Power Flow Study of Urban Center Distribution System for Grid Enhancement

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DOI: 10.56201/ijemt.vol.11.no3. 2025.pg1.14

Abstract

This paper deals with load flow study of 11kV distribution network in New GRA, Port Harcourt, Rivers state, Nigeria, with aim of grid enhancement in the network through reactive power compensation. The simulation is carried out using Newton Raphson method embedded in ETAP software. It is achieved by running a load flow of the existing 11KV distribution network, determining the losses from the load flow. Minimizing the determined losses in the distribution network by the penetration of capacitor banks. Analytical technique was used for sizing of the capacitor banks. Then, validating the percentage of loss reduction, and enhanced voltage profile in the distribution network with and without the injection of capacitor banks. The results obtained show that the base case network real and reactive power loss is 59.32kW and 78.91KVAr respectively. But, at the instant of penetrating 100KVar capacitor banks each into bus 5, bus 10 and bus 13, the real and reactive power losses reduced to 26.8kW and 31.012KVAr respectively. This indicate that when a capacitor bank (300KVAr) is injected into the system, the real power loss reduces by 55% while reactive power reduces by 60%. All the transformers maintain good loading conditions and voltage profile of all the buses fall within +5% variation as stipulated by IEEE.

Keywords: *Newton Raphson, Electrical Transient Analyzer Program, Capacitor Bank, Real Power, Reactive Power, Voltage Profile, IEEE*

I. INTRODUCTION

Availability of stable and reliable power is one of the factors that stimulates rapid socio-economic growth, and industrial development of any countries [1]. A typical power system is made up three sub-system namely; generation system, transmission system, and distribution system. Power distribution system can be explained as a service of electrical circuits that delivers electric power in the proper proportion to all categories of consumers (domestic, commercial and industrial). Power loss reduction and voltage stability enhancement are vital areas of power system to give proper attention to because of its associated advantages such as reduction in partial or total system collapse, and financial gain by the utilities company. Distribution system losses can be determined through load flow study, and significantly minimized through sufficient reactive power compensation [2]. Load flow studies are used to determine the stable state operation of an electric power system [3]. It is used to identify the need for capacitive or inductive support or compensation to maintain system voltages within specified limits and to reduce losses at each buses and total power losses in the system. The subject of distribution system loss reduction has gained a great deal of attention due to the high cost of producing electrical energy [4].

Most of the commercial and industrial loads are inductive in nature. As the load increases current drawn from the supply increases, voltage drop increases, line losses increase, reactive power consumption increases. Therefore, reactive power compensation is very vital in the smooth and proper operation of the power distribution system. Some sources of reactive power compensation are; shunt reactors, shunt capacitors and static VAR compensators [5]. The most common reactive power compensator preferred is shunt capacitor because of its merits like less power loss, less voltage drop and reasonable cost. But to achieve the benefits from shunt capacitor bank, it has to be selected in optimal manner, that is, the location to be placed and required size of the capacitor bank should be determined by an accurate method for enhancement of system performance [6]

II. Statement of the Problem

Erratic and inadequate power supply has been the burning issue encountering by the residents of the study area (New GRA, Port Harcourt) in Nigeria. The 11kV distribution network supplying power to the study area has been associated with acute power outage, low voltage profile, reactive power deficiency and huge power losses. These in turn results to damaging of equipment connected to the system, partial shutdown of small and medium scale businesses in the area, and loss of revenue by the utility company. Therefore, conducting a load flow study will be needed in order to assess and restore a stable and efficient power supply in the study area by adopting a suitable reactive power support strategy. This research seeks to propose analytical technique to optimally determine the size of capacitor bank for reactive power compensation, which will enhance voltage profile, reduce power losses and improve system overall performance.

II. LITERATURE REVIEW

Maintaining security of power system operation is all about keeping the system parameter within the statutory limit, this can be achieved by load flow study which involves investigating the system parameters (Voltage magnitude, voltage phase angle, real and reactive power) at every buses of the power system in order to determine losses and mitigate it [7]. The inconveniences and economic cost which huge power losses caused on consumers and utilities are unhealthy and enormous [8]. Modern Power Utilities Company, are all the time planning the expansion of their electrical networks to face the load growth and to properly supply their consumers always [9]. Load flow study and reactive power compensation of New GRA, 11kV distribution network through the penetration of capacitor banks using analytical technique, in order to minimize power loss and ensure voltage stability is a good approach. This will assist the power system engineers and researchers better understand and appreciate the need for the power system load flow study and reactive power support with suitable sizing strategy

According to [10], they presented a study aimed at placement of capacitor banks in the distribution network and analyze the effect as voltage drop increases in the distribution network. The power flow calculation was carried out using ETAP 12.6.0 software. The procedure was tested on Rao feeder. The existing Rao feeder is 16.806KV which has violated the standard of -10% and +5% set by PLN. The total power loss is 0.242MW and a power factor of 0.7815. When fuzzy logic method is used to determine the optimal of capacitor placement, then after the deployment of capacitor bank, the terminal voltage increase, total power losses reduced, while the power factor is improved.

In the paper presented by [11], they carried out a work titled optimal sizing of capacitor bank for increasing substation capacity. An analytical technique was used to determine the size of the capacitor to place on the Mamou substation (110/30KV) with 15MVA transformer. MATLAB software was used for the simulation. The results obtained when the shunt capacitor is deployed show that power losses reduced form 14913.978 KVA to 14010.100KVA, a reduction in the transformer load rating from 99.4% to 93.4%, a reduction in the voltage drop from 4.8% to 3.9%. The power available at the secondary of the transformer station increases from 13950KW to 14700kW that is annual saving of electrical energy is 339943.48kWhof electrical energy.

In the proposed study by [12], they investigate voltage regulation and power loss reduction with optimal capacitor placement in a distribution system using genetic algorithm for proper placement and sizing of the capacitor banks. The case study considered for investigation is Sani Abacha 11kV distribution system with emphasis on knowing the losses incurred and minimize it to enhance voltage profile improvement to ensure higher efficiency and reliability. ETAP software was used for modeling and simulation analysis. The result obtained when shunt capacitor banks is deployed show improvement in the voltage profile and significant reduction of system losses.

- **Power Flow**

Before entering to the reactive compensation in power system, power flow study or load flow study need to be kept in mind, which is a numeric analysis of the flow of electric power in an interconnected system. A power flow study usually uses simplified notation such as a one line diagram and per unit system and focuses on various aspects of AC power parameters such as voltages, voltage phase angles, real power and reactive power. It analyses the power systems in normal steady state operation. Load flow studies are essential for planning future expansion of power system as well as in determining the best operation of existing system [13]. The Newton Raphson and the Gauss Seidel methods are the conventional techniques for solving the load flow problems.

- **Load Flow Study Techniques**

There are two commonly numerical methods for solving the power flow problems. These are Newton – Raphson and Gauss – Seidel. The simplicity and reduction calculation time provided by Gauss – Seidel method are two of the most significant benefits of using it [14]. However, in circumstance when a large number of buses are added in a network, the slow rate at which convergence is reached, as well as the increasing number of iterations, are important downsides of this method. Table 1, depicts the classification of power system buses.

Table 1: Classification of Power System Buses.

Sl. No.	Bus Types	Specified Variables	Unspecified variables	Remarks
1	Slack/ Swing Bus	$\|V\|$, δ	P_G, Q_G	$\|V\|$, δ: are assumed if not specified as 1.0 and 0^0
2	Generator/ Machine/ PV Bus	P_G, $\|V\|$	Q_G, δ	A generator is present at the machine bus
3	Load/ PQ Bus	P_G, Q_G	$\|V\|$, δ	About 80% buses are of PQ type
4	Voltage Controlled Bus	P_G,Q_G, $\|V\|$	δ, a	'a' is the % tap change in tap-changing transformer

Source: [15]

IV. METHODOLOGY

The study case distribution system (11kV New GRA network) was modelled and simulated using embedded Newton Raphson technique in Electrical Transient Analyzer Program environment, for load flow studies. The system losses and voltage profiles at each bus in the network were recorded. Then, the system was compensated with reactive power through penetration of capacitor bank using analytical technique for its sizing. The load and line data of New GRA, 11kV distribution network are as shown in Table 2 and Table 3 respectively.

Table 2: Load Bus Information

Bus ID	Bus Name	Rated Voltage	Transformer kVA	Calculated Load Values kVA	kW	kvar	PF	Amp
1	Mummy B	0.415	500	308.0	261.8	162.3	0.85	428.5
2	Rebisi	0.415	500	140.5	119.4	74.03	0.85	195.5
3	Mopol 19	0.415	500	224.0	190.4	118.0	0.85	311.6
4	Crest Bridge	0.415	500	262.0	222.7	138.0	0.85	364.5
5	Etitiwo	0.415	300	278.0	236.3	146.4	0.85	386.8
6	Nyeche	0.415	500	188.5	160.2	99.28	0.85	262.2
7	Henry Worlu	0.415	500	300.0	255.0	158.0	0.85	417.4
8	Elikuma	0.415	500	261.5	222.3	137.8	0.85	363.8
9	Military Hosp.	0.415	500	302.0	256.7	159.1	0.85	420.1
10	Ohakwe	0.415	300	288.0	244.8	151.7	0.85	400.7
11	Obiri Ogbonna	0.415	500	199.5	169.5	105.1	0.85	277.5
12	Worchiolu	0.415	500	268.5	228.2	141.4	0.85	273.5
13	Elekwu	0.415	300	270.0	229.5	142.2	0.85	375.6

Source: Port Harcourt Electricity Distribution Company

Table 3: Line Data Information

Line ID	From Bus	To Bus	Line Impedance (P.u) R	X
1	1	2	0.01938	0.05917
2	2	3	0.05403	0.22304
3	3	4	0.04699	0.19797
4	4	5	0.05811	0.17632
5	5	6	0.05695	0.17388
6	6	7	0.06701	0.17103
7	7	8	0.01335	0.04211
8	8	9	0.09498	0.19890
9	9	10	0.12291	0.25581
10	10	11	0.06615	0.13027
11	11	12	0.03181	0.08450
12	12	13	0.12711	0.27038

Source: Port Harcourt Electricity Distribution Company

- **Load Flow Technique (Newton's Raphson)**

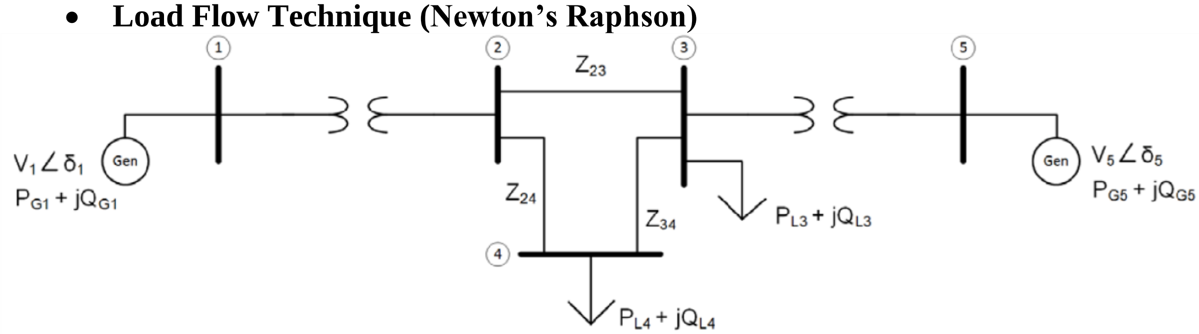

Figure 1: One Line Diagram of a Typical Power System.

The apparent power injected at the *ith* node is

$$S_i = V_i I_i^* = P_i + jQ_i \quad (1)$$

$$I_i = \left(\frac{S_i}{V_i}\right)^* = \frac{P_i - jQ_i}{V_i^*} \quad (2)$$

$$I_i = \frac{P_i - jQ_i}{V_i^*} = \sum_{k=1}^{n} Y_{ik} V_k \quad (3)$$

$$P_i - jQ_i = V_i^* \left(\sum_{k=1}^{n} Y_{ik} V_k\right) \quad (4)$$

Let $V_i^* = \mathrm{V_i}\angle - \delta_i, V_k = \mathrm{V_k}\angle\delta_k$ and $Y_{ik} = \mathrm{Y_{ik}}\angle\theta_{ik}$

$$P_i - jQ_i = V_i \ \left(\sum_{k=1}^{n} Y_{ik} V_k \angle\delta_k + \theta_{ik} - \delta_i\right) \quad (5)$$

$$P_i - jQ_i = \sum_{k=1}^{n} |Y_{ik}||\mathrm{V_i}||\mathrm{V_k}| \left[\cos(\delta_k + \theta_{ik} - \delta_i) + j\sin(\delta_k + \theta_{ik} - \delta_i)\right] \quad (6)$$

Separating the real part from the imaginary part in (1.6)

$$P_i = \sum_{k=1}^{n} |Y_{ik}||\mathrm{V_i}||\mathrm{V_k}| \cos(\delta_k + \theta_{ik} - \delta_i) \quad (7)$$

$$Q_i = -\sum_{k=1}^{n} |Y_{ik}||V_\text{i}||V_\text{k}| \sin(\delta_k + \theta_{ik} - \delta_i) \tag{8}$$

Where

Y_ik= admittance

P_i= real power

Q_i= reactive power

δ_i= phase angle

Expanding (7) and (8) in Taylors series neglecting higher order terms we have

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \begin{bmatrix} \begin{vmatrix} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n} \end{vmatrix} & \begin{vmatrix} \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(k)}}{\partial |V_n|} \end{vmatrix} \\ \begin{vmatrix} \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} \end{vmatrix} & \begin{vmatrix} \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{vmatrix} \end{bmatrix} \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \Delta \delta_n^{(k)} \\ \Delta \left|V_2^{(k)}\right| \\ \vdots \\ \Delta \left|V_n^{(k)}\right| \end{bmatrix} \tag{9}$$

With insignificant changes in real $\Delta P_i^{(k)}$ and reactive power $\Delta Q_i^{(k)}$the Jacobian matrix shows the linearized correlation between tiny changes in voltage angle $\Delta \delta_i^{(k)}$ and magnitude $\Delta \left|V_i^{(k)}\right|$

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_3 \\ J_2 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \tag{10}$$

Where

J_1, J_2, J_3, J_4 are the elements of the Jacobian matrix

The diagonal and the off-diagonal elements of J_1 are

$$\frac{\partial P_i}{\partial \delta_i} = \sum_{k \neq i} |Y_{ik}||V_\text{i}||V_\text{k}| \sin(\delta_k + \theta_{ik} - \delta_i) \tag{11}$$

$$\frac{\partial P_i}{\partial \delta_k} = -|Y_{ik}||V_\text{i}||V_\text{k}| \sin(\delta_k + \theta_{ik} - \delta_i) \qquad k \neq i \tag{12}$$

Similarly, the diagonal and off diagonal element of J_2, J_3, J_4 can be computed

$$\Delta P_i^{(k)} = P_i^{sch} - P_i^{(k)} \tag{13}$$

$$\Delta Q_i^{(k)} = Q_i^{sch} - Q_i^{(k)} \tag{14}$$

Equations 1 to 14 are the fundamental power flow equations and its solution is facilitated using the traditional Newton Raphson solution algorithm in ETAP

- **Capacitor Bank Sizing**

The size of capacitor bank was determined analytically using the equation below

$Q_c = \{\tan(\cos^{-1}(pf_1)) - \tan(\cos^{-1}(pf_2))\}$

Where

P: Injected Power to the bus
pf_{1}: Initial power factor
pf_{2}: Desired power factor

Determination of Capacitor Bank Size for Bus 5

Parameters for Bus 5:
Total Injected Power P=230.8 kW
Initial power factor Pf_1=0.85
Desired power factor Pf_2=0.96
$Q_c = P[\tan\cos^{-1}(pf_1) - \tan\cos^{-1}(pf_2)]$
$Q_c = 230.8 * [\tan\cos^{-1}(0.85) - \tan\cos^{-1}(0.96)]$
$Q_c = 230.8 * [\tan 31.788 - \tan 16.260]$
$Q_c = 230.8 * (0.6197 - 0.2917)$
$Q_c = 230.8 * (0.328)$
$Q_c = 75.8\ kvar\ \approx 100kvar$

Determination of Capacitor Bank Size for Bus 10

Parameters for Bus 10:
Total Injected Power P=238.7kW
Initial power factor Pf_1=0.85
Desired power factor Pf_2=0.96
$Q_c = P[\tan\cos^{-1}(pf_1) - \tan\cos^{-1}(pf_2)]$
$Q_c = 238.7 * [\tan\cos^{-1}(0.85) - \tan\cos^{-1}(0.96)]$
$Q_c = 238.7 * [\tan 31.788 - \tan 16.260]$
$Q_c = 238.7 * (0.6197 - 0.2917)$
$Q_c = 238.7 * (0.328)$
$Q_c = 78.3\ kvar\ \approx 100kvar$

Determination of Capacitor Bank Size for Bus 13

Parameters for Bus 13:
Total Injected Power P=223.6kW
Initial power factor Pf_1=0.85
Desired power factor Pf_2=0.96
$Q_c = P[\tan\cos^{-1}(pf_1) - \tan\cos^{-1}(pf_2)]$
$Q_c = 223.6 * [\tan\cos^{-1}(0.85) - \tan\cos^{-1}(0.96)]$
$Q_c = 223.6 * [\tan 31.788 - \tan 16.260]$
$Q_c = 223.6 * (0.6197 - 0.2917)$
$Q_c = 223.6 * (0.328)$
$Q_c = 73.3\ kvar\ \approx 100kvar$

V. RESULTS AND DISCUSSIONS

- **Network Diagrams with and Capacitor Bank.**

Figures 2 and Figure 3 show the one-line simulation diagrams of the study case network without and with capacitor bank penetration respectively. Without capacitor bank, three (3) out of the thirteen (13) load buses are critically loaded while two buses are marginally loaded. The remaining eight (8) load buses are certified well loaded. When a capacitor bank of size 100KVAr each was penetrated to the critically loaded bus 5, bus 10 and bus 13 respectively as all, the overload buses were successfully upgraded to normal loading conditions.

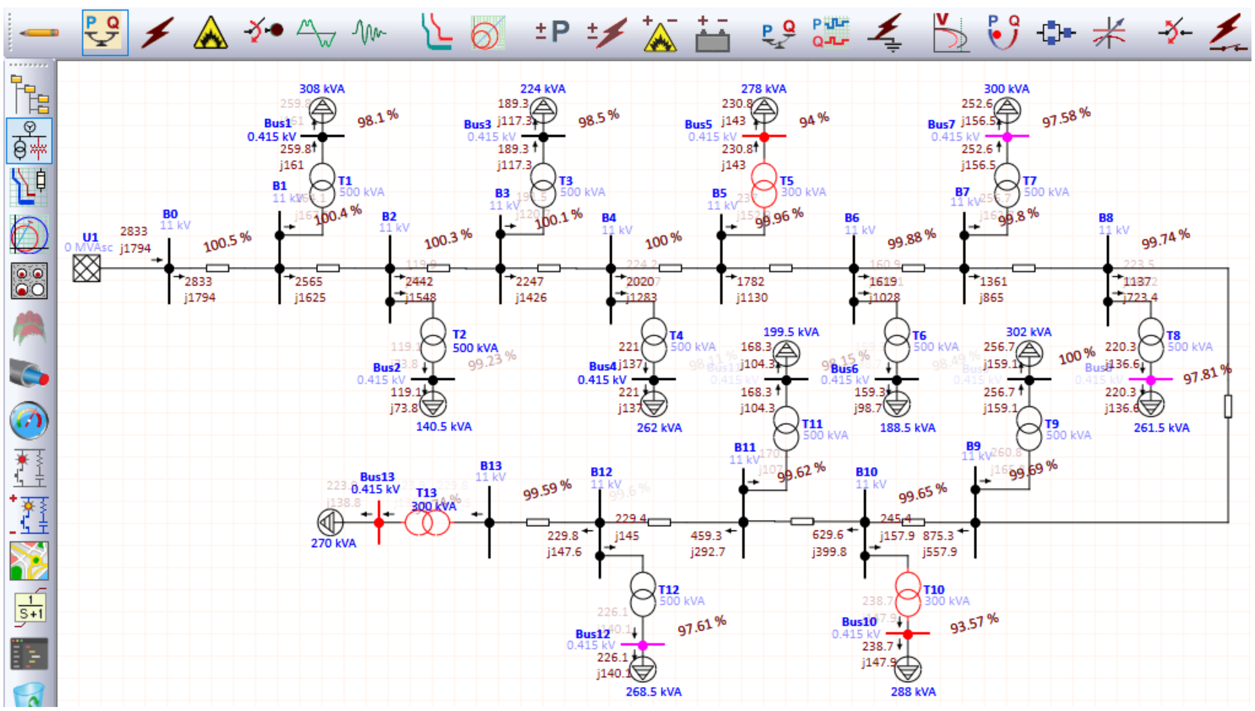

Figure 2: One Line Simulation Diagram of the Existing Network without Capacitor Bank.

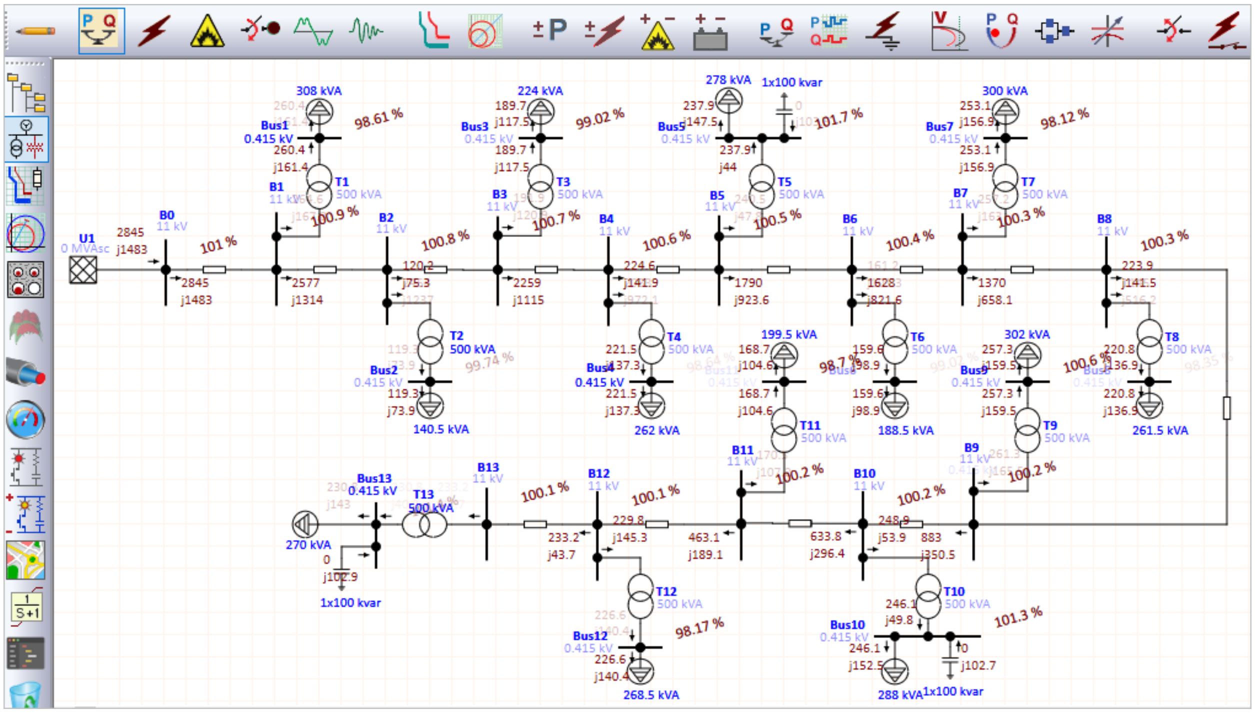

Figure 3: One Line Simulation Diagram of the Improved Network with Capacitor Bank.

- **Bus Voltage Magnitude with and Without Capacitor Bank.**

Figure 4 show a plot of percentage of bus voltage magnitude with and without penetration of capacitor bank in the network. The result indicates that three (3) out of thirteen buses are overloaded and such facing problems of under voltage in the existing network. But after integration of capacitor banks (100kVar each) at bus 5, 10 and 13, all load buses were upgraded from critical position to good loading condition and their voltages fall within the IEEE limit ±5% of acceptable voltage drop level.

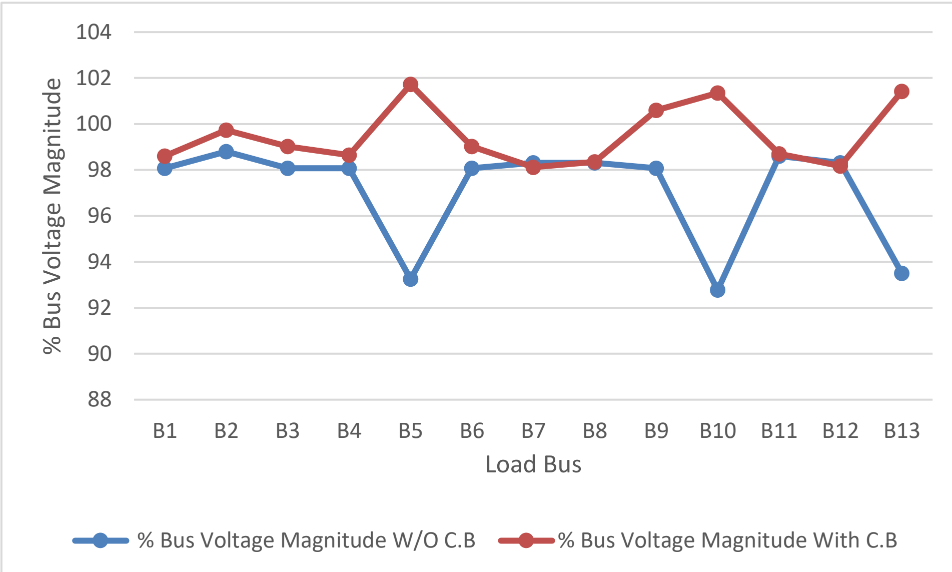

Figure 4: Plot of Percentage Bus Voltage Magnitude versus Load Bus with and Without Capacitor Bank.

- **Real Power Loss with and Without Capacitor Bank**

Figure 5, shows the real power loss result in all branch elements with and without penetration of capacitor bank. The results show that there is a reduction in real power loss in all branches when capacitor banks is injected into the network. The total real power loss without capacitor bank was 59.32kW while for that with capacitor bank is 26.68kW

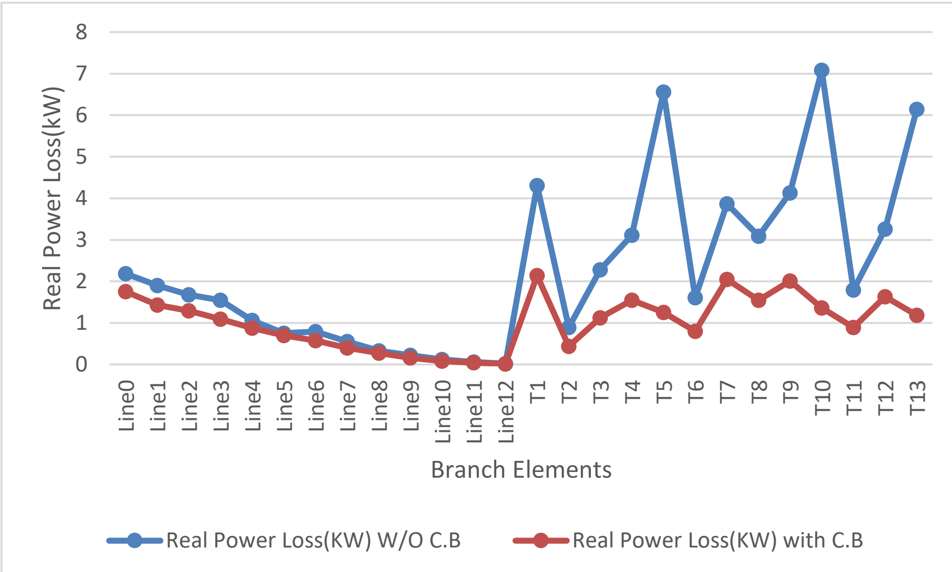

Figure 5: Plot of Real Power Loss versus Branch Elements with and without Capacitor Bank

- **Reactive Power Loss with and Without Capacitor Bank**

Figure 6, show the plot of reactive power loss amongst branch elements. The results show that there is a significant reduction in reactive power loss in all branches when CB is injected into the network. The total reactive power loss without capacitor bank was 78.91kVAr while for that with capacitor bank is 31.02kVAr

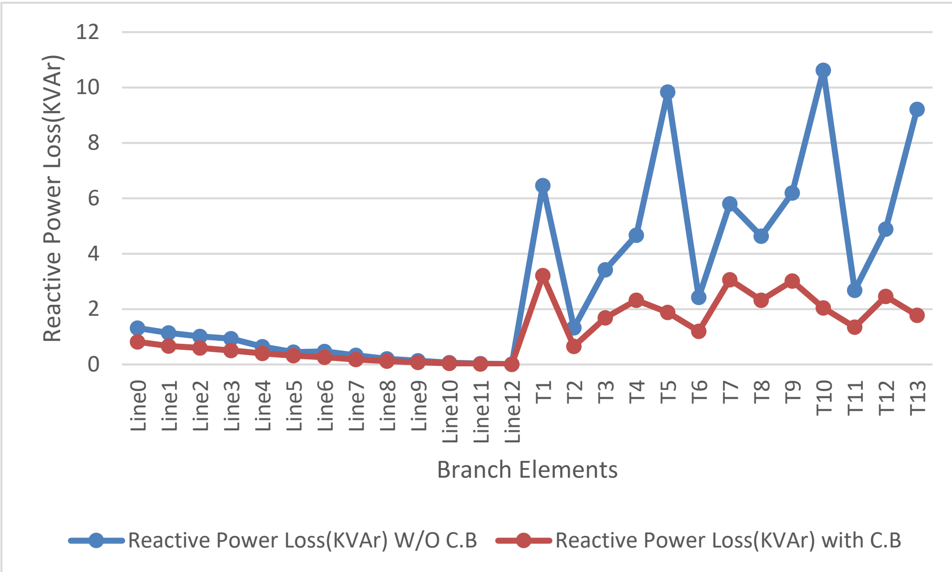

Figure 6: Plot of Reactive Power Loss versus Branch Elements with and without Capacitor Bank.

VI. Conclusion

Achieving stable and reliable power system require load flow study and reactive power support, which prove the need to the research work. The distribution load and line data of the study case network were collected from Port Harcourt Electricity Distribution Company and analyzed. ETAP software was used to carry out load flow analysis of 11kV New GRA distribution network in order to determine system losses. The determined losses in distribution network were reduced with the penetration of sizable capacitor banks at the critically loaded buses. Then validating the percentage loss reduction in improving loss in the study case distribution network by comparing the results of losses with and without capacitor banks injection. The obtained results show that the existing network real and reactive power loss is 59.32kW and 78.91KVAr respectively. When a 100KVar capacitor banks each was penetrated into bus 5, bus 10 and bus 13, the real and reactive power losses reduced to 26.8kW and 31.012KVAr respectively. This indicate that when a capacitor bank (300KVAr) is injected into the system, the real power loss reduces by 55% while reactive power reduces by 60%. Other parameters such as voltage profile, percentage voltage drop was also enhanced.

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