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Evaluation of Losses in Distribution Networks of Selected Industrial Cities in Nigeria Using ETAP

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Authors' contributions

This work was carried out in collaboration between all authors. Author HNA designed the study, performed the statistical analysis, wrote the protocol, wrote the first draft of the manuscript and managed the literature searches. Authors FII and ENCO managed the analyses of the study, literature searches and improved the final manuscript. All authors read and approved the final manuscript.

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ABSTRACT

Distribution losses contribute to energy shortages and therefore power outages in Nigeria's industries. This work evaluated the technical losses in the distribution networks of selected industrial cities in Nigeria. Power flow simulation of network data collected over the period 2011-2015 from three distribution companies (DisCos) domiciled in these cities was done by Newton-Raphson (N-R) technique using the Electrical Transient and Analysis Program (ETAP) software version 12.6. Results of the power flow simulation showed that between 2011 and 2015 covered by the study, the cities of Lagos, Kano and Port Harcourt recorded a total power loss of 15.8 MW, 36.2 MW and 6.04 MW respectively. The findings also revealed that overloaded power transformers is part of the reasons for high losses in the distribution networks of some of the cities. The outcome of the study provides a guide for system planners and utility companies in providing for prioritization and system upgrade to ensure improved efficiency of their distribution networks.

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Keywords: Electricity distribution; distribution losses; distribution networks; energy shortages; power losses; substations; transformers.

1. INTRODUCTION

The number of power outages in a given locality per year is an indication of the efficiency of power supply even as consumer dissatisfaction with electricity service is often linked to high level of outages [1-2]. Since the more the number of power outages, the less efficient the power system, it follows that given higher system losses (technical and non-technical), there would be more power outages indicating the inefficiency of the system.

The biggest challenge confronting the Nigeria's distribution sector presently is the level of distribution losses namely technical, commercial and collection losses (Fig. 1). Technical losses are due to the nature of the components in use in the network, commercial losses refer to energy not billed for, and collection losses signify energy billed but not paid for. When the distribution companies were privatised as part of the power sector reform process by the Nigeria government, the transactions assumed some particular loss levels. After the asset hand-over, however, it became clear that the losses were much higher than had been estimated. In 2014, ~46% of energy was lost through technical (12%), commercial (6%), and collection losses (28%) [3].

Over the years, scholars and researchers have attributed power outages to: Weak grid and outdated power stations, equipment overloading, inadequate compensation equipment on the system, weather and tree related factors, vandalism, poor maintenance culture, etc. [1,4,5,6]. No researcher known to this study, however, has focused on the effects of distribution losses on electricity supply failures in the Nigeria industrial sector.

It is imperative therefore to undertake an assessment of the losses in the nation's electricity distribution network in order to recommend viable and long-lasting solutions to the perennial problem of system induced power outages among industries in Nigeria. This forms the research gap which the outcome of this work tends to bridge by creating a fresh awareness among stakeholders in the power sector about the need for proactive measures towards minimizing recurrent system induced losses by ensuring improved efficiency of the country's distribution network. The resulting reliable and adequate electricity supply to the industrial sector will make the sector more vibrant thereby growing the country's gross domestic product (GDP) and creating more employment opportunities for the nation's teeming populace.

2. OVERVIEW OF THE SAMPLED DISTRIBUTION NETWORKS

2.1 Eko Distribution Network

The Eko distribution network shown in Fig. 2 comprises of the Agbara and Badagry Injection substations both of which are supplied from the 2 x 45 MVA, 132/33/11 KV transformer transmission substation at the load centre. The Agbara Injection substation rated 2 x 15 MVA, 33/11 KV feeds Beecham, Evans, OPIC, and other 11 KV outgoing feeders while the Badagry Injection substation rated 15 MVA, 33/11 KV feeds Unilever, P&G, Nestle and Guinness industrial feeders.

2.2 Kano Electricity Distribution Network

The Kano Electricity Distribution network shown in Fig. 3 comprises of the Sabon Gari and Dakata injection substations. The 30 MVA, 132/33/11 KV transformer transmission substation at the load centre supplies electricity to the Sabon Gari 2 x 15 MVA, 33/11 KV injection substation which in turn feeds Fagge, Sabon Gari, Abuja 11 KV outgoing feeders among others. The Dakata 3 x 15 MVA, 33/11 KV Injection substation feeds: Independence, Brigade, Bompia, Flour Mill and other 11 KV outgoing feeders. The Murtala outgoing feeder radiated from a 60 MVA, 33/11 KV injection substation while Gezawa is supplied directly from same 30 MVA, 132/33/11 KV substation as the Sabon Gari injection substation.

2.3 Port Harcourt Distribution Network

The Port Harcourt Electricity Distribution network shown in Fig. 4 comprises of the Trans-Amadi and Akanni injection substations. Both the Akanni and Trans-Amadi injection substations are supplied from the Port Harcourt Mains transmission lines via 60 MVA, 132/33/11 KV transformer transmission substation at the load centre. The Akanni 2 x 15 MVA, 33/11 KV

Injection substation then feeds: Rumuogba, Glass Factory, Old Aba Road and Rumurolu 11KV outgoing feeders. The Trans-Amadi 2 x 15 MVA, 33/11KV injection substation feeds: Rivoc, Nda Bros, Water Works and Fimie 11KV outgoing industrial feeders.

3. METHODOLOGY

Data and diagrams on the sampled distribution networks were collected from the three electricity distribution companies located in Nigeria's three major industrial cities under review. The distribution companies are: Eko Electricity Distribution Company (EKEDP) in Lagos city for the Agbara distribution network, Kano Electricity Distribution Company (KEDCO) in Kano city for the Sabon Gari distribution network and the Port Harcourt Electricity Distribution Company (PHEDCO) in Port Harcourt city for the Port Harcourt distribution network. In Lagos, seven industrial feeders supplied from the Agbara injection substation were considered. The industrial feeders studied are Beecham, Evans, OPIC, Unilever, Nestle, P&G and Guinness. In Kano, nine industrial feeders under the Sabon-Gari Injection substation were investigated. These are Abuja, Sabon-Gari, Fagge, Murtala, Flour Mill, Independence, Brigade and Bompia. In Port Harcourt, eight industrial feeders from two

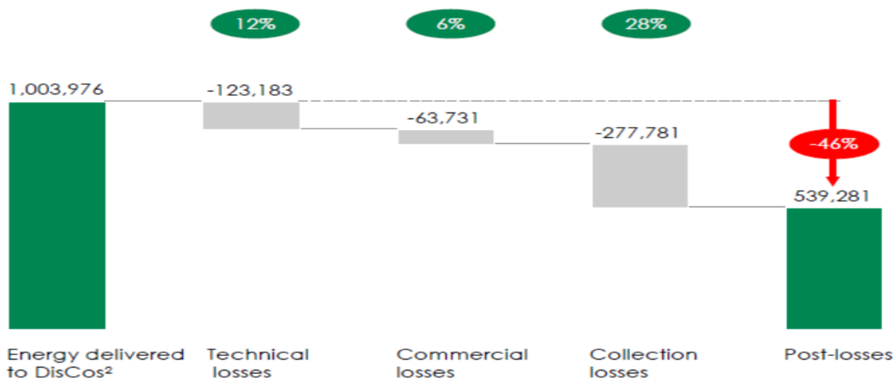

Fig. 1. Level of distribution losses in Nigeria in 2014 [3]

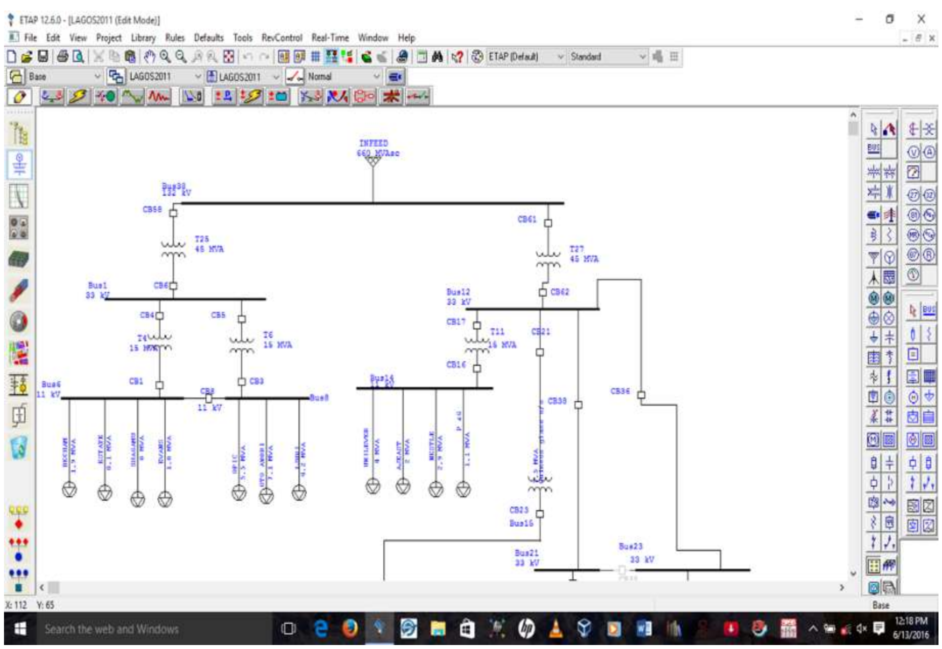

Fig. 2. ETAP view of the Agbara/Badagry injection substations in Lagos

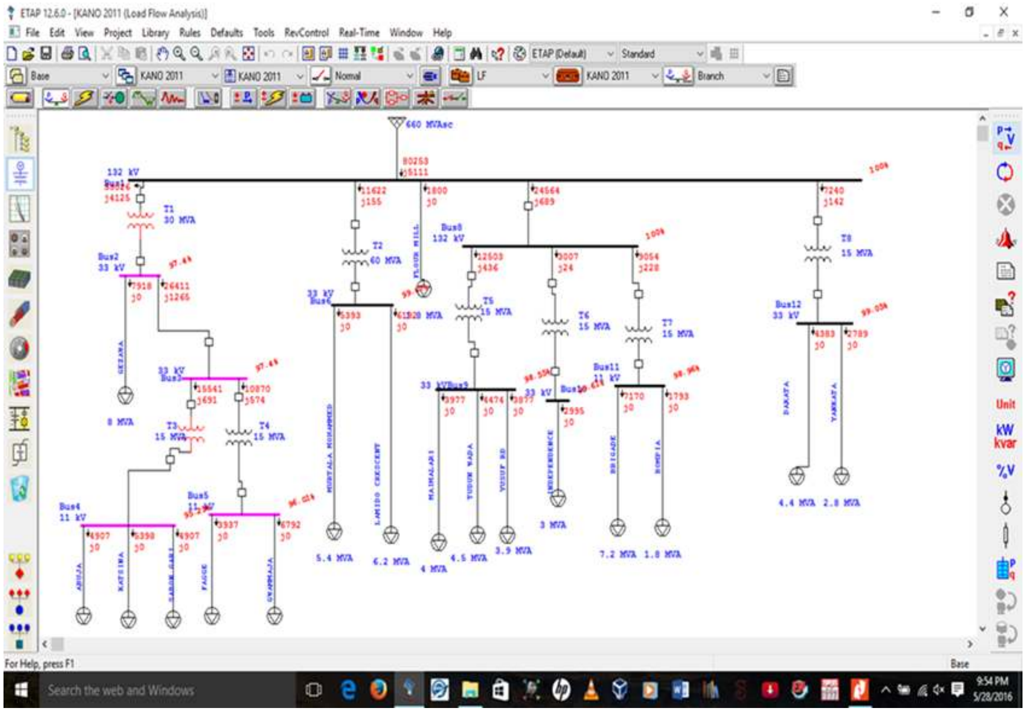

Fig. 3. ETAP view of the Sabon-Gari/Dakata injection substations in Kano

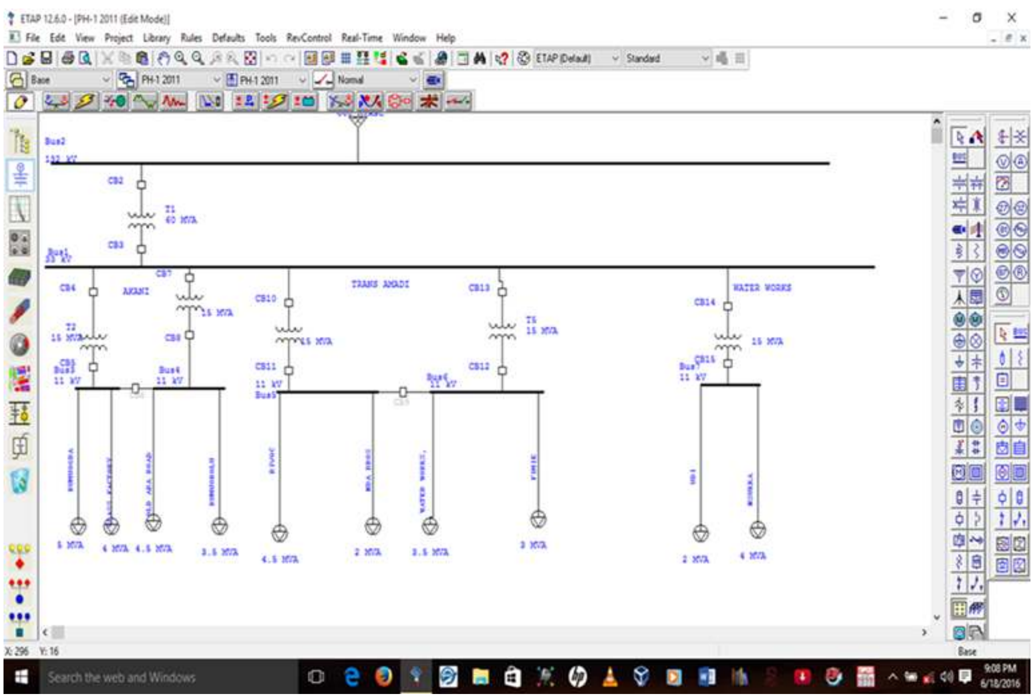

Fig. 4. ETAP view of the Akanni/Trans-Amadi injection substations in Port Harcourt

injection substations namely Akani and Trans-Amadi injection substations were studied. These are: Rumuogba, Glass Factory, Old Aba Road and Rumurolu industrial feeders under Akani injection substation and Rivoc, Nda Bros, Water Works and Fimie industrial feeders supplied from the Trans-Amadi Injection substation. The data collected include: (i) List of all transformers connected to the injection substations and their ratings. (ii) Monthly maximum loading on the feeders for the period 2011- 2015. (iii) Feeder route length. (iv) Sizes and ratings of conductors used for feeders.

These data were subsequently simulated on the Electrical Transient and Analysis Program (ETAP) software version 12.6 and the simulation results used in the computation of the technical power losses in the respective distribution networks. The power flow simulation also evaluated the level of loading of power transformers installed at the injection substations under review. This paper chose to perform the power flow simulation on the ETAP 12.6 software program owing to its fully graphical electrical transient and analysis capabilities.

3.1 Mathematical Formulation of Newton-Raphson Powerflow Equations for Distribution System

The Newton-Raphson formulates and solves iteratively the following power flow equation:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} = \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix} \tag{1}$$

Where ΔP and ΔQ are bus real power and reactive power mismatch vectors between specified value and calculated value, respectively; ΔV and $\Delta\delta$ represent bus voltage magnitude vectors and angle in an incremental form; and J_1 through J_4 are called Jacobian matrices.

The Newton-Raphson method has the attribute of fast convergence and is highly dependent on the bus voltage initial values. The convergence criteria for the Newton-Raphson method are typically set to 0.001 MW and Mvar. A careful selection of bus voltage initial values is strongly recommended. Before running load flow using the Newton-Raphson method, ETAP makes a few Gauss-Seidel iterations to establish a set of sound initial values for the bus voltages. The Newton-Raphson method is often preferred for use with most systems.

The Newton-Raphson method can be applied to the power flow studies when the bus voltages are expressed in polar form. The active and reactive power at each bus are functions of magnitudes of phase angles of bus voltages [7]. Thus

$$P_i = f_1(\delta, |V|) \tag{2a}$$

$$Q_i = f_2(\delta, |V|) \tag{2b}$$

For a system of n buses and bus 1 designated as slack bus, the equations which relate the changes in active and reactive power to changes in bus voltage magnitude and angles take the form [7],

$$\Delta P_i = \sum_{p=2}^{n} \frac{\partial P_i}{\partial \delta_p} \Delta \delta_p + \sum_{p=2}^{n} \frac{\partial P_i}{\partial |V_p|} \Delta |V_p| \tag{3a}$$

$$\Delta Q_i = \sum_{p=2}^{n} \frac{\partial Q_i}{\partial \delta_p} \Delta \delta_p + \sum_{p=2}^{n} \frac{\partial Q_i}{\partial |V_p|} \Delta |V_p| \tag{3b}$$

ΔP_i and ΔQ_i represent the differences between the specified and the calculated values of P_i and Q_i.

Replace $\Delta |V|$ by $\frac{\Delta |V|}{|V|}$ in Eq. (3), the resulting equation becomes:

$$\Delta P_i = \sum_{p=2}^{n} \frac{\partial P_i}{\partial \delta_P} \Delta \delta_p + \sum_{p=2}^{n} \frac{\partial P_i}{\partial |V|} |V_p| \frac{\Delta |V_p|}{|V_p|} \tag{4a}$$

$$\Delta Q_i = \sum_{p=2}^{n} \frac{\partial Q_i}{\partial \delta_p} \Delta \delta_p + \sum_{p=2}^{n} \frac{\partial Q_i}{\partial |V_p|} |V_p| \frac{\Delta |V_p|}{|V_p|} \tag{4b}$$

The set of equations (4) for all the n-1 buses can be written in the following matrix form,

$$\begin{bmatrix} \Delta & P \\ \Delta & Q \end{bmatrix} = \begin{bmatrix} H & N \\ J & L \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \frac{\Delta|V|}{|V|} \end{bmatrix} \tag{5}$$

The real and apparent powers at the buses are expressed as:

$$P_i = |V_i| \sum_{p=1}^{n} |Y_{ip}| |V_p| \cos(\delta_i - \gamma_{ip} - \delta_p) \tag{6a}$$

$$Q_i = |V_i| \sum_{p=1}^{n} |Y_{ip}| |V_p| \sin(\delta_i - \gamma_{ip} - \delta_p) \tag{6b}$$

The incremental values of these powers are as follows:

$$\Delta P_i = P_i(specified) - P_i(calculated) \quad (7a)$$

$$\Delta Q_i = Q_i(specified) - Q_i(calculated) \quad (7b)$$

The elements of the Jacobian are written as,

When $p \neq i$

$$H_{ip} = L_{ip} = a_p f_i - b_p e_i \quad (8a)$$

$$N_{ip} = -J_{ip} = a_p e_i + b_p f_i \quad (8b)$$

When $p = i$

$$H_{ii} = -Q_i - |V_i|^2 B_{ii} \quad (9a)$$

$$N_{ii} = P_i + |V_i|^2 G_{ii} \quad (9b)$$

$$J_{ii} = P_i - |V_i|^2 G_{ii} \quad (9c)$$

$$L_{ii} = Q_i - |V_i|^2 B_{ii} \quad (9d)$$

The Newton-Raphson algorithm for power flow studies [7] is outlined as follows:

1. Assume $|V_i|$ and δ_i at all PQ buses and δ_i at all PV buses. In the absence of any other information assume $|V_i|$ at all PQ buses equal to 1 pu and δ_i at all buses equal to zero.
2. Calculate P_i and Q_i for all PQ buses and P_i for all PV buses (except the slack bus) using the equations (5)
3. Calculate ΔP_i and ΔQ_i for all PQ buses and ΔP_i for all PV buses (except the slack bus) by using the equations (6)
4. Calculate the elements of Jacobian using Equations. (7) and (8)
5. Solve (4) for $\Delta\delta$ and $\frac{\Delta|V|}{|V|}$
6. Update the values of voltage magnitudes and phase angles for all PQ buses and the values of phase angles for all PV buses.
7. Calculate Q_i for all PV buses and check $Q_{i,\min} \triangleleft Q_i \triangleleft Q_{i,\max}$. If yes, return to Step 2 and start the next iteration. If not, set Q_i equal to $Q_{i,\min}$ or $Q_{i,\max}$ as the case may be and treat this bus as a PQ bus, return to Step 2 and start the next iteration.
8. Continue till ΔP_i and ΔQ_i at all PQ buses and ΔP_i at all PV buses are within prescribed (or assumed) tolerance.
9. Calculate line flows and slack bus powers. The flow chart for Newton-Raphson method using polar co-ordinates is given in Fig. 5.

4. RESULTS AND DISCUSSION

4.1 Power Losses in the Distribution Networks

Tables 1 - 3 shows the maximum power losses due to the injection substations of the sampled distribution networks. During the period 2011-2015 covered by the study, the Agbara/Badagry Injection substation in the Agbara distribution network in the city of Lagos showed a maximum power loss of 15.8 MW (Table 1). During the same period, the Sabon Gari/Dakata Injection substation in Sabon Gari distribution network in Kano City recorded a maximum power loss of 36.2 MW (Table 2) while the Akanni/Trans-Amadi Injection substation in the Port Harcourt distribution network in the Port Harcourt City showed maximum power loss of 6.04 MW (Table 3). It is obvious from the Tables therefore that the power losses in each network increased yearly. This phenomenon is attributable to yearly increases in load and number of overloaded transformers and other distribution components due to lack of regular inspection, preventive maintenance and absence of infrastructure upgrade [4-6].

As can be observed from the Tables also, the highest maximum average power losses during the 2011-2015 period occurred on Gezewa feeder in the Kano distribution network, while the least values were reported on the Rumurolu feeder in the Port Harcourt distribution network. The high value of power loss (16.17 MW as shown in Table 2) on the Gezawa feeder is attributable to the significant length of the feeder (405 Km). Recent studies [1,8] have shown that the longer the distribution feeder lines, the more the power that gets dissipated due to I^2R losses.

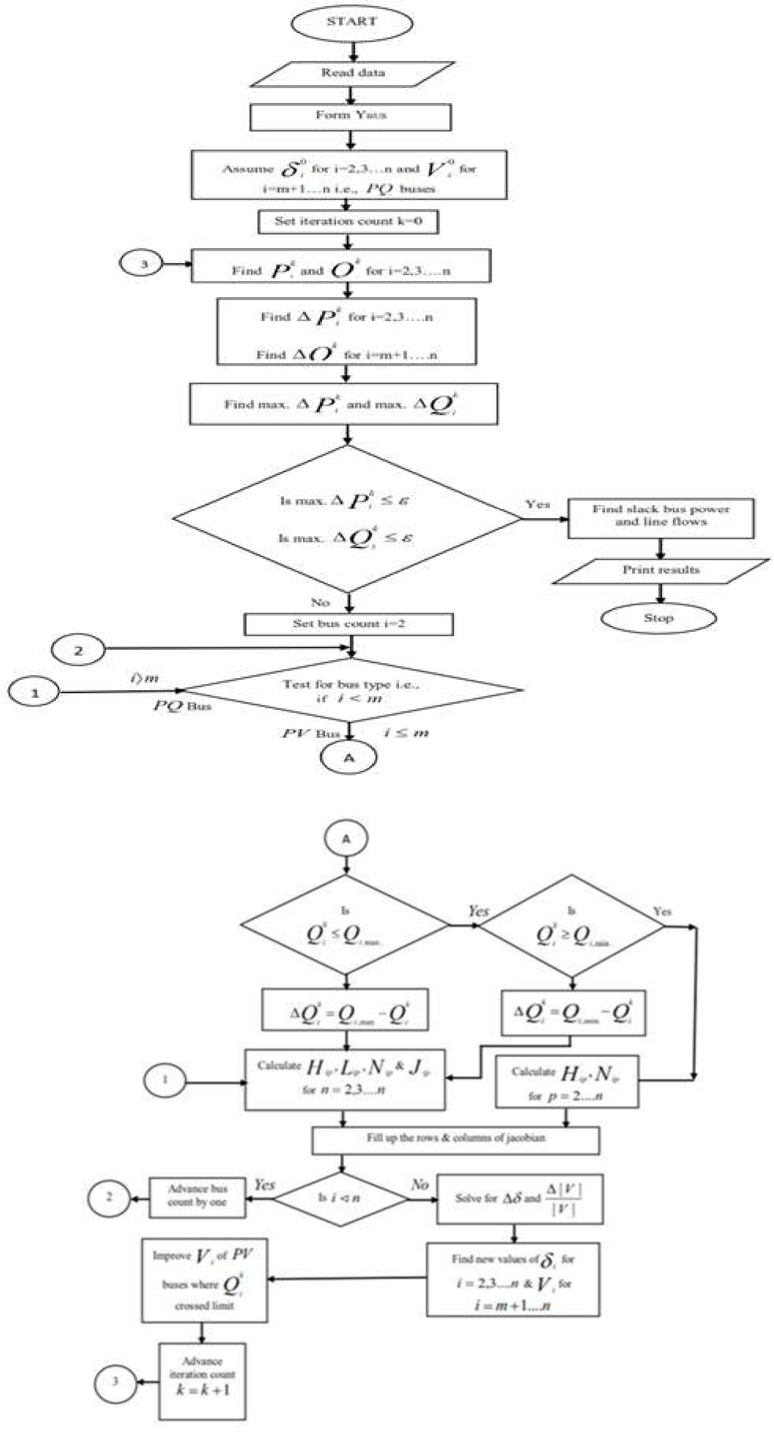

Fig. 5. Flow chart for load flow studies using Newton-Raphson method in polar co-ordinates [7]

Other factors that could be responsible for the differences in the power losses in the sampled distribution networks are increase in load, lack of good maintenance culture, aging, pattern of energy use, load density, high rate of illegal connection to the feeder resulting to overloading and then capability and configuration of the distribution system that vary for various system elements [1,9,10,11]. Figs. 6-8 show the average power losses in the respective injection substations during the 2011-2015 period.

Table 1. Maximum power losses in Agbara/Badagry per year

Feeder	Maximum power loss (MW)					Power loss (MW) 2011-2015
	2011	2012	2013	2014	2015	
Unilever	0.36	0.40	0.49	0.65	0.84	2.74
Evans	0.14	0.22	0.35	0.53	0.76	2.0
P&G	0.23	0.36	0.45	0.60	0.82	2.46
Beecham	0.17	0.24	0.37	0.56	0.79	2.13
Nestle	0.12	0.18	0.29	0.51	0.74	1.84
OPIC	0.42	0.47	0.54	0.69	0.88	3.0
Guinness	0.11	0.15	0.27	0.49	0.62	1.64
Total	1.55	2.02	2.76	4.03	5.45	**15.8**

Table 2. Maximum power loss in Sabon Gari/Dakata per year

Feeder	Maximum power loss (MW)					Power loss (MW) 2011-2015
	2011	2012	2013	2014	2015	
Sabon Gari	0.25	0.52	0.64	0.74	0.83	2.98
Independence	0.23	0.50	0.62	0.68	0.78	2.77
Abuja	0.14	0.25	0.39	0.43	0.56	1.77
Fagge	0.18	0.3	0.44	0.5	0.57	1.99
Gezewa	1.63	2.21	3.22	4.1	5.01	16.17
Brigade	0.29	0.58	0.68	0.85	0.90	3.3
Flour Mill	0.48	0.65	0.84	0.87	1.47	4.32
Bompai	0.1	0.2	0.31	0.39	0.41	1.41
Murtala	0.13	0.22	0.34	0.37	0.43	1.49
Total	3.43	5.43	7.48	8.93	10.96	**36.2**

Table 3. Maximum power losses in Akanni/Trans-Amadi per year

Feeder	Maximum power loss (MW)					Power loss (MW) 2011-2015
	2011	2012	2013	2014	2015	
Glass Factory	0.14	0.145	0.23	0.30	0.32	1.135
Rumuogba	0.008	0.110	0.112	0.12	0.13	0.48
Rumurolu	0.007	0.105	0.107	0.019	0.05	0.288
Water Works	0.009	0.112	0.115	0.1	0.12	0.456
Nda Bros	0.10	0.116	0.118	0.13	0.15	0.614
Famie	0.11	0.124	0.14	0.15	0.21	0.734
Rivoc	0.15	0.155	0.28	0.37	0.39	1.345
Old Aba Rd	0.13	0.135	0.19	0.26	0.27	0.985
Total	**0.66**	**1.00**	**1.29**	**1.45**	**1.64**	**6.04**

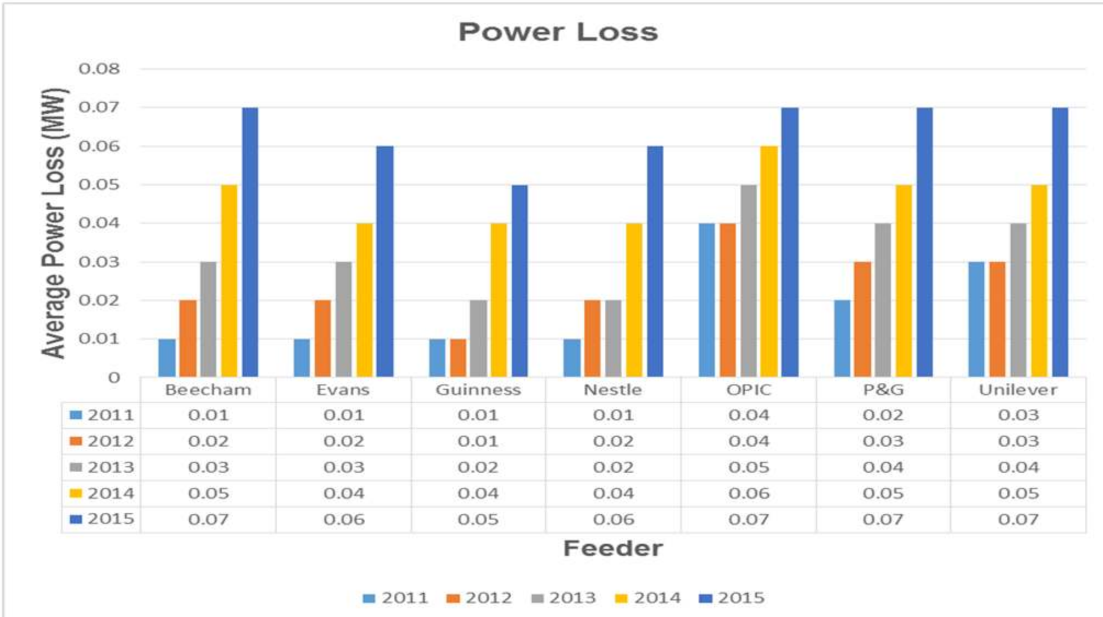

Fig. 6. Average power losses in Agbara/Badagry for 2011-2015

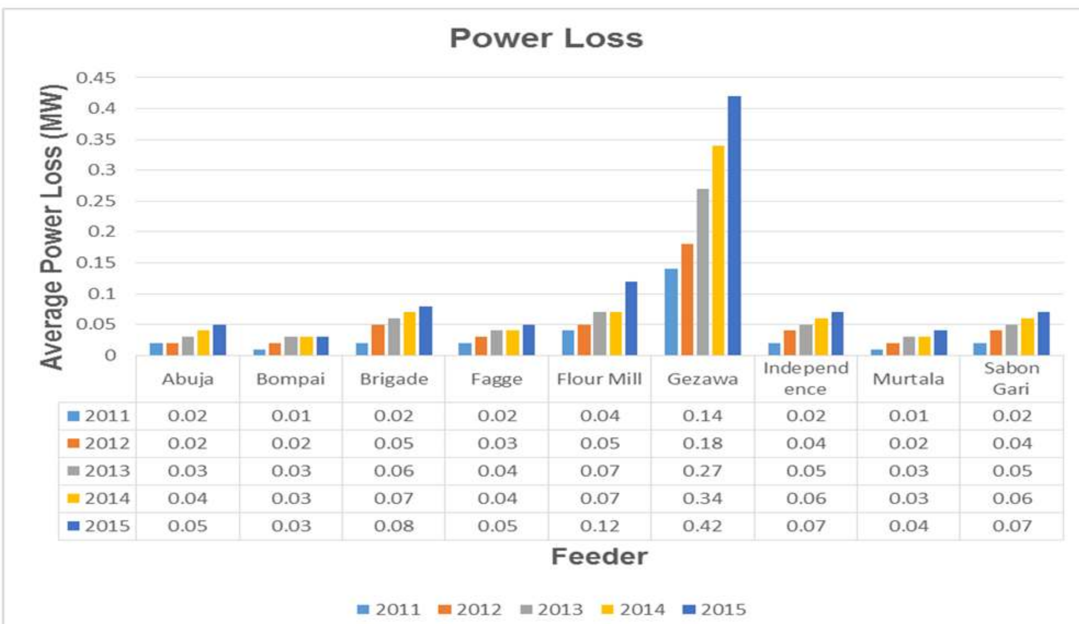

Fig. 7. Average power losses in Sabon Gari/Dakata for 2011-2015

4.2 Power Transformer Percentage MVA Loadings in the Distribution Networks

Figs. 9 -11 show the MVA loadings of some of the power transformers in the industrial substations of the samples distribution networks. As shown in Fig. 9, Transformers T1 and T3 in the Agbara/Badagry injection substation in the Agbara distribution network of Lagos City were loaded to 118% and 104% respectively in 2011 of the rated capacities. Similarly, Transformers T4, T15, T16 and T27 (Fig. 10) in the Sabon Gari/Dakata injection substation of Sabon Gari electricity distribution network in Kano City were loaded to 142%, 239.5%, 159.5% and 120.7% of the rated capacities respectively during the same period. However, as shown in Fig. 11, the transformers in the Akanni/Trans-Amadi injection substation in the Port Harcourt distribution network were loaded within limits of the rated capacities during the period covered by the study. High power losses have been traced to overloaded power transformers [4-6]. It is obvious that the relatively low power losses reported in the Port Harcourt distribution network is due to controlled loads on the power transformers.

There is urgent need therefore to reduce the existing loads and ensure balanced loading on the overloaded transformers in the Agbara/ Badagry and Sabon Gari / Dakata injection substations in the Agbara and Sabon Gari distribution networks in Lagos and Kano cities respectively so as to minimise power and energy loss levels and consequently achieve improved electricity supply reliability in the areas covered by the affected distribution network substations. Besides its negative impact on Utility companies turn-over, high distribution losses are known to scare potential investors away from investing in the power sector [1,2,12].

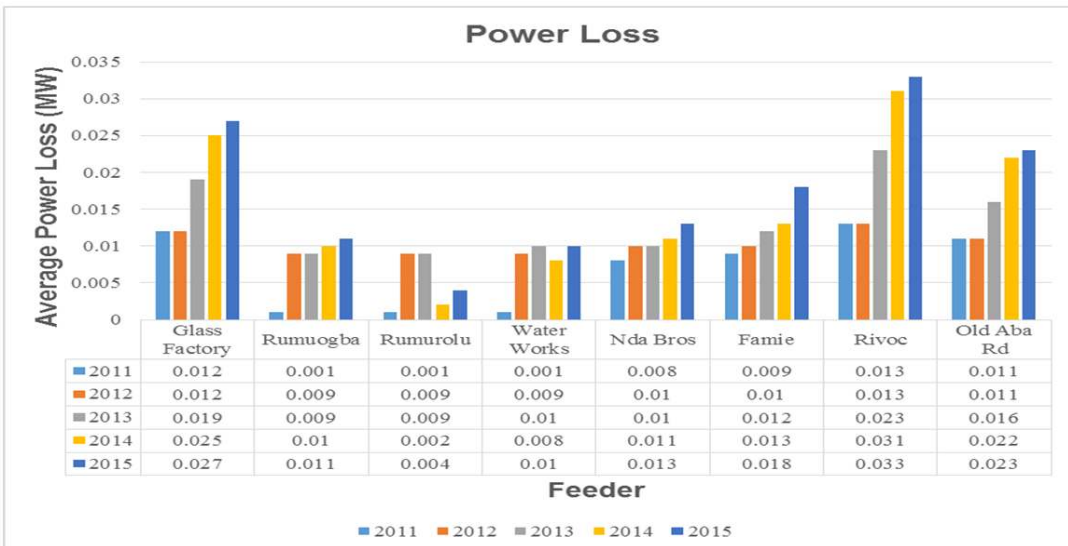

Fig. 8. Average power losses in Akanni/Trans-Amadi for 2011-2015

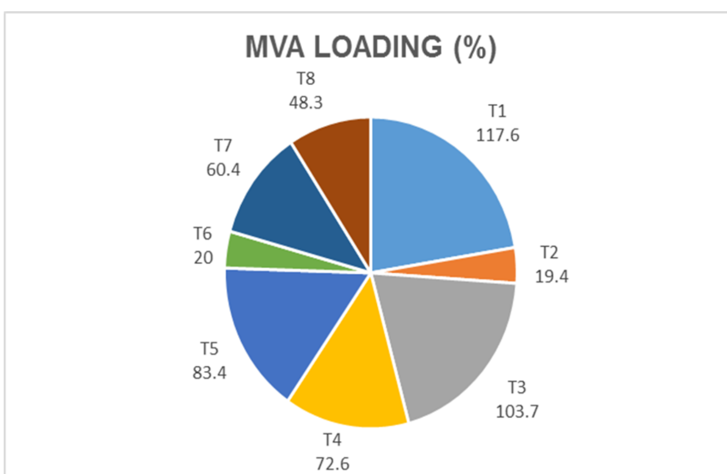

Fig. 9. MVA loading of power transformers in Agbara/Badagry in 2011

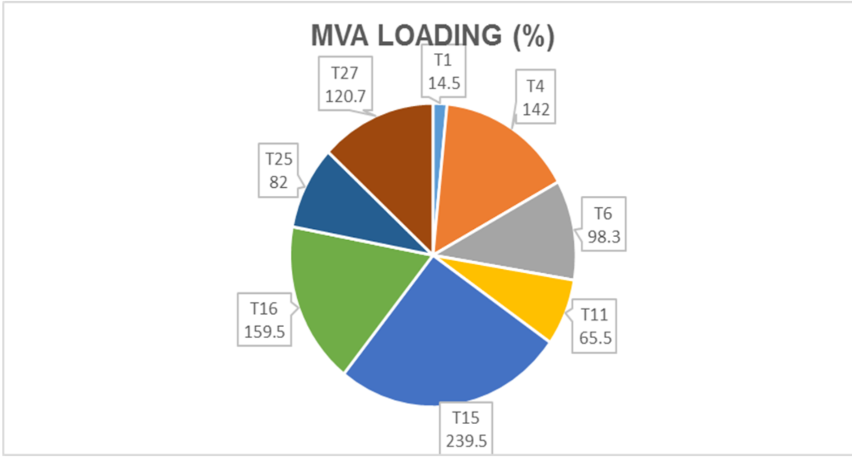

Fig. 10. MVA loading of power transformers in Sabon Gari/Dakata in 2011

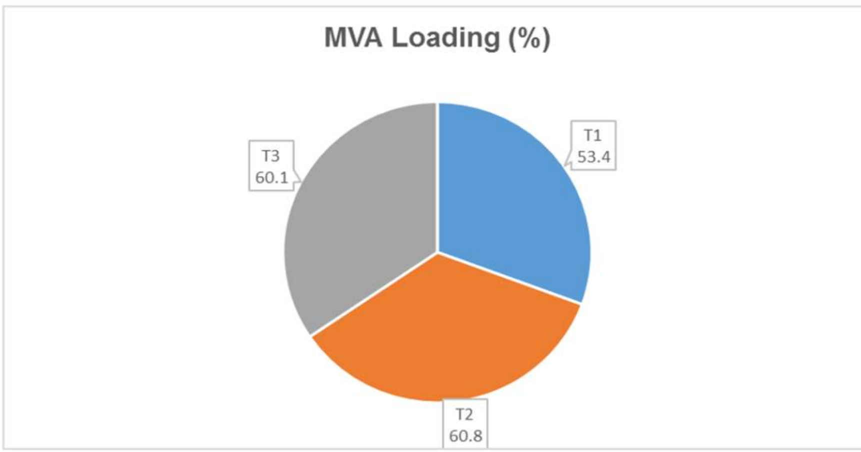

Fig. 11. MVA loading of power transformers in Akanni/Trans-Amadi in 2011

5. CONCLUSION

This work employed the Newton-Raphson Power Flow technique on the ETAP 12.6 software and evaluated technical losses in the distribution networks of the three major industrial Cities in Nigeria namely Lagos, Kano and Port Harcourt.

Results of the study showed that between 2011 and 2015 covered by the study, the Eko electricity distribution network in Lagos recorded a total power loss of 15.8 MW, the Sabon Gari electricity distribution network in Kano reported 36.2 MW while the Port Harcourt distribution network reported 6.04 MW. The results of the simulation further reveal that a significant number of power transformers in the Agbara/Badagry and the Sabon Gari/Dakata injection substations are overloaded well beyond their rated values thus contributing to high power losses in the host distribution networks.

This paper recommends that weak electrical facilities in the distribution network should be identified and strengthened to make them function better. Shunt capacitors should also be installed at appropriate points in the network in order to improve the system power factor. It is necessary to ensure reduction in the length of low tension transmission lines by relocating the existing distribution substations. Old conductors and distribution lines/cables should be promptly disposed of, only conductors and lines of appropriate sizes should be in use. Lengthy distribution lines cause high technical losses and must be avoided. Efforts should be made to avoid overloading of the feeders by ensuring balanced loads at all times. Transformers are responsible for almost half of network losses, it is advisable therefore to reduce the number of transformers in use. Using fewer but highly efficient transformers can make a significant impact on reduction of technical losses. Besides serving as a guide for utility companies in providing for prioritization and system upgrade to ensure improved efficiency of their distribution networks, the outcome of this research would find relevance among policy makers and researchers especially system planners at the distribution subsystem of power sectors.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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