NIPES
Journal of Science and Technology Research
Journal homepage: www.nipesjournals.org.ng

Distribution System Enhancement Using Optimal Capacitor Placements

F. O. Agbontaen[1,a] and N.S. Idiagi[2,b]

[1,2] Department of Electrical/Electronic Engineering, University of Benin, Benin City, Nigeria
[a]osazee.agbontaen@uniben.edu, [b]neville.idiagi@uniben.edu

Article Info

Received 11 June 2021
Revised 03 July 2021
Accepted 06 July 2021
Available online 31 August 2021

***Keywords*:**
Capacitor banks, Newton-Raphson, ETAP, Loss Sensitivity Analysis, Voltage profile, Optimal Capacitor Placement (OCP), Compensation.

https://doi.org/10.37933/nipes/3.3.2021.5

https://nipesjournals.org.ng

Abstract

Nigeria is experiencing serious challenges in its power sector. From inadequate generation capacity to weak transmission and distribution systems characterized by a huge amount of line losses and poor voltage profile, it seems the nation still has a long way to go. Efforts should be put in place by relevant authorities to improve the power sector. With the distribution network being the closest to the final consumer, efforts should be made to make it more efficient. This study therefore aims at improving the performance of poor distribution network using capacitors optimally placed and sized in the network. The Iyowa community 11/0.415 kV distribution network in Ovia North-East Local Government Area in Edo State, Nigeria was used as a case study. Relevant data collected from Benin Electricity Distribution Company (BEDC) was used to carry out load flow study on the network using Newton-Raphson iteration technique in ETAP 16.0 environment to ascertain the overall performance of the network under base loading condition. The Loss Sensitivity Analysis was used to determine the candidate buses for optimal capacitor banks placements while the Optimal Capacitor Placement (OCP) tool in ETAP 16.0 software was used to size the capacitor banks. Load flow analysis was then repeated on the enhanced network. It was observed that of the 18 buses in the original (uncompensated) network, only the Ora load bus with a voltage magnitude of 95% fell within the statutory voltage limit. When the compensation was done, the voltage profile of the network improved considerably. Only the goldland and Iyowa load buses with 93.76% and 93.89% voltage magnitudes respectively, violated the statutory voltage limit. The network obviously needs adequate compensation for a better overall performance

1.0 Introduction

Nigeria, as a developing country is faced with series of challenges economically and otherwise. The standard of living is relatively poor. These challenges can be attributed to factors like corruption, bad leadership, greed etc but a major factor that should not be neglected is the poor state of the country's power sector. This sector is very important in determining the viability of the nation's economy. A nation's Gross Domestic Product (GDP) is a reflection of its load growth rate. This can be confirmed from the fact that the United States of America consumes over 1bn megawatts of electricity as against less than five thousand megawatts in Nigeria. Thus, the electricity supply industry has to be fixed so as to be able to tackle the economic growth issues in Nigeria [1].
A country's power system is made up of the generation, transmission and distribution systems and Nigeria as a country has challenges in each of these sectors. Grappled with the problem of

insufficient generation, Nigeria also has about 40% transmission and distribution losses [2] and this is quite alarming. The distribution sector is a very weak link, with its associated losses, and it is in need of serious attention because it is the sector which has direct interaction with the consumers. The system losses lead to increased operating cost of electric utilities, leading to an increase in the cost of electricity. There is therefore an urgent need to minimize these losses as it is of great importance financially, economically and socio-economically to the utility company, the consumers and the nation at large [2]. Nigeria has been characterized by irregular power supply [2] with most homes experiencing an average of about 6 hours of electricity supply in a day [3]. The efficiency of a nation's power supply is a reflection of the number of outages experienced in the nation just as the high level of outages experienced by consumers is an expression of their dissatisfaction with the electricity service [4,5,6]. According to researchers, some of the major causes of power outages are obsolete power stations, weak grids, overloaded equipment, lack of or poor compensating devices in the system, weather factors and presence of trees, problem of vandals, insufficient maintenance, etc. [7,8,9,10]. If most of these factors listed are rectified, the problem of erratic power supply in Nigeria will be greatly reduced.
This study is aimed at improving the voltage profile and overall performance of a Nigerian 11/0.415 kV distribution network with the use of capacitor banks properly sized and optimally placed in the network.

1.1. Optimal Capacitor Placement for Power System Enhancement

The optimal capacitor placement is one of the most effective ways of reducing the losses in a distribution network as the capacitors carry out reactive power compensation in the network [11]. The method is quite cheap and simple as compared with some other sophisticated enhancement techniques. It involves determining the candidate buses where the capacitor banks need to be placed and then sizing the capacitors appropriately.
Capacitor placement problem involves techniques to determine the size, location and the number of capacitors to be placed in the network. The objectives of the problem are system losses reduction and overall voltage profile improvement so it will fall within the acceptable limit [11]. Researchers have implemented various techniques for optimal capacitor placement problems. [12] made use of the Integer programming method while [13,14] implemented the non-linear programming method. The sensitivity analysis method was used by [15,16] while [17] used the equal area criterion for selecting where fixed capacitors are to be placed. In [18], loss sensitivity factor was used to optimally determine capacitor positions while Particle Swarm Optimization technique was used to determine the optimal sizes of the capacitors. In [11] a comparison of the index vector method and the loss sensitivity approach for the optimal location of capacitors in a network was made. It was observed from the research that the loss sensitivity method was more effective.
In this study, the loss sensitivity analysis will be used to determine the optimal location of the capacitors while the Optimal Capacitor Placement (OCP) tool in ETAP 16.0 (using adaptive Newton-Raphson technique) will be used in determining the optimal sizes of the capacitors.

1.2. Loss Sensitivity Analysis

Loss sensitivity analysis is used to calculate the factor for determining the candidate nodes where enhancement devices will be placed in a network. This helps to reduce the search space [11].
The active power loss in a distribution network can be determined using Equation (1);

$$P_{linelos}(q) = \frac{[P_{eff}(q)^2 + Q_{eff}(q)^2]R_k}{V_q^2} \quad (1)$$

Where $P_{eff}\,(q)$ and $Q_{eff}\,(q)$ are the effective active and reactive power flows supplied beyond the node 'q'

$$\frac{\partial P_{linelos}(q)}{\partial\, P_{eff}\,(q)} = \frac{2^{*}P_{eff}\,(q)^{*}R_k}{V_q^2} \tag{2}$$

$$\frac{\partial P_{linelos}(q)}{\partial\, Q_{eff}\,(q)} = \frac{2^{*}Q_{eff}\,(q)\,^{*}R_k}{V_q^2} \quad [11] \tag{3}$$

Equations (2) and (3) are used to determine the sensitivity factors of the buses and they are ranked in value. The buses having high value of LSF is considered as highest priority one. It is necessary to consider LSF based on both priority and proximity of buses towards load and generation. This is due to the fact that if we consider LSF based on priority list alone, it may indicate nearby buses as optimal site for placing DGs which makes the identified sites ineffective to satisfy the objectives [19].

The actual loss formula used in determining the active power loss of the system can be obtained from the active power injected based on loss sensitivity factor

$$P_L = \sum_{i=1}^{N}\sum_{i=j}^{N} \alpha_{ij}\left(P_iP_j + Q_iQ_j\right) + \beta_{ij}\left(Q_iP_j - P_iQ_j\right) \tag{4}$$

Where,

$$\alpha_{ij} = \frac{r_{ij}}{V_iV_j}\cos\left(\delta_i - \delta_j\right);\ \beta_{ij} = \frac{r_{ij}}{V_iV_j}\sin\left(\delta_i - \delta_j\right) \tag{5}$$

Based on the active power injected on the $i\ th$ bus, the loss sensitivity factor of the particular bus can be represented as:

$$\alpha_{ij} = \frac{\partial P_L}{\partial P_i} = 2\sum_{j=1}^{N}(\,\alpha_{ij}P_j - \beta_{ij}Q_j) = \frac{2QR}{V^2} \tag{6}$$

2.0 Methodology

The study was carried out in Iyowa Community, Ovia North-East Local Government Atea, Edo State, Nigeria. The distribution network has 18 buses, each bus corresponding to the low voltage sides of the various 11/0.415 kV distribution transformers. Field data was used for this study and it was collected from Benin Electric Distribution Company, Edo State, Nigeria. Data collected include the network diagram, transformer ratings, the line parameters like impedance, route distances from one transformer to the other, load on each of the transformers, cables types and diameters etc. The collected data were from the low voltage side of the various 11/0.415 kV transformers. The network was modeled in the ETAP 16.0 environment as shown in Figure 1. The load flow analysis was done using Newton-Raphson iteration technique as shown in Figure 2 with the deficient buses appearing in red. The simulation was carried out under base bus loading condition. The overall performance of the network was noted with parameters like the bus voltages, percentage loading, etc. being taken into consideration. The loss sensitivity analysis was then used to optimally locate the capacitor banks in the deficient buses in the network while the OCP tool in ETAP 16.0 environment (using adaptive Newton-Raphson) was used to optimally size the capacitor banks after the candidate buses for enhancement were determined. The simulation procedure was then repeated for the enhanced network as shown in Figure 3 and the performance of the enhanced network was then compared to that of the original network.

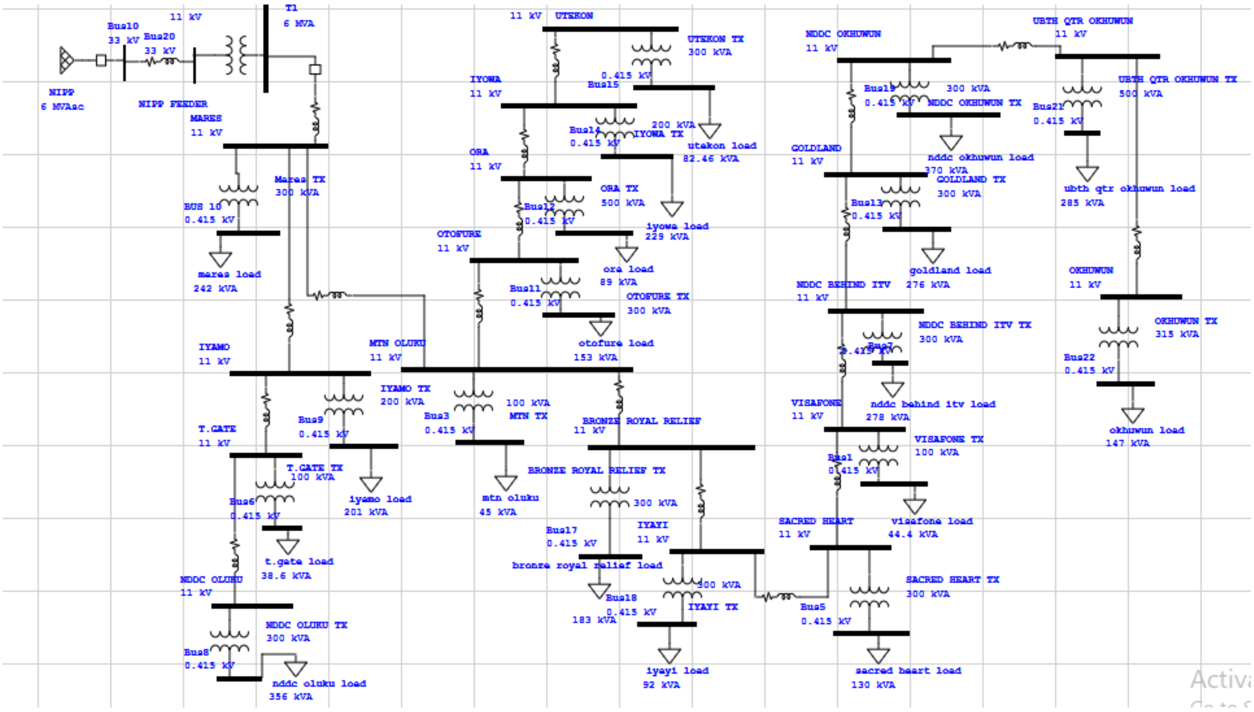

Figure 1: Iyowa 11/0.415 kV Distribution Network Diagram on Edit Mode

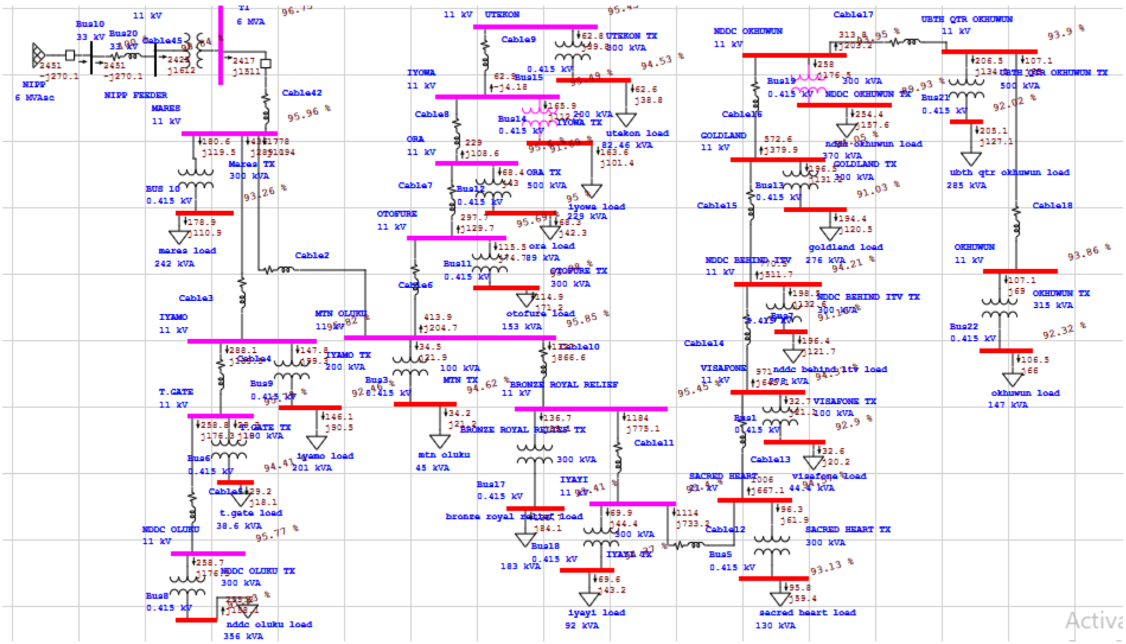

Figure 2: Load Flow Diagram of Iyowa 11/0.415 kV Distribution Network

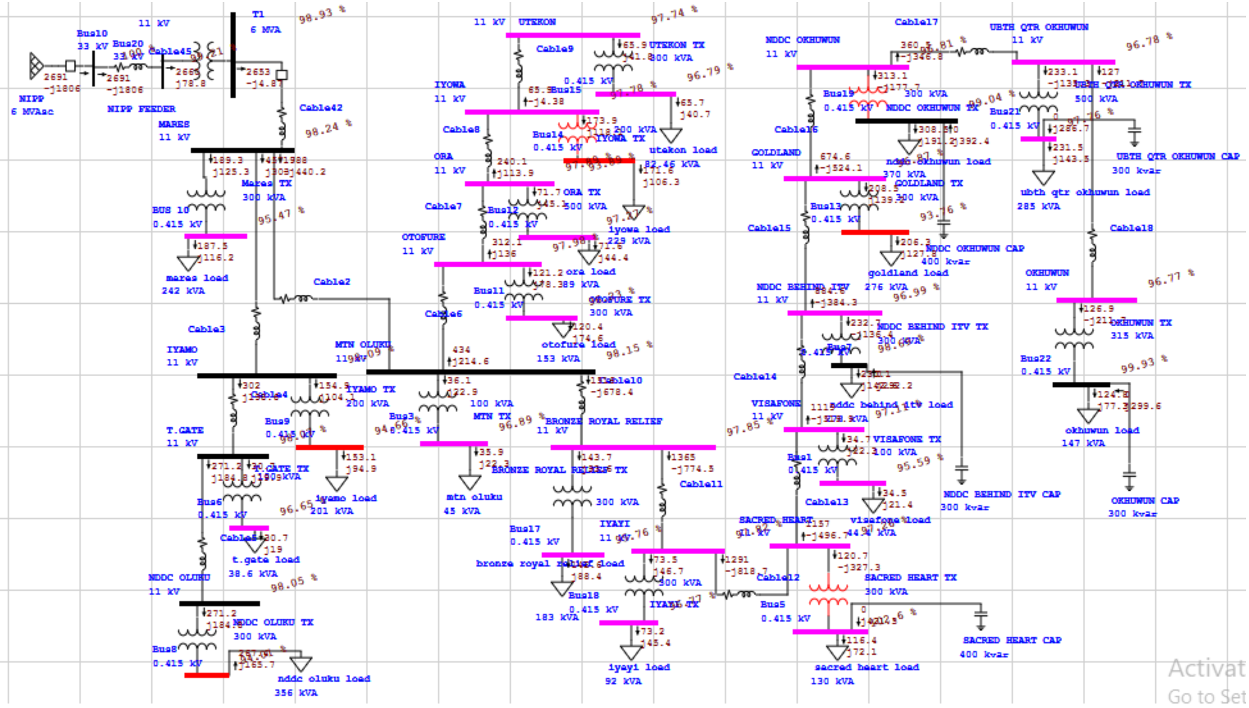

Figure 3: Load Flow Diagram of the Enhanced Iyowa 11/0.415 kV Distribution Network

3.0 Results and Discussion

Load flow analysis was carried out using Newton-Raphson iteration technique in ETAP 16.0 environment for both the original and the enhanced networks. Table 1 shows the results obtained from the analysis of the original network. A close look at Table 1 shows that only Ola load bus out of the 18 buses didn't violate the voltage limit which is within the range of 95% to 105% of the rated voltage as available in literature. Utekon and MTN load buses were close to the statutory limit with 94.53% and 94.62% voltages respectively. It therefore infers that the network seriously needs enhancement as it is very weak. When loss sensitivity analysis was carried out on the network, 8 candidate buses met the criteria for capacitor placement with toll gate load and Okhuwun load buses having the highest and lowest LSF of 0.009018073 and 0.147757075 respectively as shown in Table 2. Table 3 shows the outcome of the OCP analysis with the number and sizes of the capacitor banks clearly shown. 13 capacitor banks were strategically placed in five buses as shown in Table 3. It has been shown from available literature that due to the expensive nature of these compensation devices, it is advisable to make use of appropriate optimization techniques so as to optimally determine the number and size of the devices to be utilized. Of the eight (8) candidate buses determined by LSF (out of a total of 18 buses in the network), only five (5) were chosen for the capacitor banks placement. This is the essence of the optimization techniques. Load flow analysis was then repeated for the enhanced network. The result of the load flow analysis on the enhanced network is shown in Table 4. It can be observed from the table that the overall voltage profile of the network improved considerably with only the goldland and Iyowa load buses violating the statutory voltage limits.

Table 1: Load Flow Results for Base Bus Loading Condition of the Original Network

s/n	ID	Rating/Limit	Rated kV	kW	kvar	Amp	Voltage (%)
1	nddc okhuwun load	370 kVA	0.415	254.4	157.6	462.9	89.93
2	goldland load	276 kVA	0.415	194.4	120.5	349.5	91.03
3	nddc behind itv load	278 kVA	0.415	196.4	121.7	352.6	91.16
4	iyowa load	229 kVA	0.415	163.6	101.4	292.1	91.69
5	nddc oluku load	356 kVA	0.415	255.2	158.1	454.8	91.83

6	ubth qtr okhuwun load	285 kVA	0.415	205.1	127.1	364.9	92.02
7	okhuwun load	147 kVA	0.415	106.5	66	188.8	92.32
8	iyamo load	201 kVA	0.415	146.1	90.52	258.6	92.46
9	visafone load	44.4 kVA	0.415	32.57	20.18	57.38	92.9
10	sacred heart load	130 kVA	0.415	95.85	59.4	168.4	93.13
11	mares load	242 kVA	0.415	178.9	110.9	314	93.26
12	bronze royal relief load	183 kVA	0.415	135.7	84.11	237.8	93.41
13	otofure load	153 kVA	0.415	114.9	71.18	200	93.98
14	iyayi load	92 kVA	0.415	69.64	43.16	120.8	94.37
15	t.gate load	38.6 kVA	0.415	29.25	18.12	50.7	94.41
16	utekon load	82.46 kVA	0.415	62.63	38.82	108.4	94.53
17	mtn oluku	45 kVA	0.415	34.25	21.23	59.24	94.62
18	ora load	89 kVA	0.415	68.27	42.31	117.6	95

Table 2: Candidate Buses Meeting the Criteria for capacitor placement using LSF

S/N	BUS	MVAR	Voltage (p.u)	ROUTE RESISTANCE	LSF
1	t.gate load	0.01812	0.9441	0.22180	0.009018073
2	visafone load	0.02018	0.929	0.61371	0.028700068
3	nddc behind itv load	0.1217	0.9116	0.44257	0.129626535
4	sacred heart load	0.0594	0.9313	0.95404	0.130678211
5	ubth qtr okhuwun load	0.1271	0.9202	0.44257	0.132859637
6	nddc oluku load	0.1581	0.9183	0.37561	0.140839666
7	nddc okhuwun load	0.1576	0.8993	0.37561	0.146389293
8	okhuwun load	0.066	0.9232	0.95404	0.147757075

Table 3: Optimal Capacitor Placement Results

	Candidate Buses					Capacitor Information			
S/N		Operating Voltage Nominal kV	% Mag.	Angle	% PF	Rated kVAR/Bank	Rated kV	No of Banks	Total kVAR
1	Visafone	0.415	92.351	-3.83	85.0				
2	Sacred heart	0.415	95.779	-4.22	-77.0	200.000	0.415	2	400.000
3	t. gate	0.415	93.992	-3.97	85.0				
4	Nddc behind itv	0.415	93.233	-5.55	-99.8	100.000	0.415	3	300.000
5	Nddc oluku	0.415	90.789	-5.51	85.0				
6	Nddc okhuwun	0.415	90.167	-6.10	93.9	200.000	0.415	2	400.000
7	Ubth qtr Okhuwun	0.415	92.242	-4.33	96.1	100.000	0.415	3	300.000
8	Okhuwun	0.415	94.707	-4.37	-83.4	100.000	0.415	3	300.000
	Total							13	1700.000

Table 4: Load Flow Results for Base Bus Loading Condition of the Enhanced Network

S/N	ID	Rating/Limit	Rated kV	kW	Kvar	Amp	Voltage (%)
1	bronze royal relief load	183 kVA	0.415	142.6	88.4	243.8	95.76
2	SacredHaert CAP	-400 kvar	0.415	0	-421.3	571.1	102.62
3	NDDC Behind ITV CAP	-300 kvar	0.415	0	-292.2	411.9	98.69
4	NDDC Okhuwun CAP	-400 kvar	0.415	0	-392.4	551.1	99.04
5	UBTH QTR Okhuwun CAP	-300 kvar	0.415	0	-286.7	408	97.76
6	Okhuwun CAP	-300 kvar	0.415	0	-299.6	417.1	99.93

7	goldland load	276 kVA	0.415	206.3	127.8	360	93.76
8	iyamo load	201 kVA	0.415	153.1	94.88	264.7	94.66
9	iyayi load	92 kVA	0.415	73.22	45.38	123.9	96.77
10	iyowa load	229 kVA	0.415	171.6	106.3	299.1	93.89
11	mares load	242 kVA	0.415	187.5	116.2	321.4	95.47
12	mtn oluku	45 kVA	0.415	35.91	22.25	60.66	96.89
13	nddc behind itv load	278 kVA	0.415	230.1	142.6	381.7	98.69
14	nddc okhuwun load	370 kVA	0.415	308.5	191.2	509.8	99.04
15	nddc oluku load	356 kVA	0.415	267.4	165.7	465.6	94.01
16	okhuwun load	147 kVA	0.415	124.8	77.33	204.4	99.93
17	ora load	89 kVA	0.415	71.58	44.36	120.4	97.27
18	otofure load	153 kVA	0.415	120.4	74.63	204.8	96.23
19	sacred heart load	130 kVA	0.415	116.4	72.12	185.6	102.62
20	t.gate load	38.6 kVA	0.415	30.65	19	51.9	96.65
21	ubth qtr okhuwun load	285 kVA	0.415	231.5	143.5	387.6	97.76
22	utekon load	82.46 kVA	0.415	65.67	40.7	111	96.79
23	visafone load	44.4 kVA	0.415	34.49	21.37	59.05	95.59

4.0 Conclusion

It can be inferred from results of this study that the Iyowa Community 11/0.415 kV distribution network is quite deficient with only 1 of the 18 buses operating within the statutory voltage limit. When the LSF and OCP analyses were done, the outcome showed that 2 banks of 200 kVAR, 3 banks of 100 kVAR, 2 banks of 200 kVAR, another 3 banks of 100 kVAR and 3 banks of 100 kVAR capacitors needed to be optimally placed on 5 selected buses in the network. When the placement was done and the load flow analysis repeated, the results obtained showed that the voltage profile of the network improved as only 2 of the 18 load buses violated the statutory voltage limit. It is therefore recommended that the Iyowa community distribution network should be enhanced and the capacitor placement technique or any cheaper alternative should be used.

References

[1] Okafor F.N. (2017); “Improving Electric Power Sector Performance: The Role of the Nigeria Electricity Regulatory Commission”; Nigerian Academy of Engineering 2017 Public Lecture.

[2] Anumaka M. C., (2012); “Analysis of Technical Losses in Electrical Power System (Nigerian 330kv Network as a Case Study)”. International Journal of Research and Reviews in Applied Sciences. Vol. 12(2). Pp. 320-327.

[3] Ajao K.R., Ogunmokun A.A., Nangolo F. and Adebo E.O., (2016); “Electricity transmission losses in Nigerian Power Sector: A Smart Grid Approach”. “ATBU Journal of Science, Technology and Education (JOSTE). ISSN 2277-0011; Vol. 4(3) pp47-63

[4] Amadi H.N, Okafor E.N.C., (2015); The effects of technical and non-technical losses on power o utages in Nigeria”. International Journal of Scientific and Engineering Research. Vol. 6(9).

[5] The World Bank. (2009); “Reducing Technical and Non-Technical Losses in the Power Sector”. Background Paper for the World Bank Group Energy Sector Strategy.

[6] Amadi H.N., Izuegbunam F.I. and Okafor E.N.C. (2016); “Evaluation of Losses in Distribution Networks of Selected Industrial Cities in Nigeria Using ETAP”. British Journal of Applied Science & Technology (BJAST) Volume 17(6): pp 1-12. ISSN: 2231-0843, NLM ID: 101664541

[7] Amadi H.N., Okafor E.N.C. (2015); “The Effects of Technical and Non-Technical Losses on Power Outages in Nigeria”. International Journal of Scientific and Engineering Research. Volume 6(9).

[8] Udoh B.E. (2014); “The Causes and Effect of Electric Power Outages in the North East Zone of Nigeria, Using Mubi in Adamawa State as a Case Study”. International Journal of Industrial Electronics and Electrical Engineering. Volume 2(2).

[9] Samuel I, Katende J, and Ibikunle F. (2012); “Voltage Collapse and the Nigerian National Grid. EIE’s 2nd Intl’ Conf. Comp., Energy, Net., Robotics and Telecom.

[10] Lave L, Apt J, and Morgan G. (2005); “Worst Case Electricity Scenarios: The Benefits & Costs of Prevention”. CREATE Symposium. University of South California, Aug; 2005.

[11] Ramachandra Murthy K.V.S., Ramalinga Raju M., Govinda Rao G. and Narasimha Rao K. (2010); "Comparison of Loss Sensitivity Factor & Index Vector Methods in Determining Optimal Capacitor Locations in Agricultural Distribution". 16th National Power Systems Conference, Department of Electrical Engineering, University. College of Engineering., Osmania University, Hyderabad, A.P, INDIA. 15th-17th December, 2010. Pp 26-30.
[12] Wang J., Chiang H., Nan Minu, K. and Darling G. (1997); "Capacitor Placement and Real Time Control in Large-Scale Un-balanced Distribution Systems:" Part I & II, IEEE Trans. On Power Delivery 12, 1997, pp 953–964.
[13] Carpinelli G., Varilone P, Di Vito V. and Abur A. (2005); "Capacitor Placement in Three-phase Distribution Systems with Nonlinear and Unbalanced Loads". IEEE Proc.-Gener. Trans. Distrib, 152 No. 1, pp. 47–52.
[14] Chiang H., Wang J. and Darling G. (1995); "Optimal Capacitor Placement, Replacement and Control in Large-Scale Unbalanced Distribution Systems:" Part I & II, IEEE Trans. On Power Systems 10, 1995, pp. 356–369.
[15] Huang Y.C., Yang H.T and Huang C.L. (1996); "Solving the Capacitor Placement Problem in a Radial Distribution System Using Tabu Search Application". IEEE Trans. On Power Systems 11, 1996, pp 1868–1873.
[16] Gallego R.A., Monticelli A.J. and Romero R. (2001); "Optimal Capacitor Placement in Radial Distribution Networks". IEEE Trans. On Power Systems 16, 2001, pp 630–637.
[17] Grainger J.J. and Lee S.H. (1981); "Optimum Size and Location of Shunt Capacitors for Reduction of Losses on Distribution Feeders". IEEE Trans. On Power Appar. A. Syst.", PAS-100, 1981, pp. 1105–1118.
[18] Prakash K. and Sydulu M. (2007); "Particle Swarm Optimization Based Capacitor Placement on Radial Distribution Systems". Power Engineering Society General Meeting, June, 2007, Tampa, FL, pp1-4.