compliance with the SSSC characteristics. The net reference real power output of the SSSC increased by 90 MW when the breaker opened. The increase in the real power led to decrease in congestion on bus 5. This can be seen by the power variation at every bus. Relating to the reactive power, when the breaker opened the oscillations of reactive power was finished and reactive power was then constant at -17MVAr. The main concern lies at the SSSC controllable region. The region defined in the graph is such that the SSSC can only act under these conditions; else the SSSC behaves like open to transmission link. The voltage levels were also increase so to meet the real power demand.

Voltage injection using SSSC: The voltage is iinseted by the series controller by the series transformer. The voltage

Table 1: Bus data

Bys no.	Rating voltage
1	16.5
2	18.0
3	13.8
4	230
5	230
6	230
7	230
8	230
9	230

Table 2: Transmission lines data

Line no.	Power (MVA)	Voltage (KV)	Resistance	Reactance	Susceptance
1	100	230	0.0119	0.1008	0.1045*2
2	100	230	0.0085	0.0720	0.0745*2
3	100	230	0.0390	0.1700	0.179*2
4	100	230	0.0320	0.1610	0.153*2
5	100	230	0.0100	0.0850	0.088*2
6	100	230	0.0170	0.0920	0.079*2

Table 3: Loads data

Load no.	Power rate (MVA)	Voltage rate (KV)	Active power (pu)	Reactive power(pu)
1	100	230	1.25	0.50
2	100	230	0.90	0.30
3	100	230	1.00	0.35

Table 4: Transformers data

Trans no.	Power rate (MVA)	Primarty voltage	Secondary voltage	Resistance	reactance
In line 7	100	18.0	230	0	0.0625
In line 8	100	13.8	230	0	0.0586
In line 9	100	16.5	230	0	0.0576

Table 5: Slack bus connected to bus 1 data

Slack bus connected to bus 1	
Power rate (MVA)	100
Voltage rate (KV)	16.5
Voltage magnitude (pu)	1.04
Reference phase (rad)	0
Qmax (pu)	99
Qmin (pu)	-99
Vmax (pu)	1.1
Vmin (pu)	0.9
Active power guess (pu)	0.8

Table 6: Synchronous machine data

Specifications of synchronous machine	Synchronous machine		
	Connected to bus 1	Connected to bus 2	Connected to bus 3
Power rate	100	100	100
Voltage rate	16.5	18	13.8
Ra	0	0	0
Xl	0	0	0
Xd	0.146	0.8958	1.3125
X'd	0.0608	0.1198	0.1813
X"d	0	0	0
T'do	8.96	6	5.89
T"do	0	0	0
Xq	0.0969	0.8645	1.2578
X'q	0.0969	0.1969	0.25
X"q	0	0	0
T'qo	0.310	0.5350	0.6
T"qo	0	0	0
M = 2H	2*23.64	12.80	6.02

Table 7: PV bus for load flow data

Specifications of PV bus	PV buses	
	Connected to bus 2	Connected to bus 3
Power rate (MVA)	100	100
Voltage rate(KV)	18	13.8
Active power	1.63	0.85
Voltage magnitude	1.025	1.025
Qmax (pu)	99	99
Qmin (pu)	-99	-99
Vmax (pu)	1.1	1.1
Vmin (pu)	0.9	0.9

Table 8: Characteristics of SSSC

Power rated	100
Voltage rated	230
Frequenct	60
Resistance of the DC circuit	600
Capacitance Of the DC circuit	0.0143
Resistance Of the TA transformer	0.0001
Capacitance of the TA transformer	0.105
Resistance of filter in ac circuit	0.0001
reactance of filter in ac circuit	0.00015

Table 9:Active and Reactive power flow results in transmission lines without and with UPFC

From bus	To bus	line	Active power flow (p.u.)		Reactive power flow(p.u.)	
			Without sssc	With sssc	Without sssc	With sssc
9	8	1	0.24183	- 0.64561	0.03120	- 0.49412
7	8	2	0.76380	0.60819	- 0.00797	- 0.40733
9	6	3	0.60817	0.44577	- 0.18075	- 0.22193
7	5	4	0.86620	1.02180	- 0.08381	- 0.0116
5	4	5	- 0.40680	- 0.25947	- 0.38687	- 0.3482
6	4	6	- 0.30537	- 0.46178	- 0.16543	- 0.18801
2	7	7	1.63000	1.63000	0.06654	- 0.25695
3	9	8	0.85000	0.85000	- 0.10860	0.17234
1	4	9	0.71641	0.72635	0.27046	0.25487
9	8	10	-	1.04980	-	0.84644

Table 10: Bus voltage magnitude and angle with and without SSSC

Bus no.	MAG. of Voltages (p.u)		Angle of Voltage (rad)	
	Without sssc	With sssc	Without sssc	With sssc
1	1.04000	1.0400	0	0
2	1.02500	1.0250	0.16197	0.19002
3	1.02500	1.0250	0.08142	0.04479
4	1.02580	1.0267	- 0.03869	- 0.03919
5	0.99563	1.0019	- 0.06962	- 0.05811
6	1.01270	1.0083	- 0.06436	- 0.07848
7	1.02580	1.0454	0.06492	0.09481
8	1.01590	1.0638	0.01270	0.05293
9	1.03240	1.0163	0.03433	- 0.00304
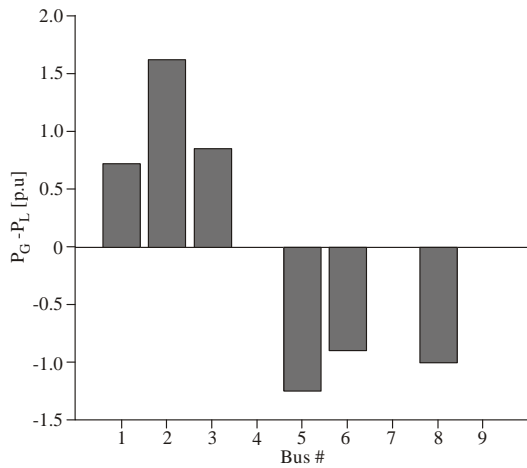
Fig. 5: Changing active power in buses system without SSSC
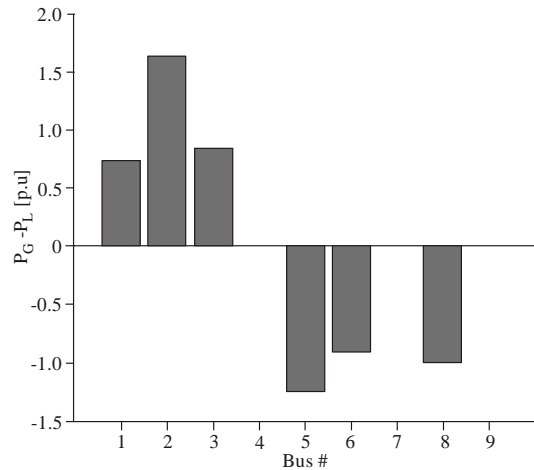
Fig. 6: Changing active power in buses system with SSSC

is injected by increase in magnitude as well as angle to meet the characteristics as in Fig. 3. Considering SSSC controllable region, during this mode the results get verified in accordance with Fig. 3. Also the voltage level increases sharply. This shows that the voltage profile of the system has gets better which increases the net power flow between transmission lines.
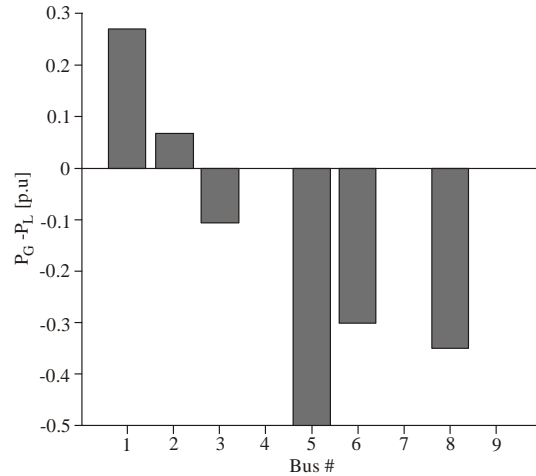

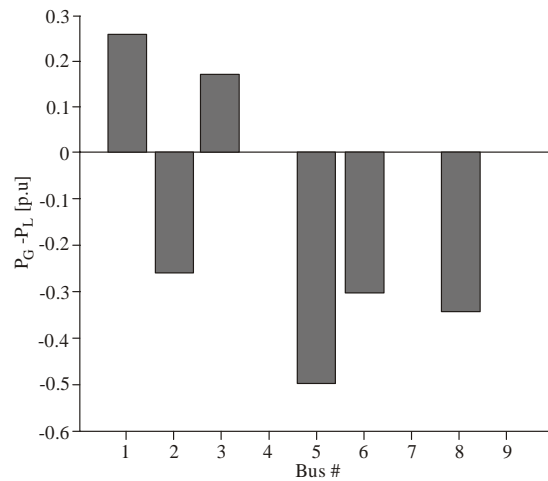Fig. 7: Changing reactive power in buses system without SSSC

Fig. 8: Changing reactive power in buses system with SSSC

Grid characteristics: The information of test power system including Buses data, transmission lines data, power plants data loads data and transformer and slack and pv busese are listed as Table 1-8.

RESULTS AND DISCUSSION

Operation mode of SSSC:
Power flow control mode: The results are in compliance with the SSSC characteristics. The net reference real power output of the SSSC increased by 90 MW when the breaker opened. The increase in the real power led to decrease in congestion on bus 5. This can be seen by the power variation at every bus. Relating to the reactive power, when the breaker opened the oscillations of reactive power was finished and reactive power was then constant at -17MVAr. The main concern lies at the SSSC
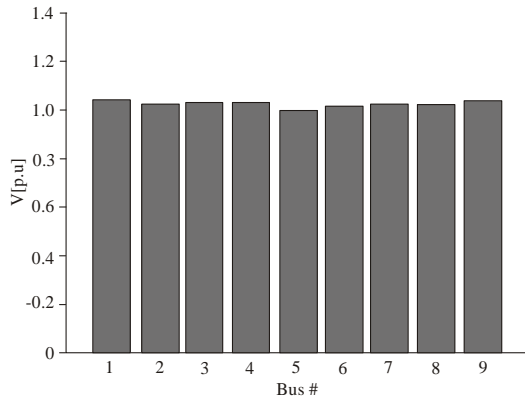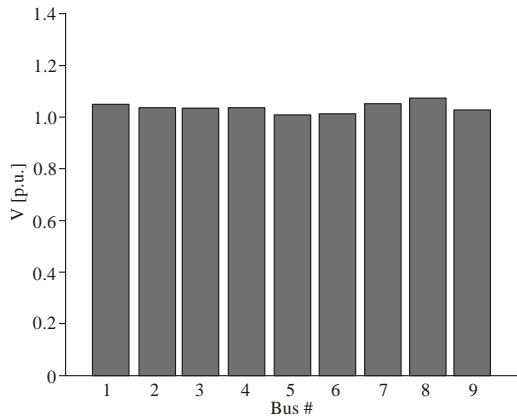
Fig. 9: Voltage buses without SSSC

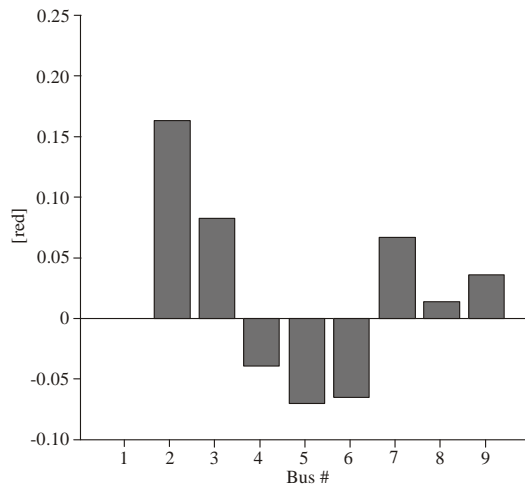

Fig. 10: Voltage buses with SSSC

Fig. 11: Teta angle of buses voltage without SSSC

controllable region. The region defined in the graph is such that the SSSC can only act under these conditions; else the SSSC behaves like open to transmission link. The voltage levels were also increase so to meet the real power
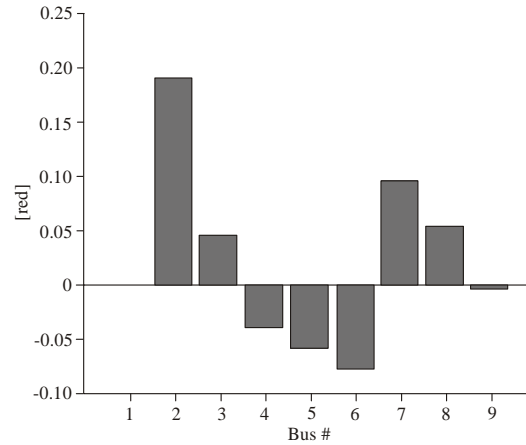

Fig. 12: Teta angle of buses voltage with SSSC

demand. The results of power flow as real and reactive power are listed and descried in Table 9.

For better understanding of effect of SSSC the results of power flow as real and reactive are presented as Fig. 5-8.

Voltage injection using SSSC: The voltage is inserted by the series controller by the series transformer. The voltage is injected by increase in magnitude as well as angle to meet the characteristics as in Fig. 3. Considering SSSC controllable region, during this mode the results get verified in accordance with Fig. 3. Also the voltage level increases sharply. This shows that the voltage profile of the system has gets better which increases the net power flow between transmission lines. These results are listed and presented in Table 10.

For better understand of SSSC on profile voltage the changing magnitude and angle of voltage are shown in Fig. 9-12.

CONCLUSION

In power system transmission, it is desirable to maintain the voltage magnitude, phase angle and line impedance. Therefore, to control the power from one end to another end, this concept of power flow control and voltage injection is applied. Modeling the system and investigating the results have given an indication that SSSC are very useful when it comes to organize and maintain power system. Following conclusions are made:

* Power flow control is achieved and congestion is less
* Transient stability is improved
* Faster Steady State achievement
* Improved Voltage Profile

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