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Enhancing Power System Performance by Interaction of FACTS Controllers in Multi-Machine Environments with Integrated Unified Power Flow Controller

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Abstract

This dissertation entails obtaining optimum placement of STATCOM on Nigeria's North East 330 / 132 KV transmission system in other to improve the overall voltage profile of the transmission system and to minimize losses in the system. Static compensation devices are electrical devices which when placed on power systems improves the quality of the system. In this research work, STATCOM was placed on a Nigerian North East 12 bus flexible alternating current transmission system (FACTS). This was achieved by modelling the actual FACTS device using power systems analysis tool box of the MATLAB software. After modelling the system, particle swarm optimization technique was written in MATLAB and was used to determine the optimum placement of STATCOM on the 12-bus system, thereby improving the quality of the system. At the end of this research work, it was discovered that for the North East transmission system, the optimum placement of STACOM occurred at bus 11, that is the Yola 132 KV sub-transmission system, for single placement and at bus 11 and 12 (Yola and Bauchi sub-transmission system) for double placement of STATCOM.

Keywords: FACTS Devices, STATCOM, Interconnected Power Systems, MATLAB, PSO

INTRODUCTION

Nigeria electric power system is undergoing changes as a result of constant power demand increase due to economic activities, population growth, and social advancement thus stretching it beyond their stability and thermal limit (Bindeshwar *et al.*, 2012). This drastically affects the power output delivered by the power system. Power systems should be flexible to respond to generation, transmission, distribution and the load patterns. Solving the problem of increasing power demand by only building more power generating stations and transmission lines is not economical or environmentally friendly (Aishvarye & Srivasta, 2015). So other methods of enhancing power system capacity must be sought.

Nowadays, fixed or mechanically switched shunt and series capacitors, reactors and synchronous generators are being to provide some type of stability augmentation (Ye *et al.,* 2005). In many parts of the world, utilities are doing their best to devise modern means of extending the power enhancement capabilities of its transmission lines so as to maintain the quality of power delivered through them. In Nigeria, load shedding is widely used by the then Power Holding Company of Nigeria (PHCN) to minimize consequences of poor power generation and delivery, and this has impacted negatively on its power system reliability (Adepoju & Komolafe, 2011).

In recent years, many techniques have been developed to enhance the voltage level of power utilities. In this thesis study of FACTS devices is done with the view to explore its applicability to the Nigerian 330/132kV North East electric power network. It looks towards seeking for ways to enhance performance of the existing power network for better utilization.

FACTS devices are power electronic based system which together with other static equipment provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability (Aarti, 2013). Facts controllers has the ability to boost transmission control, dependability, operation and also improve the distribution power system quality (Shih-Min, 1999). FACTS technology is a concept based on the use of power electronics controllers which are fast acting and cost effective for controlling power flow in electric power networks (Hingorani & Gyugyi, 1999). They have faster response than switching capacitors and reactors for reactance compensation.

One member of FACTS devices is the Static Synchronous Compensator (STATCOM) connected in shunt with the power systems is highly effective in improving the performance parameters of power system like reactive power compensation (RP), transient stability (TS), steady state voltage stability (SSVS), enhancement of power transfer (PT) capability and protection (Hingroni & Gyugyi, 1999).

One power instability problem confronting Nigerian power system is inadequate and inefficient supply of reactive power into its power network (Emmanuel *et al.,* 2016). Power generation and transmission is a complex process. It requires the working of many components of the power system concurrently to maximize the output. One of the main components is the reactive power needed in the power system. It is required to maintain the voltage to deliver the active power through the lines. Motor loads for example require reactive power for their operation (Orlando & Tzung-Lin, 2016). To improve the performance of ac power systems, there is need to manage this reactive power in an efficient way and this is known as reactive power compensation. Thus, FACTS devices such as STATCOM provides a good control of adequate and efficient supply of reactive power into power systems (Roonam & Siraparapu, 2015).

This work focuses primarily on the examination of the effects of applying STATCOM for bus voltage enhancement capability in Gombe 132 kV transmission substation, 12-bus system as a case study. STATCOM is a shunt-connected device capable of injecting or absorbing reactive power to regulate the voltage profiles of the power system bus to which it is connected (Agrawal *et al.,* 2016). In this research, the distribution substation power network will be modeled in PSAT tool in MATLAB environment.

The Nigerian power system has always experienced poor voltage profile, inadequate power dispatch and poor control infrastructure. It has radial and fragile network, frequent system collapse, and exceedingly high transmission losses. These results in reduction of maximum power transfer capability on the line, thereby contributing to the constant power failure in Nigerian power system (Chawla & Singh, 2013).

The poor voltage profile has also been experienced at the receiving end in Gombe 132kV transmission substation (Ogbuefi & Madueme, 2015). As a result, there is a limited power transfer capacity to the neighboring states and to other towns within the network. The transmission line losses, and associated instability have often resulted in system collapse leading to power outages in the entire 12-bus network. The power network is confronted with low voltage level, insufficient supply of reactive power

from the power infeed leading to unstable power flow and poor network system operation.

The major loads in this area include: Ashaka Cement Factory, Gombe-Potiskum 132 kV line, Gombe-Yola 132kV, Gombe-Biu 132 kV, Biu-Damboa 132kV, and Damboa-Maiduguri 132 kV. With the increase in the power demand in the region, the Gombe 132 kV network is stressed and limited in power transfer capability.

The aim of the research work is to investigate ways of improving voltage profile of Gombe 132kV power network through the application of STATCOM technology.

The following are the objectives of the work:

i. To determine the voltage variations of Gombe 132 kV transmission network to ascertain if they are within the prescribed regulatory limit of ±5% of the nominal voltage.
ii. To improve the voltage magnitude of the 12 buses using STATCOM so as to minimize number of blackouts.
iii. To improve the performance of the power network using two STATCOMs.
iv. To reduce power losses in Gombe 123 kV, 12- bus network through proper control of real and reactive power using STATCOM.

METHODOLOGY

The following method is proposed to study the effectiveness of STATCOM in improving the voltage of Gombe 132 kV, 12-bus power network. The power system is first modeled and simulated without STATCOM and then with STATCOM using PSAT in MATLAB environment. The optimal placement of single and double STATCOM was realized by the use of PSO technique.

MATERIALS

The materials to be used for the power network analysis include PSAT software in MATLAB/SIMULINK environment, Gombe 132 kV single line diagram and its parameters.

PSAT in MATLAB/SIMULINK environment

Software for the simulation of the power distribution network with the power word simulation program using Power System Analysis Toolbox (PSAT) in the MATLAB environment incorporating SIMULINK will be used. This is to characterize the

behavior of the distribution network System with and without the installation of STATCOM. The command line version of PSAT is also GNU octave compatible. All operations can be assessed by means of graphical User Interfaces (GUIs) and a SIMULINK-based library provides a user-friendly tool for network design. PSAT includes bridges to General Algebraic Model System (GAMs) and UWPFLOW programs, which highly extended PSAT ability of performing optimization and continuation power flow analysis (Federico, 2008).

GOMBE 132 KV SINGLE LINE DIAGRAM

The single-line diagram of the existing 330/132 kV, 12-bus network with the line contingency control variables will be used as a case study. The interconnections of power grid network stretching from Gombe 132 kV to various distribution substations is as shown in Figure 1.

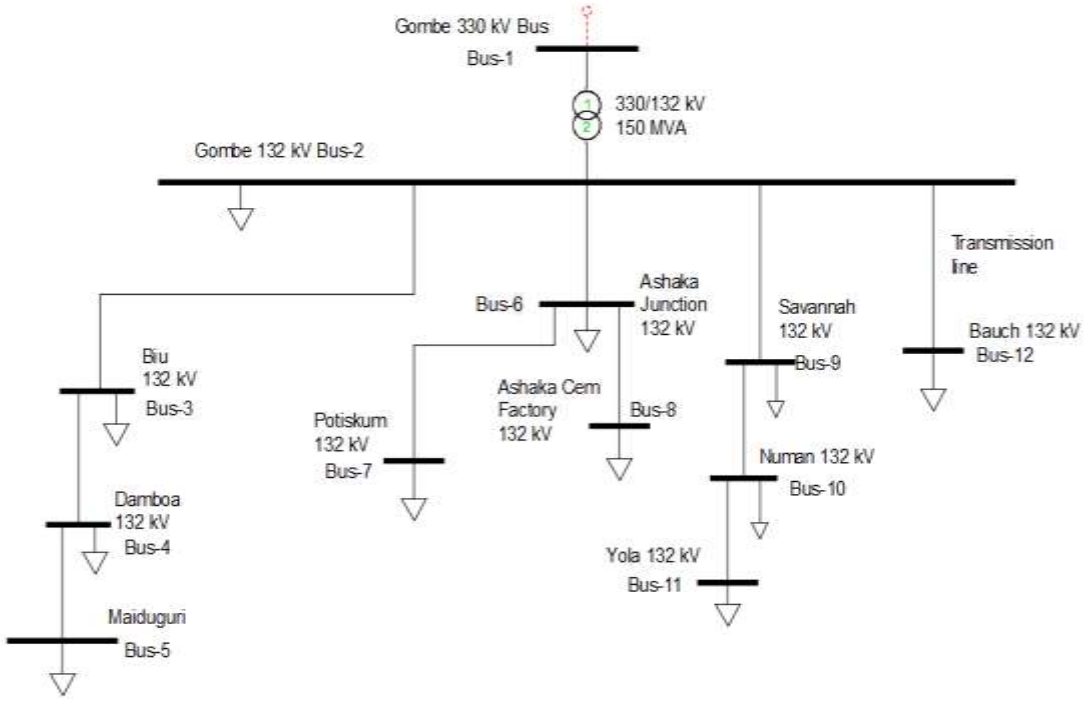


Figure 1: Single Line Diagram of Northeast 132 kV Power Network

GOMBE 132 KV TRANSMISSION LINE PARAMETERS

The input data needed for the analysis and simulation include the parameters (resistance, reactance and susceptance) of the transmission line, voltages and transformer/load data of Northeast 330/132kV buses and the 330kV Jos in-feed

substations so as to identify those major centers that suffers from the low voltage profile problems with changing system demands. The operating data obtained from the Transmission Company of Nigeria (TCN) Gombe are presented in the following tables:

i. Table 1 presents line parameters in p.u on 100 MVA base specifying the line voltage, length, impedances comprising of resistance, reactance and half-line charging susceptance of the line.

ii. Table 2 lists the power network bus data specifying bus voltage, average load on each bus, real and reactive power loading on each bus.

Table 1: Transmission Line Parameters in P.U on 100MVA Base

S/N	Name of Branch	Type	Length (km)	Rated Voltage (kV)	Current Limit (A)	R (p.u)	X (p.u)	B (p.u)
i.	Jos-Gombe	Bison	265	330	1360	0.0095	0.051	1.010
ii	Jos-Bauchi	Bison	118	132	400	0.140	0.280	0.057
iii	Bauchi-Gombe	Bison	146	132	306	0.172	0.344	0.042
iv	Gombe-Biu	Hyena	126	132	400	0.221	0.311	0.059
v	Biu-Damboa	Wolf	92	132	400	0.162	0.227	0.042
vi	Gombe-Ashaka Junction	Hyena	84	132	400	0.098	0.197	0.041
vii	Ashaka/junction-Factory	Hyena	10	132	306	0.118	0.024	0.005
viii	Ashaka -Potiskum	Wolf	94	132	306	0.110	0.221	0.046
ix	Gombe-Savannah	Hyena	95	132	306	0.166	0.233	0.044
x	Savanah-Numan	Hyena	85	132	306	0.149	0.211	0.039
xi	Numan-Yola	Hyena	50	132	306	0.087	0.123	0.023
xii	Damboa-Maiduguri	Wolf	85	132	400	0.149	0.209	0.039

Source: Jos Electricity Distribution Company (JEDCO) Gombe, Nigeria, (2016).

Table 2: Bus Data the Transmission Network

Bus No.	Bus Name	Bus Voltage (kV)	Average load on Bus (MW)	Real Power P(MW)	Reactive Power Q(MVAR)
1	Jos	330	98.30	50.00	20.00
2	Gombe	132	23.40	20.01	16.01
3	Biu	132	4.80	1.50	1.20
4	Damboa	132	11.90	1.21	0.98
5	Maiduguri	132	76.60	32.50	26.01
6	Ashaka junction	132	30.00	9.10	6.00
7	Potiskum	132	28.00	15.5	8.90
8	Ashaka Cement Factory	132	3.51	1.40	2.40
9	Savannah	132	3.60	2.81	2.20
10	Numan	132	3.60	2.80	2.30
11	Yola	132	41.80	9.00	3.60
12	Bauchi	132	30.00	30.00	24.02

Source: Jos Electricity Distribution Company (JEDCO) Gombe, Nigeria, (2016).

In order to achieve the objectives of the research work, the 12-bus network of North east 132 kV transmission is modeled and simulated using PSAT in MATLAB environment. The buses are classified as load bus, generator bus and slack bus or the PV bus. Data for the simulation include bus data, transmission line data, and generator data. The following methods are adopted for the power flow analysis:

i. Run the power system GUI written in MATLAB and enter parameters like communication port and phone number that will receive the text message
ii. Run the power flow of the existing power network without STATCOM (without compensation) to arrive at results known as the base case. The base case shows the voltage level, real/reactive power level and power losses at all the buses without inclusion of STATCOM.
iii. Locate single STATCOM one by one into the buses so as to find its best position of placement.

iv. Locate two STATCOMs into the buses using PSO technique to find its optimal location in the power network.

v. Investigate real/reactive power flow control and power losses in the network with and without STATCOM.

The following method is adopted to study the effect of using STATCOM devices in improving the

voltage level of North East 132 kV, 12-buspower network. First, the existing power network is built by Graphic user interface (GUI) of PSAT in MATLAB environment as shown in Figure 2.

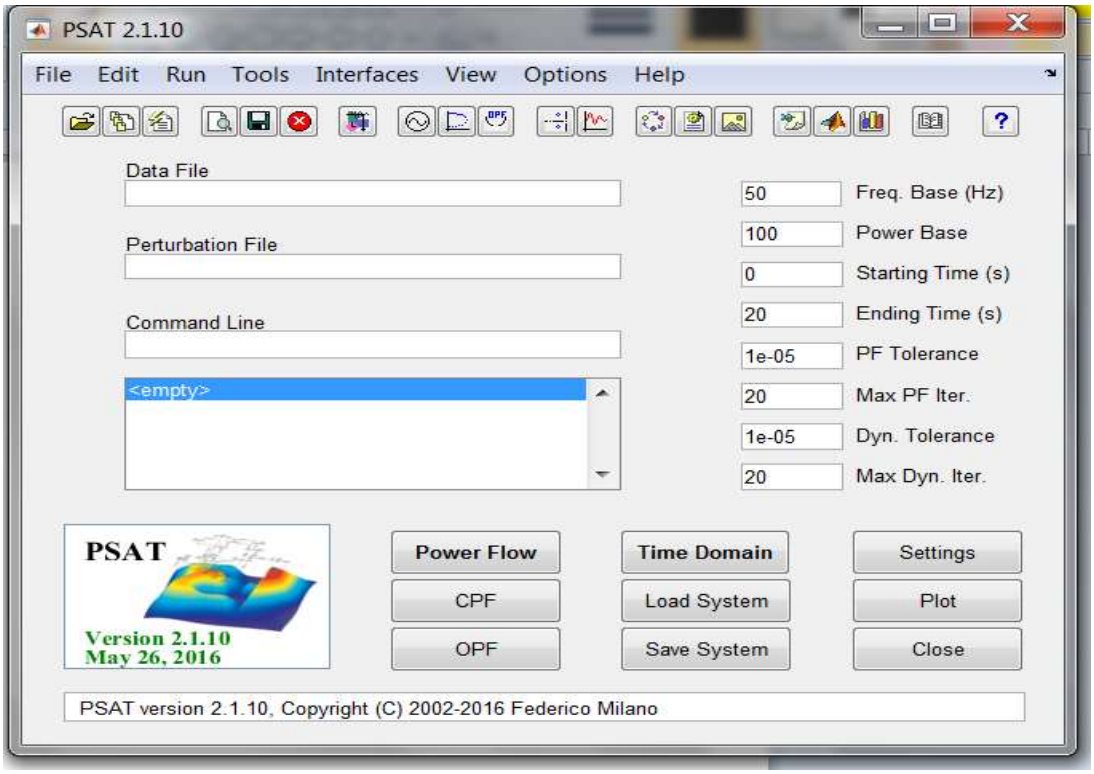


Figure 2: Graphic User Interface (GUI) Environment of PSAT Software

Network design

The single line diagram of Northeast 132 kV, 12-bus power network as shown in Figure 2 is first designed using the PSAT/SIMULINK environment by dragging and dropping the symbols of buses, generators, transmission lines, etc., as appeared on the diagram. All the transmission line parameters as in Table 1, and the power network bus data as in Table 2 were entered.

The design of the single line diagram of the power network designed by the PSAT GUI environment is as shown in Figures 3.

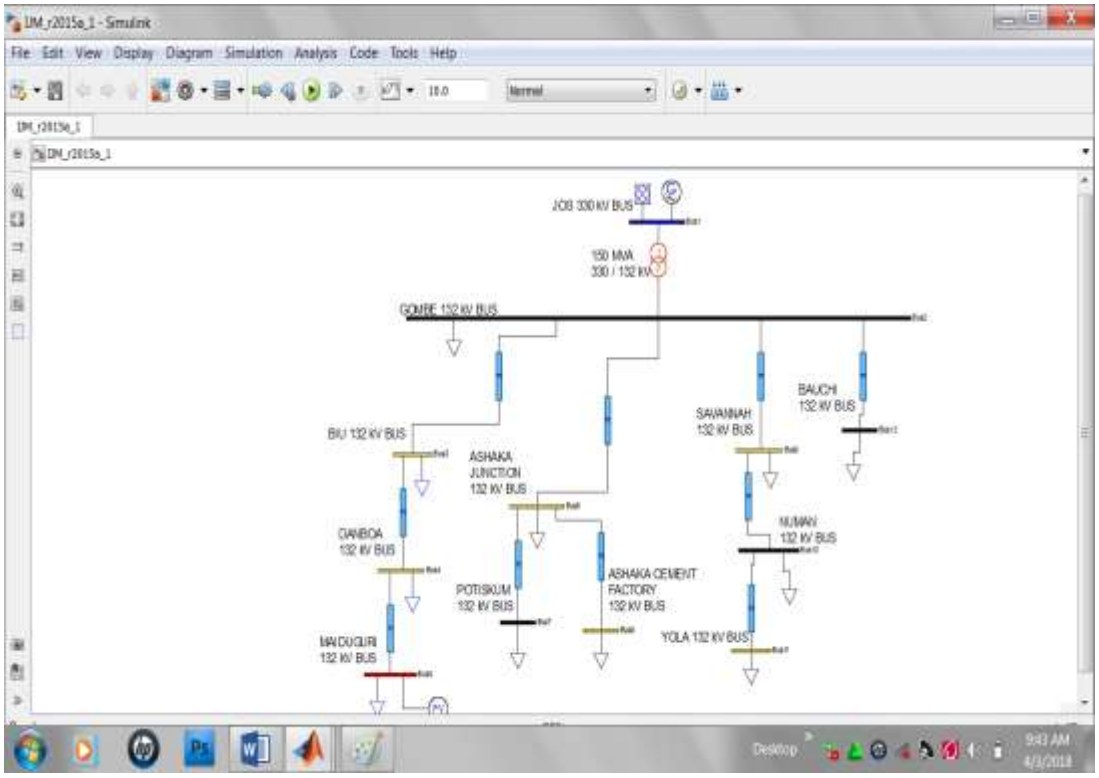


Figure 3: Network Model without STATCOM in PSATMATLAB Environment

VOLTAGE LEVEL WITHOUT STATCOM (BASE CASE)

The power flow of the designed existing network in PSAT/SIMULINK mode in Figure 3is run without STATCOM to arrive at a results known as the base case. The results displayed by PSAT GUI environment known as the static report is as displayed in Figure 4.

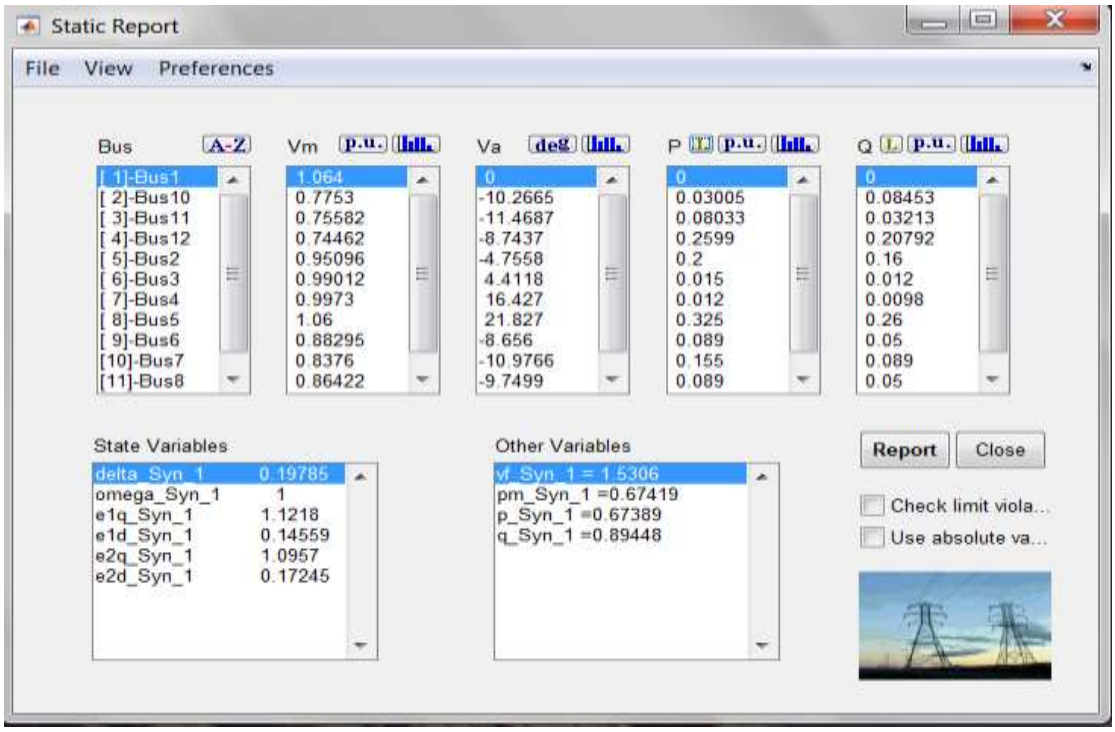


Figure 4 GUI Power Flow Static Report of PSAT in MATLAB Environment

The power flow static report shows the status of the voltage magnitude, real/reactive power generated, real/reactive power losses, total power generated in all the buses without the inclusion of STATCOM. In addition to the PSAT GUI static report in Figure 3, the detailed power flow report is also viewed through the PSAT GUI as shown in Figure 5by clicking at view file to arrive at the corresponding.

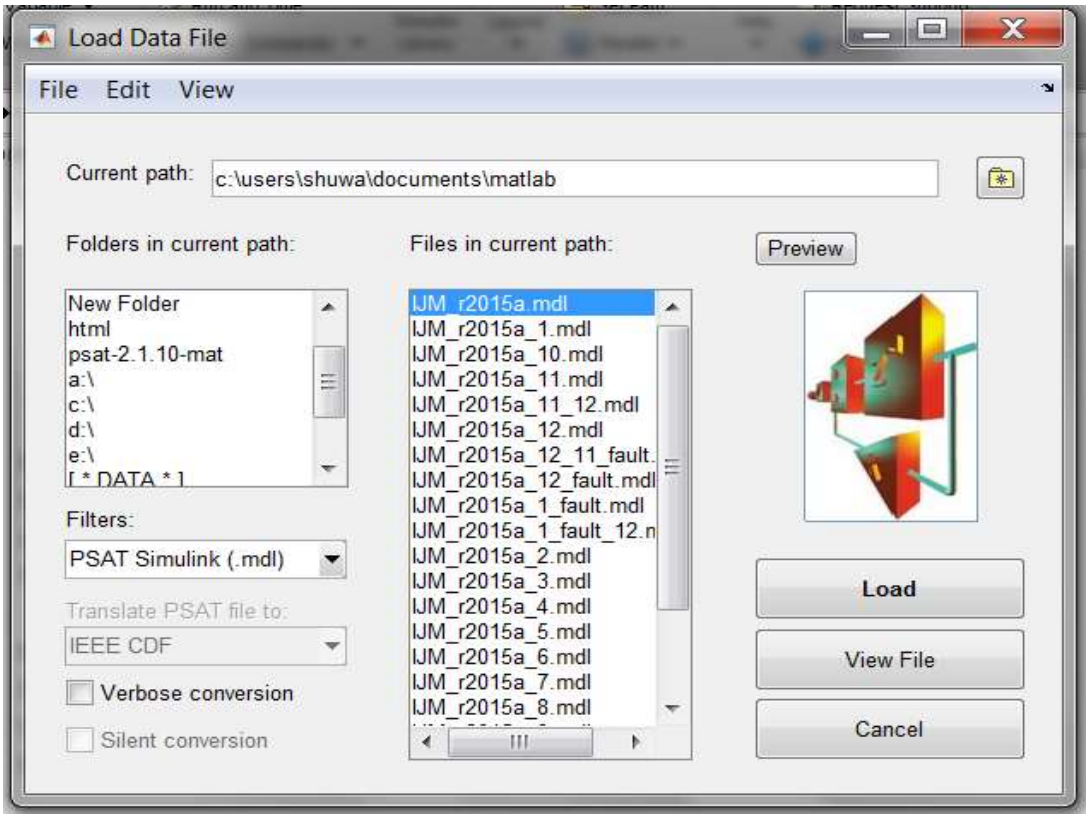


Figure 5: PSAT GUI Detail Power Flow Report in MATLAB Environment

Voltage Level with Single STATCOM

Next step, a single STATCOM is included in the power network buses built in PSAT in MATLAB environment one at a time on each of the buses excluding slack bus-1 and PV bus-5.

LOCATION OF STATCOM AT BUS-2

A single STATCOM is located at bus-2 as shown in Figure 6, then power flow is run to obtain results with compensation. The power flow static report generated contained the magnitude of the voltage level, real/reactive power generated, real/reactive power losses and total power generated in bus-2 with STATCOM.

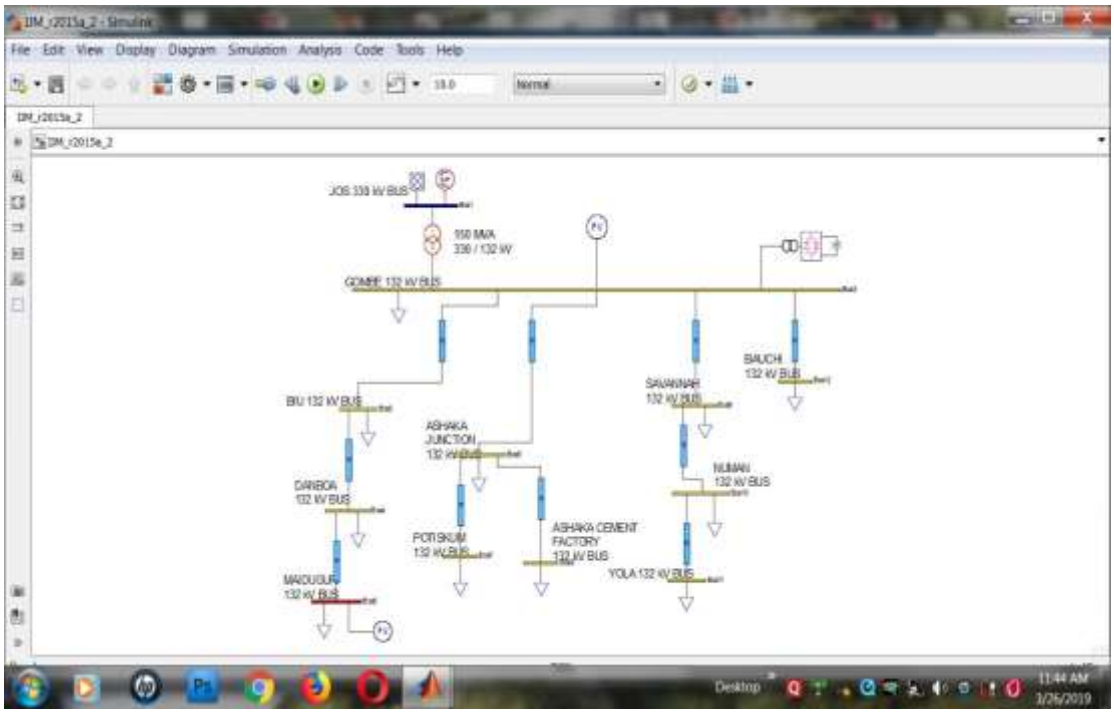


Figure 6: Network Model with STATCOM at bus-2 in PSAT MATLAB Environment

LOCATION OF STATCOM AT BUS-3

Single STATCOM is located at bus-3 as displayed in Figure 7and the power flow is run to arrive at a results with STATCOM at bus-3.

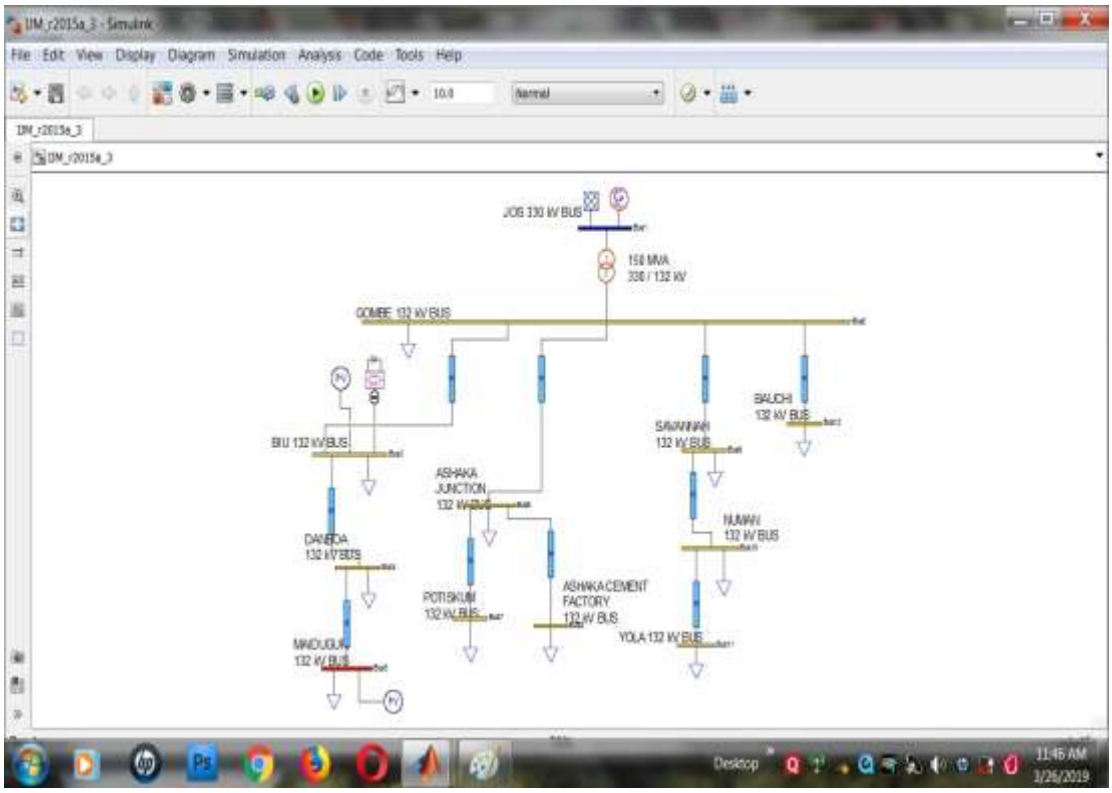


Figure 7: Network Model with STATCOM at bus-3 in PSAT MATLAB Environment

LOCATION OF STATCOM AT BUS-4

Similarly, a Single STATCOM is located at bus-4 as shown in Figure 8 and the power flow is run to arrive at a results with STATCOM at bus-4.

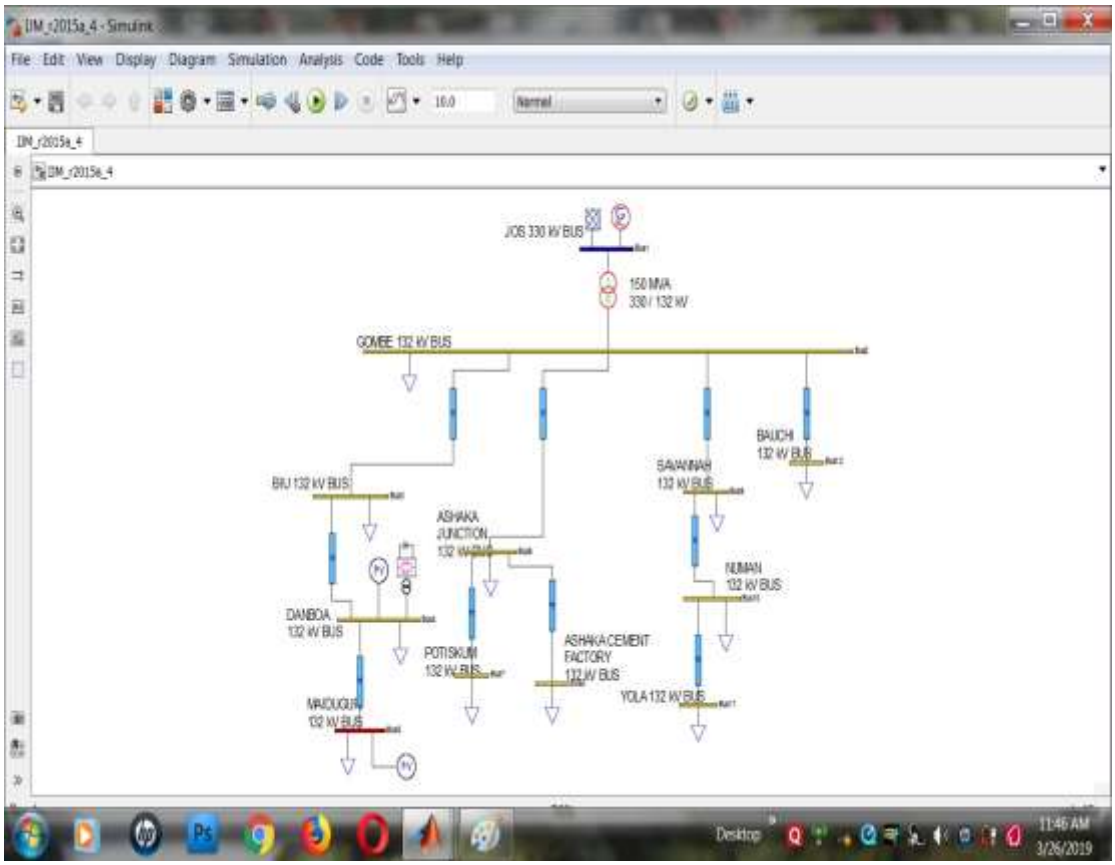


Figure 8: Network Model with STATCOM at bus-4 in PSAT MATLAB Environment

The process continued as described in the previous scenarios by locating a single STATCOM one by one into the remaining buses 6, 7, 8, 9,10, 11 and 12. Their corresponding model in PSAT MATLAB/SIMULINK environment is as shown in Figures 9, 10, 11, 12,13, 14 and 15 respectively. Similarly, each time the power flow is run static report displayed results for each scenario to arrive at their respective bus voltages, real and reactive power profiles.

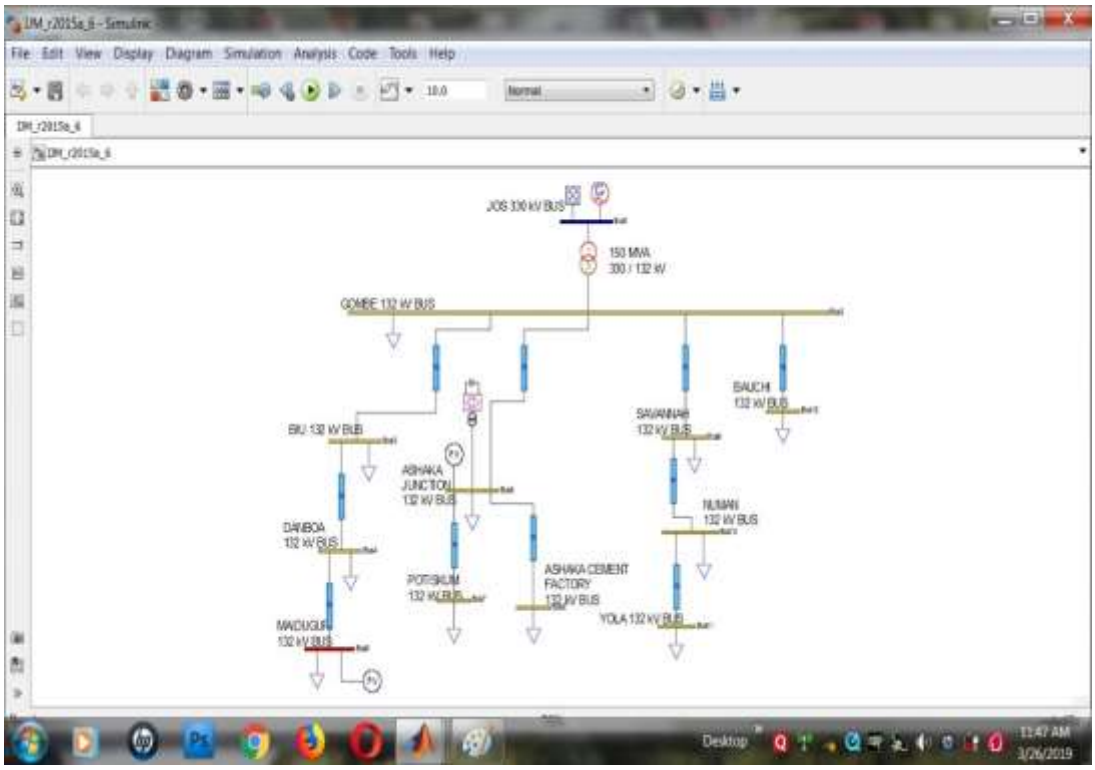


Figure 9: Network Model with STATCOM at bus-6 in PSAT MATLAB Environment

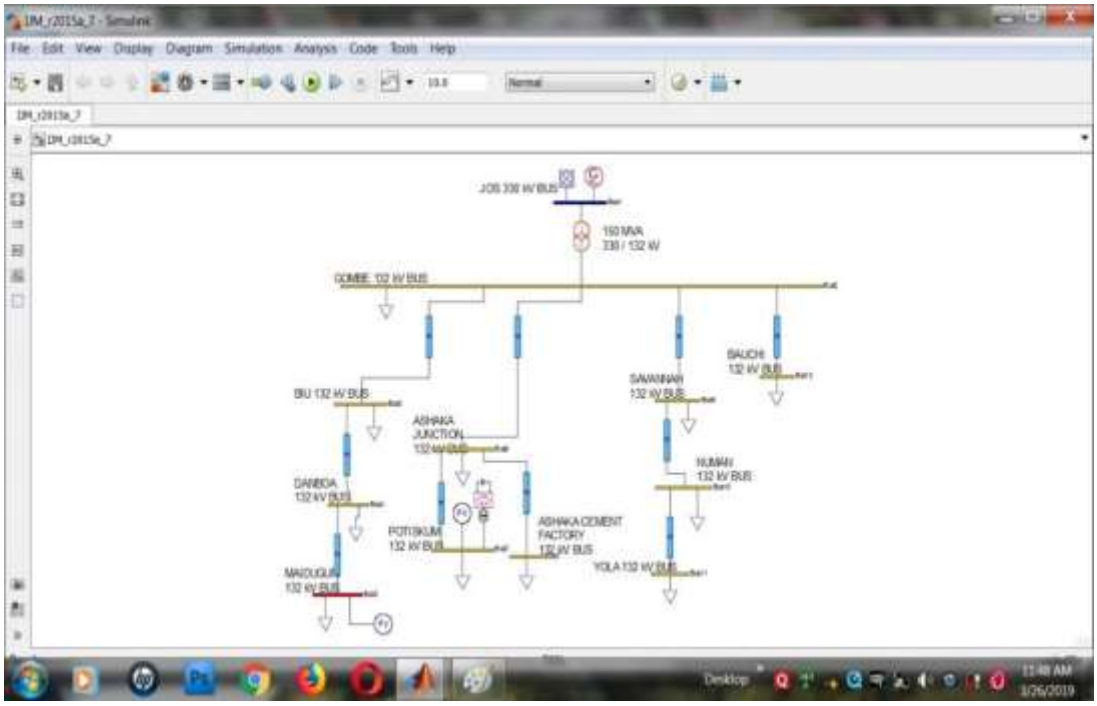


Figure 10: Network Model with STATCOM at bus-7 in PSAT MATLAB Environment

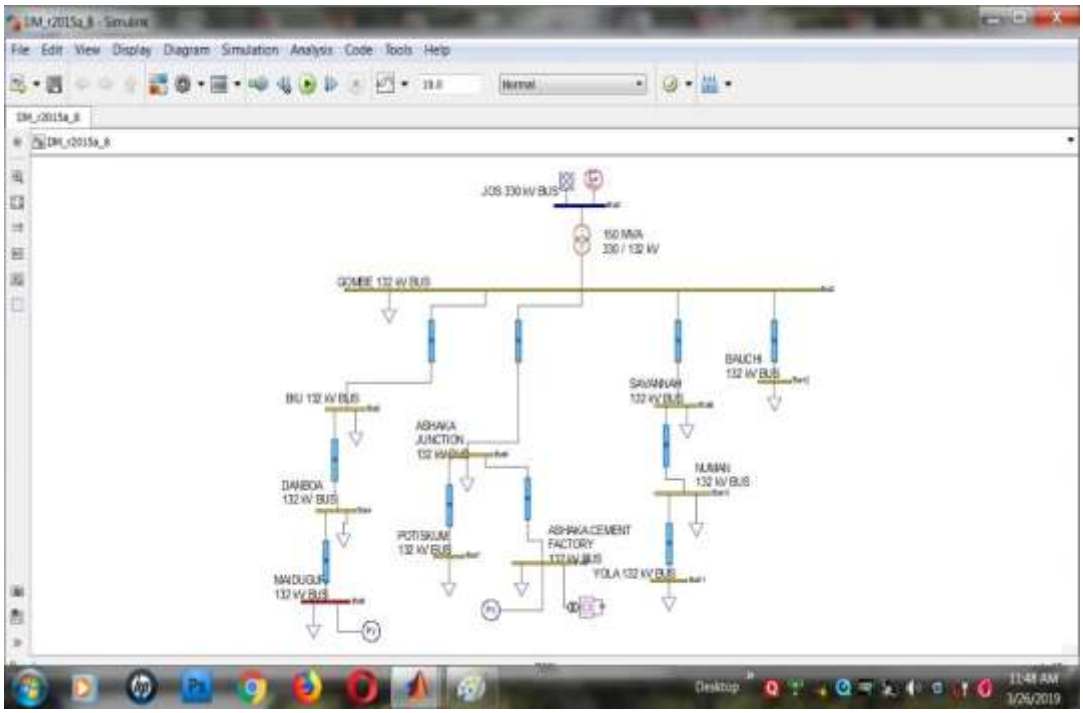


Figure 11: Network Model with STATCOM at bus-8 in PSAT MATLAB Environment

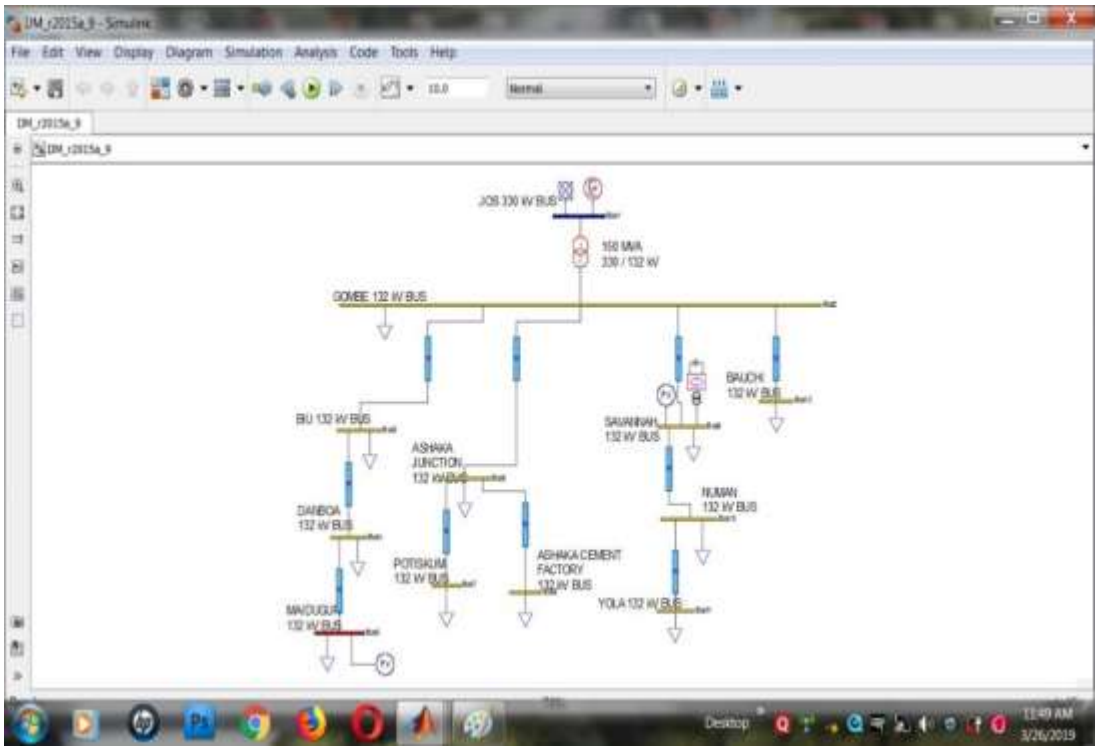


Figure 12: Network Model with STATCOM at bus-9 in PSAT MATLAB Environment

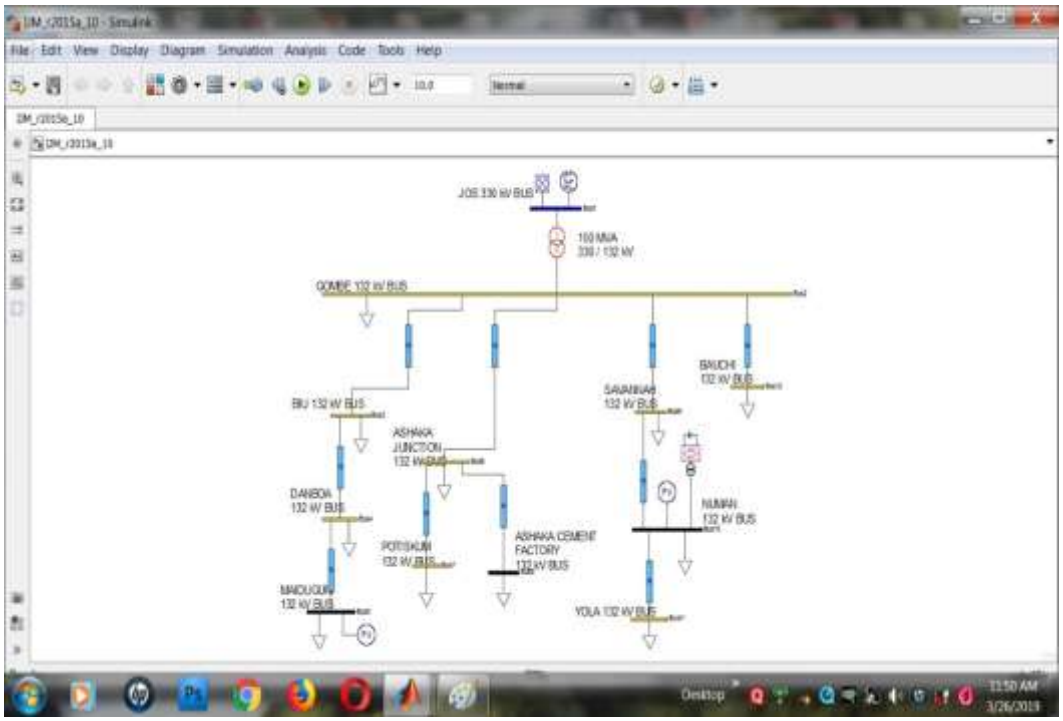


Figure 13: Network Model with STATCOM at bus-10 in PSAT MATLAB Environment

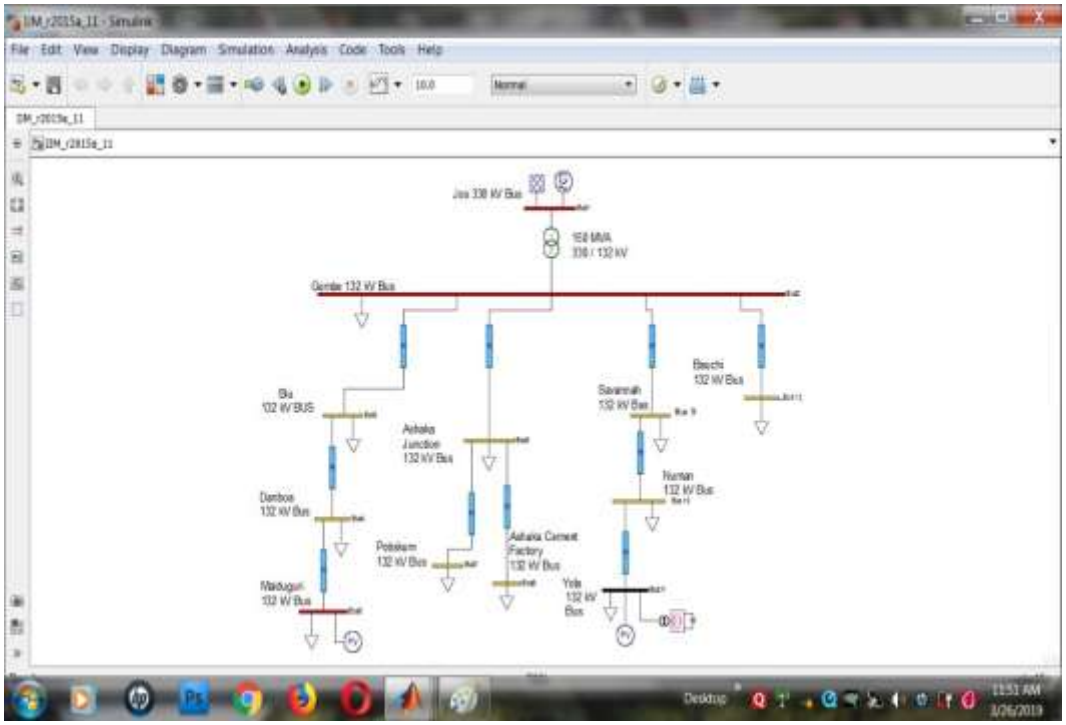


Figure 14: Network Model with STATCOM at bus-11 in PSAT MATLAB Environment

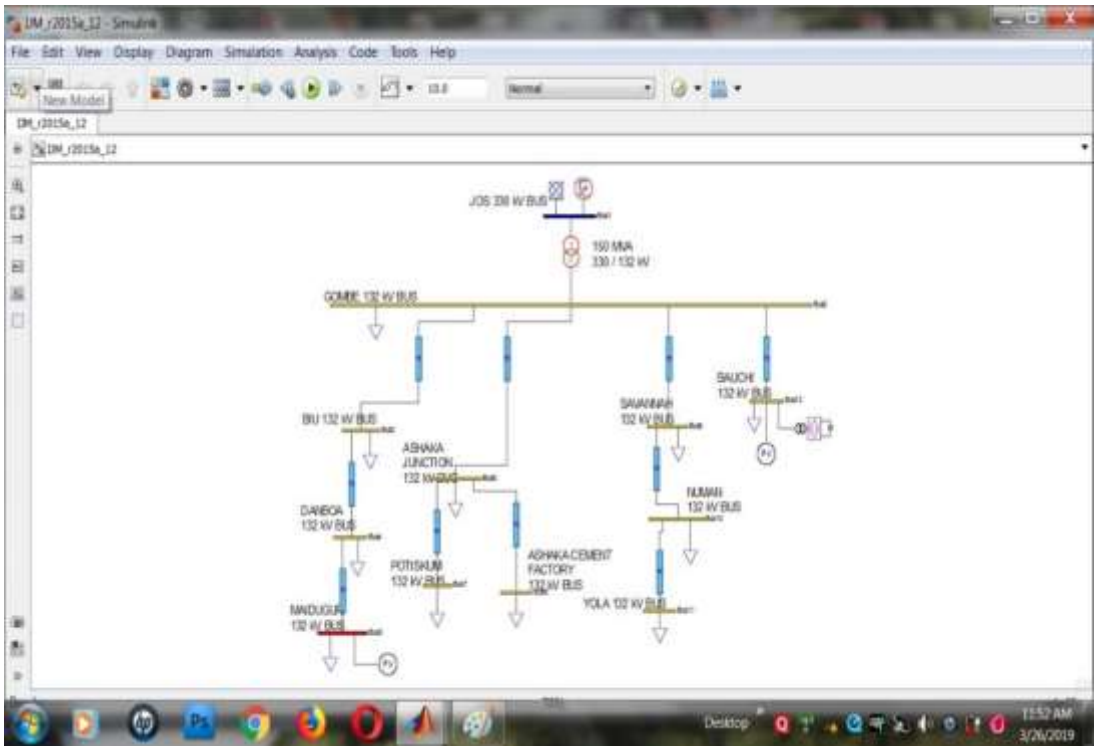


Figure 15: Network Model with STATCOM at bus-12 in MATLAB Environment

LOCATION OF A SINGLE STATCOM USING PSO ALGORITHM

PSO algorithm is used to determine the best placement of single STATCOM into Gombe 132 kV, 12-bus network to determine its optimal placement. The network is run using PSO algorithm program codes as shown in appendix B.

LOCATION OF A SINGLE AND TWO STATCOMS USING PSO ALGORITHM

PSO algorithm is used to obtain the best position to locate a single and two STATCOMs into the power network to determine its optimal placement.

OBJECTIVE FUNCTION OF PSO POWER FLOW ANALYSIS

The objective function (J) is a r.m.s value of voltage deviation. It is taken as:

$$J = \sqrt{\sum_{i=1}^{12}(V_i - 1)} \quad ^2$$

… (12)

The main objective is to minimize the voltage deviation from the nominal and achieve good voltage stability in the power system network.

PSO PARAMETERS

PSO parameters are taken and applying hit and trail method. The following are the parameters taken for the PSO analysis:

i. A constant inertia weight $w_i$is taken as a function which decrease randomly from 0.9 to 1.
ii. Number of particle taken is 5 with random initial STACOM position.
iii. Two constants were taken, the acceleration constant and the social acceleration constant. The individual acceleration constant is the constant used to show the impact of individual particle best position gain by particle itself on the next value of velocity of that particle denoted by c_1. For this study it is taken as c_1=2.6. Social acceleration constant is the constant used to show the effect of best position gained by any particle(gbest) on the next value of velocity of that particle denoted by c_2. Similarly, for this study it is taken as c_2=1.4.
iv. No of iterations taken is 10 for a single STATCOM and 30 for two STATCOMs.

For each of the scenarios, the results obtained are compared between the base case (without compensation) where no STATCOM is used and with inclusion of STATCOM (with compensation). Wherever a STATCOM is located in the buses and the power flow is run using PSAT, the real/reactive power generated and power losses are recorded per bus and the results tabulated. The effectiveness of STATCOM is drawn from comparing the results with and without STATCOM.

RESULTS

In this section, simulation results of placement of STATCOM into the Gombe 132kV, 12-bus power network is presented. The STATCOM is located one at a time into the buses and PSO methods to ascertain the optimal placement of the device to enhance the bus voltage magnitude of the power network. The results of the simulation with and without STATCOM using PSAT were tabulated and plotted.

SIMULATION RESULTS WITHOUT STATCOM (BASE CASE)

For the system without a STATCOM, Table 3 shows the power flow results indicating the voltage profile, real and reactive power generated. The bar graph of the voltage magnitudes versus the bus number of the power network is depicted in Figure 31.

Table 3: Voltage Magnitude Without STATCOM (Base Case)

Bus No	V m (p.u)	Phase (Deg.)	P gen (p.u)	Q gen (p.u)	P Load (p.u)	Q Load P.u)
1	1.06400	0.00000	0.67389	0.89448	0.00000	0.00000
2	0.95096	-4.75580	0.00000	0.00000	0.20000	0.16000
3	0.99012	-4.41180	0.00000	0.00000	0.01500	0.01200
4	0.99730	16.42700	0.00000	0.00000	0.01200	0.00980
5	1.06000	21.82700	0.80000	0.25553	0.32500	0.26000
6	0.88295	-8.65600	0.00000	0.00000	0.08900	0.05000
7	0.83760	-10.97660	0.00000	0.00000	0.15500	0.08900
8	0.86422	-9.74990	0.00000	0.00000	0.08900	0.05000
9	0.85091	-6.85091	0.00000	0.00000	0.02800	0.02200
10	0.77530	-10.26650	0.00000	0.00000	0.03005	0.08453
11	0.75582	-11.46870	0.00000	0.00000	0.08033	0.03213
12	0.74462	-8.74370	0.00000	0.00000	0.25990	0.20792

It can be seen that voltage at different buses vary with bus-12 in Figure 16 having the lowest voltage magnitude in the power flow and nearby buses also suffer from low voltage. Most of the bus voltages are less than the acceptable voltage range between 0.95p.u. and 1.05p.u. The voltage values of bus-1 and bus-5 in Figure 16 are higher than the others, because bus-1 is a slack bus while bus-5 is a PV bus.

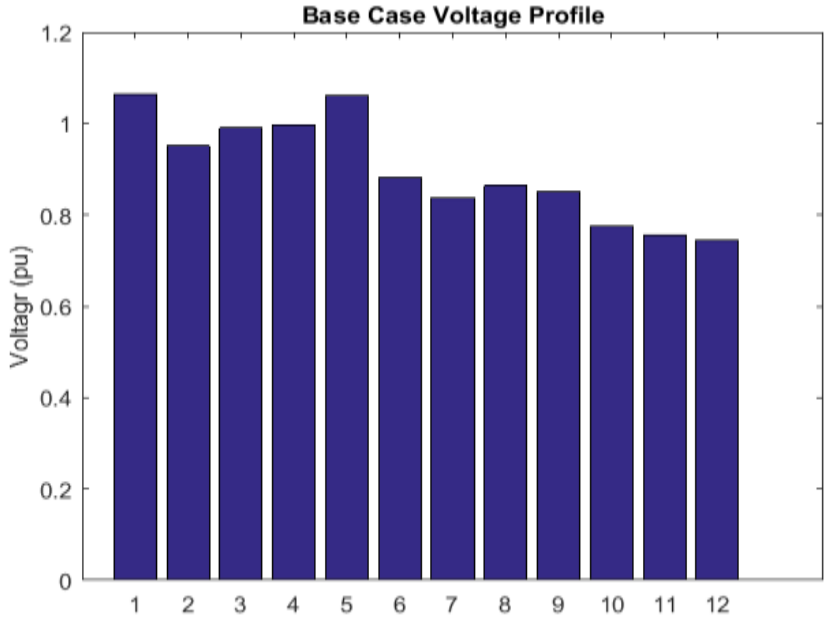


Figure 16: Voltage Magnitude Without STATCOM (Base Case)

RESULTS FOR LOCATION OF A SINGLE STATCOM

In section 3.4the need to locate the STATCOM at the buses to study its performance of power enhancement capability in the network was indicated. The STATCOM was located on every bus one by one excluding the slack bus-1 and PV bus-5, so as to choose the best location. The essence of placing the STATCOM one by one is to find the best location that will improve the bus voltage level in the network.

RESULTS FOR LOCATING STATCOM AT BUS-2

Results for placement of a single STATCOM at bus-2 is as shown in Table 4 and a bar graph plot of the voltage magnitude versus the bus number is as shown in Figure 17. The placement of a STATCOM at bus-2 improved the buses voltage level when compared to that without STATCOM. This improvement did not give the best results as most of the voltage level fell outside the voltage bound constraint limit defined by 0.95p.u. ≤ V≤ 1.05 p.u.

Table 4: Bus Voltage Magnitude with a Single STATCOM

Bus no	Voltage magnitude with STATCOM at each bus									
	2	3	4	6	7	8	9	10	11	12
1	1.064	1.064	1.064	1.064	1.064	1.064	1.064	1.064	1.064	1.064
2	1.000	0.954	0.951	0.993	0.984	0.982	0.986	0.979	0.977	1.020
3	1.023	1.000	0.992	1.018	1.012	1.011	1.013	1.010	1.007	1.031
4	1.007	1.004	1.000	1.006	1.004	1.004	1.005	1.003	1.003	1.010
5	1.060	1.060	1.060	1.060	1.060	1.060	1.060	1.060	1.060	1.060
6	0.939	0.887	0.884	1.000	0.976	0.970	0.923	0.916	0.913	0.953
7	0.901	0.842	0.838	0.962	1.000	0.930	0.881	0.872	0.870	0.942
8	0.922	0.868	0.865	0.985	0.960	1.000	0.906	0.900	0.895	0.945
9	0.900	0.854	0.851	0.892	0.882	0.880	1.000	0.971	0.961	0.940
10	0.823	0.778	0.776	0.814	0.805	0.802	0.937	1.000	0.983	0.956
11	0.802	0.759	0.756	0.794	0.784	0.782	0.920	0.984	1.000	0.960
12	0.783	0.747	0.745	0.777	0.771	0.769	0.772	0.767	0.765	1.000

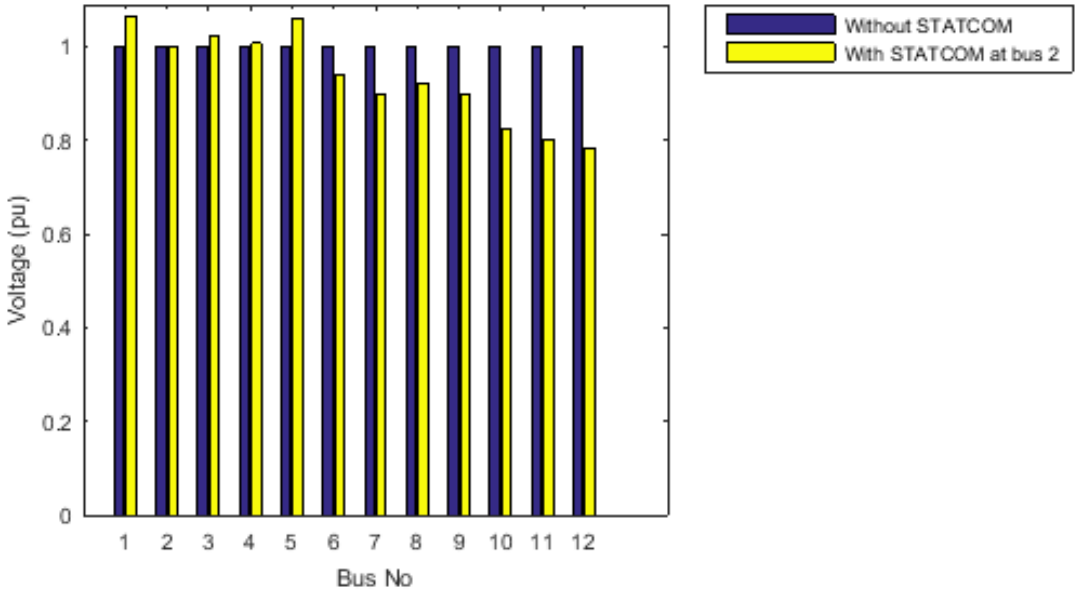


Figure 17: Voltage Magnitude with Single STATCOM at Bus-2

RESULTS FOR LOCATING STATCOM AT BUS-3

The results obtained for location of STATCOM at bus-3 is as seen in general Table 4 while the plot is as depicted in Figure18.

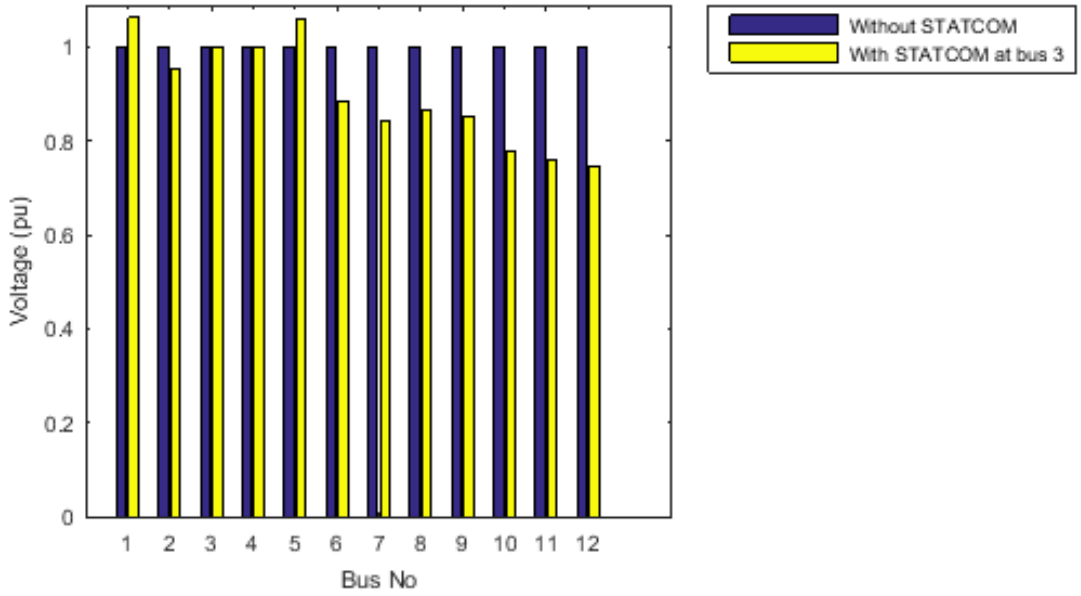


Figure 18: Voltage Magnitude with a Single STATCOM at Bus-3

As can be seen in Table 4, addition of STATCOM at bus-3 did not give good results as some of the buses voltage level are worse than in the previous case. It could be seen in Figure 33 that there is little or no improvement of the bus voltages.

RESULTS FOR LOCATING STATCOM AT BUS-4

Table 4 shows the results for locating STATCOM at bus-4. The plot is as shown in Figure19

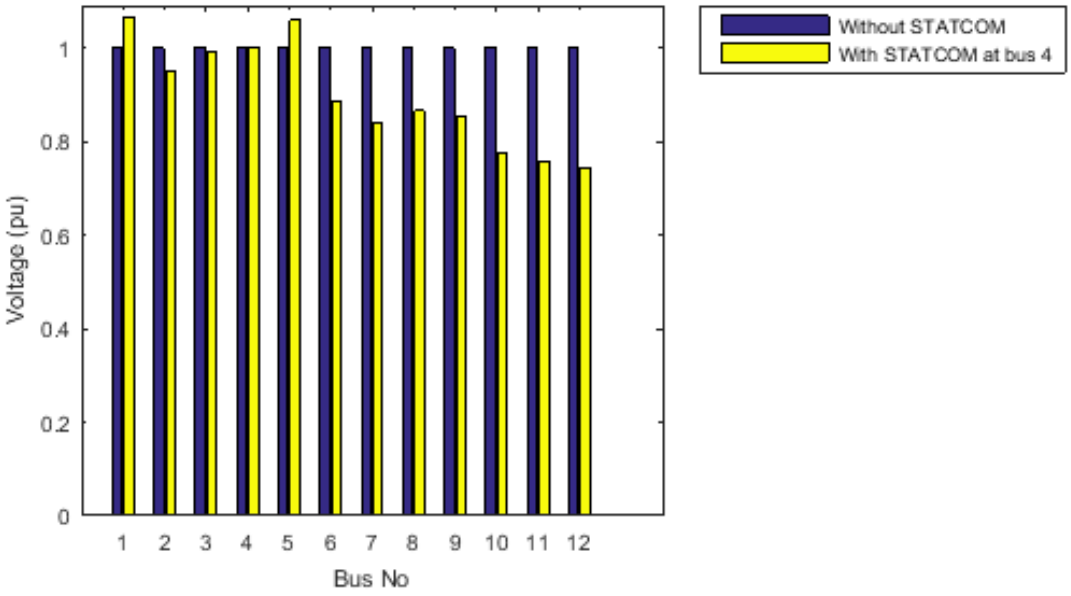


Figure 19: Voltage Magnitude with a Single STATCOM at Bus-4

It shows that the voltage profile of the whole buses has not been improved as compared to the results without STATCOM (base case) as shown in Figure 34. The results show that there is no effect for location of STATCOM at bus-4.

RESULTS FOR LOCATING STATCOM AT BUS-6

Table 4 and Figure 20 shows results of placing STATCOM at bus-6.It follows that with STATCOM at bus-6 there is an improvement in voltage magnitude within the voltage bound constraint limit of 0.95p.u. ≤ V≤ 1.05 p.u in buses 1, 2, 3, 4, 5, 6, 7, and 8 better than when STATCOM is located in previous cases i.e. in buses 2, 3, and 4.

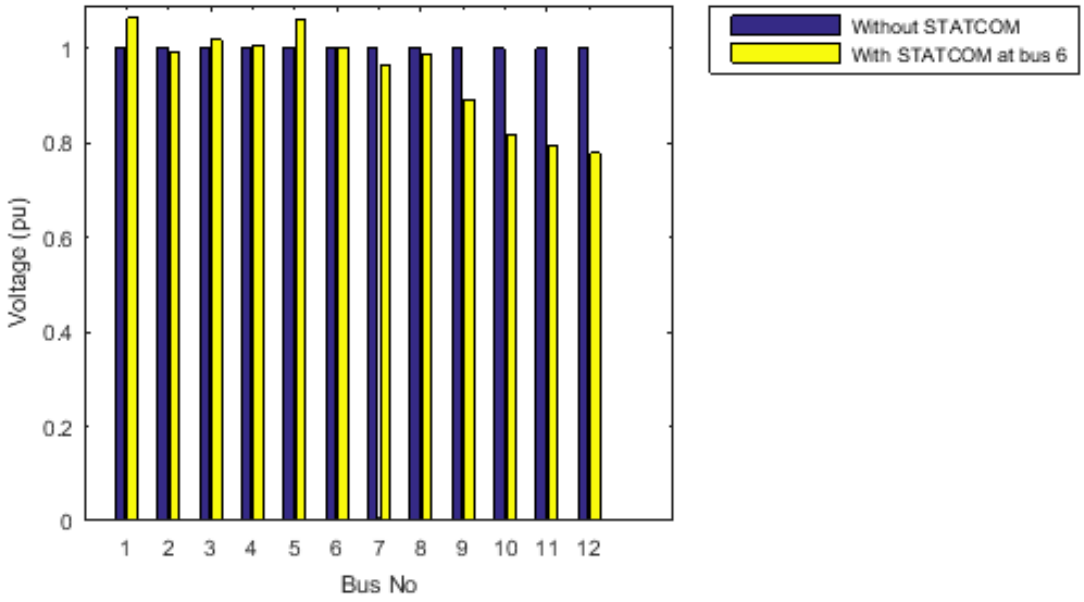


Figure 20: Voltage Magnitude with a Single STATCOM at Bus-6

RESULTS FOR LOCATING STATCOM AT BUS-7

Table 4 shows the results when STATCOM is located at bus-7. When STATCOM is connected to bus-7 the voltage magnitudes of the buses have been improved than the system without STATCOM as shown in Table 4. Buses 1, 2, 3, 4, 5, 6, 7, and 8 are within voltage bound constraint limit of 0.95p.u. ≤ V≤ 1.05 p.u, while buses 9, 10, 11 and 12 are less than the limit, but have been improved more than the base case as shown in Figure 21.

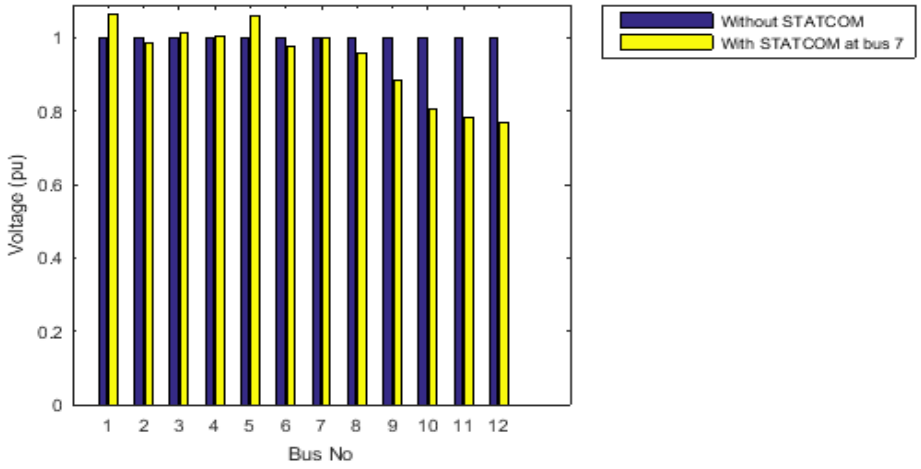


Figure 21: Voltage Magnitude with a Single STATCOM at Bus-7

RESULTS FOR LOCATING STATCOM AT BUS-8

Figure 22 shows the comparison of voltage level at bus-8 with and without STATCOM. For the system with STATCOM at bus-8, the voltage level of buses 1, 2, 3, 4, 5, 6 and 8 have been improved within the constraint limit as shown in Table 4, while buses 7, 9, 10, 11 and 12 fell out of the voltage bound limit.

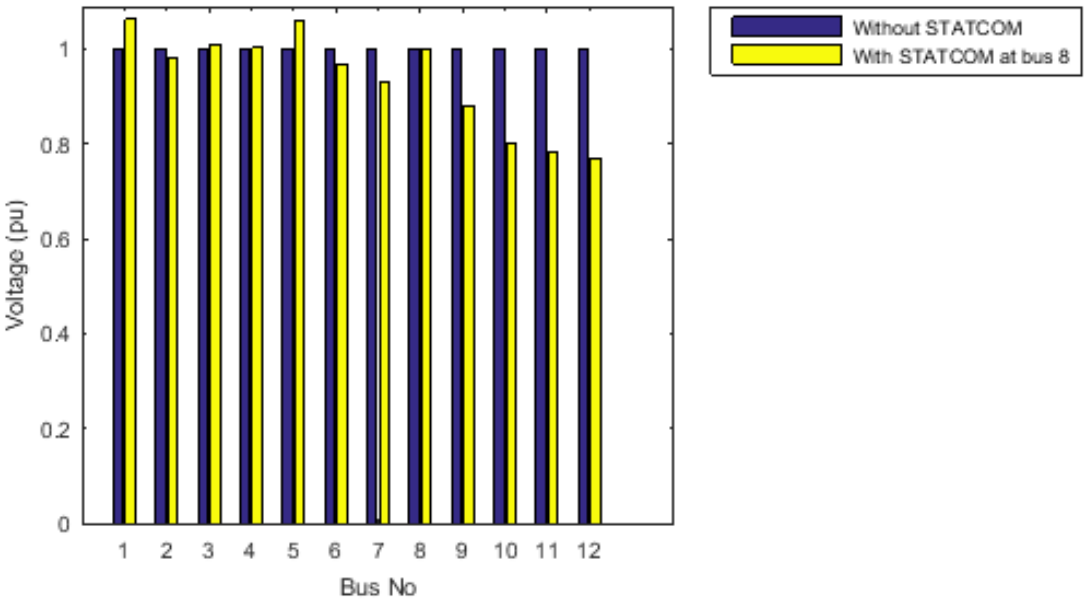


Figure 22: Voltage Magnitude with a Single STATCOM at Bus-8

Table 4 and Figure 23 shows the voltage magnitudes of the buses with STATCON at bus-9. As seen in Table 4 and Figure 38, the voltage magnitudes of the buses quite reasonable than in the previous cases. Buses 1,2,3,4, 5, 6, 8, 9, 10 and 11are within 0.920p.u. ≤V≤ 1.064p.u. while buses 7 and 12 with voltage magnitude of 0.881p.u. and 0.772p.u. respectively which are better than the system without STATCOM.

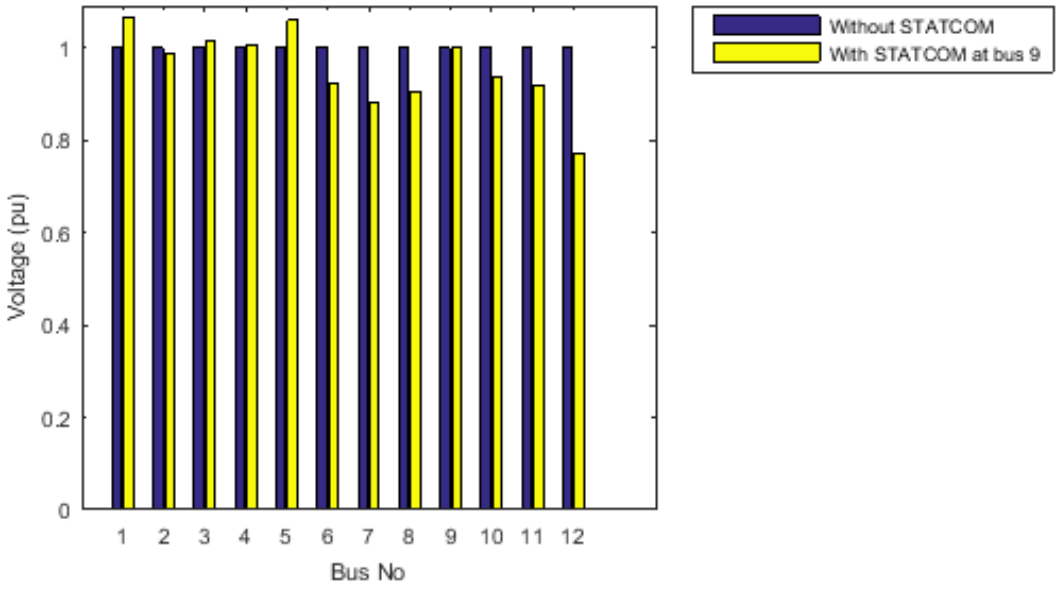


Figure 23: Voltage Magnitude with a Single STATCOM at Bus-9

RESULTS FOR LOCATING STATCOM AT BUS-10

Voltage improvement level with STATCOM located at bus-10 is as shown in Table 4 and is depicted in Figure24. With the addition of STATCOM at bus-10, it is shown in Table 4 that STATCOM does increase the voltages at most of the buses to a reasonable value, but fail to raise the voltage at buses 7 and 12 as shown in Figure 39. However, this location is not the best as some bus voltages fell out of the voltage bound constraint.

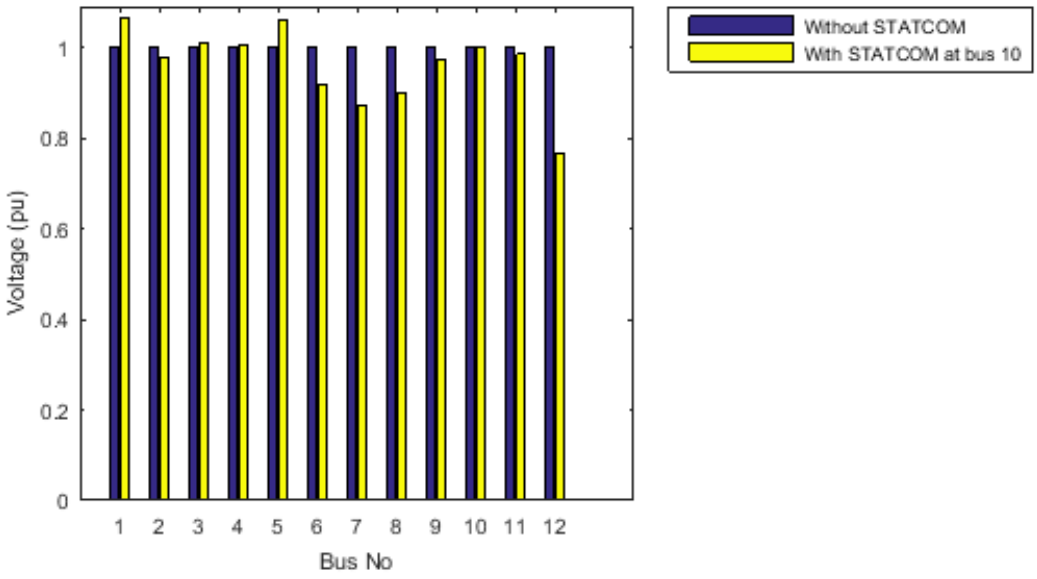


Figure 24: Voltage Magnitude with a Single STATCOM at Bus-10

RESULTS FOR LOCATING STATCOM AT BUS-11

Figure 25 shows a voltage enhancement of the 12-bus network with a single STATCOM at bus-11. After setting STATCOM at bus-11, it was observed that the voltage magnitude in buses have improved as shown in Table 4. Most of the bus voltages are within/approaching the acceptable voltage limit.

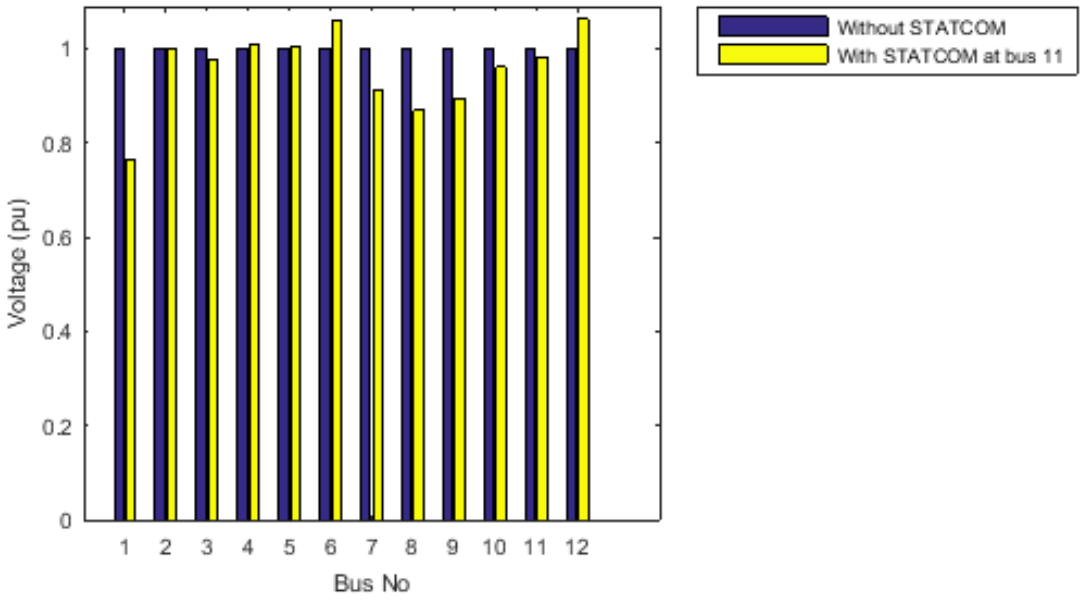


Figure 25: Voltage Magnitude with a Single STATCOM at Bus-11

RESULTS FOR LOCATING STATCOM AT BUS-12

Results obtained when STATCOM is located at bus-12 is as shown in Table 4 and Figure 26. After adding STATCOM at bus-12, it was observed from the results in Table 4 that the voltages at most buses have increased to a range between 0.942 p.u and 1.05 p.u. Some of the bus voltages are within the acceptable voltage limit while others are approaching the voltage limit as seen in Figure 41. Comparing the results of different locations, with STATCOM at bus-12 (Bauchi) provides the best result as voltages magnitude across the whole buses have been improved, hence it is the best point, under the given circumstances.

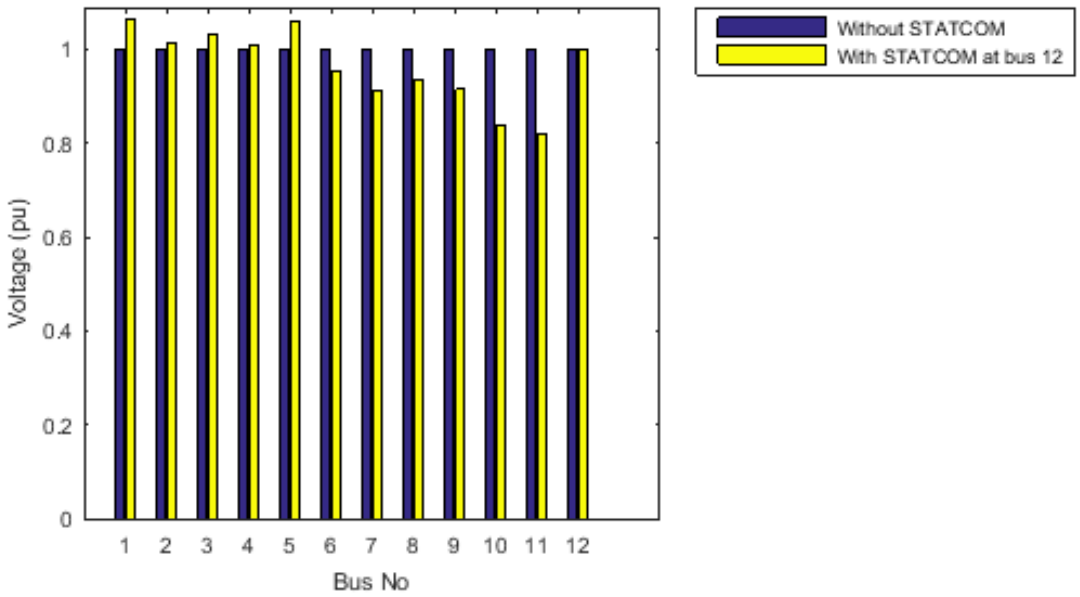


Figure 26: Voltage Magnitude with a Single STATCOM at Bus-12

RESULTS FOR PSO BASED OPTIMAL LOCATION OF A SINGLE STATCOM

PSO results obtained for the best placement of a single STATCOM at the Northeast132 kV, 12-bus power network is as shown in Table 4. PSO to optimally locate the best bus for placing a single STATCOM and same results were obtained as from the bus by bus placement of a single STATCOM in bus-12. It was therefore ascertained that the best location of a single STATCOM in the power network is at bus-12 (Bauchi). The same result displayed as that of PSAT/SIMULINK environment. The power flow results obtained by PSO is the same as the one obtained using bus by bus location as shown in Tables 4 with the same plot as depicted in Figure 41. This implies that PSO yields the same result at a faster time.

RESULTS FOR PSO BASED FOR OPTIMAL LOCATION OF TWO STATCOMS

With only single STATCOM it is easier to find the best location for the 12-buses using one by one placement, but is very difficult task to find the best location of two

STATCOMs using one by one method. So, it was easier and faster to use the PSO optimization techniques to optimally site two STATCOMs into the power network. When PSO algorithm is run the results obtained for the placement is at buses-11 and 12 as displayed in Figure 27.

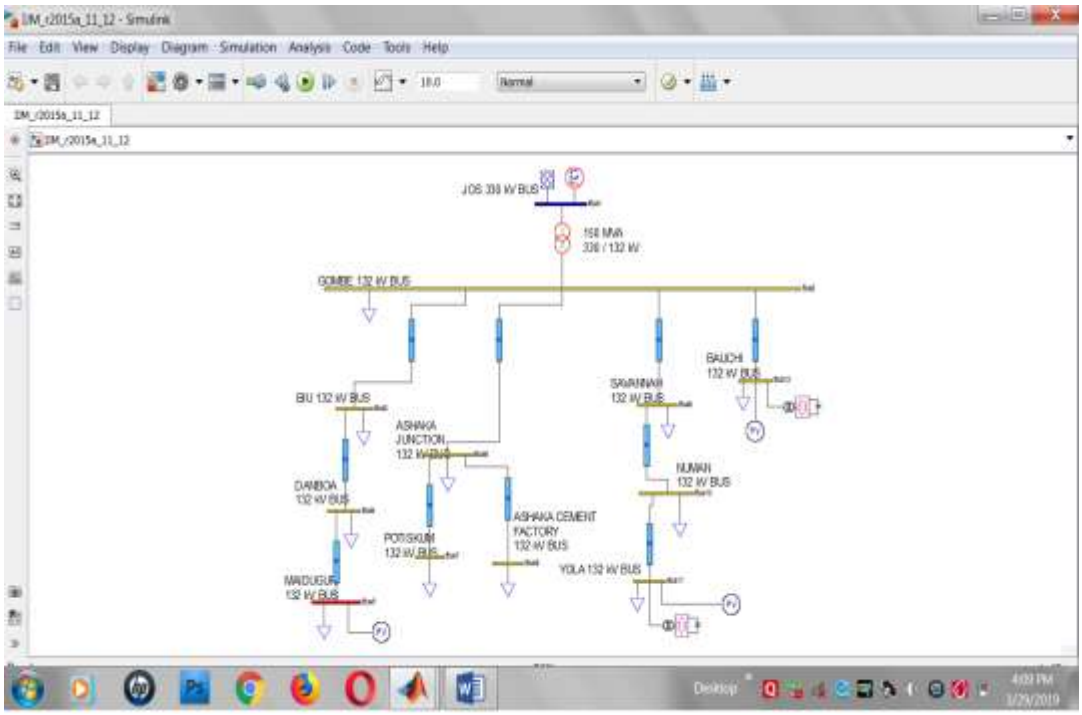


Figure 27: PSO algorithm Siting of Two STATCOMs in PSAT MATLAB Environment

Table 5 shows the power flow results for PSO algorithm used to determine the best bus position to place two STATCOMs into the 12-bus network. Figure 27 shows the plot of bus voltage magnitude in p.u. versus bus number on addition of two STATCOMs in the power network. Incorporating two STATCOMs an improved voltage profile was observed as compared to the results of incorporating single STATCOM. The corresponding power flow static report is as shown in Appendix A, showing the voltage magnitude, real and reactive power generated and real and reactive power loss status of the buses. From the PSO algorithm the optimal location of two STATCOMs is at bus-11 (Yola) and bus-12 (Bauchi). Table 6 gives a complete summary of the power network voltage profiles without STATCOM, with a single

STATCOM and with two STATCOMs for easy comparison and their plot is depicted in Figure 28.

When using double STATCOM the voltages improves to a range between 0.95051 p.u. and 1.064 p.u which is within the acceptable limit. It can also be observed that the location of STATCOM has an effect on the power flow. The two STATCOMs has improved the injection of reactive power into the network more than the use of a single STATCOM.

Table 5: Bus Voltage Magnitude with Two STATCOMs

Bus No	Vm (p.u)	Phase (Deg)	P gen (p.u)	Q gen (p.u)	P Load (p.u)	Q Load (p.u)
1	1.06400	0.00000	0.69383	0.28687	0.00000	0.00000
2	1.02720	-4.75470	0.00000	0.00000	0.20000	0.16000
3	1.04070	4.13650	0.00000	0.00000	0.01500	0.01200
4	1.01300	15.81280	0.00000	0.00000	0.01200	0.00980
5	1.01300	21.72500	0.80000	0.18103	0.32500	0.26000
6	0.97010	-8.14900	0.00000	0.00000	0.08900	0.05000
7	0.95051	-10.08350	0.00000	0.00000	0.15500	0.08900
8	0.95389	-9.07260	0.00000	0.00000	0.08900	0.05000
9	0.99528	-8.88150	0.00000	000000	0.02800	0.02200
10	0.99289	-12.40850	0.00000	0.00000	0.03200	0.09000
11	1.00000	-14.11920	0.00000	0.12053	0.09000	0.03600
12	1.00000	-14.61250	0.00000	0.00000	0.30000	0.24000

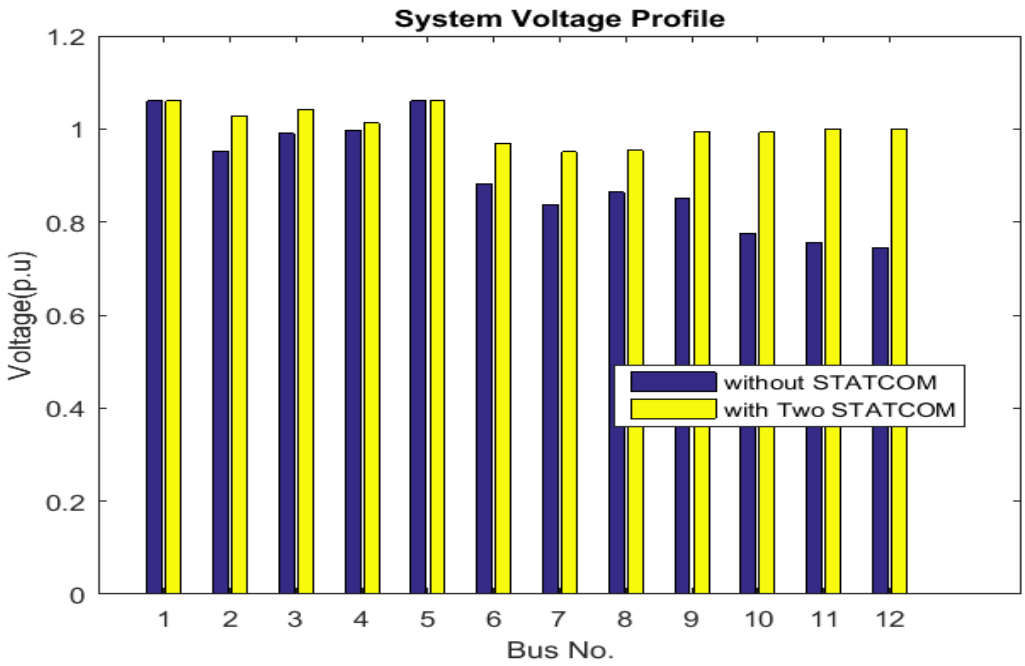


Figure 28: Voltage Magnitude with Two STATCOMs

Table 6: Voltage Profile of the Network with and Without STATCOM

Bus no	Voltages without STATCOM (p.u)	Voltages with single STATCOM (p.u)	Voltages with two STATCOM (p.u)
1	1.0600	1.06400	1.06400
2	0.95096	1.01200	1.02720
3	0.99012	1.03060	1.04070
4	0.99730	1.00990	1.01300
5	1.06000	1.06000	1.06000
6	0.88295	0.95284	0.97010
7	0.83760	0.94220	0.94651
8	0.86422	0.93616	0.95389
9	0.85091	0.91462	0.99528
10	0.77530	0.94010	0.99289
11	0.75582	0.88010	1.00000
12	0.74462	1.00000	1.00000

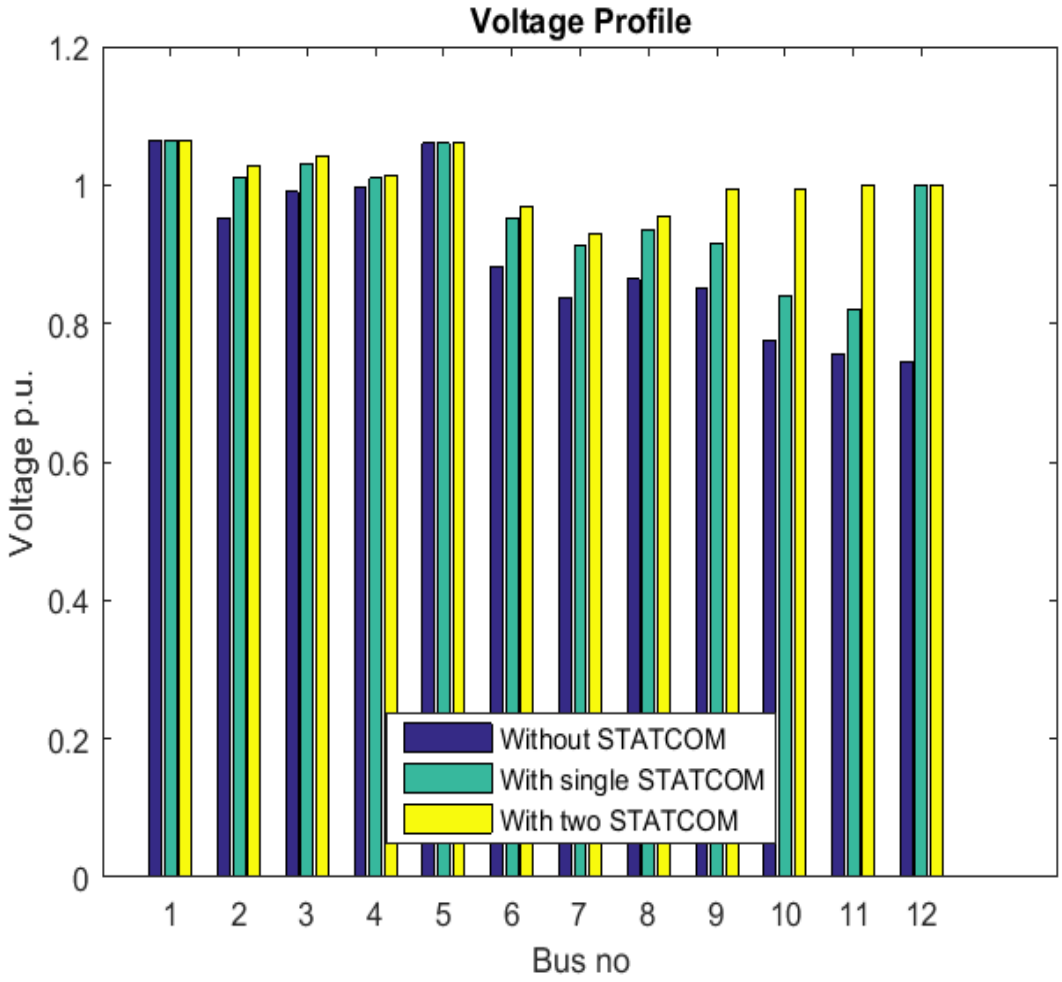


Figure 29: Voltage Magnitude with Single and Two STATCOMs

RESULTS FOR LOCATION OF STATCOM FOR REAL AND REACTIVE POWER CONTROL

Table 8 shows the result of reactive power generated by the power system with STATCOM at each bus and its corresponding plot is shown in Figure 30. As can be seen in Table 8 and Figure 30, it indicates that the reactive power generation varies with the location of STATCOM. It can also be seen that the reactive power increases at the buses where STATCOM is located. It can also be noted that STATCOM is able to supply correct amount of reactive power to the points where it is needed.

Table 8: Total Power Generation on the Network with STATCOM

STATCOM at buses	Total real power generation (p.u)	Total reactive power generation (p.u)
2	1.407	1.158
3	1.475	1.142
4	1.474	1.148
6	1.509	1.088
7	1.503	1.100
8	1.501	1.105
9	1.505	1.088
10	1.497	1.086
11	1.498	1.093
12	1.507	1.043

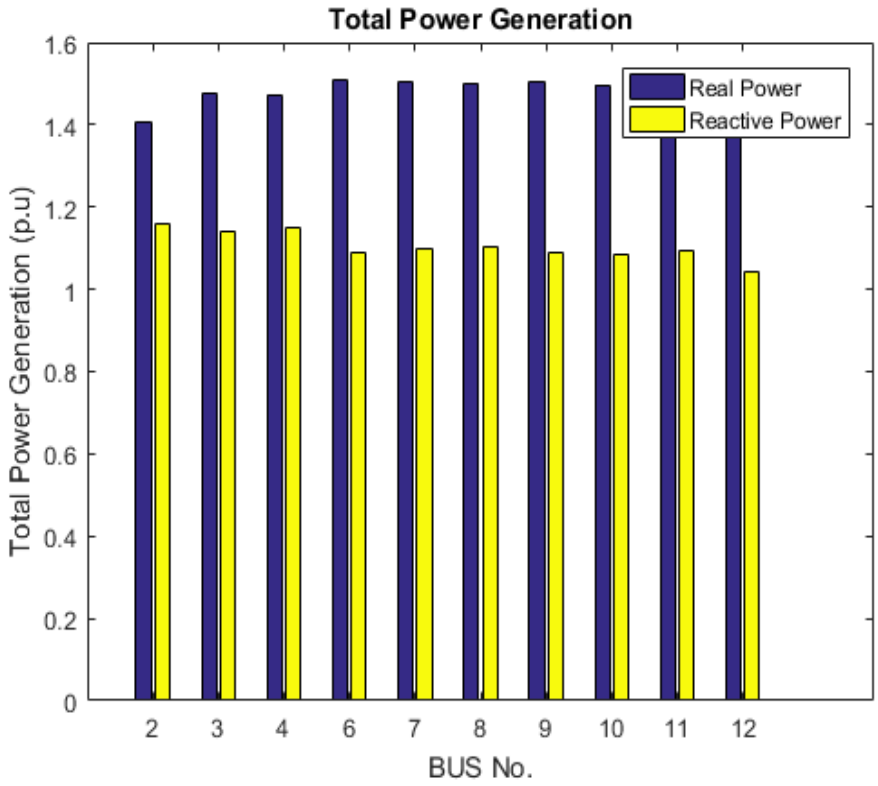


Figure 30: Total Real and Reactive Power Generation with Single STATCOM at Each Bus

RESULTS FOR REAL POWER LOSS WITH AND WITHOUT STATCOM

Table 9 gives the real power loss with and without inclusion of STATCOM into the power network. A plot of real power loss is as shown in Figure 46. It can be observed from the results in Table 9 that generally, with STATCOM there was reduction of real power losses in most of the transmission line branches. A plot of real power loss is as shown in Figure 31. The real power loss is lower in most of the lines with single STATCOM than the system without STATCOM and further reduced with two STATCOMs. It implies that inclusion of two STATCOMs improves more on the performance of the system.

Table 9: Real Power Loss on the Transmission Line

Transmission line/no of buses	Real power losses without STATCOM (pu)	Real power losses with single STATCOM (pu)	Real power losses with two STATCOM (pu)
2-3/1	0.0365	0.03667	0.0369
3-4/2	0.02056	0.02089	0.02107
4-5/3	0.02998	0.03043	0.0307
6-7/4	0.00522	0.00433	0.00433
10-11/5	0.00155	0.00164	0.00227
6-8/6	0.00124	0.00104	0.00099
2-12/7	0.05448	0.04229	0.03679
9-10/8	0.00396	0.00397	0.00178
2-9/9	0.01291	0.01247	0.00749
2-6/10	0.01683	0.01396	0.01336
1-2/11	0.00739	0.00393	0.00332

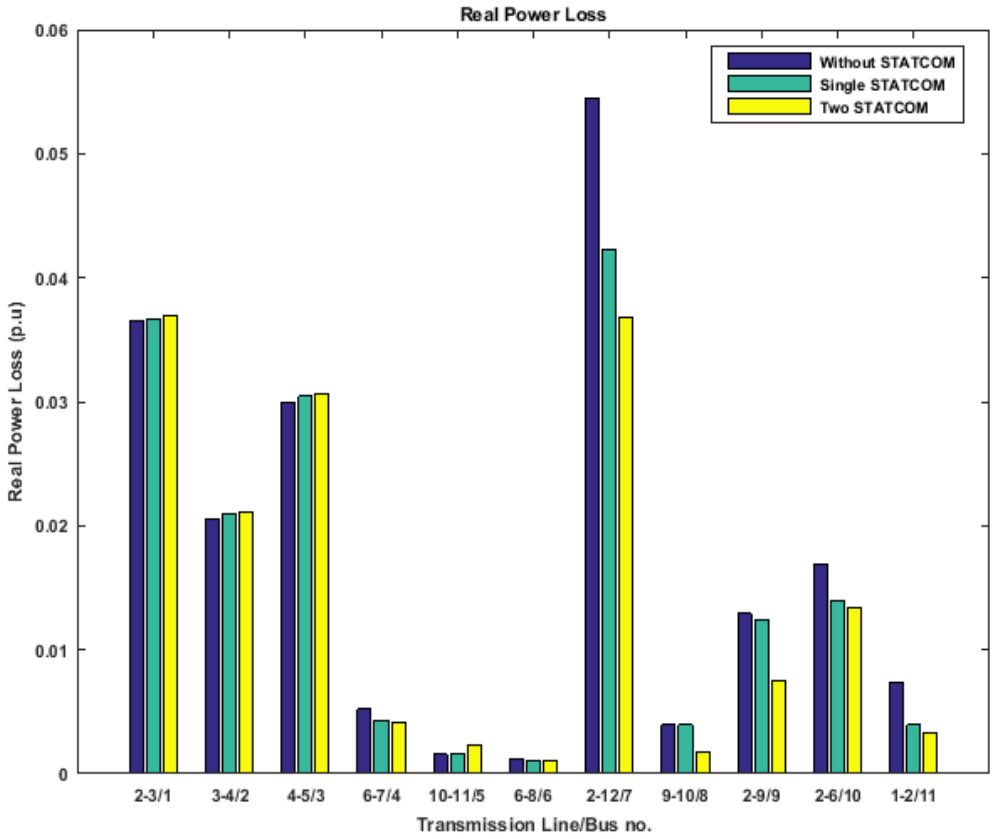


Figure 31: Real Power Loss with and Wtithout STATCOM

RESULTS FOR REACTIVE POWER LOSS WITH AND WITHOUT STATCOM

Table 10 indicates the reactive power flow with and without locating STATCOM into the power network and its corresponding plot as shown in Figure32.The results in the table shows positive reactive power loss caused by inductive loads such as motors, transformers etc and negative reactive power loss caused by capacitive loads as in lighting ballasts, variable speed drives for motors, computer equipment etc. In the same way the reactive power loss was also recorded and compared. It can be observed from the results in Table 10 that reactive power loss is higher in the network without STATCOM and less with a single STATCOM. As can be seen in Figure 32 that more reduction in reactive power loss is achieved with placing two STATCOMs.

Table 10: Reactive Power Loss on the Transmission Lines

Transmission line/ no of buses	Reactive power losses without STATCOM (pu)	Reactive power losses with single STATCOM (pu)	Reactive power losses with two STATCOMs (pu)
2-3/1	0.00078	-0.0048	-0.00596
3-4/2	0.07454	0.07519	0.07581
4-5/3	0.03154	0.03205	0.03238
6-7/4	-0.02737	-0.03574	-0.03781
10-11/5	-0.01525	-0.0182	-0.02637
6-8/6	-0.02958	-0.0354	-0.03689
2-12/7	0.02368	-0.01282	-0.02145
9-10/8	0.00773	0.00625	-0.00619
2-9/9	-0.03928	-0.04801	-0.06133
2-6/10	-0.00187	-0.01279	-0.01533
1-2/11	0.14772	0.07851	0.06639

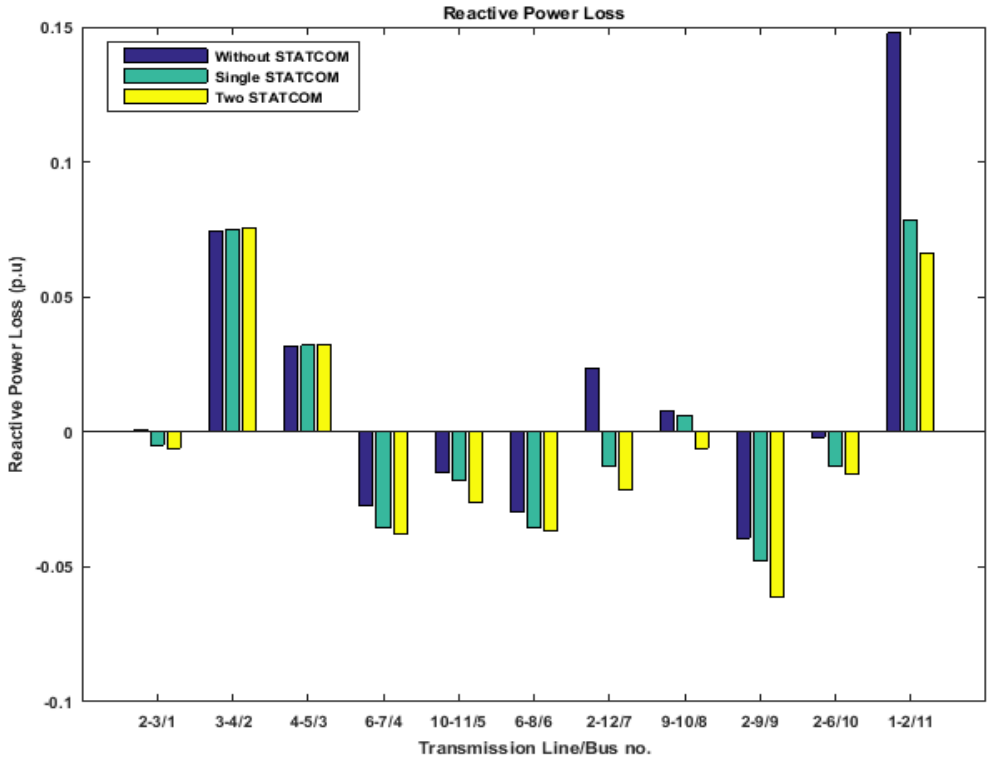


Figure 32: Reactive Power Loss with and without STATCOM

CONCLUSION

A number of conclusions are made based on the analysis and simulation results presented in chapter four. Recommendations are also made for further research in respect of beneficial effects of locating STATCOM intoNortheast132kV, 12-bus power network.

In this study, the 12-bus Northeast 132 kV network was considered and its power flow run using PSAT platform. The voltage, real and reactive power profiles were simulated without the placement of STATCOM. Placing a single STATCOM on each bus, all the profiles were again simulated to identify the best bus for placement. Using PSO the profiles were studied for best placement of two STATCOMs on the network.

The results presented shows that through proper location of STATCOM, the power network is capable of improving its voltage profile, regulates real and reactive power flow, thereby reduced power losses in the transmission lines.

The study investigated voltage enhancement of Northeast 132 kV power network as a case study by the application of STATCOM and its optimal placement on the 12 buses. A single STATCOM was placed one by one on the buses, while PSO algorithms the optimization technique is used for optimal siting of a single and two STATCOMs. The results obtained with and without application of STATCOM were discussed and the following conclusion are drawn:

i. Location of STATCOM on the best position provides voltage level improvement for the Northeast 132 kV, 12-bus power network within operating range of $0.95 \leq v \leq 1.05$ p.u through proper control of real and reactive power flow.
ii. Proper siting of two STATCOMs on the power network further improved the voltage magnitude at a higher value than the use of a single STATCOM.
iii. The best performance of the network has been achieved by locating single STATCOM at bus-12, while two STATCOMs is at buses 11 and 12.
iv. The use of STATCOM have reduced real power loss on the transmission network by 9.9%, and the reactive power loss is reduced by 51.17%.

Recommendations for Further Research

In this thesis, simulation studies showed that the voltage profile of the 12-bus power network has been improved with the use of STATCOM. However, the following recommendations are made for further work:

i. This study can be extended to a larger system to evaluate the voltage upgrade provided by the use of a larger size STATCOM.
ii. The study work concentrates on the enhancement of the voltage level, it can be further improved to include the use of STATCOM for cancellation of harmonics introduced into the power network as a result of switching of power electronic equipment.
iii. Further research can be done for voltage upgrade by the use of STATCOM in conjunction with one of the renewable energy power generations such as solar power plant.

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