Understanding the Capacitor Placement Approach for Power Loss Reduction in Distribution Network

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Abstract - This paper presents a new technique for high power loss minimization in the distribution network. The research scope focussed on the Thinkers Corner distribution network. The types, causes, and techniques for loss reduction in distribution networks were presented. The heuristic technique for high power loss minimization is adopted in our research due to its relatively high efficiency in loss reduction over other methods. This technique indicates the sizes and actual location of the capacitors to be placed at the network with less computational time. The Newton Raphson's technique for Load flow studies was used in modeling the distribution network as a single line diagram in MATLAB software environment. The load variation, cost of installation of the capacitor as well as the economic power factor to achieve maximum energy savings were considered. The heuristic technique is applied to 30 bus, 11kV, 15MVA distribution networks having an initial power factor rating of 0.85. From the analysis, it's shown that power losses are minimized from 0.556 MW to 0.277 MW on the application of maximum capacitor rating of 1200 (750 + 450) kVAR at a power factor of 0.96.

Keywords - active power, compensation, distribution network, MATLAB, power flow

I. INTRODUCTION

The electrical distribution network consists of electrical light energy, power from the generation point to the utilities. A distribution network is divided into two parts: the primary distribution network which connects the generating station or substation with the distribution transformer and the secondary distribution network which extends from the distribution transformer to the point of utilization. A distribution network can be either overhead or underground configuration. The overhead configuration is used by Enugu distribution network and this offer the following advantages:

a. It doesn't cost much for the implementation
b. When a fault occurs, it is easier to detect and repair.

The bare and insulated conductors are used in the design of an overhead distribution network. The insulated conductors are used as service cables, on poles and houses to prevent short-circuiting of the conductors when they come in contact with any metal[1]. Enugu Electricity Distribution Company supplies electricity to the Thinkers Corner distribution line. It receives its energy from Onitsha at 330 kV. The voltage level is stepped down to 132 kV in Onitsha and transmitted from Onitsha to New-Haven transmission station. The New-Haven transmission voltage is stepped down to 33 kV and transmitted to various injection substations which include; Thinkers Corner, 9th Mile, Emene Industrial Layout, Ituku-Ozara, and Kingsway Independent Layout. At these stations, the 33 kV is further stepped down to 11 kV and it is distributed to various places in Enugu which include 11 kV Thinkers Corner. Thinkers Corner distribution line where we focus on the minimization of high power losses occurring on the lines. An electrical grid is a network with the sole function of delivering electricity from the point of generation to the end-users(consumers). It comprises of the generating stations, transmission stations, and distribution stations. Transmission stations transmit electricity through transmission lines from power plants to demand centers while distribution lines connect individual consumers. In this paper, we focus on the distribution lines (network) to achieve a sustainable electricity supply to consumers through power loss minimization with capacitor placement

A) The Distribution Network

The distribution network is generally of radial configuration. This is referred to as a Radial Distribution Network[2]. The consumers are supplied with the distribution network of 11 kV lines or feeders downstream of 33 kV substations. The 11 kV lines emanate from the 33 kV substations branches further into several 11 kV lines that supply the load centers at various load points. At this load point, a transformer steps down the 11 kV to 415 V. This provides a connection through 415 feeders as known as Low Tension(LT) lines to various customers in Enugu at 240 V voltage level for single-phase connection but as 415 V voltage level for a three-phase connection.

B) Elements of The Distribution Network

The distribution network is derived from the electrical system which supplies electrical energy to the consumers. Hence, there a is need for distribution of electrical power at a sustainable voltage magnitude to the consumers. One-line diagram for a typical low tension (LT) distribution network is shown in Fig.1. It generally consists of feeders, circuit breakers, and the service mains. Electricity distribution involves primary and secondary voltage transformation into high, medium and low voltage levels using appropriate transformation equipment [3].

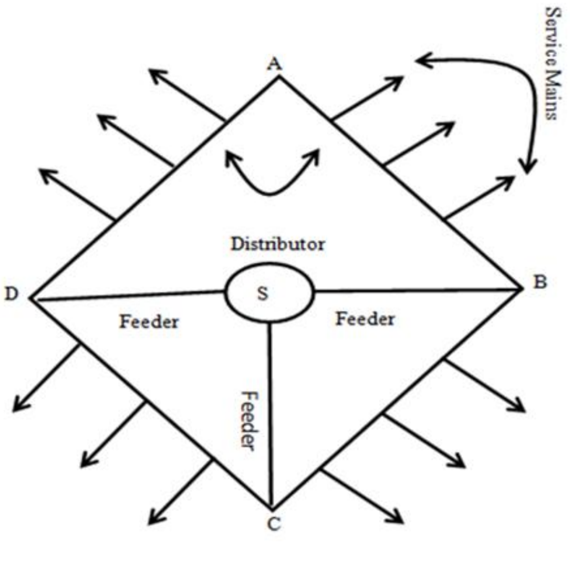

Fig. 1. Single line diagram of a typical LT distribution network.

1. Primary Distribution Network (PDN)

Primary distribution network is a section of the electricity supply chain between the substations and distribution transformers. This distribution network is design to supply 11 kV and the 33 kV voltages through the primary and sub-primary substations. The substations are linked with the high voltage transmission lines and the lines also supply electricity to large energy consumption consumers like cement manufacturing industries, refineries, flour mills, and breweries.

2. Secondary Distribution Network

The secondary circuits, step-down distribution transformers, the consumer energy consumption meters, and consumer services are regarded as secondary distribution network. When the secondary distribution network serves industrial or commercial customers, they are configured as three-phase while serving residential customers they are single-phase[4].

This networks are low voltage feeders emanating from secondary transformers located on main roads and streets. The consumers feeder lines comes from this network and terminates at consumers load points. There are different alternating current (AC) distribution configurations for residential consumers. They include:

a. Single phase(2-wires) configuration

b. Single phase (3-wires) configuration

c. Three phase(3-wires) configuration

d. Three phase (four wires) configuration

In all the configurations, single phase (2-wires) and the three phase (four-wires) configurations can be seen in Nigeria distribution networks.

The 11kV Thinkers Corner distribution network uses this same configuration for electricity supply to the consumers.

Distribution networks are fed by a set of voltage reduction and protection devices named “substation”. The essence of substation is to reduce high voltage of transmission lines to supply customers connected at the distribution network [5].

II. DISTRIBUTION NETWORK LOSSES

Due to an increased rate of electricity demand which causes an increase in the power supply. The distribution network has experienced high power loss due to power distribution [6]. When current flows through a conductor it encounters resistance in the direction of flow of current thereby producing heat that is dissipated to the surroundings. This type of loss is termed ohmic loss. This is also known as line loss in the distribution network which occurs as a result of resistance of conductors against current flow [7].

The types of losses that occurs in a distribution network are divided into technical and commercial losses.

A) Causes of Technical Losses on Distribution Network

Since the power losses on distribution system are considered to be entirely due to copper losses, it can be calculated using equation 1[8].

$$P_L = I^2 R \tag{1}$$

Thinkers Corner Enugu has experienced several losses which are mostly technical. Technical losses occur due to overloaded transformers, undersized conductors, low system voltages and low system power factor.

Voltages in the Enugu distribution network are generally low due to general system overloading [9]. These low voltages contributes to high power loss in the network. Mathematically, low voltages can lead to power loss as follows;

Power factor is given as;

$$\cos\theta = \frac{kW}{kVA} \tag{2}$$

where kVA is the rated or complex power of the substation. kW the real or active power. For three-phase (3ϕ) supply,

$$I_L = \frac{1000\,kVA}{\sqrt{3}V_L} \tag{3}$$

where V_L is the distribution line voltage.

I_L is the distribution line current.

B) Methods of Loss Minimization

Electricity utilities spend huge amounts of money due to losses occurring in the distribution network hence the need for its minimization. During electrification of an area, designing and installation of electrical components, the following methods should be adopted by the electrical engineers to minimize high power loss to the barest minimum.

i. Siting of substations should be carefully selected to minimize the length of distribution lines.
ii. Appropriate high voltages that are practicable for lines should be used to limit the line currents and transformer windings [9, 10].
iii. The use of bundled conductors with high resistivity especially copper cables.

At this distribution network which is an already existing distribution network. The following rules should be applicable for an optimum high power loss minimization [11].

i. Replacement of already existing conductors with larger ones.
ii. Reconfiguration of switches by changing the method of supply to the loads.
iii. Strategic means of shunt capacitor bank placement in the network.
iv. System load alteration to reduce the huge effect of copper losses on the delivery network components.

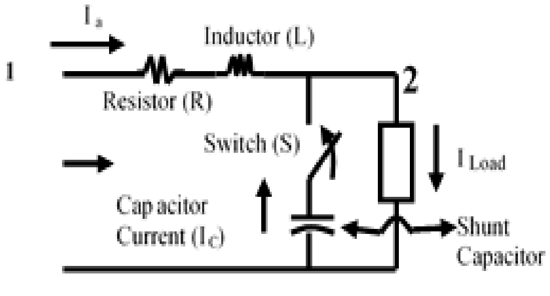

Fig. 2. Capacitive power loss minimization

Power loss reduction with shunt capacitor placement is shown in Fig. 2. When there is no incorporation of capacitor in the circuit, it is known as the off state or when the switch, S is open. In this state, the amount of current flow in the line I_a is equal to the current flow through the load current I_{Load}. Based on the existing power factor, line current I_a contains both the real and imaginary parts. Therefore, the magnitude of current contributes to real power losses in the line. When there is an addition of capacitor, it is called the ON state or when the switch, S is closed. The capacitor injects reactive power (kvar) into the line. The number of kvar injected introduced purely imaginary current, hence, caused a reduction in the amount of components of imaginary current flow in the lines. The decrease in the components of the imaginary current also introduced the Reduction in the magnitude of current flow, Reduced voltage drop, it improves the power factor by reducing the phase angle between the voltage and current and it Reduces the I^2R power losses in the distribution line.

III. MATERIALS AND METHODS

The materials and methods adopted in this research include:

a. The 11 kV feeder at Thinkers Corner injection substation which carries an average load of 3,709.2 kW and 2,298.8 kvar distributed over 30 load points.

b. The feeder load and bus data collected from the Enugu Electricity Distribution Company (EEDC).

c. Power System Analysis Toolbox(PSAT) software embedded in MATLAB software

d. Newton Raphson's load flow studies technique

A) Heuristic Technique

In this paper, the heuristic technique is used. This is a technique in which the buses whose voltage levels fall above or below the permissible limits(i.e $\pm 5\%$) are improved by the installation of capacitor banks to the most sensitive nodes. The Power System Analysis Toolbox (PSAT) is an embedded MATLAB software used for load flow studies. The flow chart for the heuristic technique is shown in Fig. 3. Compensation is applied to the critical buses to achieve an improved distribution network with minimal power losses.

The Fig. 4 shows the single line diagram of 11kV Thinker's Corner Injection Substation distribution feeder understudy with four lateral branches. The substation line voltage is 11KV. The bus and line data are shown in Table 1 and Table 2.

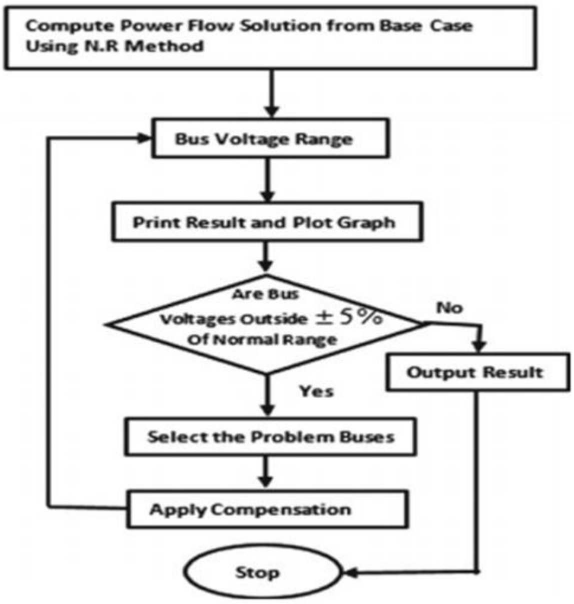

Fig. 3. Flow chart for heuristic technique using shunt capacitor placement approach [12].

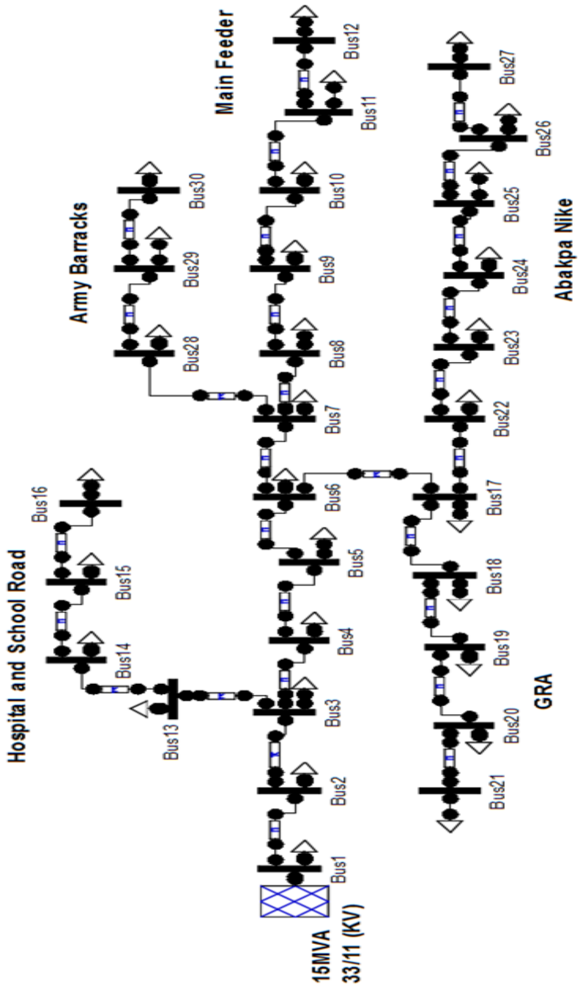

Fig. 4. Single Line Diagram Showing the Thinker's Corner Distribution Network without Capacitor Placement.

A) Per Unit Calculation

All the data collected from the Enugu Electricity Distribution Company (EEDC) were converted to their various per unit values. In this paper, calculations were done using the apparent power value $S_B = 100MVA$, phase voltage value $V_B = 11kV$ and the base impedance $Z_b = V_b^2 / S_b$ .The distribution network considered has an installed capacity of $15MVA$ with an average power factor of 0.85.

Table 1. Bus Data

Bus No.	**Load**	
	P (kW)	**Q (kvar)**
1	0	0
2	230	142.5
3	0	0
4	230	142.5
5	230	142.5
6	0	0
7	0	0
8	230	142.5
9	230	142.5
10	57	34.5
11	230	142.5
12	72	45
13	230	142.5
14	72	45
15	72	45
16	13.5	7.5
17	230	142.5
18	230	142.5
19	230	142.5
20	72	45
21	230	142.5
22	137	85
23	230	142.5
24	230	142.5
26	230	142.5
27	137	85
28	75	48
29	75	48
30	57	34.5

Table 2. Line Data

Lines	**Resistance**	**Reactance**	**Length** (km)	**Impedance**
	$R(\Omega/km)$	$X(\Omega/km)$		$R + j\,X\,(\Omega)$
1 - 2	0.1950	0.0800	0.6002	0.117+ j0.048
2 - 3	0.1951	0.0810	0.6001	0.117+ j0.044
3 - 4	0.2990	0.0831	0.5501	0.162+ j0.045
4 - 5	0.2991	0.0831	0.5011	0.149+ j0.042
5 - 6	0.5420	0.0901	0.5021	0.149+ j0.042
6 - 7	0.5421	0.0901	0.6012	0.314+j 0.054
7 - 8	0.5420	0.0910	0.4011	0.201+ j0.036
8 - 9	0.5422	0.0901	0.6012	0.101+ j0.018
9 - 10	0.5421	0.0900	0.4012	0.157+ j0.027
10 - 11	0.5420	0.0901	0.2501	0.209+ j0.036
11 - 12	0.5421	0.0901	0.2012	0.105+ j0.018
12 - 13	0.5420	0.0901	0.3002	0.157+ j0.027
13 - 14	0.5422	0.0902	0.4012	0.209+ j0.036
14 - 15	0.5420	0.0900	0.2000	0.105+ j0.018
15 - 16	0.5421	0.0900	0.1000	0.052+ j0.009
6 - 17	0.2990	0.0832	0.6001	0.178+ j0.049
17 - 18	0.2990	0.0832	0.5502	0.164+ j0.046
18 - 19	0.3782	0.0861	0.5501	0.201+ j0.047
19 - 20	0.3781	0.0861	0.5010	0.181+ 0.043
20 - 21	0.3782	0.0862	0.5010	0.189+ j0.043
21 - 22	0.5424	0.0902	0.5000	0.262 + j0.045
22 - 23	0.5424	0.0901	0.5000	0.262+ j0.045
23 - 24	0.5424	0.0900	0.6010	0.314+ j0.054
24 - 25	0.5423	0.0900	0.4000	0.209+ j0.036
25 - 26	0.5421	0.0900	0.2500	0.131+ j0.023
26 - 27	0.5420	0.0910	0.2000	0.102+ j0.018
7 - 28	0.5422	0.0910	0.3002	0.157+ j0.027
28 - 29	0.5424	0.0921	0.3021	0.157+ j0.027
29 - 30	0.5424	0.0920	0.3022	0.157+ j0.027

[Source : EEDC Thinker's Corner injection bubstation]

IV. RESULTS AND DISCUSSIONS

The outcome of the analysis done was shown in Fig. 7 to 9. It describes the varying behaviours of the distribution network showing the existing state and its improved state before and after compensation using heuristic technique for capacitor placement.

The voltage profile in Fig.5 shows the existing state of 11 kV Thinkers' Corner distribution network. This distribution network as simulated in the Power System Analysis Toolbox (PSAT) embedded in a MATLAB software is shown as a 30 bus single line diagram.

The result shows voltage violations(voltage magnitudes outside 0.95-1.05 p.u. range) in 29 buses. Two buses (bus 11 and 26) were critically violated. Because of the voltage drops and high amount of losses recorded on the network, capacitor banks were integrated optimally using the flow chart in Fig. 3 at bus 11 and 26 where the voltage violations are critical. This injects reactive power in the buses (substations) and also improves the power factor from 0.85 to 0.96 thereby improving the entire distribution network having all the voltage magnitudes within the normal range of (1.00 ± 5%) p.u.

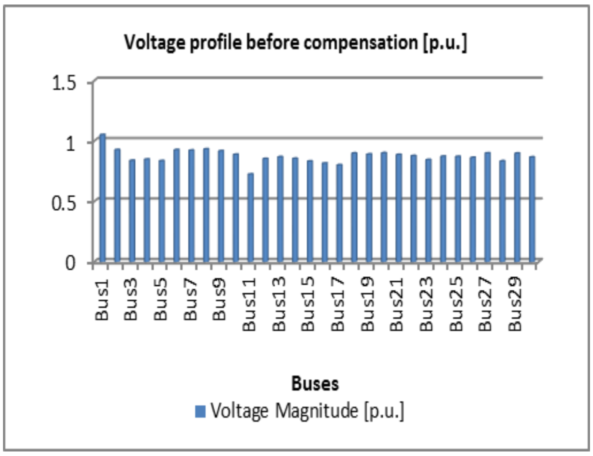

Fig. 5. Bus voltage level profile without capacitor bank integration.

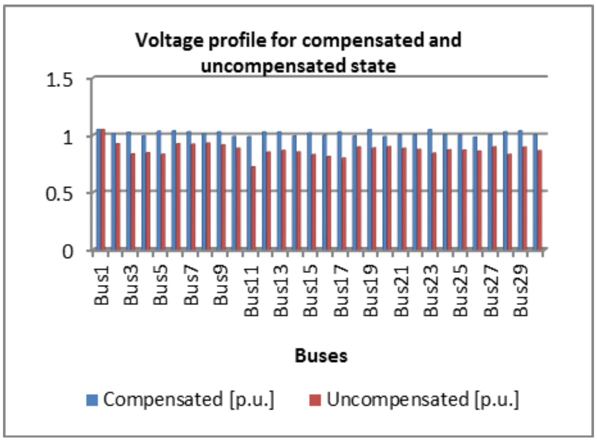

Fig. 6. Bus voltage level profile with capacitor bank integration.

A comparative check was made between the network's existing state(i.e uncompensated state) with an improved condition on the network(i.e compensated state) as presented in Table 3. and it's graphically shown in Fig. 6. The result shows an improved voltage profile with minimal losses on the network.

Table 3. Voltage Magnitude on the existing state and improved state on the distribution network.

Buses	**Bus voltage magnitudes** $(p.u)$	
	Without compensation	**With compensation**
Bus1	1.05	1.05
Bus2	0.855907	1.026591
Bus3	0.837026	1.026303
Bus4	0.794733	1.016473
Bus5	0.834226	1.026342
Bus6	0.825539	1.046255
Bus7	0.821199	0.989985
Bus8	0.731454	1.031454
Bus9	0.805886	1.005886
Bus10	0.886571	1.029866
Bus11	0.637362	1.029736
Bus12	0.851932	1.039519
Bus13	0.867098	1.049671
Bus14	0.853483	1.018535
Bus15	0.830865	0.990865
Bus16	0.814048	0.998405
Bus17	0.843029	1.028996
Bus18	0.797328	1.027973
Bus19	0.798694	1.027187
Bus20	0.899647	1.016996
Bus21	0.885487	1.026855
Bus22	0.876099	1.016761
Bus23	0.843453	1.029435
Bus 24	0.871407	1.026714
Bus25	0.869935	0.986994
Bus26	0.676993	1.048699
Bus27	0.798294	1.017983
Bus28	0.932543	0.993254
Bus29	0.896271	1.006963
Bus30	0.864949	0.989495

It has been shown in Fig.7 a reduction in the voltage phase angles by comparing the existing state with an improved state of the network.

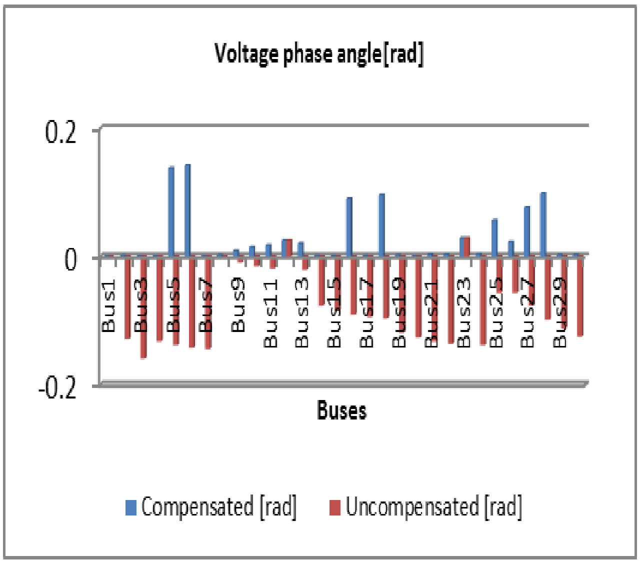

Fig.7. Bus voltage phase angles before and after compensation.

The distribution network recorded a great reduction in line losses with shunt capacitor placements as shown in Fig.8. The high power losses were minimized from 0.556MW to 0.277MW on the application of maximum capacitor rating of 1200 (750 + 450) kVAR at a power factor of 0.96.

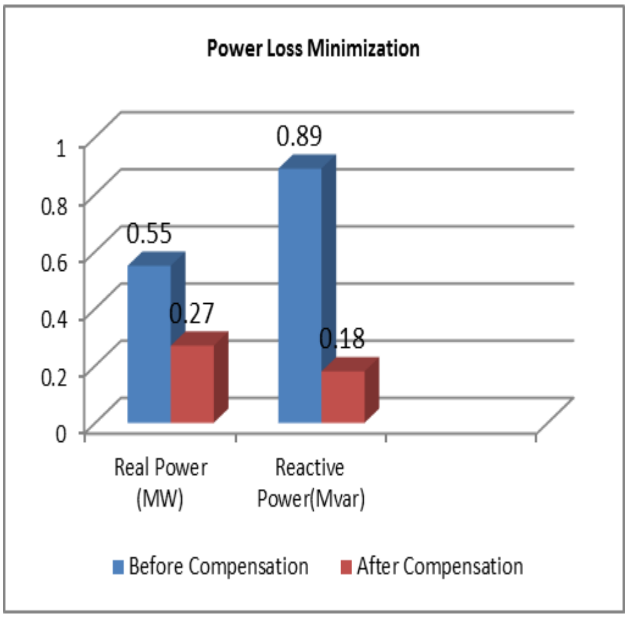

Fig. 8. Power loss minimization on the distribution network before and after compensation.

V. CONCLUSION

This paper presents a vital technique for the minimization of high power losses encountered on a distribution network. These loses arises from the flow of reactive power in the network and it can be minimized by optimal capacitor bank placement or allocation at the critical nodes. This method has been applied to a 3-phase, 11KV 50Hz Thinkers corner distribution network here in Enugu state, Nigeria. The results from the analysis done shows an improved performance of the network by achieving a considerable high power loss reduction and improved voltage profile. The heuristic technique is used to achieve optimal allocation of capacitors on the network. This is achieved by examining the solution set of the most critical buses termed sensitive nodes on the network. It is at these critical buses that a sizeable capacitor banks are placed or installed for compensation in order to achieve high power loss reduction in Enugu distribution network.

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