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ANALYSIS OF COORDINATED CONTROL AND INTERACTIONS BETWEEN FACTS CONTROLLERS WITH INTEGRATED UNIFIED POWER FLOW CONTROLLER TO IMPROVE POWER SYSTEM PERFORMANCE

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Abstract

The integration of renewable energy sources and the increasing complexity of power systems have heightened the need for advanced control and mitigation strategies to ensure grid stability and reliability. Static Synchronous Compensator (STATCOM) has emerged as a vital device for voltage regulation and power quality improvement in interconnected power systems. This paper presents a comprehensive analysis of the optimal placement of STATCOM within the North East (Gombe State, Nigeria) 330/132 KV transmission system. Utilizing advanced optimization techniques and power system simulations, the study evaluates various candidate locations for STATCOM installation to enhance voltage stability and mitigate transient stability issues. 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 single STATCOM on the 12-bus system, thereby improving the quality of the system. At the end of this research work, it was discovered that

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

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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. This provides valuable insights for power system operators and planners in effectively enhancing the performance and reliability of interconnected power systems.

INTRODUCTION

The North East region of Nigeria, with Gombe State as a focal point, represents a dynamic and interconnected power system characterized by diverse generation sources, varying demand patterns, and transmission constraints. The 330/132 KV transmission system serving this region plays a pivotal role in facilitating the transfer of bulk power across multiple nodes. However, the increasing complexity of the grid and the intermittent nature of renewable energy sources introduce voltage fluctuations and transient stability concerns (Emmanuel, 2016).

Static Synchronous Compensator (STATCOM) has emerged as a versatile device for reactive power compensation and voltage regulation in power systems (Kundur, 1994). By injecting or absorbing reactive power instantaneously, STATCOM can mitigate voltage variations and enhance the transient stability of the grid (Aishvarya & Srivasta, 2015). Optimal placement of STATCOM within the transmission network is essential to maximize its effectiveness in addressing voltage stability and transient stability issues (Aarti, 2013).

Previous research has explored various methodologies for optimal STATCOM placement in power systems, considering factors such as load characteristics, network topology, and system operating conditions (Zheng et al., 2011), (Serei et al, 2013), (Sundar et al., 2014) (Merini, & Gherbi, 2014). However, the specific challenges and operational characteristics of the North East (Gombe State, Nigeria) 330/132 KV transmission system necessitate a tailored approach to determine the optimum location for STATCOM deployment.

The poor voltage profile has also been experienced at the receiving end in Gombe 132 kV 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 132 kV, Gombe-Biu 132 kV, Biu-Damboa 132 kV, 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 this paper, we present a detailed investigation into the optimal placement of STATCOM within the North East (Gombe State, Nigeria) 330/132 KV transmission system. Leveraging

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advanced optimization techniques and power system simulations, we aim to identify strategic locations for STATCOM installation that maximize voltage stability, improve power quality, and enhance transient stability performance. By conducting a comprehensive case study, we seek to provide actionable insights for power system operators and planners to enhance the reliability and efficiency of the interconnected power system in the North East region. In this research, the distribution substation power network will be modeled in PSAT tool in MATLAB environment.

OBJECTIVES OF THE RESEARCH

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

In this work the power system is modeled and simulated without STATCOM, followed by simulations with STATCOM integration (Adepoju & Komolafe, 2011), utilizing PSAT within the MATLAB environment. The placement optimization of both single and double STATCOM units is achieved employing the Particle Swarm Optimization (PSO) technique (Bindeshwar et al., 2012).

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

The simulation of the power distribution network will be conducted using Power System Analysis Toolbox (PSAT) within the MATLAB environment, integrating SIMULINK (Agrawal et al.,2016). This software setup facilitates the characterization of the distribution network's behavior with and without the implementation of STATCOM. Additionally, the command line version of PSAT is compatible with GNU Octave. The software offers graphical User Interfaces (GUIs) for easy access to operations, while a SIMULINK-based library provides a user-friendly tool for network design. PSAT also features bridges to General Algebraic Model System (GAMS) and UWPFLOW programs,

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significantly expanding its capabilities for optimization and continuation power flow analysis (Federico, 2008).

Northeast 132 Kv Single Line Diagram

The existing 330/132 kV, 12-bus network's single-line diagram, augmented with line contingency control variables, serves as the focal point of this case study. Figure 1 illustrates the interconnectedness of the power grid network, extending from the Gombe 132 kV station to various distribution substations.

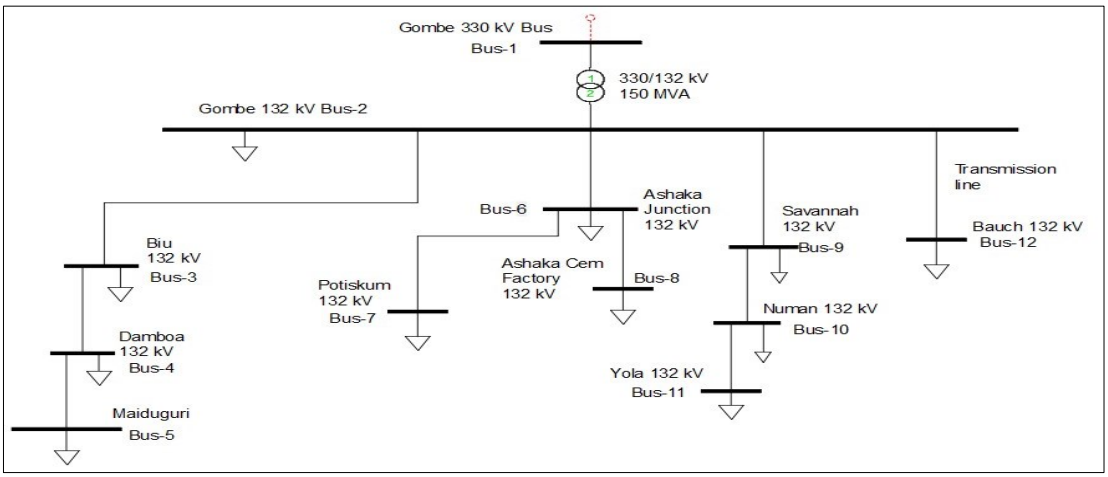


Figure 1: Single Line Diagram of North east 132 kV Power Network.

Northeast (Gombe) 132 Kv Transmission Line Parameters

The analysis and simulation require input data encompassing various parameters, including the resistance, reactance, and susceptance of transmission lines, as well as voltage and transformer/load data for Northeast 330/132 kV buses and the 330 kV Jos in-feed substations. These inputs aim to identify major centers experiencing low voltage profile issues amidst changing system demands. Operational data sourced from the Transmission Company of Nigeria (TCN) Gombe are presented in the following tables:

i. Table 1 presents line parameters in per unit (p.u) on a 100 MVA base, detailing line voltage, length, and impedances comprising resistance, reactance, and half-line charging susceptance.

ii. Table 2 provides power network bus data, delineating bus voltage, average load on each bus, as well as real and reactive power loading on each bus.

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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. ii iii iv v vi	Jos-Gombe Jos-Bauchi Bauchi-Gombe Gombe-Biu Biu-Damboa Gombe-Ashaka Junction	Bison Bison Bison Hyena Wolf Hyena	265 118 146 126 92 84	330 132 132 132 132 132	1360 400 306 400 400 400	0.0095 0.140 0.172 0.221 0.162 0.098	0.051 0.280 0.344 0.311 0.227 0.197	1.010 0.057 0.042 0.059 0.042 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

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simulation include bus data, transmission line data, and generator data. The following methods are adopted for the power flow analysis:

i. Utilize the MATLAB-based power system GUI to input parameters such as communication port and phone number for text message notifications.

ii. Conduct power flow analysis of the existing power network without STATCOM (i.e., uncompensated) to establish the base case. This provides insight into voltage levels, real/reactive power levels, and power losses at all buses without STATCOM integration.

iii. Sequentially introduce single STATCOM units into the buses to identify the optimal placement for each unit.

iv. Implement the Particle Swarm Optimization (PSO) technique to position two STATCOMs within the buses, aiming to determine their optimal locations in the power network.

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

To study the impact of STATCOM devices on improving the voltage level of the North East 132 kV, 12-bus power network, the following method is employed: Initially, the existing power network is constructed using the graphical user interface (GUI) of PSAT within the MATLAB environment, as depicted in Figure 2.

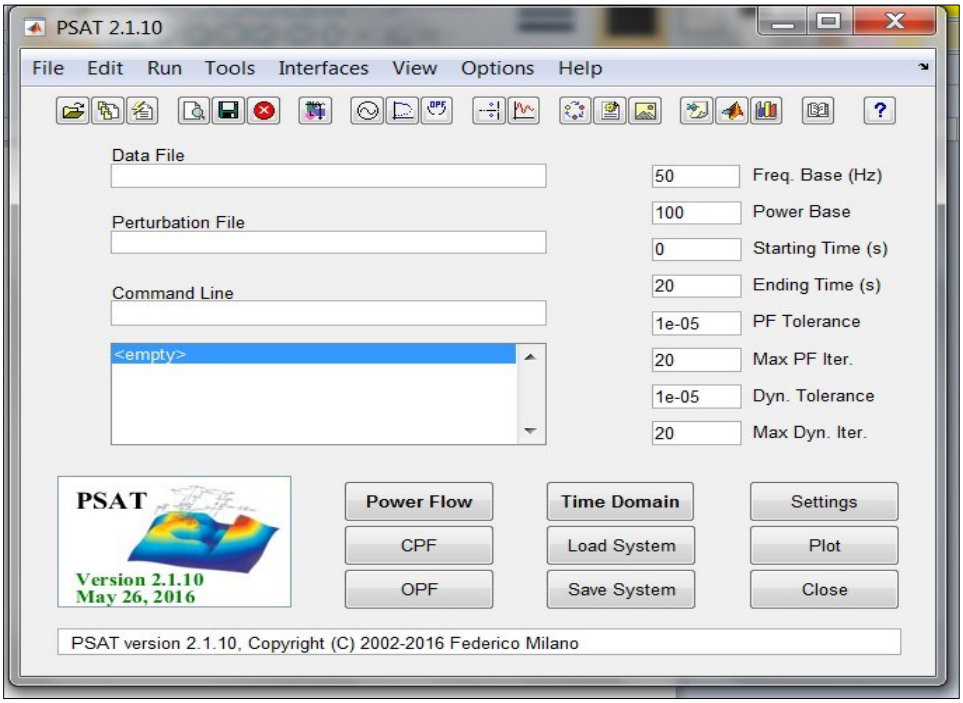


Figure 2: Graphic User Interface (GUI) Environment of PSAT Software

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Network Design

Initially, the single-line diagram of the Northeast 132 kV, 12-bus power network, depicted in Figure 2, is crafted utilizing the PSAT/SIMULINK environment. This is achieved by intuitively dragging and dropping symbols representing buses, generators, transmission lines, and other components onto the diagram. All transmission line parameters from Table 1 and power network bus data from Table 2 are inputted accordingly.

The single-line diagram of the power network, designed using the PSAT GUI environment, is illustrated in Figures 3.

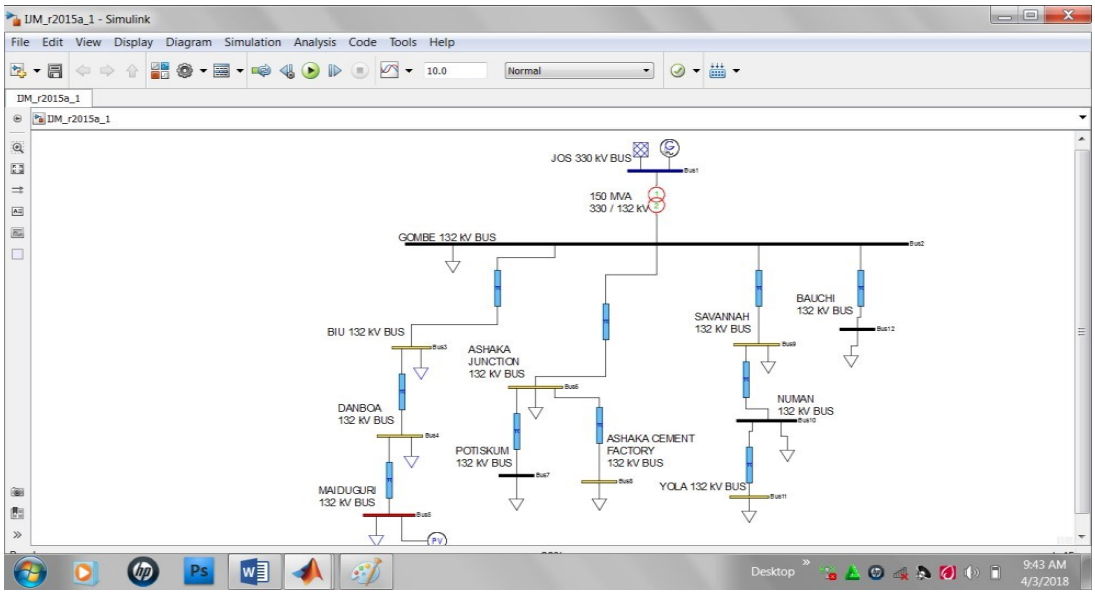


Figure 3: Network Model without STATCOM in PSAT MATLAB Environment

Voltage Level Without STATCOM (Base Case)

The power flow analysis of the designed network in PSAT/SIMULINK mode, as depicted in Figure 3, is executed without STATCOM to establish the base case. The outcomes, generated by the PSAT GUI environment and termed as the static report, are illustrated in Figure 4.

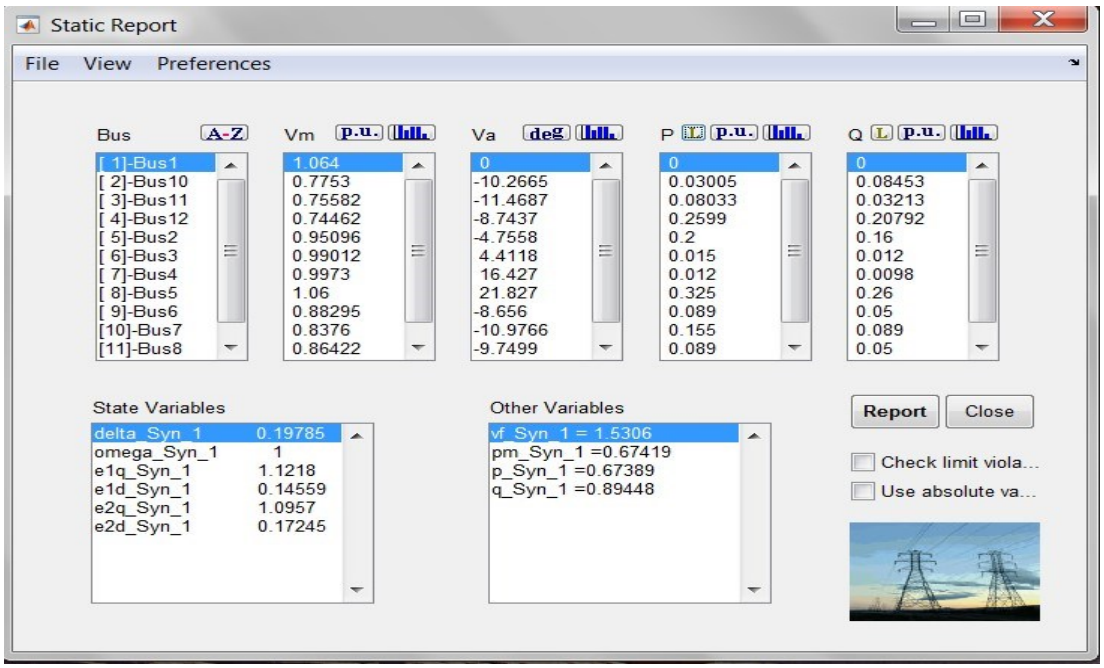


Figure 4: GUI Power Flow Static Report of PSAT in MATLAB Environment

The power flow static report provides an overview of various parameters including voltage magnitude, real/reactive power generated, real/reactive power losses, and total power generated across all buses, excluding STATCOM integration. Apart from the static report displayed in Figure 3 within the PSAT GUI, a more detailed power flow report is accessible by clicking on "view file," as demonstrated in Figure 5, to examine corresponding data.

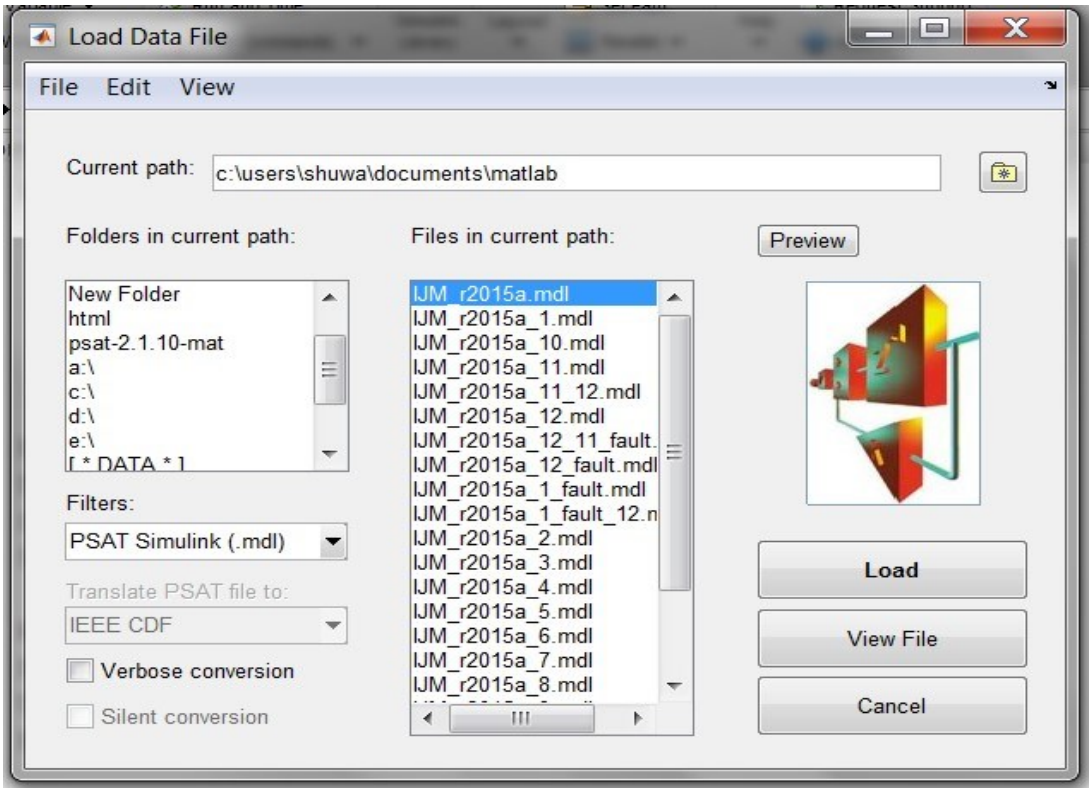


Figure 5: PSAT GUI Detail Power Flow Report in MATLAB Environment

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 positioned at bus-2, as depicted in Figure 6, followed by the execution of power flow analysis to obtain results with compensation. The resulting power flow static report includes data such as voltage magnitude, real/reactive power generated, real/reactive power losses, and total power generated at bus-2 with the inclusion of STATCOM.

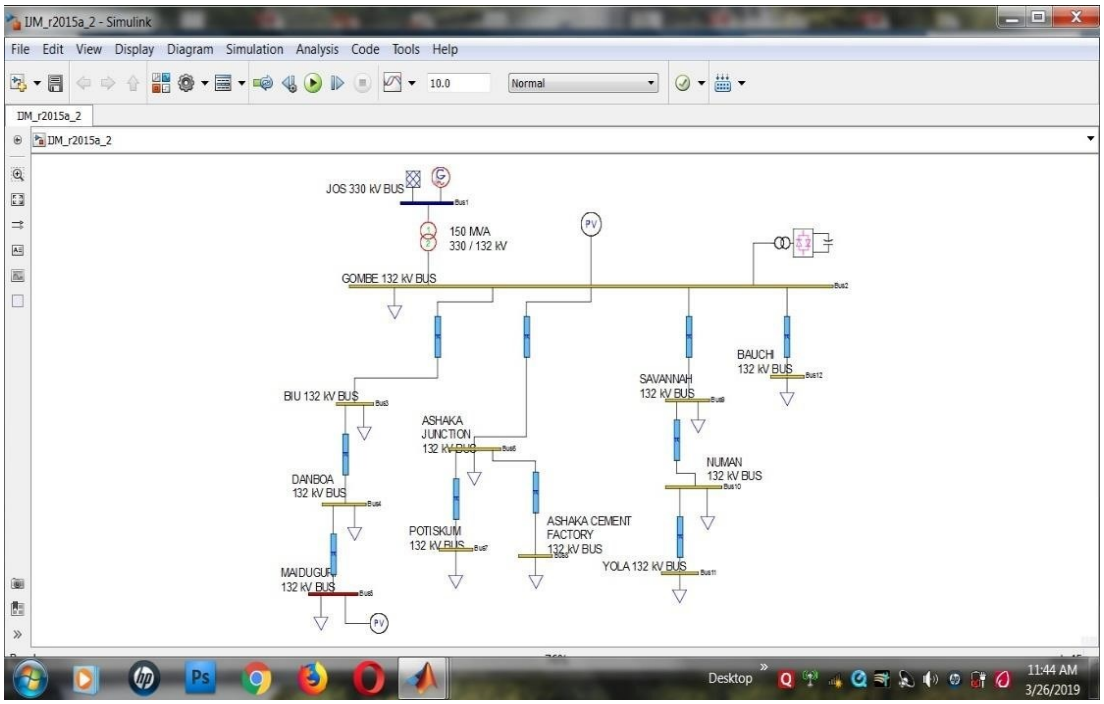


Figure 6: Network Model with STATCOM at bus-2 in PSAT MATLAB Environment

Location of STATCOM at Bus-3

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

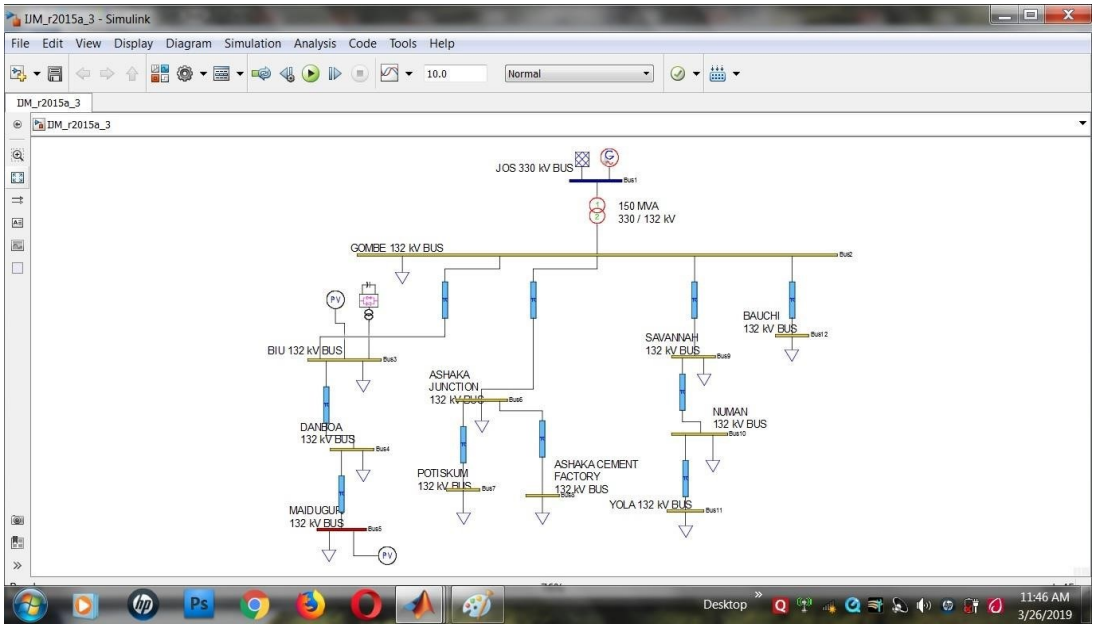


Figure 7: Network Model with STATCOM at bus-3 in PSAT MATLAB Environment

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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 result with STATCOM at bus-4.

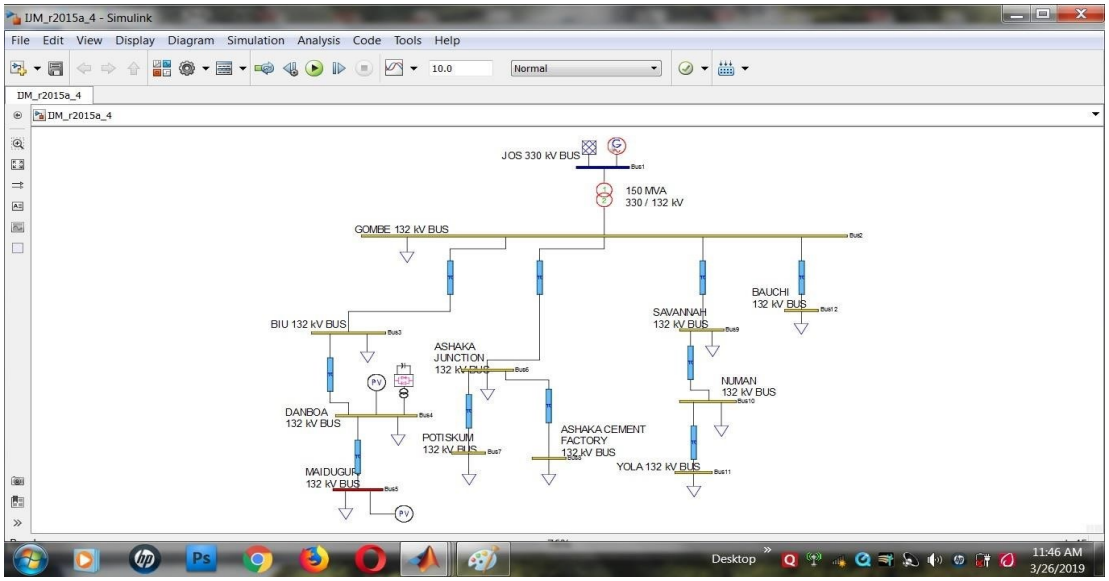


Figure 8: Network Model with STATCOM at bus-4 in PSAT MATLAB Environment

The process was iterated as outlined in the preceding scenarios by consecutively placing a single STATCOM into the remaining buses 6, 7, 8, 9, 10, 11, and 12. Their corresponding models within the PSAT MATLAB/SIMULINK environment are depicted in Figures 9, 10, 11, 12, 13, 14, and 15, respectively. Similarly, with each iteration, the power flow analysis was conducted, and the static report presented the outcomes for each scenario, revealing the respective bus voltages, as well as real and reactive power profiles.

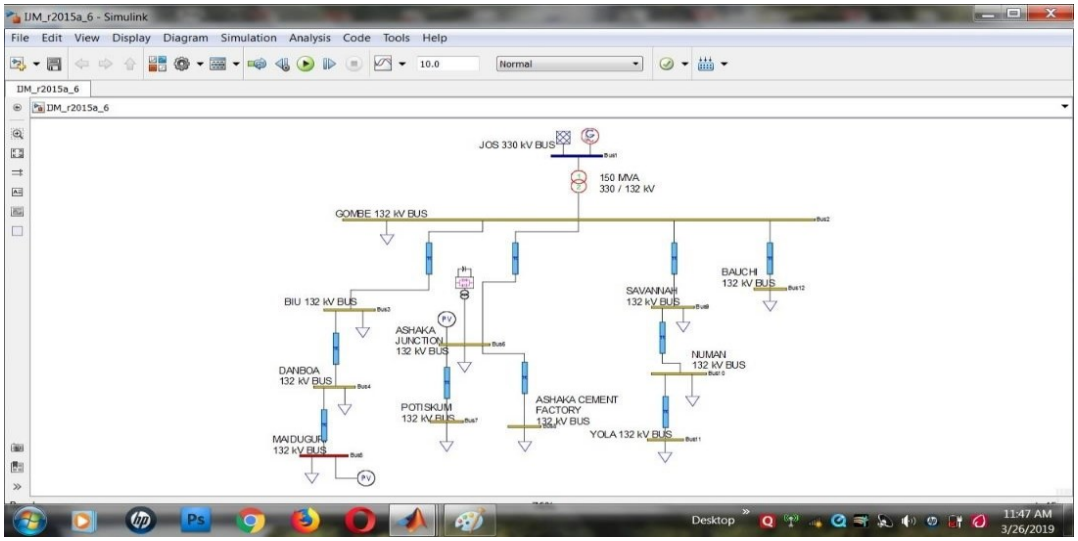


Figure 9: Network Model with STATCOM at bus-6 in PSAT MATLAB Environment

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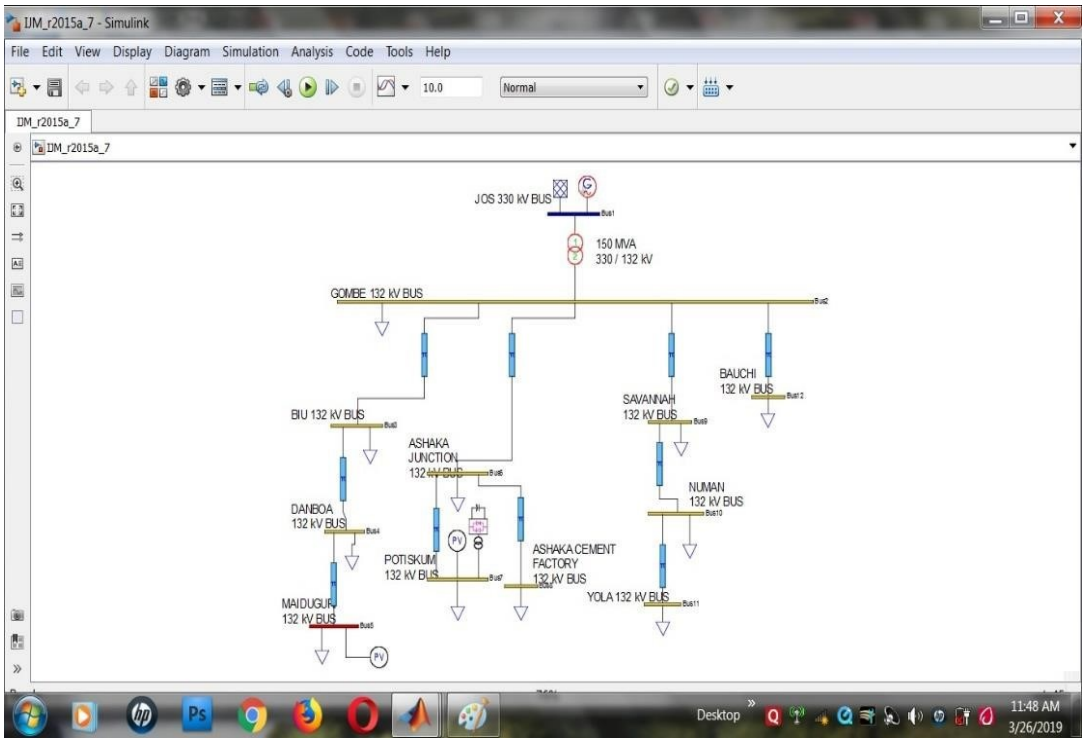


Figure 10: Network Model with STATCOM at bus-7 in PSAT MATLAB Environment

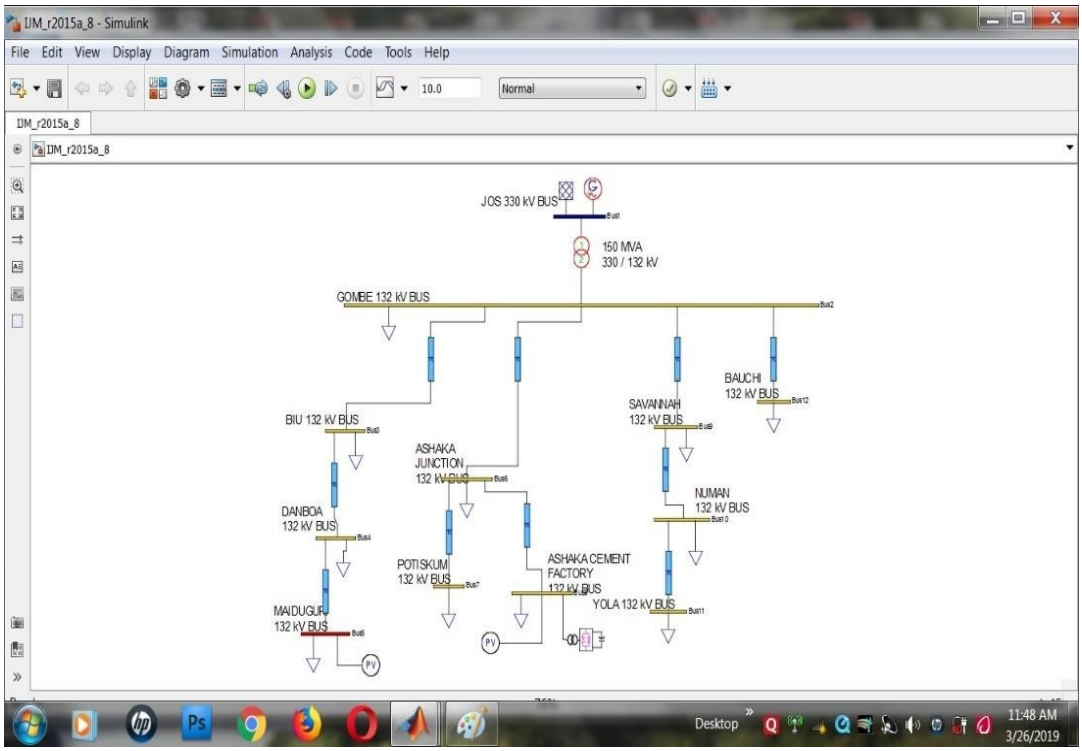


Figure 11: Network Model with STATCOM at bus-8 in PSAT MATLAB Environment

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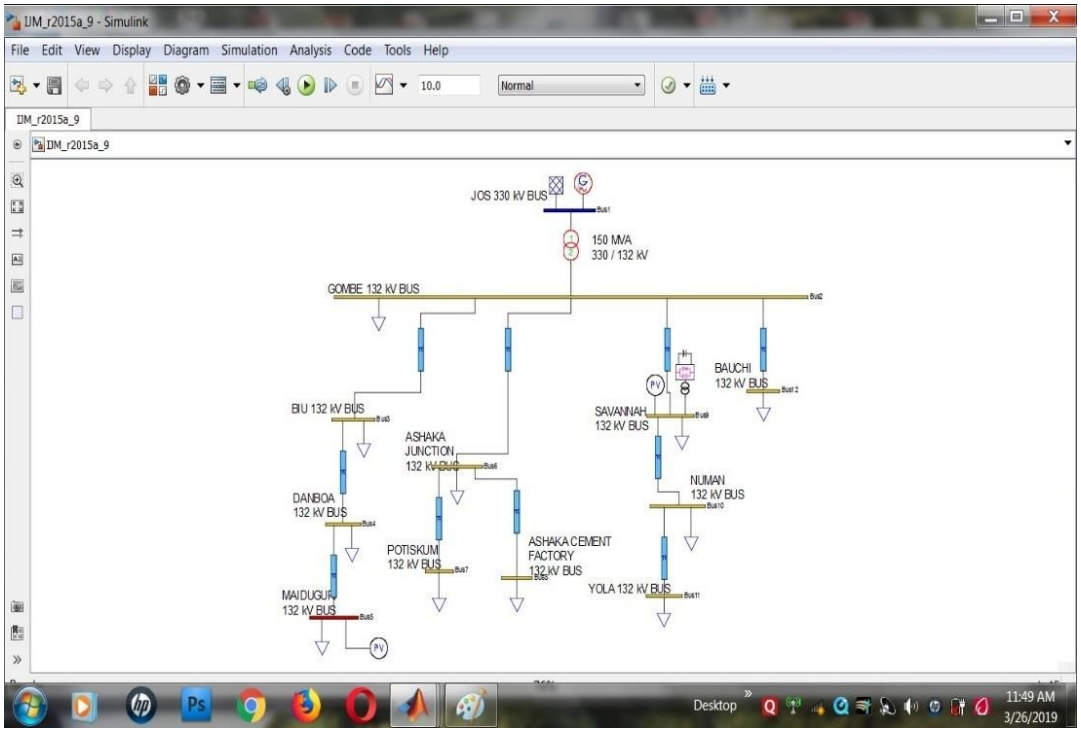


Figure 12: Network Model with STATCOM at bus-9 in PSAT MATLAB Environment

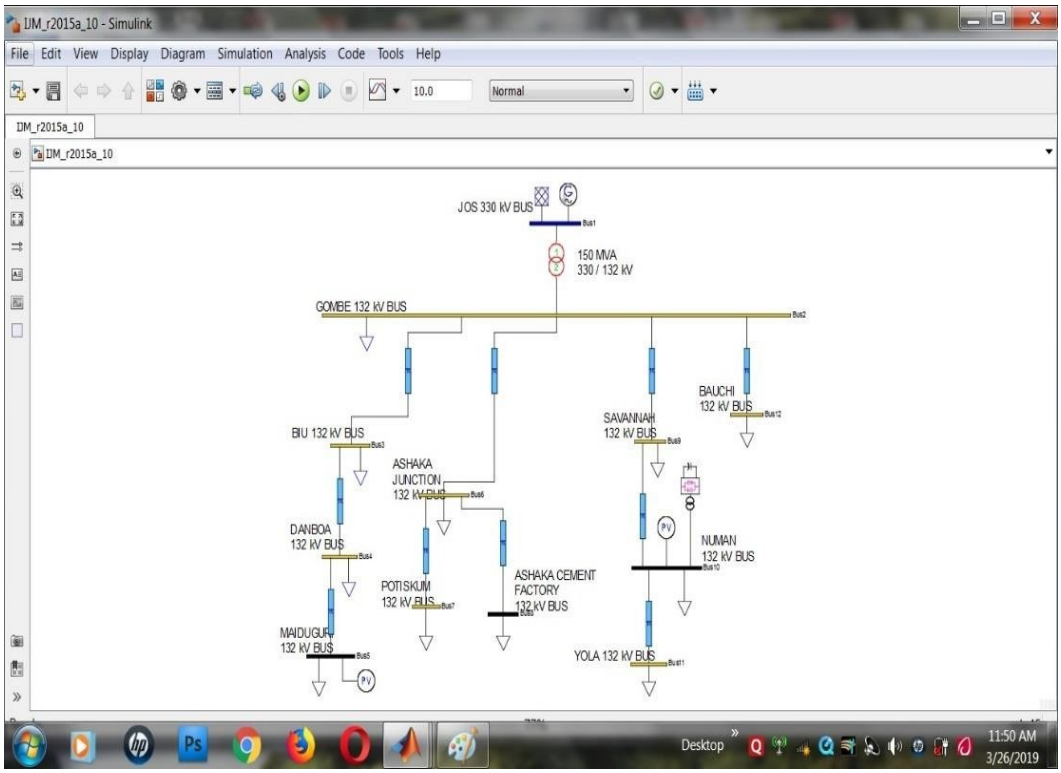


Figure 13: Network Model with STATCOM at bus-10 in PSAT MATLAB Environment

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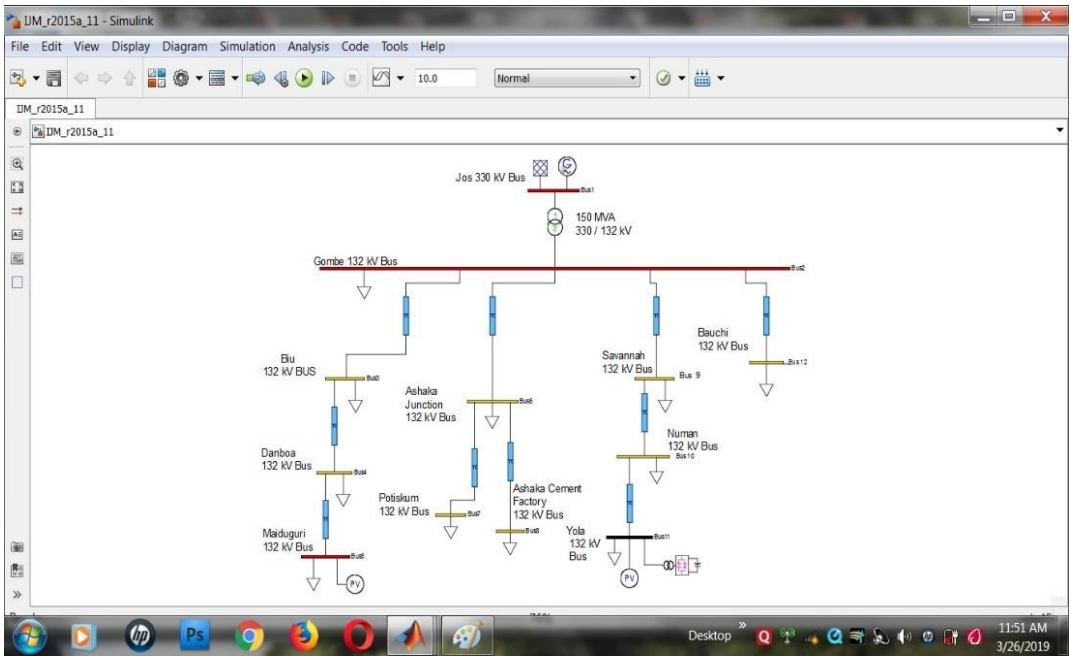


Figure 14: Network Model with STATCOM at bus-11 in PSAT MATLAB Environment

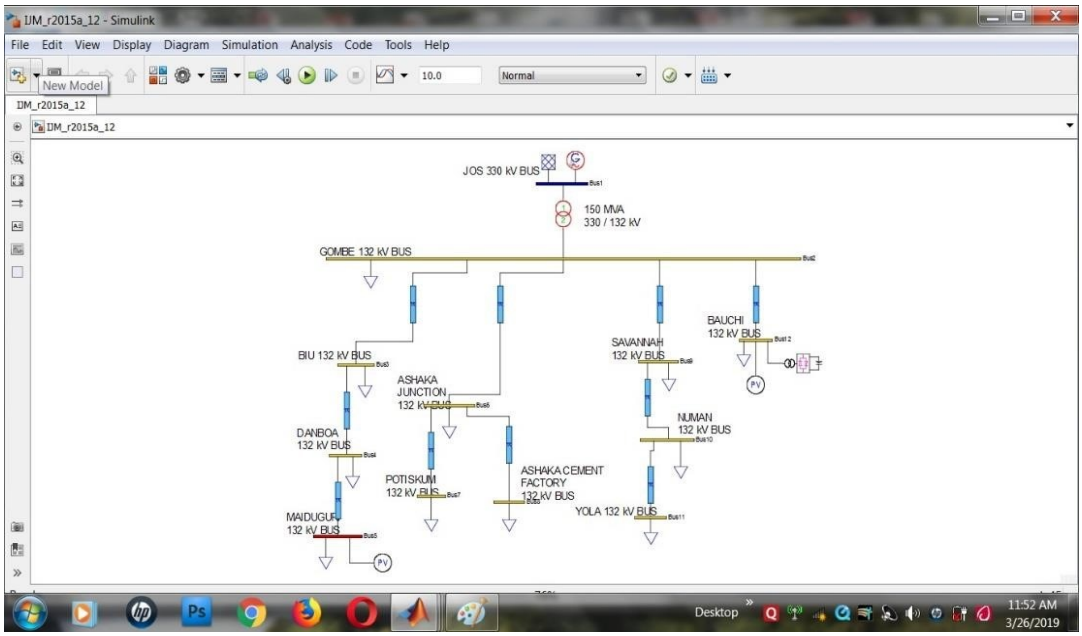


Figure 15: Network Model with STATCOM at bus-12 in MATLAB Environment

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 (Sharma et al.,2013). The network is run using PSO algorithm program codes as shown in appendix B.

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Objective Function of PSO Power Flow Analysis

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

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

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 particles 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/DISCUSSION

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.

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Table 3: Voltage Magnitude Without STATCOM (Base Case)

Bus	V m (p.u)	Phase (Deg.)	P gen (p.u)	Q gen (p.u)	P Load (p.u)	Q Load No (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.

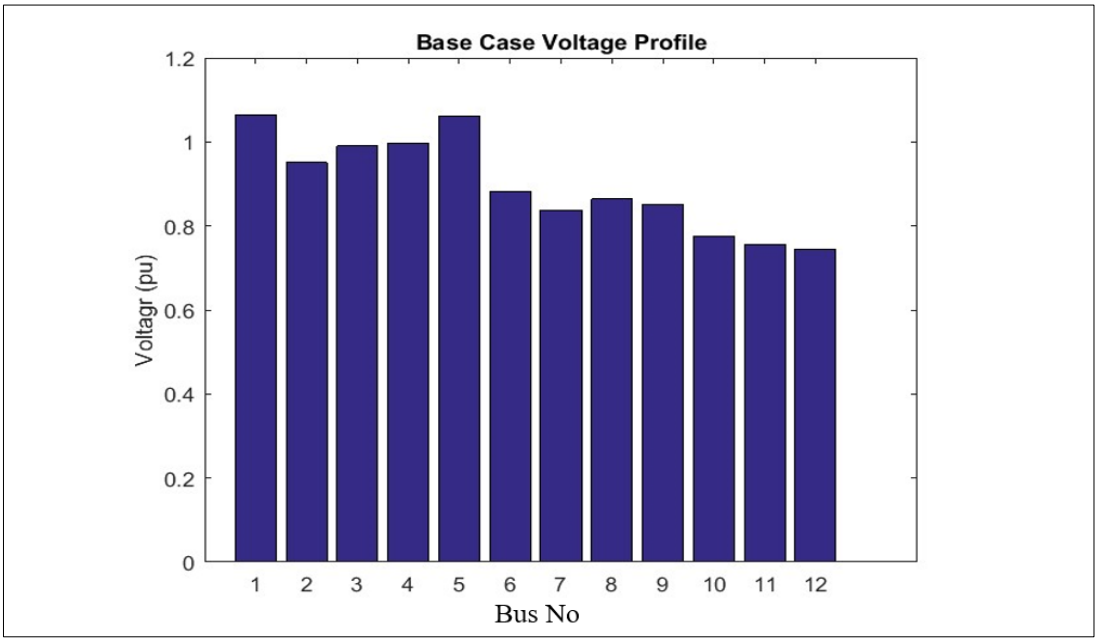


Figure 16: Voltage Magnitude Without STATCOM (Base Case)

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Results for Location of A Single STATCOM

In section 3.4 the 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.

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

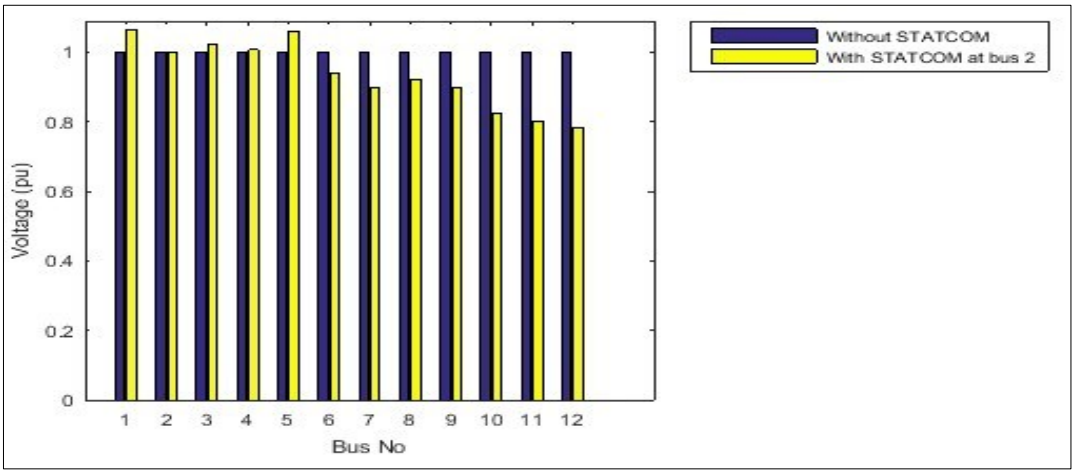


Figure 17: Voltage Magnitude with Single STATCOM at Bus-2

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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 Figure 18.

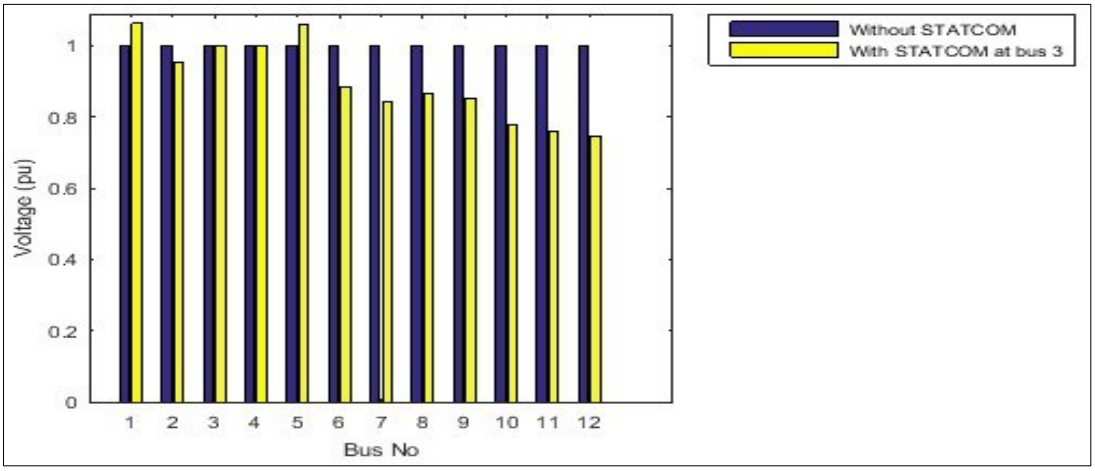


Figure 18: Voltage Magnitude with a Single STATCOM at Bus-3

As can be seen in Table 4, addition of STATCOM at bus-3 did not give good results as some of the buses voltage levels 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 Figure 19

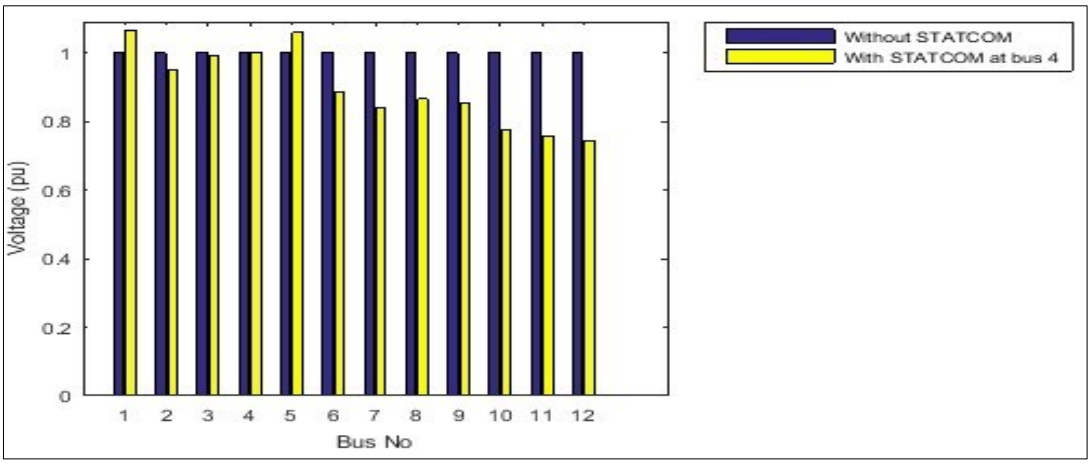


Figure 19: Voltage Magnitude with a Single STATCOM at Bus-4

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.

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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.

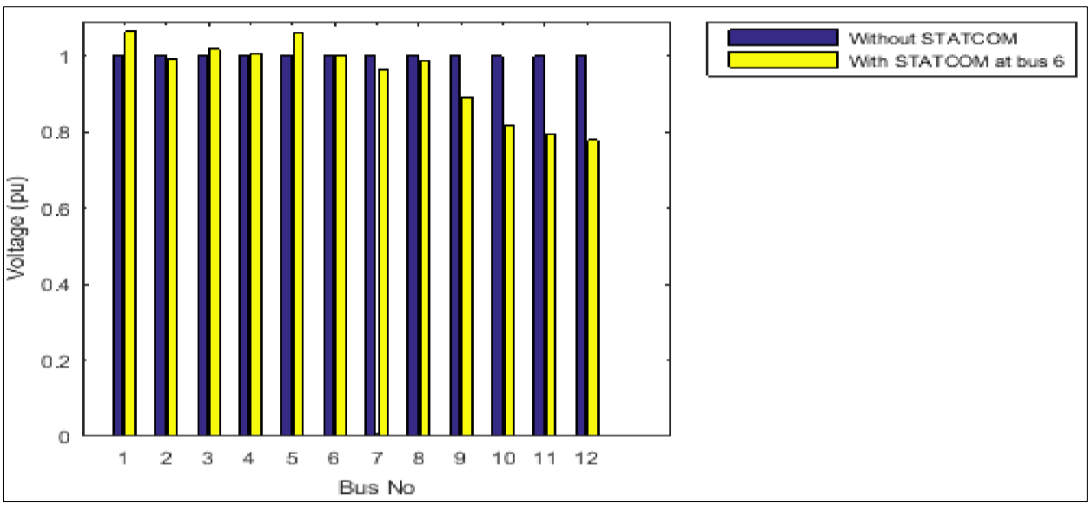


Figure 20: Voltage Magnitude with a Single STATCOM at Bus-6

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.

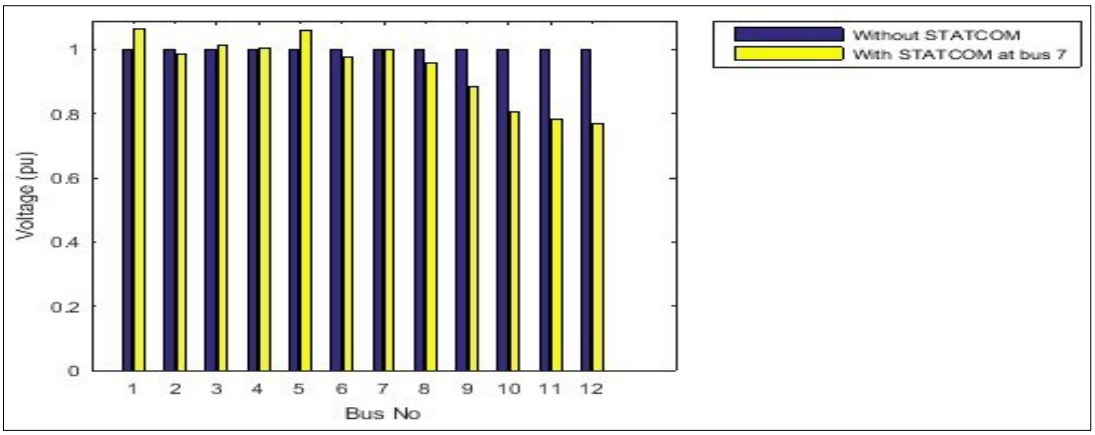


Figure 21: Voltage Magnitude with a Single STATCOM at Bus-7

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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.

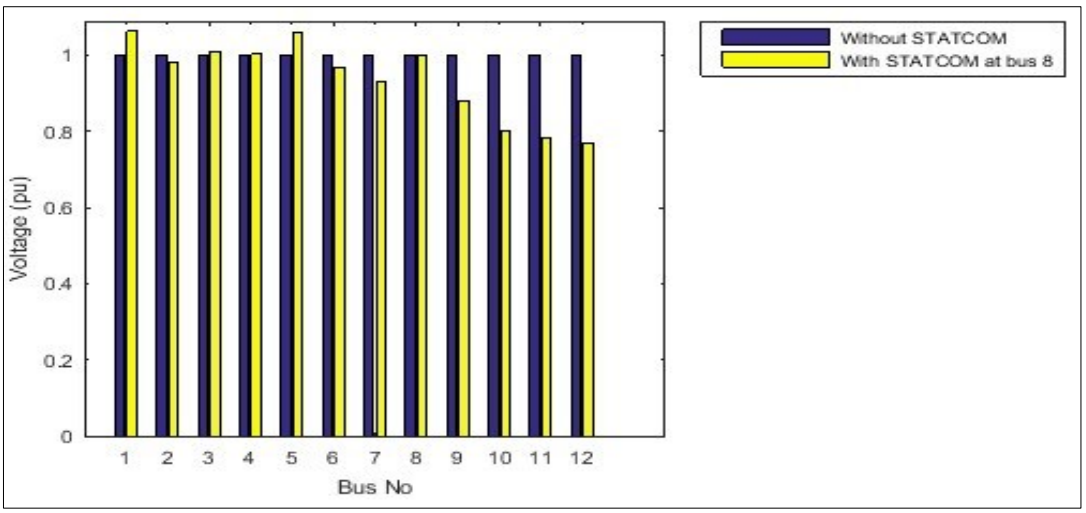


Figure 22: Voltage Magnitude with a Single STATCOM at Bus-8

Results for Locating STATCOM At Bus-9

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.

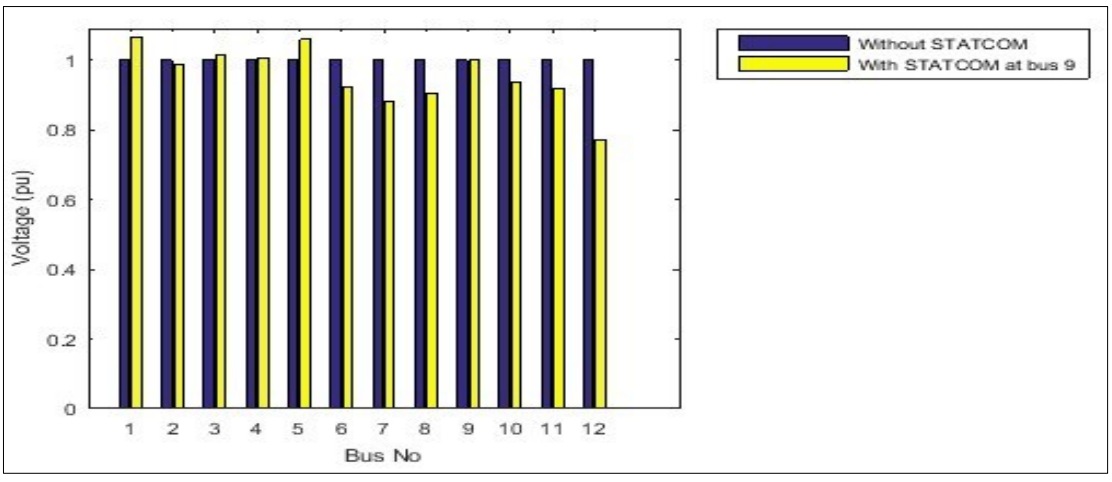


Figure 23: Voltage Magnitude with a Single STATCOM at Bus-9

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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 Figure 24. 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.

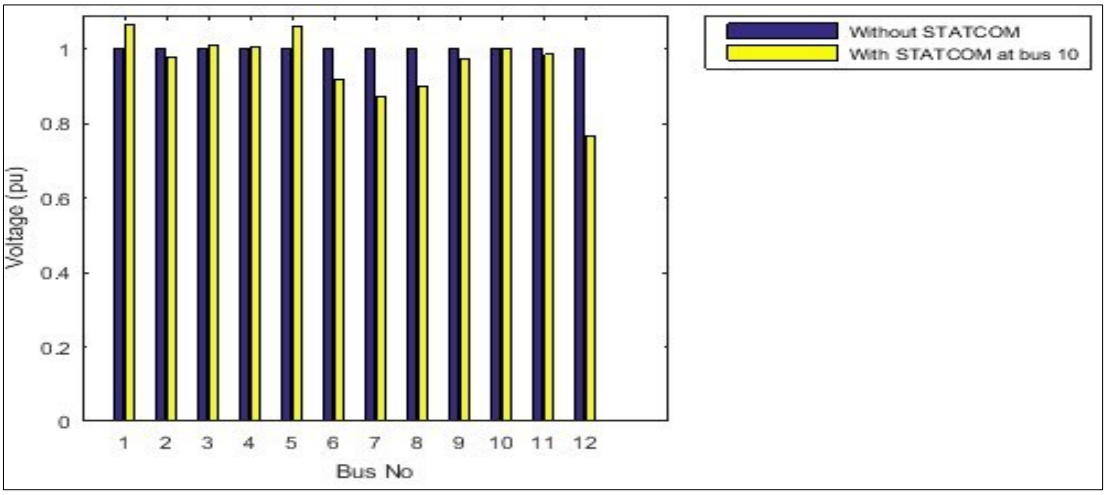


Figure 24: Voltage Magnitude with a Single STATCOM at Bus-10

Results for Locating STATCOM at Bus-11

Figure 25 shows a voltage enhancement of the 12-bus network with a single STATCOM at bus11. 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.

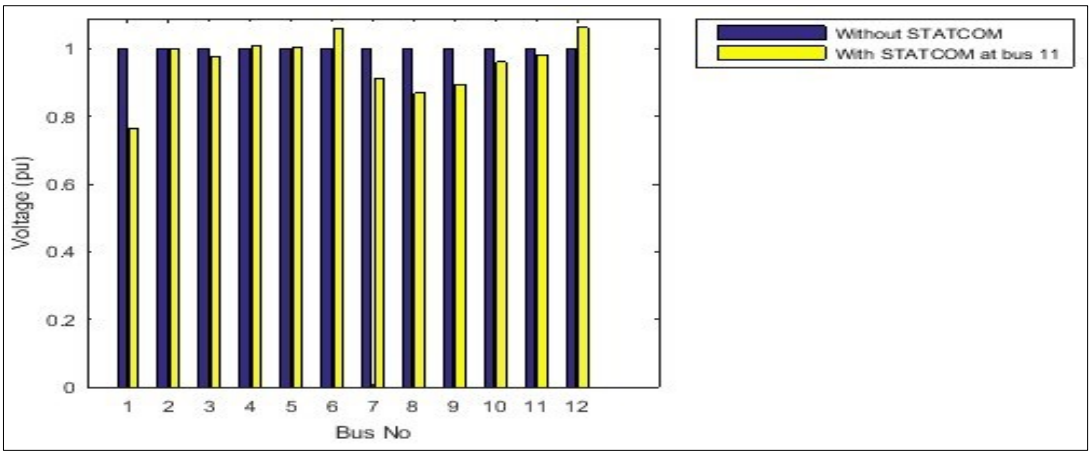


Figure 25: Voltage Magnitude with a Single STATCOM at Bus-11

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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.

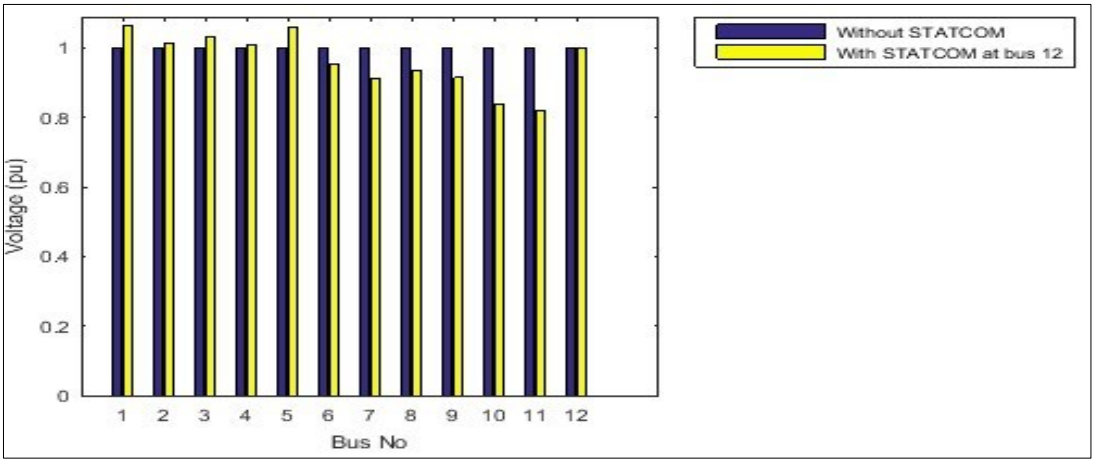


Figure 26: Voltage Magnitude with a Single STATCOM at Bus-12

Results for Pso Based Optimal Location of a Single STATCOM

PSO results obtained for the best placement of a single STATCOM at the Northeast 132 kV, 12bus 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 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

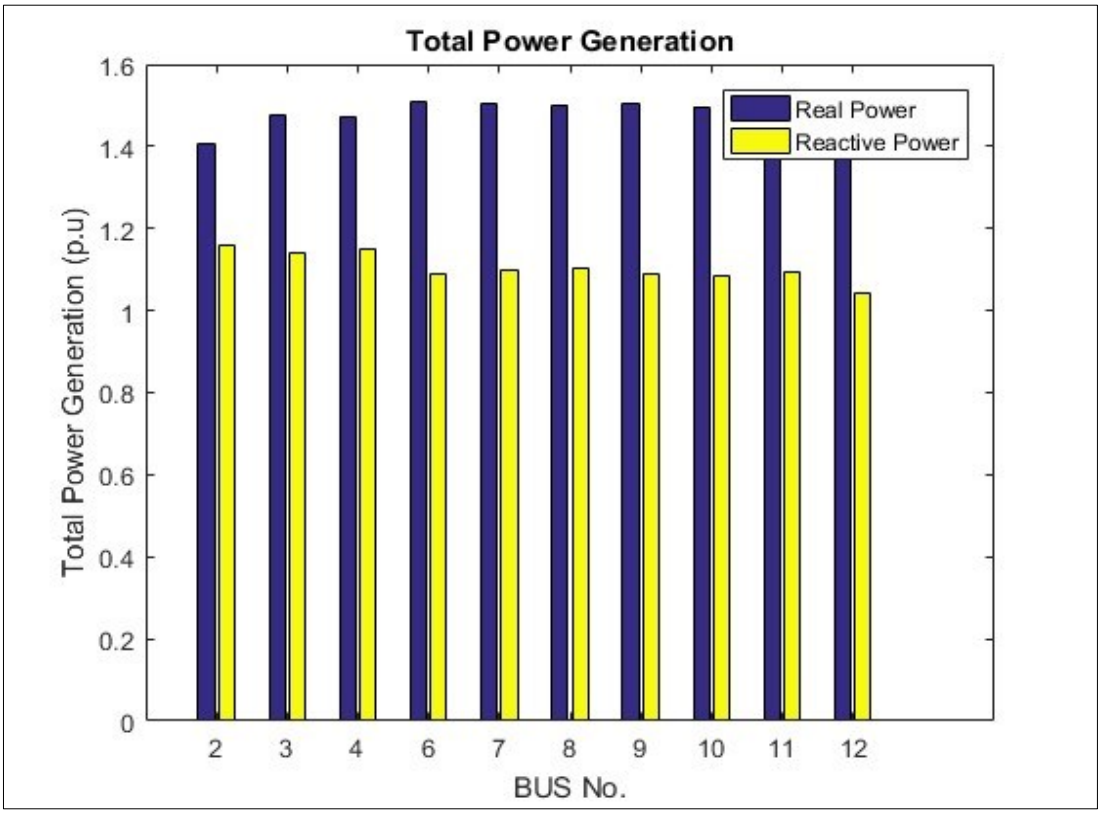


Figure 30: Total Real and Reactive Power Generation with Single STATCOM at Each Bus

Results for Real Power Loss with and Without STATCOM

The procedure followed the outlined sequence, with single STATCOM installations successively placed into buses 6, 7, 8, 9, 10, 11, and 12. Corresponding models representing these configurations within the PSAT MATLAB/SIMULINK environment are illustrated in Figures 9 through 15, respectively. Consistently, after each iteration, power flow analysis was performed, and the static report provided the outcomes for each scenario, elucidating the respective bus voltages, as well as real and reactive power profiles.

Table 9: Real Power Loss on the Transmission Line Transmission Real power losses Real power losses Real power losses line/no of without with single with two buses

Transmission line/ no of buses	Reactive power losses without STATCOM (pu)	Reactive power losses with single STATCOM (pu)	Reactive 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

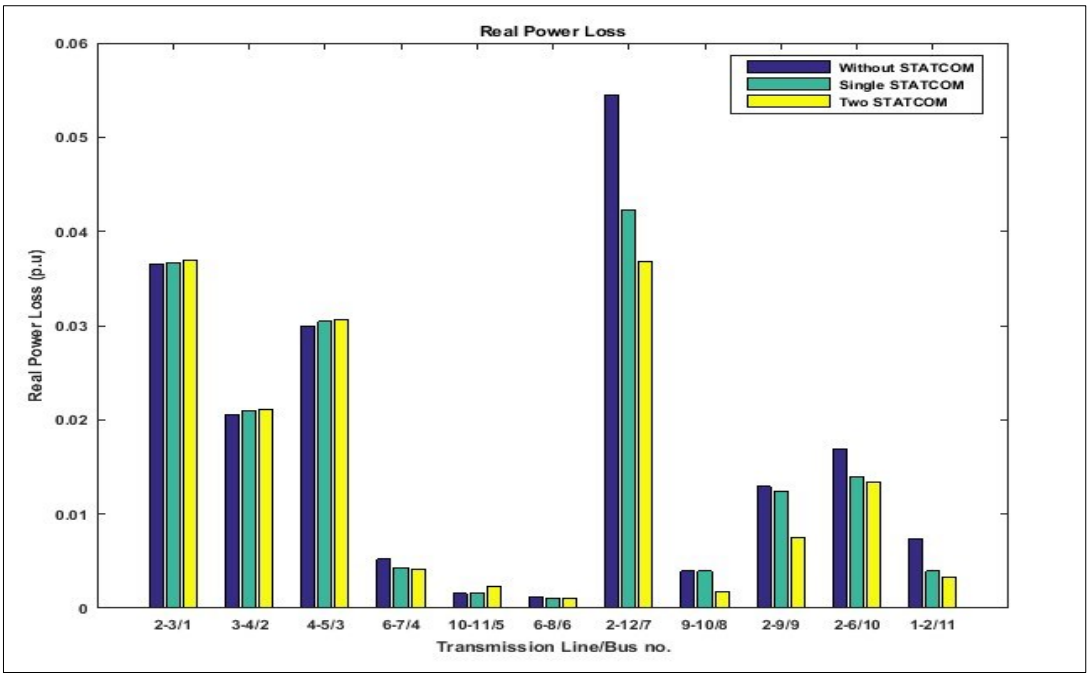


Figure 31: Real Power Loss with and Without STATCOM

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Results for Reactive Power Loss with and Without STATCOM

Table 10 presents the comparison of reactive power flow with and without the placement of STATCOM within the power network, accompanied by its corresponding plot depicted in Figure 32. The table displays positive reactive power losses attributed to inductive loads such as motors and transformers, alongside negative reactive power losses caused by capacitive loads such as lighting ballasts and computer equipment. Similarly, reactive power loss is recorded and juxtaposed for comparison. Analysis of the results in Table 10 reveals that reactive power loss is higher in the network without STATCOM and lower with the inclusion of a single STATCOM. Furthermore, Figure 32 illustrates that a more substantial reduction in reactive power loss is achieved with the placement of 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

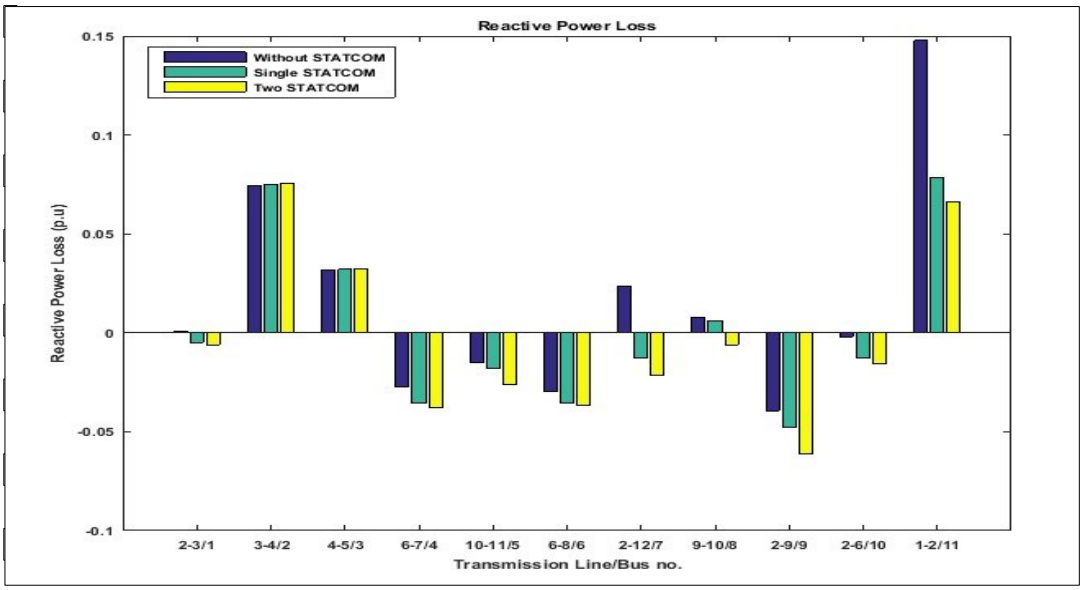


Figure 32: Reactive Power Loss with and without STATCOM

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CONCLUSION

Chapter four presents a comprehensive analysis and simulation results, leading to several conclusions and recommendations regarding the beneficial effects of integrating STATCOM into the Northeast 132 kV, 12-bus power network. Initially, the power flow of the 12-bus network was conducted using the PSAT platform, simulating voltage, real and reactive power profiles without STATCOM placement. Subsequently, single STATCOM units were sequentially placed on each bus, and the profiles were re-simulated to identify optimal bus locations. Additionally, the PSO algorithm was employed to study the optimal placement of two STATCOMs within the network.

The results demonstrate that strategic placement of STATCOM units enables voltage profile improvement, regulation of real and reactive power flow, and reduction of power losses in transmission lines. The study specifically focused on voltage enhancement within the Northeast 132 kV power network, employing STATCOMs on the 12 buses. Key conclusions drawn from the analysis include:

i. Optimal placement of STATCOMs significantly enhances voltage levels within the operating range of $0.95 \leq v \leq 1.05$ per unit (p.u) by effectively controlling real and reactive power flow.
ii. The strategic positioning of two STATCOMs yields higher voltage magnitudes compared to using a single STATCOM.
iii. The most effective configuration involves locating a single STATCOM at bus-12, while two STATCOMs are placed at buses 11 and 12.
iv. The integration of STATCOM results in a notable reduction in real power loss on the transmission network by 9.9%, along with a substantial 51.17% reduction in reactive power loss.

Recommendations for Further Research

Based on the results obtained from this research 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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