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Power Quality Improvement of a Distribution Network for Sustainable Power Supply

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Abstract: This paper presents a heuristic technique for improving the voltage profile and reducing power loss in a distribution network. These components are to be maintained at a certain standard to boost the electricity supply power of a distribution network. The shunt capacitor placement technique is applied to achieve a sustainable electric power supply. The issue of power loss has been a major threat to the distribution network. A distribution network is expected to operate at a certain voltage level to meet consumers' energy demand. Power flow studies have been conducted using Newton Raphson's technique on the 30 bus, 11 kV Onuiyi-Nsukka distribution network. It was found that the voltage profile on buses 19 and 26 was critically violated with voltage amplitudes of 0.72 pu and 0.79 pu respectively. The feeder power quality was improved using a shunt capacitor placement technique and the installation of a 1200KVAr shunt capacitor to keep bus voltage amplitudes within the legal limit of (0.95-1.05) pu. The voltage profile, active and reactive power losses on the network were determined. Active power loss and reactive power loss are reduced from 0.27MW to 0.12MW and 0.76Mvar to 0.14Mvar, respectively. Therefore, the distribution network voltage profile is improved and the power loss on the network significantly reduced.

Keywords: Active power, compensation, distribution network, power loss reduction, power flow, PSAT, MATLAB

1. Introduction

The distribution part of the electricity supply chain has been saddled with the responsibility of sustaining power supply. For the past decades, a huge section of customers have been experiencing the debilitating effects of shortages, epileptic, unstable and unreliable electricity supply, and increased breakdown of power infrastructure due to high power loss due to inductive loads, the voltages at the buses are low likewise the current flow [1]. The traditional power network is expected to be sustainable and reliable for optimal power supply [2]. The presence of power loss and low bus voltage profile limits the optimal performance of the power system components. Such phenomena have contributed immensely to the incessant power failures, instability and unreliability of the power system. The demand for electricity increases on a daily basis and the outcome has been geared towards an increase in per unit production cost. Again, sustainable power flow and enhanced power quality during disturbances become challenging [3]. An increase in electricity demand has caused power line overloading and this overloading causes the voltage on each bus to reduce [4]. Many customers, especially those on industrial, commercial and technological sectors have experienced the debilitating effect of electric power loss, blackouts and shortage of power supply as it affects their businesses. In a distribution system, capacitors are

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*Corresponding author: ifeanyi.ohanu@unn.edu.ng installed to compensate for reactive power, regulate electric distribution voltage, enhance operational security and reduce power or energy losses. Distribution system collapse is a problem that is peculiar to local load buses, which generates faults and system imbalances. This depends mostly on load conditions in the system. At present, distribution network voltage profile improvement has attained immense significance due to the integration of nonlinear loads into the power system network [5, 6]. The most economical and efficient way to achieve an improved voltage profile in a distribution network is through the compensation of the reactive loads. This has been possible with the application of fixed or adjustable capacitor banks to the distribution system.

2. A Brief Review of Recent Research Works

Several researchers reported work on capacitor placement and sizing using different techniques. The use of the analytical method of voltage regulators to proffer solutions for shunt capacitor sizing and placement on the distribution network is reported in [7] by Grainger and Civanlar. Sayeed Ishtiaque presented the optimization of electrical power supply to rural areas for domestic consumption[8]. This study analysed the development of the power sector of Bangladesh since its inception using cutting-edge technology. From the literature [9,10], it has been shown that photovoltaic (PV) in electricity generation increases the reliability of distribution networks. The transient and steady-state violations hinders the capacity of a distribution network in accepting large three-phase PV installations. However, other researchers in [11-16] conducted research on the placement of shunt capacitors in distribution systems for voltage profile improvement and power loss minimization using optimization function principles. Optimal power flow was used in the literature for voltage profile improvement in addition of shunt capacitors in distribution networks. To solve the multi-objective optimization problem, the algorithms of some metaheuristic optimization techniques were used. Optimization techniques like Penalty Free Genetic Algorithm, Group Search Optimization (GSO), genetic algorithm (GA), Gbest guided artificial bee colony algorithm (Gbest-ABC) and Particle Swarm Optimization are used. These techniques ensure Optimal Capacitor Placement (OCP) to enhance the voltage profile, minimize power loss and improve power quality [17-21]. The limitation of any metaheuristic method is its sensibility to the choice of initial parameters and population size. The authors of [22] reported the use of a single branch exchange method for a single loop for energy loss reduction by reconfiguration and optimal capacitor placement in the distribution network. The purpose of this paper is to investigate the electric power supply to a distribution network for improved power quality in terms of voltage and power losses using a shunt capacitor placement technique on weak buses or nodes. This approach is targeted specifically at buses with the lowest voltage amplitudes, which serve as suitable points for shunt capacitor placement. By providing an approximate point of capacitor location for distribution network compensation, this has reduced the time spent on capacitor location and sizing.

The remaining part of this paper has been arranged according to the following sections: Section 3 discusses the materials and methods adopted for the simulation and analysis of the distribution system and details the various problem functions. Section 4 explains the heuristic technique algorithm with the steps for shunt capacitor placement. Sections 5 and 6 detail the results obtained from the proposed technique and acquired conclusions respectively.

3. Materials and Methods

The Power System Analysis Toolbox (PSAT) software embedded in MATLAB has been used to analyse the Onuiyi-Nsukka distribution network. Therefore, the materials required in this analysis are the single line diagram of a 30 bus MATLAB model of the Onuiyi-Nsukka distribution network shown in Figure1. The distribution network data which is provided by the Enugu Electricity Distribution Company (EEDC) which is provided in [26]. The collected data is converted to per unit values using the network's base voltage (V_{base}) of 11kV and the base apparent power of 100 MVA.

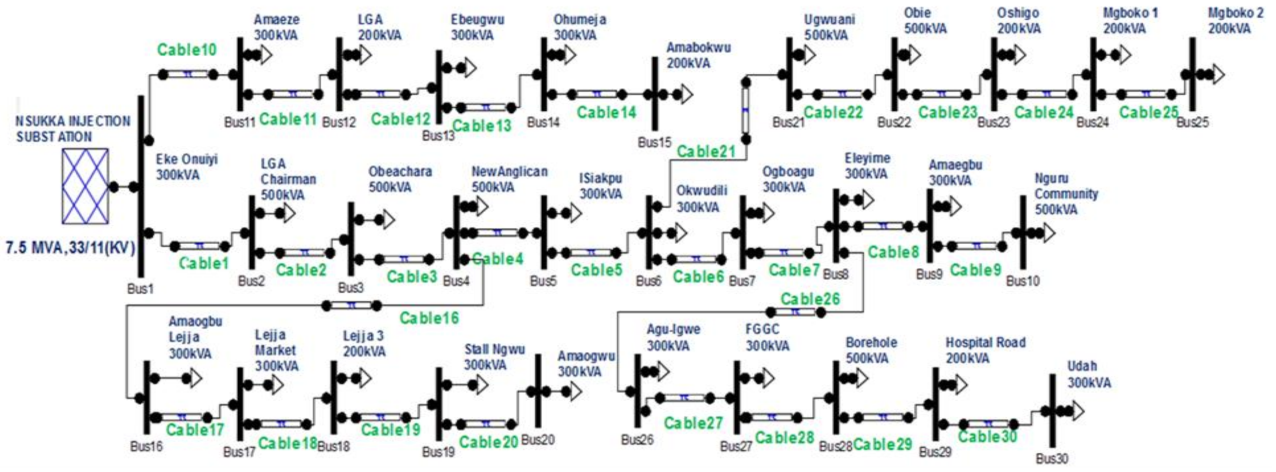

Fig. 1 - Single-line diagram of the 30 bus onuiyi-nsukka distribution network

The load data collected from the distribution network is raw data that must be processed and converted using eq. (1). This is done before it is applied to the PSAT software, which simulates the network for analysis.

$$S_{pu} = \frac{S_{actual}}{S_{base}} = \frac{P_l + jQ_l}{P_{base} + jQ_{base}} \tag{1}$$

where S is the base complex power of the network. $P_l + jQ_l$are the given values for the load buses' real and reactive power. As a result, eq (2) is used to calculate the base line impedance (Z_{base}).

$$Z_{base} = \frac{V_{base}^2}{S_{base}} \tag{2}$$

The per unit value of the impedance is the ratio of the actual impedance value of the line with the determined base impedance as shown in eq (3).

$$Z_{pu} = \frac{Z_{actual}}{Z_{base}} \tag{3}$$

3.1 Power Loss Reduction

It is important to compensate reactive power loss or power consumed by inductive loads connected to the system. The capacitor bank injects reactive power into the system for compensation. The active and reactive power loss in the distribution system, on the other hand, is taken into account in this paper. Figure 2 depict a simple distribution network model. Using the model, we calculated the current at bus i as, as shown in eq (4).

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \tag{4}$$

Where Y_{ij} is the admittance at the nodes, and V_j is the bus voltage. When equation (1) is converted to polar form, the distribution network admittance can be easily multiplied by the polar form current in eq. (3) to calculate voltage drops along distribution lines

$$I_i = \sum_{j=1}^{n} |Y_{ij}||V_j| \angle\theta_{ij} + \delta_j \tag{5}$$

Where θ_{ij} is the voltage angle on the bus and δ_j is the node angle As shown in eq., we compute the complex power S as shown in eq.(3). Eq. (2) is multiplied by the polar form of the voltage to obtain the network's complex power.

$$S = V_i \times I_i = P_i - jQ_i \tag{6}$$

Therefore, we obtained the active and reactive power of the distribution network using eq. (7).

$$P_i - jQ_i = |V_i| \angle - \delta_i \sum_{j=1}^{n} |Y_{ij}||V_j| \angle\theta_{ij} + \delta_j \tag{7}$$

Separating the real and imaginary parts, we can express the equations as

$$P_i = \sum_{j=1}^{n} |V_i||V_j| |Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \tag{8}$$

$$Q_i = -\sum_{j=1}^{n} |V_i||V_j| |Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \tag{9}$$

The power losses at each line becomes

$$P_{Loss(ij)} = |I_{ij}|^2 R_{ij} \tag{10}$$

while the total power loss in the distribution network is

$$P_{TL(ij)} = \sum_{i=1}^{n} |I_{ij}|^2 R_{ij} \tag{11}$$

Therefore, the objective function of the problem formulation becomes

$$f_{min\,P_{TL}} = \sum_{i=1}^{nbr} \left|I_{ij}\right|^2 R_{ij} \tag{12}$$

where $f_{min\,P_{TL}}$ is the first objective function for the system power loss minimization, I_i is the current at line i of distribution network. R_i represents resistance of the line i of distribution network and nbr is number of lines.

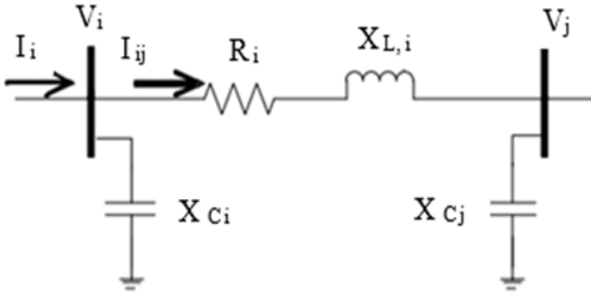

Fig. 2 - A simple distribution system

3.2 Minimization of Voltage Deviation

The sum of voltage deviations from the specified range will be minimized to achieve an improved voltage profile. Eq (13) represents the voltage stability index of $nbus$.

$$f_{min\,V} = \sum_{i=1}^{nbus} abs\left(\frac{(V_{nom} - V_i)}{V_{nom}}\right) \tag{13}$$

where V_{nom} is the nominal system bus voltage, V_i is the i^{th} bus voltage, and $f_{min\,V}$ is the second objective function for voltage profile improvement. Our goal is to keep the voltage profile of all buses within acceptable limits. The voltage constraints presented in [23] are depicted in Equations (14) to (17).

$$P_G = P_D + P_L \tag{14}$$

Where P_G is the active power generated equals P_D the active power demanded by the consumers, and power loss along the lines is P_L. The Inequality Constraints are as follows:

$$P_{gslack}^{\min} \le P_{gslack} \le P_{gslack}^{\max} \tag{15}$$

$$Q_{gi}^{\min} \le Q_g \le Q_{gi}^{\max}\ ,\ i \in N_g \tag{16}$$

$$V_{\min} \le V \le V_{\max}\ ,\ i \in N_g \tag{17}$$

In this paper, we assumed a minimum voltage of V_{min}= 0.95 pu and a maximum voltage of V_{max}= 1.05 pu. The minimum and maximum voltage limits under consideration are based on a 5% tolerance of a given distribution bus operating voltage level. For optimal network performance, the bus minimum and maximum voltage limits should not be exceeded. When the specified voltage limit is exceeded, the system becomes unstable. This results in voltage drops, power loss, and poor network performance. This type of behavior can occur as a result of a fault or when a transformer is loaded above its rated value.

3.3 Annual Cost of Energy Demand Reduction

The improvement of voltage profiles in distribution networks via shunt capacitor placement reduces the high cost of energy. Due to high power loss and a low voltage profile, consumers are overcharged. Costs for power loss compensation include the purchase, installation, and operation of capacitors. Because the location and size of the capacitors are determined independently, the annual cost of energy (CE) function mathematical model is given in [24] and is expressed in eq (18).

$$f_{\min\ CE} = K_P \times \sum_{i=1}^{nbus} P_{Loss} + \alpha \left[\left(C_{inst} \times n \right) + C_{cap} \sum_{i=1}^{n} Q_{CBi} \right] + C_{ope} \times n \tag{18}$$

where $f_{min\,CE}$is the third objective function for calculating the annual cost of energy savings. is the annual cost per unit power loss in dollars per kWh, $Q_{Loss}$is the total reactive power loss, is the depreciation factor applied to the cost of purchasing and installing a capacitor, $C_{inst}$is the cost of installing the capacitor, n is the maximum number of candidate buses for capacitor placement, C_{cap} is the cost of the purchased capacitor, and Q_{Ci} is the size of the shunt capacitor installed on the bus n . C_{ope} is the capacitor's operating cost. Because of the shunt capacitor placement, this has a reactive power injection constraint. The allowable reactive power value of the supplied shunt capacitor should fall within the range shown in eq (19).

$$Q_{CB}^{\min} \leq Q_{CB} \leq Q_{CB}^{\max} \tag{19}$$

Where Q_{CB} is the location of the capacitor bank value, $Q_{CB}^{min}$and Q_{CB}^{max} are the lower and upper capacitor bank value limit to be maintained during placement. The capacitor value range used in this paper is determined by equation (20) and the shunt capacitor sizing approach $150 \leq Q_{CB} \leq 2000Kvar$ is in multiples of 50. Because the calculated shunt capacitor size is a multiple of 50, the shunt capacitor sizing on the two violated buses was calculated specifically using eq (20).

4. Heuristic Technique and Shunt Capacitor Placement

In this paper, the Heuristic technique for shunt capacitor location and sizing in the distribution network is presented. Capacitor sizing and placement are critical for reactive power compensation in order to achieve an improved voltage profile and reduce power loss. Furthermore, shunt capacitor placement increased feeder availability and distribution network loading capacity [25]. Figure 3 shows a flow chart that was created using a procedural heuristic technique and applied to Figure 1 in the PSAT environment to generate the desired load flow report for the distribution network. The proposed technique's procedure is as follows:

Step 1: initialize the bus and line data by computing them into the PSAT model of the network.
Step 2: perform power flow for the base case using Newton Raphson's (NR) technique.
Step 3: compute all the bus voltage amplitudes and losses. Print the load flow report and plot the graphs.
Step 4: select the critically violated bus (bus with the minimum p.u. voltage amplitude) in the network for reactive power compensation through shunt capacitor placement.
Step 5: place a sized shunt capacitor bank at the critically violated bus to improve the power quality.
Step 6: perform power flow again to ensure that voltage magnitude for all buses are within the voltage acceptable limit. If some buses are marginally violated, repeat step 5 by resizing or replacing a suitable sized shunt capacitor at the bus with minimum p.u voltage amplitude until all the bus are within the acceptable limits.
Step 5: finally, place the suitable sized shunt capacitor at the appropriate location for reactive power compensation to achieve improved voltage profile and minimal power loss in the network.

4.1 Shunt Capacitor Placement and Sizing

The governing equation for reactive power compensation as stated in (20) has been applied on the distribution network after power flow studies to determine the size of shunt capacitor that will improve the power quality of the network.

$$Q_C = \frac{P}{pf_1} \times sin\,\varphi_1 - \frac{P}{pf_2} \times sin\,\varphi_2 \tag{20}$$

where;
Q_C = Capacitor size for correction.
P = The total load active power .
pf_1= Existing power factor of the load.
pf_2 = Desired power factor to be used for correction.

$$\varphi_1 = cos^{-1}(pf_1) \tag{21}$$

$$\varphi_2 = cos^{-1}(pf_2) \tag{22}$$

$$Q_C = \frac{P}{pf_1} sin(cos^{-1}(pf_1)) - \frac{p}{pf_2} sin(cos^{-1}(pf_2)) \tag{23}$$

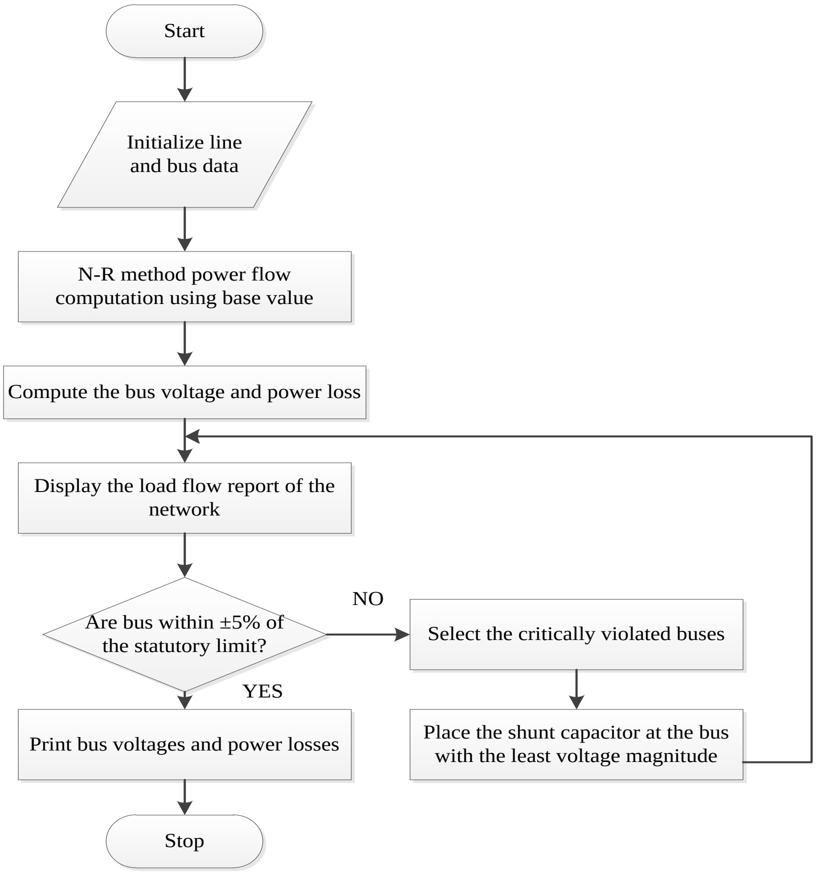

Fig. 3 - Flow chart for the heuristic technique

5. Results and Discussions

The network's base voltage is 11 kV, and its apparent power capacity is 7.5 MVA. It has a combined active and reactive power load of 3.4 MW and 2.0 MVAr. The network's single line diagram of 30 buses was modelled in the Power System Analysis Toolbox (PSAT) within the MATLAB/Simulink software, as shown in Figure 1. To validate the proposed technique, different states of the network were compared. In this paper, two cases were examined.

5.1 Case 1: Existing State (base case) Network Operation

To determine the bus voltage magnitudes and losses, power flow studies were performed on the network depicted in Figure 1. Figure 4 depicts the voltage profile, while Figure 5 depicts the state of the network following load flow. Figure 4 depicts the voltage profile of the Onuiyi-Nsukka distribution network in its current state, without the addition of capacitors. The voltage profile shows that buses 1, 2, and 11 are operating within the statutory voltage limit of 0.95 to 1.05, while the other twenty-seven buses are operating outside of it. Buses 19 and 26 are severely violated due to their low voltage amplitudes of 0.72pu and 0.79pu, respectively, while the remaining 25 buses are only marginally violated. The abnormalities discovered in the violated buses are the result of the transformer being overloaded beyond its load carrying capacity. It was also caused by the frequent faults that occurred along the lines. As a result, shunt capacitor placement is required for compensation to relieve the overloaded buses, improve the voltage profile, and reduce power losses.

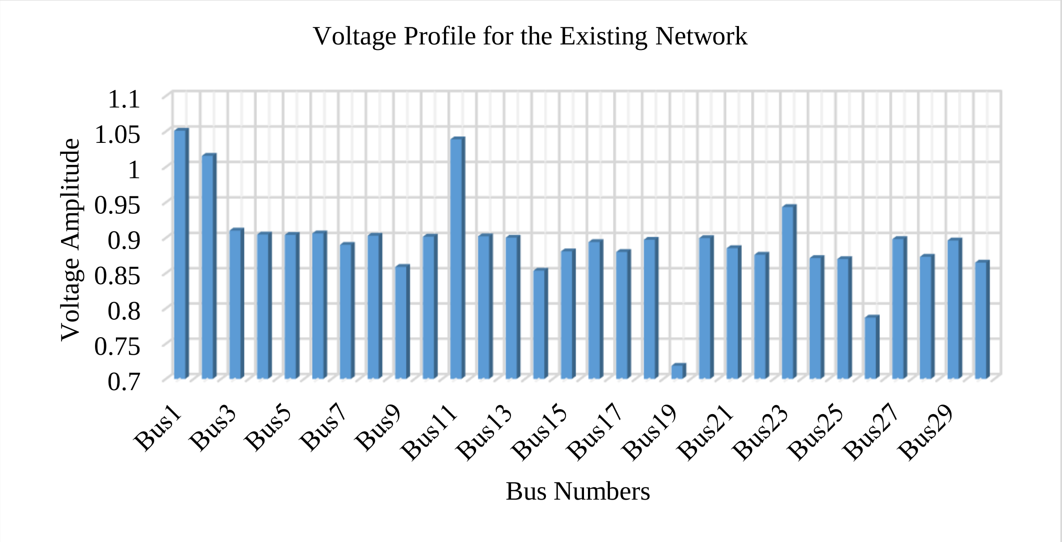

Fig. 4 - Voltage profile of the network without compensation

5.2 Shunt Capacitor Sizing and Placement at Critically Violated Buses

The appropriate size of the shunt capacitor was determined using equation (20) for compensation using the available data as stated below. The capacitor placement at Stall Ngwu and Agu-Igwe Substations (bus 19 and bus 26) was determined using Newton Raphson's power flow technique and sized with the parameters provided.

i. Installed transformer capacity = 300 kVA
ii. Existing power factor pf_1 = 0.77
iii. Desired power factor for correction pf_2 = 0.95 (at this power factor, the network operates at a minimal loss)
iv. Total active power on the load (KW)= 2400 kW

$\varphi_1 = cos^{-1}(0.77) = 39.65^o$

$\varphi_2 = cos^{-1}(0.95) = 18.19^o$

$$Q_C = \left(\frac{2400}{0.77} sin(39.65) - \frac{2400}{0.95} sin(18.19)\right) = 1200 Kvar$$

5.3 Case 2: Sized Shunt Capacitor Application

In PSAT, the heuristic technique is first applied to the considered network, followed by a load flow analysis to determine the amount of losses and the voltage profile. Shunt capacitors with capacities ranging from $50KVAR \leq Q_{CB} \leq 1500KVAR$ are placed on the two buses with the smallest voltage amplitudes. Table 3 displays the capacitor sizes for each bus.

Table 3 - The sized capacitors for each section by PSAT

Bus Name	**Stall Ngwu**	**Agu-Igwe**
Bus number	19	26
Capacitor size (KVAR)	450	750

The 450 KVAr and 750 KVAr capacitors were chosen because their sum equals 1200 KVAr, and they were installed on the network's two buses with the lowest voltage amplitudes (buses 19 and 26), as shown in Figure 6. Because of their high power loss and low voltage magnitudes, these two locations were chosen. When compared to a lump size of 1200 KVAR, the selected capacitor sizes are also cost-effective in application. The compensation enhanced the entire network while keeping bus voltage magnitudes within the statutory voltage limits of p.u. The voltage profile of the existing state of nature before and after compensation was calculated using the results obtained after compensating the distribution network as shown in Figure 6.

Table 4 shows the percentage voltage reduction on each bus, with buses 19 and 26 having improved voltage amplitudes of 1.02 pu. and 1.00 pu, respectively. Where the minimum and maximum percentage voltage magnitudes are 0.95 pu and 1.05 pu.

Table 4 - Voltage magnitudes before and after compensation

Bus No.	**Bus Name**	**Voltage magnitudes (pu) Before and After Compensation**	**Percentage voltage reduction (%)**

				Before and After Compensation	
		Before	**After**	**Before**	**After**
Bus1	Eke Onuiyi	1.05103	1.051031	0%	0%
Bus2	LGA Chairman	1.01559	1.041559	3%	1%
Bus3	Obeachara	0.91026	1.041937	14%	1%
Bus4	New Anglican	0.90473	1.009473	15%	4%
Bus5	Isiakpu	0.90423	1.039942	15%	1%
Bus6	Okwudili	0.90626	0.989255	14%	4%
Bus7	Ogboagu	0.89012	0.999212	16%	4%
Bus8	Eleyime	0.90315	1.031454	15%	2%
Bus9	Amaegbu	0.85886	1.005886	20%	4%
Bus10	Nguru Community	0.90166	1.029866	15%	2%
Bus11	Ameaze	1.03893	1.049736	3%	0%
Bus12	LGA	0.90219	1.029919	15%	2%
Bus13	Ebugwu	0.90027	1.019971	15%	4%
Bus14	Ohumeja	0.85348	1.023483	20%	3%
Bus15	Amabokwu	0.88087	1.019831	17%	4%
Bus16	Amaogbu Lejja	0.89405	1.041405	16%	1%
Bus17	Lejja Market	0.88003	1.028029	17%	2%
Bus18	Lejja 3	0.89733	1.019973	16%	4%
Bus19	Stall Ngwu	0.71869	1.02518	33%	2%
Bus20	Amaogwo	0.89965	1.029996	16%	2%
Bus21	Ugwuani	0.88549	0.988553	16%	4%
Bus22	Obie	0.87611	1.019961	18%	4%
Bus23	Oshigo	0.94345	1.043453	11%	1%
Bus24	Mgboko 1	0.87141	1.048714	18%	0%
Bus25	Mgboko 2	0.86994	1.004987	11%	4%
Bus26	Agu-Igwe	0.78699	1.005087	26%	4%
Bus27	FGGC	0.89829	1.028983	16%	2%
Bus28	BoreHole	0.87325	1.028325	18%	2%
Bus29	Hospital Road	0.89627	1.029963	16%	2%
Bus30	Udah	0.86495	0.998649	20%	4%

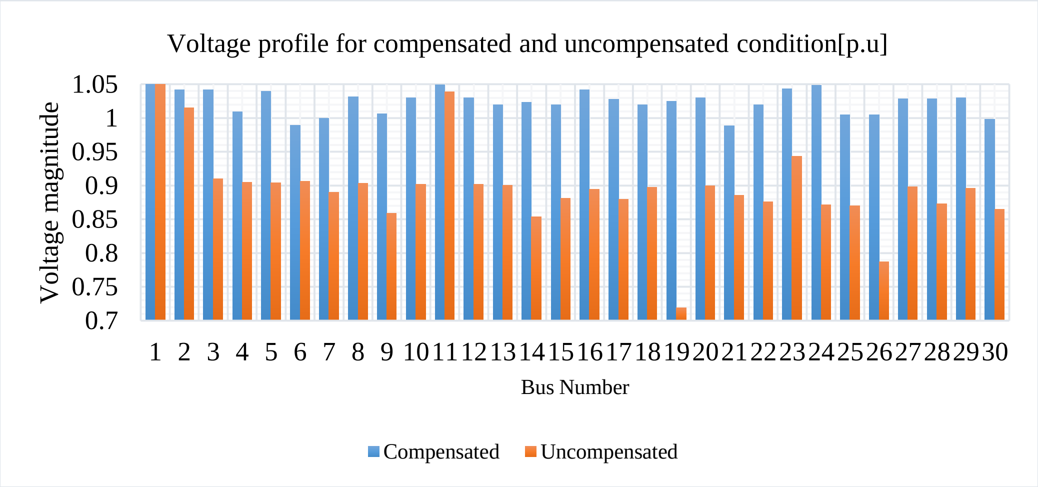

Fig 7 - Voltage profile of the network for the uncompensated and compensated condition

5.4 Heuristic Technique Impact on Power Loss

The network's current state after power flow studies are performed without compensation. There was a total active power loss of 0.27 MW and a reactive power loss of 0.76 MVAr. The network power loss was reduced to 0.12 MW for active power loss and 0.14 MVAr for reactive power loss by installing shunt capacitors on the critically violated buses, i.e. with compensation. This results in a 55.5 percent reduction in real power loss before compensation and an 81.6 percent reduction in reactive power loss after compensation. Figure 8 depicts the results of a comparison of the performance of the shunt capacitor placement technique for power loss reduction. It has been shown that total power flow along the distribution lines for the compensated state of the distribution network was significantly reduced when compared with the uncompensated state (the base case). From Figure 7, we can see that power loss reduction along the lines was achieved with network compensation. This shows a great sign of voltage profile improvement and loss reduction, thereby improving the distribution network's voltage profile.

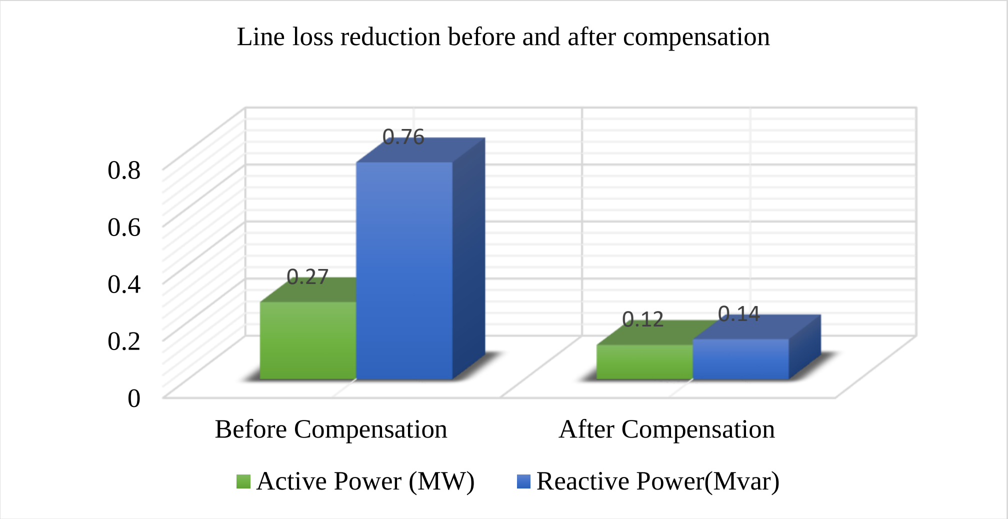

Fig. 8 - Active and reactive power loss

6. Conclusion

In this paper, we determined the power loss from power flow analysis using Newton-Raphson's iterative method on the Onuiyi-Nsukka 11 kV 30 bus distribution network. After that, shunt capacitors were sized using a capacitor sizing equation to determine the actual capacitor size and they were placed appropriately to improve the voltage profile and to minimize losses. Capacitor placement is complex, time-consuming and introduces greater power loss when it is not suitably sized and located in the network. This drawback has been solved with the application of the Newton Raphson power flow technique for capacitor placement. The network's real and reactive power loss was reduced from 0.27MW to 0.12MW and 0.76MVAr to 0.14MVAr respectively. There is an improvement in the voltage profile, cost of energy demand, net energy saving and electricity supply for the case study. This technique also creates awareness of the benefits of an improved voltage profile in a distribution network running along transmission lines to improve electricity generation.

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