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Modeling of STATCOM with Six Pulse SPWM based VSC and its Power Flow Study

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ABSTRACT

One of the main reasons of the voltage instability is the reactive power limit of the system. To improve system reactive power handling capacity Flexible AC Transmission Systems (FACTS) is the best solution which can prevent voltage instability. In this paper one of the FACTS devices Static Synchronous Compensator (STACOM) is designed with six pulse Sinusoidal Pulse Width Modulation (SPWM) based Voltage Source Converter (VSC); this can remain all the advantages of the ideal switch and eliminate its disadvantages. This model is designed in Matlab/ Simulink software and characteristics are analyzed. The STATCOM power flow equations are developed for this model and total generation, total load and line losses are evaluated by using Newton-Raphson method power flow program which is developed in MATLAB of the standard IEEE 30 bus system.

Keywords: *Flexible AC Transmission Systems (FACTS), Static Synchronous Compensator (STACOM), Sinusoidal Pulse Width Modulation (SPWM), Newton-Raphson method.*

1. INTRODUCTION

Flexible AC Transmission Systems (FACTS) based on power electronics offer an opportunity to improve controllability, stability, and power transfer capability of AC transmission systems [1]. In general, FACTS controllers can be classified into two different generations. The first generation is based on the line-commutated thyristor devices with only gate turn-on but no gate turn-off capability. These are Static Var Compensator (SVC) and Thyristor Controlled Series Capacitor (TCSC). The second generation of FACTS controllers is based on self-commutated voltage sourced converters (VSC), which utilize thyristors/transistors with gate turn-off capability. In general there are many VSC based FACTS controllers, among all these types the Convertible Series Compensator (CSC) is the most versatile FACTS device, which can be operated as Static Synchronous Compensator (STATCOM), which is a shunt type controller, Static Series Compensator (SSSC), which is a series type controller and the Unified Power Flow Controller (UPFC), a combined series-shunt type controller [1].

2. BASIC OPERATION OF STATCOM

STATCOM is a voltage sourced inverter using GTOs and DC capacitor to generate a three phase synchronous voltage at fundamental frequency. The STATCOM is shunt connected to the transmission system via a step-down transformer; it can generate or absorb reactive power to regulate the voltage profile of the bus at which it is connected [2]. STATCOM generates or absorbs reactive power at a faster rate because no moving parts are involved. A schematic representation of the STATCOM and its equivalent circuit are shown in Figure 1 (a) and 1(b).

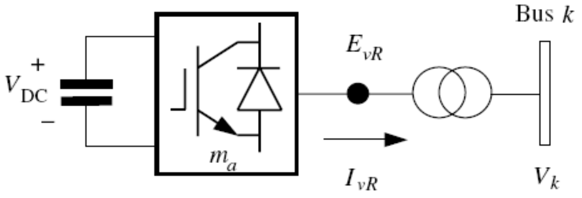

Figure1.a

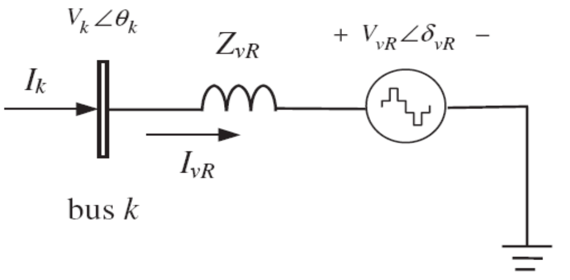

Figure1.b

Figure 1. Static Compensator (STATCOM) system: (a) basic Voltage Source Converter the (VSC) connected to the AC network via a shunt connected transformer; (b) STATCOM equivalent circuit.

The shunt voltage source of the three phase STATCOM is represented by:

$$E_{vR}^{\rho} = V_{vR}^{\rho}(\cos \delta_{vR}^{\rho} + \mathrm{j}\ \sin\delta_{vR}^{\rho}) \qquad (1)$$

Where ρ indicates phase quantities a, b, and c. V_{vR}^{ρ} is the voltage magnitude which will give maximum and minimum limits, which are a function of the STATCOM capacitor rating. δ_{vR}^{ρ} is the phase angle we may take any value between 0 and 2π radians. The power flow equations for the STATCOM are derived by using its equivalent circuit shown in figure (b) Based on the shunt connection shown in figure (b), the equation may be written:

$$S_{vR} = V_{vR} I_{vR}^{*} = V_{vR} Y_{vR}^{*}(V_{vR}^{*} - V_{k}^{*}) \qquad (2)$$

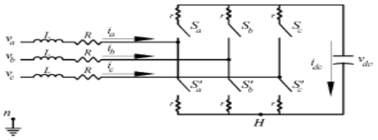

Figure 2. Basic six pulse converter circuit

A Six pulse VSC shown in figure 2 requires the generation of three square wave voltages using the three poles A, B, and C. If v_a,v_b and v_c are the three square wave voltages and the corresponding fundamental components are $v_{a,1}$, $v_{b,1}$ and $v_{c,1}$. After solving the equations for v_a,v_b and v_c, the sum of three voltages in equation is

$$v_a + v_b + v_c = v_{DC} \sum_{n=1}^{\infty} 2/n\pi\ [\sin (n\theta) + \sin n\ (\theta - 120^0) + \sin n\ (\theta + 120^0)] \qquad (3)$$

The three square wave voltages are a combination of a fundamental and odd harmonic component. The fundamental component is a set of three phase positive sequence voltages. Among the harmonic components, the n=6k+1 components are in positive sequence; the n=6k-1 components are in negative sequence, where k=1, 2, 3 and so on; by substituting equation (3) in equation (1) and after some complex operations, the active and reactive power equations for the converter and bus k are

$$P_{vR} = V_{vR}^2 G_{vR} + V_{vR} V_k [G_{vR} \cos (\delta_{vR} - \theta_k) + B_{vR} \mathrm{Sin}\ (\delta_{vR} - \theta_k)], \qquad (4)$$

$$Q_{vR} = -V_{vR}^2 B_{vR} + V_{vR} V_k [G_{vR} \sin (\delta_{vR} - \theta_k) - B_{vR} \mathrm{Sin}\ (\delta_{vR} - \theta_k)], \qquad (5)$$

$$P_k = V_k^2 G_{vR} + V_{vR} V_k [G_{vR} \cos (\theta_k - \delta_{vR}) + B_{vR} \mathrm{Sin}\ (\theta_k - \delta_{vR})], \qquad (6)$$

$$Q_k = -V_k^2 B_{vR} + V_{vR} V_k [G_{vR} \sin (\theta_k - \delta_{vR}) - B_{vR} \mathrm{Cos}\ (\theta_k - \delta_{vR})] \qquad (7)$$

Using these power equations, the linearised STATCOM model is given below, where the voltage magnitude V_{vR} and phase angle δ_{vR} are taken to be the state variables:

$$\begin{bmatrix} \Delta P_k \\ \Delta Q_k \\ \Delta P_{vR} \\ \Delta Q_{vR} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_k}{\partial \theta_k} & \frac{\partial P_k}{\partial V_k} V_k & \frac{\partial P_k}{\partial \delta_{vR}} & \frac{\partial P_k}{\partial V_{vR}} V_{vR} \\ \frac{\partial Q_k}{\partial \theta_k} & \frac{\partial Q_k}{\partial V_k} V_k & \frac{\partial Q_k}{\partial \delta_{vR}} & \frac{\partial Q_k}{\partial V_{vR}} V_{vR} \\ \frac{\partial P_{vR}}{\partial \theta_k} & \frac{\partial P_{vR}}{\partial V_k} V_k & \frac{\partial P_{vR}}{\partial \delta_{vR}} & \frac{\partial P_{vR}}{\partial V_{vR}} V_{vR} \\ \frac{\partial Q_{vR}}{\partial \theta_k} & \frac{\partial Q_{vR}}{\partial V_k} V_k & \frac{\partial Q_{vR}}{\partial \delta_{vR}} & \frac{\partial Q_{vR}}{\partial V_{vR}} V_{vR} \end{bmatrix} \begin{bmatrix} \Delta \theta_k \\ \frac{\Delta V_k}{V_k} \\ \Delta \delta_{vR} \\ \frac{\Delta V_{vR}}{V_{vR}} \end{bmatrix}.$$

The six pulse voltage source converter required for this work is designed in Simulink which is shown in below figure 3.

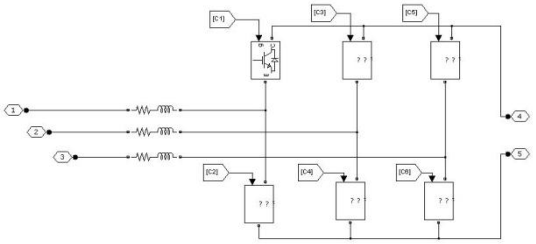

Figure 3. Six pulse converter circuit designed in Simulink.

2.1 Sinusoidal Pulse Width Modulation (SPWM)

Among all PWM schemes, SPWM is one of the most popular methods and its working is explained below. As shown in figure 4, a sine wave is compared with a triangle wave (carrier wave) and the instantaneous value of the triangular wave is less than that of the sine wave, the

PWM output signal is in high level (1). Otherwise it is turned into the low level (0).

The SPWM process is explained in figure 4(a) and the corresponding switching function is shown in figure 4(b). This switching function S corresponds to one phase and for three phase it is given in figure 5.

Due to high carrier frequency f_c, T_c is much shorter than that shown in figure 4(a). A high carrier frequency f_c directly improves the reproduction of the original signal v_s. The frequency modulation ratio m_f is defined as the ratio of f_c and f_s. Higher m_f implies a high switching frequency.

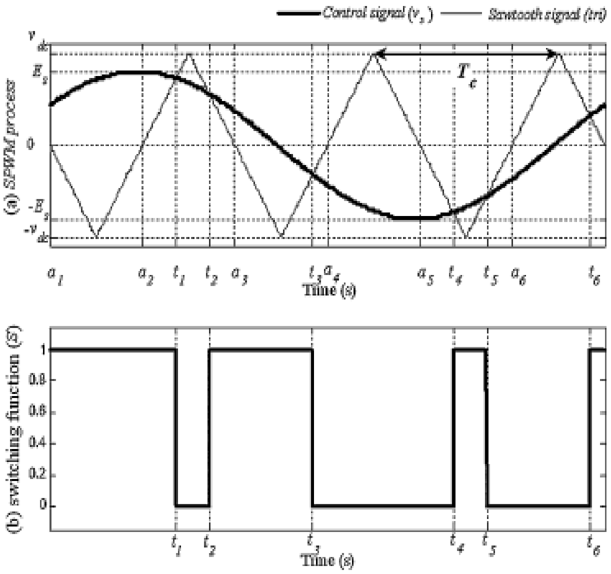

Figure 4. Transforming desired continuous signal v_s into a SPWM signal. (a) SPWM process (b) Switching function (s).

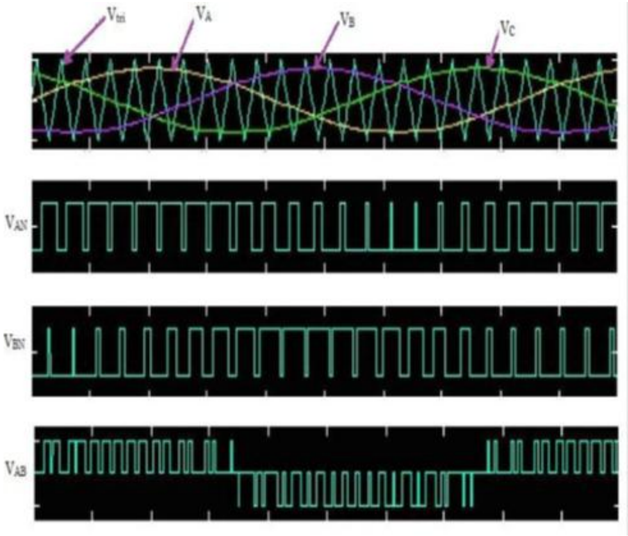

Figure 5. 3-Phase SPWM waveforms.

3. MODELING OF STATCOM WITH SIX PULSE SPWM BASED VSC

SPWM generator circuit is designed in SIMULINK software which is shown in figure 6 (a). Input of this circuit is one reference voltage signal v_s and triangular wave and the output of the signal is square waveform which represents the switching function S. Using the concept of control system a power system is taken to implement the use of STATCOM. This study is carried out to verify the utility of FACTS device. Figure6 (b) illustrates the study state of a STATCOM used to relieve power congestion in a transmission system. A Static Synchronous Compensator (STATCOM) circuit with six pulse SPWM based voltage sourced converter (VSC) is designed in SIMULINK, which is shown in figure6(c). The output of this circuit is shown in figure 6(d), which shows the capacitor voltage v_{dc}, the terminal voltage at node 1, and the phase of the series current.

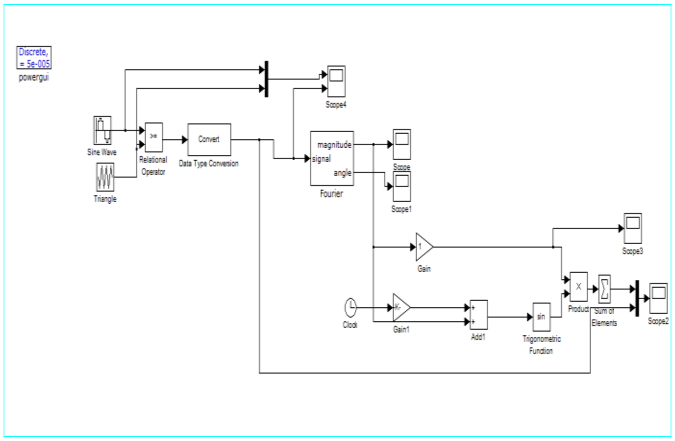

Figure 6(a)

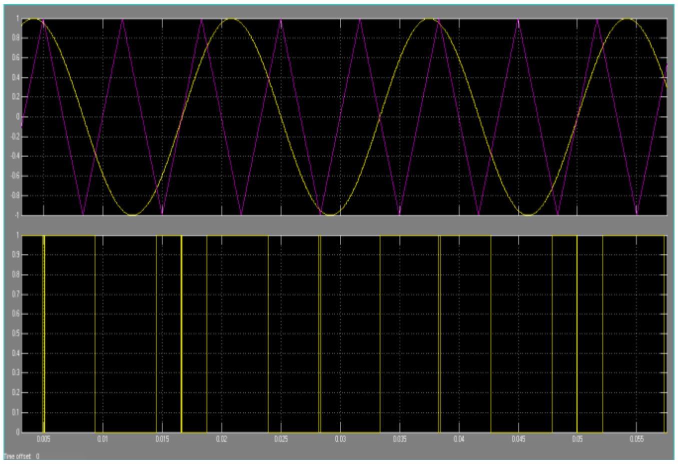

Figure 6(b)

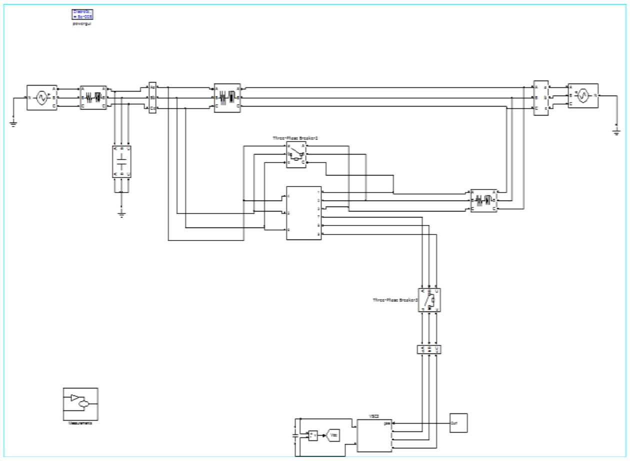

Figure 6(c)

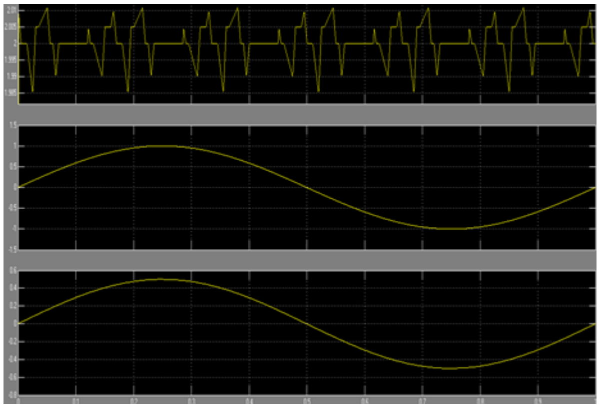

Figure 6(d)

Figure6. (a) Modeling of SPWM (b) SPWM output waveforms (c) Modeling of STATCOM with six pulse SPWM based VSC (d) STATCOM output waveforms.

4. STUDY OF POWER FLOW ANALYSIS

Load-flow studies are very common in power system analysis. Load flow allows us to know the present state of a system, given previous known parameters and values. The power that is flowing through the transmission line, the power that is being generated by the generators, the power that is being consumed by the loads, the losses occurring during the transfer of power from source to load, and so on, are iteratively decided by the load flow solution, or also known as power flow solution. In this paper power flow is calculated for IEEE 30 bus system which is shown in figure 7. In first case without inserting any FACTS device voltage magnitude, angle, generation power, load power, maximum power mismatch and line loss are calculated at each bus. From these values total generation, total load and total line losses are evaluated by using Newton-Raphson method power flow program which is developed in MATLAB. In second case all these parameters are evaluated by placing STATCOM with six pulse SPWM based VSC between bus 29 and bus 30. For these calculations bus data and line data are given in appendix A. For bus data code 0, code 1, and code 2 are used for the load buses, the slack bus and the voltage controlled buses and for line data columns 1 and 2 are the line bus numbers. Columns 3 to 5 contain the line resistance, reactance, and one-half of the total line charging susceptance in per unit on the specified MVA base. The last column must be 1 for lines, or the tap setting values for transformers with off-nominal turn ratio.

5. RESULTS

The results of power flow bus data without using any FACTS device are outlined in table 1(a) and with STATCOM are outlined in table 1(b). Total active and reactive power across line is given in table 2. In first case the voltage magnitude at bus 30 is 0.995, after inserting STATCOM its value increased to 1.046. The maximum power mismatch in first case is 7.54898e-007 in four number of iterations and in second case it is reduced to 5.2677e-007. Similarly total line loss is 17.599MW and 22.244Mvar, and for the second case it is reduced to 15.141MW and 11.489Mvar respectively. Comparison of voltage magnitude and angle for without STATCOM and with STATCOM are shown in figure 8(a) and (b).

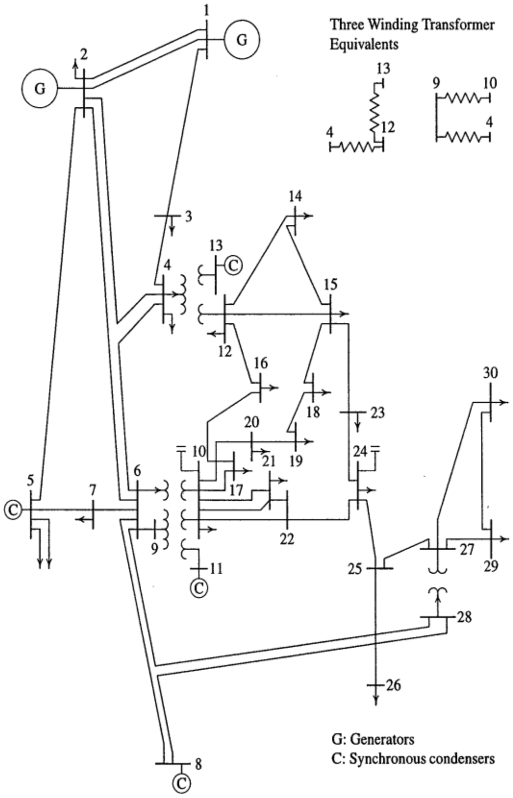

Figure7. IEEE 30 bus system.

Figure 8(a)

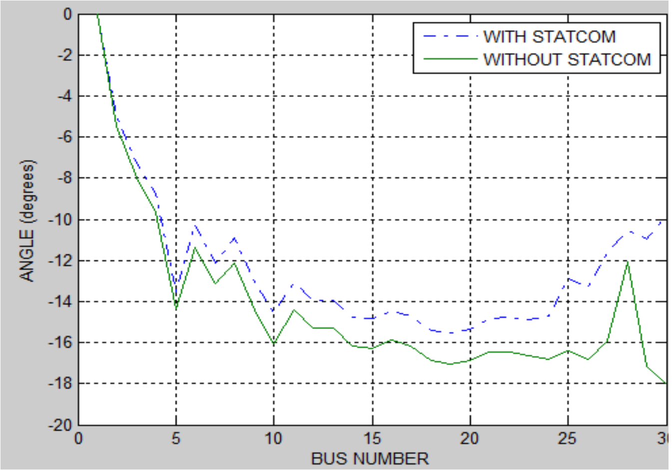

Figure 8(b)

Figure 8. (a) Comparison of voltage magnitude without STATCOM and with STATCOM and (b) angle comparison without STATCOM and with STATCOM.

6. CONCLUSION

A STATCOM model with six pulse SPWM based VSC model has been developed with all the necessary components and controllers and power flow analysis of IEEE 30 bus system without and with STATCOM are analyzed. The values of the voltage magnitude, angle, and generation power, load power, maximum power mismatch and line loss are calculated at each bus. From these values total generation, total load and line losses are evaluated by using Newton-Raphson method power flow program which is developed in MATLAB. The comparison of voltage magnitude, angle and total line loss show that the performance of STATCOM with six pulse SPWM based VSC.

Table1. (a) Power flow without STATCOM: Bus results

Bus No.	Voltage mag.(pu)	Angle	Load		Generator		Injected
		(Degree)	(MW)	(Mvar)	(MW)	(Mvar)	(Mvar)
1	1.06	0	0	0	261	-17.02	0
2	1.043	-5.497	21.7	12.7	40	48.822	0
3	1.022	-8.004	2.4	1.2	0	0	0
4	1.013	-9.661	7.6	1.6	0	0	0
5	1.01	-14.381	94.2	19	0	35.975	0
6	1.012	-11.398	0	0	0	0	0
7	1.003	-13.15	22.8	10.9	0	0	0
8	1.01	-12.115	30	30	0	30.826	0
9	1.051	-14.434	0	0	0	0	0
10	1.044	-16.024	5.8	2	0	0	19
11	1.082	-14.434	0	0	0	16.119	0
12	1.057	-15.302	11.2	7.5	0	0	0
13	1.071	-15.302	0	0	0	10.423	0

14	1.042	-16.191	6.2	1.6	0	0	0
15	1.038	-16.278	8.2	2.5	0	0	0
16	1.045	-15.88	3.5	1.8	0	0	0
17	1.039	-16.188	9	5.8	0	0	0
18	1.028	-16.884	3.2	0.9	0	0	0
19	1.025	-17.052	9.5	3.4	0	0	0
20	1.029	-16.852	2.2	0.7	0	0	0
21	1.032	-16.468	17.5	11.2	0	0	0
22	1.033	-16.455	0	0	0	0	0
23	1.027	-16.662	3.2	1.6	0	0	0
24	1.022	-16.83	8.7	6.7	0	0	4.3
25	1.019	-16.424	0	0	0	0	0
26	1.001	-16.842	3.5	2.3	0	0	0
27	1.026	-15.912	0	0	0	0	0
28	1.011	-12.057	0	0	0	0	0
29	1.006	-17.136	2.4	0.9	0	0	0
30	0.995	-18.015	10.6	1.9	0	0	0
Total			**283.4**	**126.2**	**301**	**125.1**	**23.3**

Table1. (b) Power flow with STATCOM: Bus results

Bus No.	Voltage mag.(pu)	Angle	Load		Generator		Injected
		(Degree)	(MW)	(Mvar)	(MW)	(Mvar)	(Mvar)
1	1.06	0	0	0	238.54	-13.72	0
2	1.043	-5.015	21.7	12.7	40	43.243	0
3	1.023	-7.252	2.4	1.2	0	0	0
4	1.015	-8.743	7.6	1.6	0	0	0
5	1.01	-13.566	94.2	19	0	35.013	0
6	1.014	-10.27	0	0	0	0	0
7	1.005	-12.148	22.8	10.9	0	0	0
8	1.01	-10.887	30	30	0	23.95	0
9	1.052	-13.051	0	0	0	0	0
10	1.045	-14.51	5.8	2	0	0	19
11	1.082	-13.051	0	0	0	15.699	0
12	1.058	-13.975	11.2	7.5	0	0	0
13	1.071	-13.975	0	0	0	10.204	0
14	1.043	-14.788	6.2	1.6	0	0	0
15	1.039	-14.801	8.2	2.5	0	0	0
16	1.045	-14.475	3.5	1.8	0	0	0
17	1.04	-14.707	9	5.8	0	0	0
18	1.029	-15.392	3.2	0.9	0	0	0
19	1.026	-15.553	9.5	3.4	0	0	0
20	1.03	-15.349	2.2	0.7	0	0	0
21	1.033	-14.839	17.5	11.2	0	0	0
22	1.034	-14.788	0	0	0	0	0
23	1.029	-14.899	3.2	1.6	0	0	0

24	1.025	-14.679	8.7	6.7	0	0	4.3
25	1.029	-12.919	0	0	0	0	0
26	1.011	-13.33	3.5	2.3	0	0	0
27	1.039	-11.58	0	0	0	0	0
28	1.015	-10.583	0	0	0	0	0
29	1.038	-10.946	2.4	0.9	0	0	0
30	1.046	-9.797	10.6	1.9	20	0	0
Total			**283**	**126.2**	**298.5**	**114.4**	**23.3**

Table 2: Comparison of Line Results

Parameter	Without STATCOM	With STATCOM
Maximum Power Mismatch(MW)	7.54898e-007	5.2677e-007
Line loss Active power(MW)	17.599	15.141
Line loss Reactive power(Mvar)	22.244	11.489

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APPENDIX A

BUS DATA

		Voltage Mag.	Angle	Load		Generator				Injected
Bus No.	Bus code	(pu)	(Degree)	(MW)	(Mvar)	(MW)	(Mvar)	Qmin	Qmax	(Mvar)
1	1	1.06	0	0	0	0	0	0	0	0
2	2	1.043	0	21.7	12.7	40	0	-40	50	0
3	0	1	0	2.4	1.2	0	0	0	0	0
4	0	1.06	0	7.6	1.6	0	0	0	0	0
5	2	1.01	0	94.2	19	0	0	-40	40	0
6	0	1	0	0	0	0	0	0	0	0
7	0	1	0	22.8	10.9	0	0	0	0	0
8	2	1.01	0	30	30	0	0	-10	60	0
9	0	1	0	0	0	0	0	0	0	0
10	0	1	0	5.8	2	0	0	-6	24	19
11	2	1.082	0	0	0	0	0	0	0	0
12	0	1	0	11.2	7.5	0	0	0	0	0
13	2	1.071	0	0	0	0	0	-6	24	0
14	0	1	0	6.2	1.6	0	0	0	0	0
15	0	1	0	8.2	2.5	0	0	0	0	0
16	0	1	0	3.5	1.8	0	0	0	0	0
17	0	1	0	9	5.8	0	0	0	0	0
18	0	1	0	3.2	0.9	0	0	0	0	0
19	0	1	0	9.5	3.4	0	0	0	0	0
20	0	1	0	2.2	0.7	0	0	0	0	0
21	0	1	0	17.5	11.2	0	0	0	0	0
22	0	1	0	0	0	0	0	0	0	0
23	0	1	0	3.2	1.6	0	0	0	0	0
24	0	1	0	8.7	6.7	0	0	0	0	4.3
25	0	1	0	0	0	0	0	0	0	0
26	0	1	0	3.5	2.3	0	0	0	0	0
27	0	1	0	0	0	0	0	0	0	0
28	0	1	0	0	0	0	0	0	0	0
29	0	1	0	2.4	0.9	0	0	0	0	0
30	0	1	0	10.6	1.9	0	0	0	0	0

LINE DATA

Bus	Bus	R	X	1/2 B	Line code for lines =1
nl	nr	p.u.	p.u.	p.u.	> 1 or < 1 tr. tap at bus nl
1	2	0.0192	0.0575	0.0264	1
1	3	0.0452	0.1852	0.0204	1
2	4	0.057	0.1737	0.0184	1
3	4	0.0132	0.0379	0.0042	1
2	5	0.0472	0.1983	0.0209	1
2	6	0.0581	0.1763	0.0187	1
4	6	0.0119	0.0414	0.0045	1
5	7	0.046	0.116	0.0102	1
6	7	0.0267	0.082	0.0085	1
6	8	0.012	0.042	0.0045	1
6	9	0	0.208	0	0.978
6	10	0	0.556	0	0.969
9	11	0	0.208	0	1
9	10	0	0.11	0	1
4	12	0	0.256	0	0.932
12	13	0	0.14	0	1
12	14	0.1231	0.2559	0	1
12	15	0.0662	0.1304	0	1
12	16	0.0945	0.1987	0	1
14	15	0.221	0.1997	0	1
16	17	0.0824	0.1923	0	1
15	18	0.1073	0.2185	0	1
18	19	0.0639	0.1292	0	1
19	20	0.034	0.068	0	1
10	20	0.0936	0.209	0	1
10	17	0.0324	0.0845	0	1
10	21	0.0348	0.0749	0	1
10	22	0.0727	0.1499	0	1
21	22	0.0116	0.0236	0	1
15	23	0.1	0.202	0	1
22	24	0.115	0.179	0	1
23	24	0.132	0.27	0	1
24	25	0.1885	0.3292	0	1
25	26	0.2544	0.38	0	1
25	27	0.1093	0.2087	0	1
28	27	0	0.396	0	0.968
27	29	0.2198	0.4153	0	1
27	30	0.3202	0.6027	0	1
29	30	0.2399	0.4533	0	1
8	28	0.0636	0.2	0.0214	1
6	28	0.0169	0.0599	0.065	1

STATCOM DATA

Bus No.	Voltage Mag. p.u.	Angle (Degree)	STATCOM	
			QS_{min}	QS_{max}
29	1	0	-0.5	0.5
30	1	0	-0.5	0.5