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Optimal Allocation and Sizing of Reactive Power Source for Voltage Profile Improvement on Nigerian 330kV, 24-Bus Grid System

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Abstract: *Complete or partial blackout, poor power quality and damage to connected electrical pieces of equipment at the consumer end among others are day to day experience in Nigeria. One of the major causes of this scenario can be attributed to inability of electric power system to maintain a proper voltage level throughout the entire system. This paper addresses the problem of voltage violation on Nigerian 330kV, 24-bus grid system using shunt capacitor injection at defective buses. Newton-Raphson power flow solution method was use to carry out load flow analysis with and without shunt capacitor injection. The acceptable voltage limit ranges from 0.95 p.u to 1.05 p.u, voltage at bus 4, 9, 13, 14, 16 and 19 were found to fall below the minimum acceptable limit of 0.95 p.u, to improve the voltage at these buses a calculated amount of Mvar was injected at each buses respectively using the following capacitor sizes (110 Mvar, 3μF), (90Mvar, 26 μF), (58Mvar, 17μF), (50 Mvar, 16μF), (38Mvar, 12μF) and (20Mvar, 7μF). The study shows that the injected MVAr via shunt-type capacitors significantly improve the system voltage profile, voltage angles andthe total system losses before compensation was found to be 82.5982MWand after compensation the losses reduced drastically to 82.2826MW.*

Keywords: *Load Flow Analysis, Newton-Raphson Iterative Method, Shunt Capacitor Compensation, Voltage Profile Improvement, Voltage Violation.*

I. Introduction

One of the key operational challenges facing the electricitysupply utilities in most third world countries of the world including Nigeria is the problem of system voltage fluctuation on the power grid [1]. The quality of service supplied by power utilities to consumer loads such as residential loads, industrial loads and public service sector loads is undermined by fluctuation in system voltage from their nominal values throughout the entire power system. Attempt to keep the system voltage profile within the range of nominal values can be achieved either by controlling the production, absorption and flow of reactive power at all levels within the system [2, 3].

Generally, in power system, tap changing transformers and shunt capacitor injection are vital pieces of discrete controller for voltage profile and reactive power control and management [4]. The optimal candidate placement for the shunt capacitor injection is either at end of transmission line or at the load buses to appreciably increasethe power transfer capability of a transmission system without requiring new lines or larger conductors[5].

Compensating system voltage's profile improves active power of the network by raising its power factor and also decreases harmonic components due to large loads fluctuations from non-linear pieces of equipment [6]. This paper uses shunt capacitor injection for voltage profile improvement on Nigerian 330kV, 24-bus transmission grid system because of its inherent advantages such as low initial cost, it has no moving part and its reaction to failures is quite adequate.

II. Concept of voltage stability and shunt capacitor reactive compensation

Power system ability to maintain a steady acceptable voltages at all buses during normal operating conditions and also after being subjected to a disturbance is termed voltage stability [7]. Power system voltage stability aimed at ensuring that voltages at the terminals of all equipment in the system are kept within the range of nominal values limits so as to avoid malfunction of and damage to the consumers' connected pieces of equipment.Keeping voltages close to these acceptable limits for which stabilizing controls are designed enhance system stability and as well guarantee maximal utilization of the transmission system [8].

Voltage instability on the other hand is the inability of power system to maintain acceptable voltages at all system buses under normal conditions and after being subjected to disturbances [9]. Causes of system voltage instability includes voltage drop due to active and reactive power flow through inductive reactance of the transmission network, reactive power demand beyond the sustainable capacity of the available reactive power resources as result of increase in system's disturbance, nature of transmission lines, problem of long transmission lines and poor power quality[11]. In general, its impact on the system has a wide spread as it depends on the relationship between real power (P) transmitted, injected reactive power (Q) and the voltage at the receiving end (V_R). These relationships play a crucial role in power system stability analysis [2, 10].

Optimal allocation and sizing of reactive powersources is one of the core issues in grid systempower management aimed at keeping the system voltage profile at each load centers (buses) within acceptable limit, which will consequently bring a significant reduction in total system losses [12]. Reactive power sources for compensation could either be series or shunt type, since this paper uses the latter, the candidate placement for shunt-type capacitor could either be installed near the load, in a distribution substation, along the distribution feeder, or in a transmission substation but at the transmission substation both inductive and capacitive reactive compensation are installed [12,13].

The advantages of shunt capacitor reactive compensation on power system includes voltage regulation (control the voltage within required levels), system power losses reduction brought about by power factor improvement and lastly, it increases utilization of connected pieces of equipment at the consumer end.

III. Problem formulation

A. NEWTON RAPHSON LOAD FLOW METHOD

Load flow analysis enables us to determine the voltage magnitude and phase angle at each bus together with the real and reactive power flowing along the line. Solution methodologies available for solving load flow problem includeGauss-Seidel Method, Fast Decouple Newton-Raphson and Newton-Raphson method. Newton-Raphson method has superior advantages over others in term of convergence rate (quadratic convergence), less prone to divergence with ill-conditions and the number of iterations required is independent on the system's size.

In Newton-Raphson load flow method, the voltage magnitude is held constant at 1.0 per unit and the acceptable nominal values limits ranges from 0.95 per unit to 1.05 per unit. The candidate placements for reactive compensation are the weak points in the system with voltage magnitude less than 0.95 per unit.

B. MATHEMATICAL MODELING OF NEWTON-RAPHSON LOAD FLOW METHOD

The complex power flow equations for uncompensated transmission system solved by Newton-Raphson's iterative method are defined thus:

$$P_i - Pd_i = \sum_{j=1}^{n} |V_i V_j Y_{i,j}| \cos(\theta_{ij} + \delta_j - \delta_i) \;\; i = 1,2,3 \ldots, n \quad (1)$$

$$Q_i - Qd_i = -\sum_{j=1}^{n} |V_i V_j Y_{i,j}| \sin(\theta_{ij} + \delta_j - \delta_i) \;\; i = 1,2,3 \ldots, n \quad (2)$$

where P_i= Real power generated at bus i^{th},Q_i= Reactive power generated at bus i^{th},Pd_i= Real power consumed at bus i^{th},Qd_i= Reactive power consumed at bus i^{th}, V is the bus voltage, δ is the angle associated with V, $Y_{i,j}$ is the element of bus admittance matrix, θ is the angle associated with $Y_{i,j}$.

The solution of equations (1) and (2) enables us to identify weak points in the system where the voltage magnitude are less than 0.95 per unit, these weak buses need reactive compensation, for compensated transmission system, equation (2) is modified and is defined by equation (3)

$$Q_i - Qd_i + Qc_i = -\sum_{j} |V_i| \, |V_j| Y_{i,j} \sin(\theta_{ij} + \delta_j - \delta_i) \quad (3)$$

Qc_i= additional reactive power support at bus i^{th}.

C. MATHEMATICAL MODELING OF SHUNT CAPACITOR RATING

The power factor of the system was raised from 0.85 to 0.96 for compensation purpose, the value of Qc (additional reactive power) to be injected at buses where voltage violation occurred is given by equation (4) below:

$$Qc = \frac{P}{Power\ \ Factor_{\ (1)}} sin(cos^{-1}(PF_1)) - \frac{P}{Power\ \ Factor_{\ (2)}} \sin(cos^{-1}(PF_2)) \quad (4)$$

where P= Real Power for uncompensated system, $Power\ Factor_{(1)}$= Uncompensated system (0.85), $Power\ Factor_{(2)}$= Compensated system (0.96)

The required capacitance value for compensation is given thus;

$$C = \frac{Qc}{2\Pi f V^2} \qquad (5)$$

IV. Results and discussion

This section shows the result of power flow calculations simulated in MATLAB (R2013a) for 330kV Nigerian 24-bus system comprising of four thermal stations and three hydro stations.It was run on a portable computer with an Intel Core2 Duo (1.8GHz) processor, 2GB RAM memory and MS Windows 7 as an operating system.

The accuracy of $1.000e^{-003}$ was specified in the power flow program, the maximum power mismatch of $3.49553e^{-07}$ was obtained and convergence occurred after the fifth iterations. Bus number 1 was taken as the reference bus since it has the highest generated power (MW) with voltage phase angle of zero degree. Figure 1 below shows the one-line diagram of the case study.

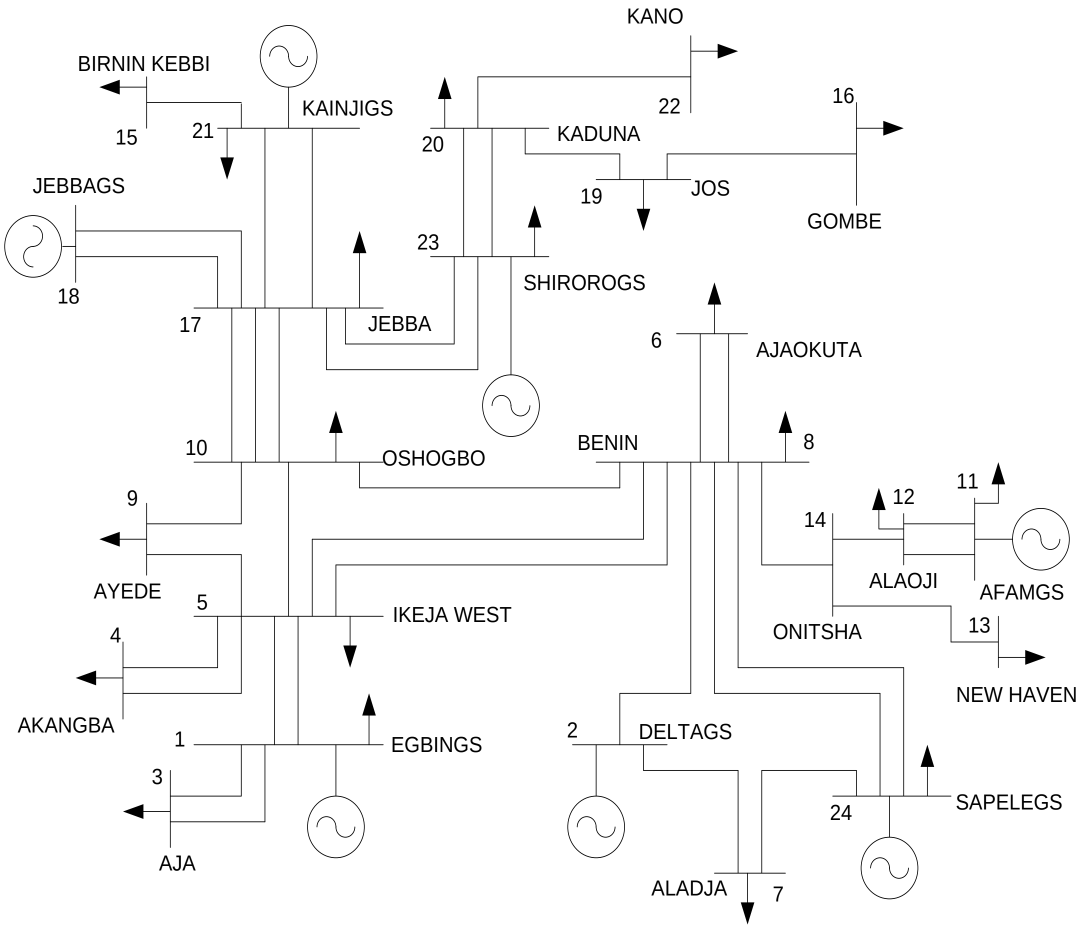

Figure 1: One-line diagram of Nigerian 330kV, 24-buses
(Source**:** National Control Centre, Power Holding Company of Nigeria, 2007)

A. NEWTON-RAPHSON'S BASED POWER FLOW SOLUTIONS WITHOUT SHUNT-CAPACITOR COMPENSATION

Table1: Power flow solution without shunt compensation

Bus No.	Voltage Mag.	Angle Degree	------Load------ MW	Mvar	---Generation--- MW	Mvar	Injected Mvar
1	1.050	0.000	68.90	51.70	1483.40	769.01	0.00
2	1.050	-1.066	0.00	0.00	670.00	3.01	0.00
3	1.045	-0.284	274.40	205.80	0.00	0.00	0.00
4	0.948	-5.609	344.70	258.50	0.00	0.00	0.00
5	0.996	-5.159	633.20	474.90	0.00	0.00	0.00
6	1.054	-6.916	13.80	10.30	0.00	0.00	0.00
7	1.046	-2.635	96.50	72.40	0.00	0.00	0.00
8	1.034	-6.556	383.30	287.50	0.00	0.00	0.00
9	0.934	-7.689	275.80	206.80	0.00	0.00	0.00
10	1.026	-4.785	201.20	150.90	0.00	0.00	0.00
11	1.050	-17.192	52.50	39.40	431.00	464.88	0.00
12	1.033	-17.816	427.00	320.20	0.00	0.00	0.00
13	0.929	-18.816	177.90	133.40	0.00	0.00	0.00
14	0.791	-16.010	184.60	138.40	0.00	0.00	0.00
15	1.010	-3.768	114.50	85.90	0.00	0.00	0.00
16	0.875	-31.975	130.60	97.90	0.00	0.00	0.00
17	1.050	-1.409	11.00	8.20	0.00	0.00	0.00
18	1.050	-1.149	0.00	0.00	495.00	-58.89	0.00
19	0.945	-24.431	70.30	52.70	0.00	0.00	0.00
20	1.004	-17.167	193.00	144.70	0.00	0.00	0.00
21	1.050	1.752	7.00	5.20	624.70	-114.67	0.00
22	1.013	-15.453	199.80	149.90	0.00	0.00	0.00
23	1.050	-11.883	320.10	256.10	388.90	480.64	0.00
24	1.050	-5.046	20.60	15.40	190.30	213.41	0.00
Total			4200.70	3166.20	4283.30	1757.40	0.00

Voltage at bus 4, 9, 13, 14, 16 and 19 were found to fall below the minimum acceptable limit of 0.95 p.u, to improve the voltage at these buses a calculated amount of Mvar was injected at each buses using the following capacitor sizes at bus 4 (110 Mvar, $3\mu F$), at bus 9 (90Mvar, 26 μF), at bus 13 (58Mvar, $17\mu F$), at bus 14 (50 Mvar, $16\mu F$), at bus 16 (38Mvar, $12\mu F$) and at bus 19 (20Mvar, $7\mu F$). The result of power flow solutions with injection of shunt compensation is presented in Table 2 below.

B. NEWTON-RAPHSON'S BASED POWER FLOW SOLUTIONS WITH SHUNT-CAPACITOR COMPENSATION

Table 2: Power flow solutions with shunt compensation

Bus No.	Voltage Mag.	Angle Degree	------Load------ MW	Mvar	---Generation--- MW	Mvar	Injected Mvar
1	1.050	0.000	68.90	51.70	1483.29	744.87	0.00
2	1.050	-1.063	0.00	0.00	670.00	-22.18	0.00
3	1.045	-0.284	274.40	205.80	0.00	0.00	0.00
4	0.989	-5.609	344.70	258.50	0.00	0.00	110.00
5	0.996	-5.158	633.20	474.90	0.00	0.00	0.00
6	1.054	-6.914	13.80	10.30	0.00	0.00	0.00
7	1.046	-2.633	96.50	72.40	0.00	0.00	0.00
8	1.034	-6.553	383.30	287.50	0.00	0.00	0.00
9	0.975	-7.688	275.80	206.80	0.00	0.00	90.00
10	1.026	-4.784	201.20	150.90	0.00	0.00	0.00
11	1.050	-17.177	52.50	39.40	431.00	440.05	0.00
12	1.034	-17.808	427.00	320.20	0.00	0.00	0.00
13	0.999	-18.806	177.90	133.40	0.00	0.00	58.00
14	0.972	-16.004	184.60	138.40	0.00	0.00	50.00
15	1.010	-3.766	114.50	85.90	0.00	0.00	0.00
16	0.975	-31.974	130.60	97.90	0.00	0.00	38.00
17	1.050	-1.408	11.00	8.20	0.00	0.00	0.00
18	1.050	-1.148	0.00	0.00	495.00	-58.95	0.00
19	0.955	-24.430	70.30	52.70	0.00	0.00	20.00
20	1.004	-17.166	193.00	144.70	0.00	0.00	0.00
21	1.050	1.753	7.00	5.20	624.70	-114.68	0.00
22	1.013	-15.452	199.80	149.90	0.00	0.00	0.00
23	1.050	-11.881	320.10	256.10	388.90	480.63	0.00
24	1.050	-5.044	20.60	15.40	190.30	187.58	0.00
Total			**4200.70**	**3166.20**	**4283.19**	**1657.34**	**366 .00**

D. RESULT SUMMARY

The summary of the voltage improvement as well as reduction in total system loses caused by the injected Mvar is presented in Table 3 below:

Table 3: Shows the Summary of result obtained from the power flow Analysis

Bus No	Voltage Magnitude with Shunt Capacitor Compensation	Voltage Magnitude without Shunt Capacitor Compensation	Voltage Angle with Shunt Capacitor Compensation	Voltage Angle without Shunt Capacitor Compensation	Total System Real Power Losses with Shunt Capacitor Compensation	Total System Real Power Losses (without)
1	1.050	1.050	0.000	0.000	82.**2826**	82.**5982**
2	1.050	1.050	-1.063	-1.066		
3	1.045	1.045	-0.284	-0.284		
4	**0.989**	**0.948**	-5.609	-5.609		
5	0.996	0.996	-5.158	-5.159		
6	1.054	1.054	-6.914	-6.916		
7	1.046	1.046	-2.633	-2.635		
8	1.034	1.034	-6.553	-6.556		
9	**0.975**	**0.934**	-7.688	-7.689		
10	1.026	1.026	-4.784	-4.785		
11	1.050	1.050	-17.177	-17.192		

12	**1.034**	**1.033**	-17.808	-17.816		
13	**0.999**	**0.929**	-18.806	-18.816		
14	**0.972**	**0.791**	-16.004	-16.010		
15	1.010	1.010	-3.766	-3.768		
16	**0.975**	**0.875**	-31.974	-31.975		
17	1.050	1.050	-1.408	-1.409		
18	1.050	1.050	-1.148	-1.149		
19	**0.955**	**0.945**	-24.430	-24.431		
20	1.004	1.004	-17.166	-17.167		
21	1.050	1.050	1.753	1.752		
22	1.013	1.013	-15.452	-15.453		
23	1.050	1.050	-11.881	-11.883		
24	1.050	1.050	-5.044	-5.046		

E. GRAPHICAL ILLUSTRATIONS

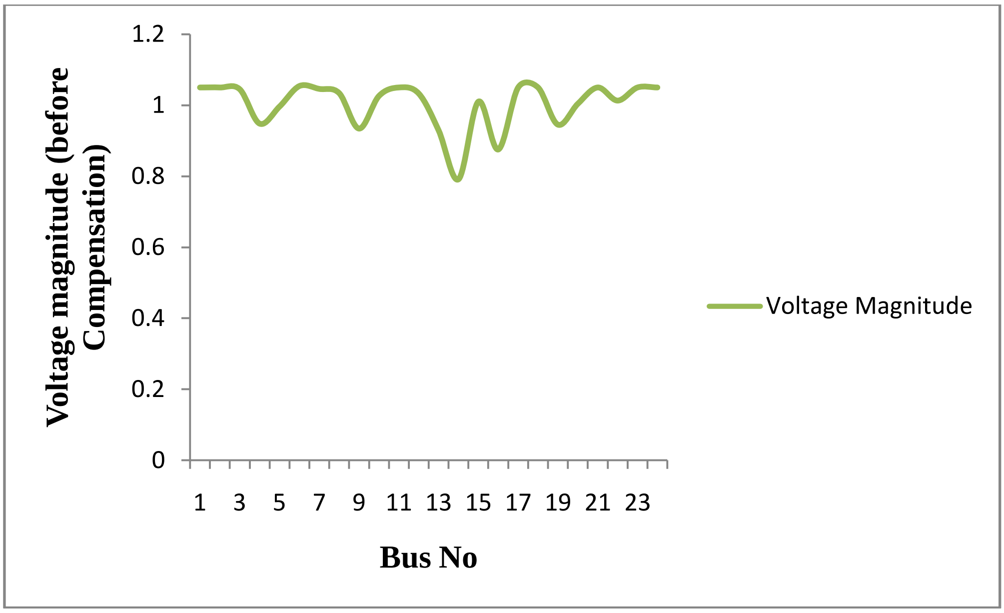

Figure 2: Bus No versus Voltage Magnitude (for shunt compensated System)

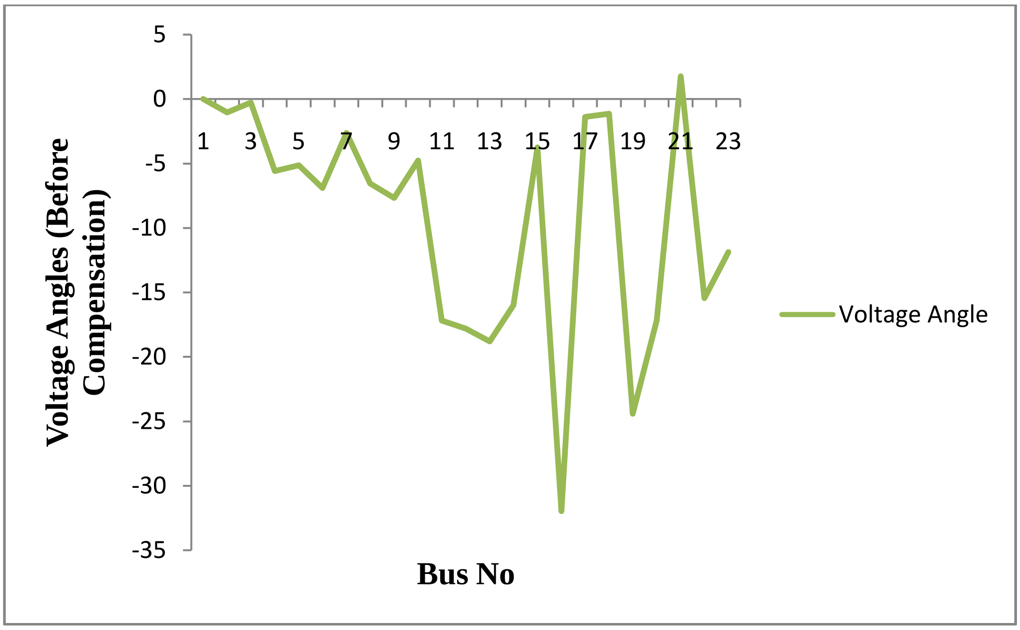

Figure 3: Voltage Angle (Uncompensated) versus Bus No

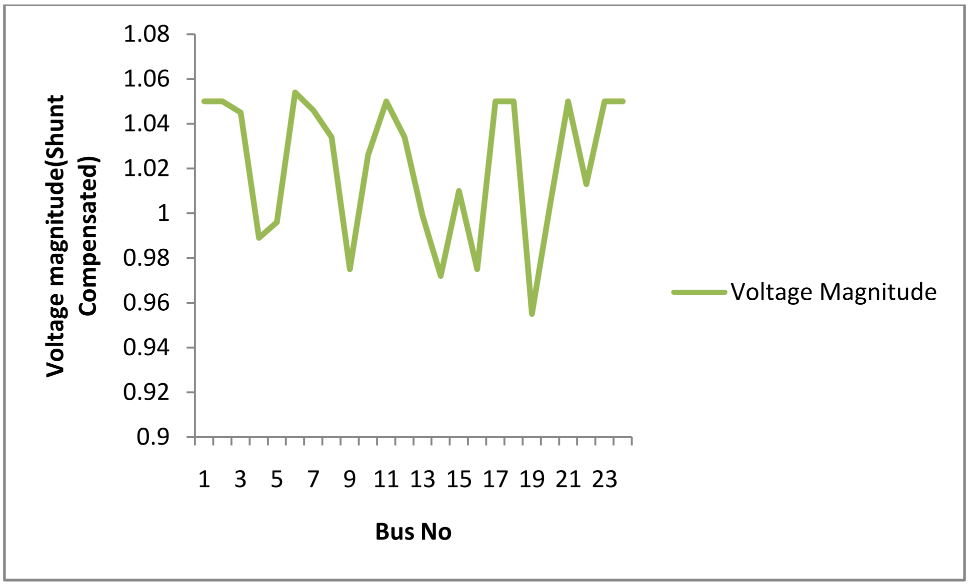

Figure 4: Voltage Magnitude (Compensated) versus Bus No

Figure 5: Voltage Angle (Compensated) versus Bus No

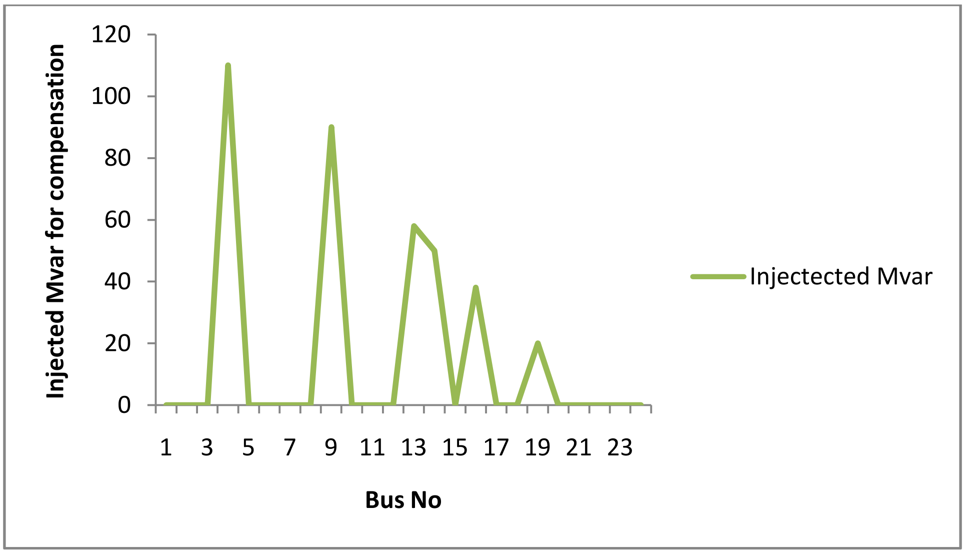

Figure 6: Injected Mvar versus Bus No

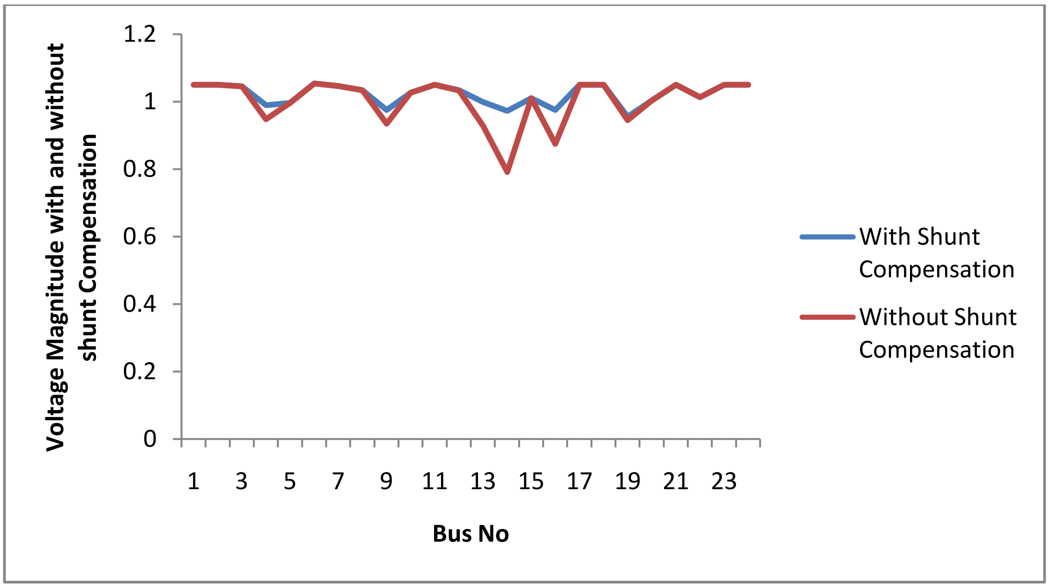

Figure 7: Voltage Magnitude (with and without compensation) versus BusNo

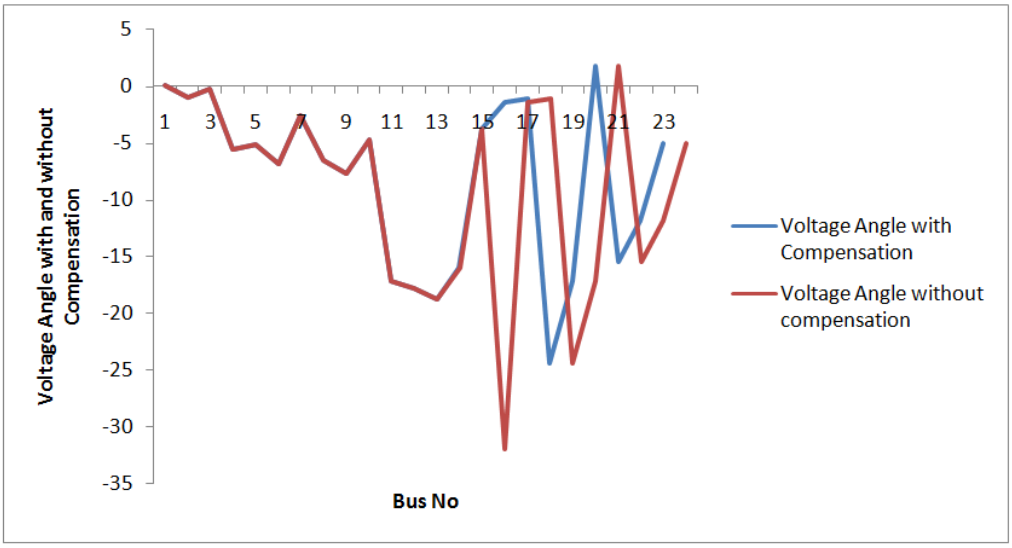

Figure 8: Voltage Angle (with and without compensation) versus Bus No

V. Conclusion

Optimal allocation and sizing of reactive power source for voltage profile improvement using power flow program implemented in MATLAB (R2013a version) environment has been presented. The Nigerian 330kV, 24-bus grid system was used as the case study. Newton-Raphson algorithm was used to carry out the power flow analysis with and without shunt compensation, buses with voltage magnitude less than 0.95 p.u were identified, a calculated amount of reactive power injected to raise the voltage within acceptable limit of 0.95-1.05 p.u.

The study shows that the injected MVAr via shunt-type capacitors significantly improve the system voltage profile, voltage angles and the total system losses at steady state condition was found to be **82.5982MW,** with shunt compensation the total system losses reduced drastically to **82.2826MW.**

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