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Application of Three-Phase Power Flow Analysis to the Nigerian Distribution Networks

Samson Oladayo Ayanlade[1], Abdulrasaq Jimoh[2], Funso Kehinde Ariyo[2], Adedire Ayodeji Babatunde[3], Abdulsamad Bolakale Jimoh[4], Fatina Mosunmola Aremu[5]
[1]Department of Electrical and Electronic Engineering, Lead City University, Nigeria
[2]Department of Electronic and Electrical Engineering, Obafemi Awolowo University, Nigeria
[3]Department of Electrical and Electronic Engineering, Olabisi Onabanjo University, Nigeria
[4]Department of Electrical and Electronic Engineering, University of Ilorin, Nigeria
[5]Department of Electrical Electronic Engineering, Kwara State University, Nigeria

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ABSTRACT

Single-phase power flow analysis is used to study most distribution networks in Nigeria. The use of single-phase-power flow analysis assumes that the network is balanced and that the conductor phases act identically. However, Nigerian distribution networks are highly imbalanced because of untransposed lines, irregularly distributed loads in conductor phases, mismatched conductor sizes, and spacing. Consequently, single-phase modeling of the networks fails to reflect actual network behavior, resulting in an incorrect power flow solution. This research presents the three-phase modeling of radial distribution networks for a three-phase-power flow study of Nigerian distribution networks. Olusanya's 54-bus and Ajinde's 62-bus distribution networks in Nigeria were evaluated, both of which were very imbalanced. Without making any assumptions about the network components, these two distribution networks were properly modeled. Each network's three-phase power flow study was carried out in the MATLAB environment. The power flow solutions for each network demonstrated unevenness in the voltage profile for each network phase, as well as inequality in the real and reactive power losses in each phase, indicating that the deployed three-phase-power flow analysis properly mirrored the underlying network characteristics. Therefore, applying three-phase power flow analysis to distribution networks is critical for proper assessment of distribution network performance.

Corresponding Author:

Samson Oladayo Ayanlade,
Department of Electrical and Electronic Engineering,
Lead City University,
Lagos/Ibadan Express Way, Toll-Gate Area, Ibadan, Nigeria.
Email: samson.ayanlade@lcu.edu.ng/ayanladeoladayo@gmail.com

1. INTRODUCTION

Because of its importance in the network, the distribution network is considered the heart of the power system. Without distribution networks, a power system cannot fulfill its intended function, leaving the power system ineffective [1]. Distribution networks are often built in a radial pattern. However, there are relatively few of them in ring/mesh arrangements [2]. Radial distribution systems are quite prominent around the world, particularly in Nigeria, where all distribution networks are radially developed. There are several advantages to radial distribution networks over ring or mesh distribution networks. One of them is that it is incredibly inexpensive and simple to build [3].

The status of Nigeria's electricity grid is deplorable, since practically all of the country's distribution networks are not built to international standards. The majority of Nigerian distribution networks have highly unbalanced load distribution in the conductor phases, as well as unevenly spaced conductor spacing and unequal sizes of phase conductors that are not transposed. As a result, the majority of Nigeria's distribution networks are severely imbalanced and inefficient. Furthermore, the networks are subjected to massive voltage breaches, with almost all bus voltage magnitudes falling outside of the allowed voltage tolerances. As a result of the aforementioned issues affecting Nigeria's electricity distribution networks, utility businesses in Nigeria have generally lost money [4].

For planning and expansion, power flow analysis is a vital instrument for evaluating the performance and operation of any power system [5, 6]. Several assumptions were made in single-phase power flow analysis in order to simplify the power flow problems. The impact of mutual inductance is low, the load on all three phases of the networks is balanced, and the phase conductors are uniformly placed and scaled, to name a few assumptions. The application of single-phase power flow analysis, however, would result in severe inaccuracies in highly unbalanced networks, and the underlying features of the networks would not be accurately reflected in the power flow solutions.

Nigerian scholars have utilized single-phase power flow analysis on distribution networks in Nigeria, as documented in the literature. The power flow problem of the Imalefalafia 32-bus radial distribution network was addressed by [7], using the Newton-Raphson power flow approach. Due to the extremely imbalanced structure of the network, several assumptions were made throughout the study, resulting in inaccurate conclusions for the power flow solution. Ref. [8] used a backward-forward sweep power flow method to analyze the power flow of two radial Nigerian distribution networks, the Imalefalafia 32-bus and Yale 17-bus radial distribution systems of the Ibadan Electricity Distribution Company of Nigeria (IBEDC). Because the networks were severely imbalanced, the findings produced were not very precise, and single-phase power flow analysis was used to tackle the power flow problems. A single-phase power flow analysis based on a backward-forward sweep approach was used by [9] in the sizing and placement of D-STATCOM on a typical Nigerian Ayepe 34-bus radial distribution network. The network was imbalanced to the extreme. As a result, the true nature of the network was misrepresented. In [10], the Agip Estate 33/0.415 kV distribution network of the Port Harcourt Electricity Distribution Company of Nigeria (PHEDN) in Rivers State, Nigeria, was studied using single-phase power flow analysis. Furthermore, various assumptions were made in the network modeling, resulting in an insufficiently accurate power flow solution.

To assess the performance of Nigeria's radial distribution systems, precise modeling of the networks is essential to reflect the features of Nigeria's distribution systems. The deployment of three-phase power flow analysis is the right strategy, which necessitates three-phase mathematical modeling of the network components with a restricted number of assumptions. The unbalanced radial distribution networks' true features are reflected in the three-phase power flow analysis [11]. This power flow analysis, on the other hand, necessitates a great deal of data and sophisticated analysis. Due to these substantial challenges, many researchers typically use the single-phase power flow technique, in which the power flow problems are drastically simplified with a plethora of assumptions without taking into account the implications of these assumptions on the power flow problems' authenticity.

In the literature, many three-phase power flow analysis approaches have been presented for dealing with the power flow problems of highly imbalanced radial distribution networks. Reference [12] presented a three-phase power flow approach based on Carson's equations and distribution network impedance modeling. In [13], the sequence component technique was utilized to investigate three-phase power flow. Reference [14] investigated radial distribution networks and used an approach based on Kirchhoff's Laws and a multiport compensation method for weakly-meshed topologies. The distribution transformers were modeled into the backward and forward-sweep power flow algorithms in [15]. The backward/forward technique was used to simulate the constant impedance, constant current load, and constant power of distribution equipment such as switches, transformers etc., in [16]. Reference [17] investigated the load's analytical equations and expanded single-phase Newton-Raphson load flow approaches to three-phase power flow problems using applied numerical testing. Reference [18] presented a three-phase load flow for distribution network analysis based on distribution network load flow calculation. The three-phase model utilized takes into consideration the unbalanced status of the distribution networks.

According to the literature review conducted so far as part of this study, no material has been located in which three-phase power flow analysis has been used to address power flow issues in Nigerian distribution networks. In addition, no single Nigerian author was discovered to have used single-phase power flow analysis to tackle radial distribution network power flow problems. As a result, this study used three-phase power flow analysis to address the power flow problems of Nigerian distribution networks that are highly unbalanced, such as the Olusanya 54-bus and Ajinde 62-bus networks, by accurately modeling the network components without making any assumptions that would cause the actual characteristics of the networks to not be truly reflected. Furthermore, the results of the three-phase power flow algorithm were validated by comparison with those of the single-phase algorithm. The remainder of the paper is organized as follows: The methodology employed in this research is presented next, followed by the results and discussion section, and finally by the conclusion section.

2. RESEARCH METHOD

This portion of the study discusses the three-phase mathematical modeling as well as load modeling of the networks. The distribution networks' conductor lines were properly modelled using modified Carson's equations, and the three-phase load flow problems of the networks were solved using Newton-Raphson based three-phase load flow solution.

2.1. Distribution Line Modeling

The heart of the three-phase power flow study is three-phase distribution line modeling. The influence of mutual inductances between conductor phases is taken into account in this modeling, and the earth's influence is also considered. Provided a distribution line segment as shown in Figure 1, the current at node *k* is given as follows:

$$\begin{bmatrix} I_{ak} \\ I_{bk} \\ I_{ck} \end{bmatrix} = \frac{1}{2}\begin{bmatrix} y_{aa} & y_{ab} & y_{ac} \\ y_{ba} & y_{bb} & y_{bc} \\ y_{ca} & y_{cb} & y_{cc} \end{bmatrix}\begin{bmatrix} V_{ak} \\ V_{bk} \\ V_{ck} \end{bmatrix} + \begin{bmatrix} I_{akj} \\ I_{bkj} \\ I_{ckj} \end{bmatrix} \quad (1)$$

Similarly, at node j, the current is expressed as

$$\begin{bmatrix} I_{aj} \\ I_{bj} \\ I_{cj} \end{bmatrix} = -\begin{bmatrix} I_{akj} \\ I_{bkj} \\ I_{ckj} \end{bmatrix} + \frac{1}{2}\begin{bmatrix} y_{aa} & y_{ab} & y_{ac} \\ y_{ba} & y_{bb} & y_{bc} \\ y_{ca} & y_{cb} & y_{cc} \end{bmatrix}\begin{bmatrix} V_{aj} \\ V_{bj} \\ V_{cj} \end{bmatrix} \quad (2)$$

Applying Kirchhoff Voltage law to the branch model

$$\begin{bmatrix} I_{aj} \\ I_{bj} \\ I_{cj} \end{bmatrix} = -\begin{bmatrix} I_{akj} \\ I_{bkj} \\ I_{ckj} \end{bmatrix} + \frac{1}{2}\begin{bmatrix} y_{aa} & y_{ab} & y_{ac} \\ y_{ba} & y_{bb} & y_{bc} \\ y_{ca} & y_{cb} & y_{cc} \end{bmatrix}\begin{bmatrix} V_{aj} \\ V_{bj} \\ V_{cj} \end{bmatrix} \quad (3)$$

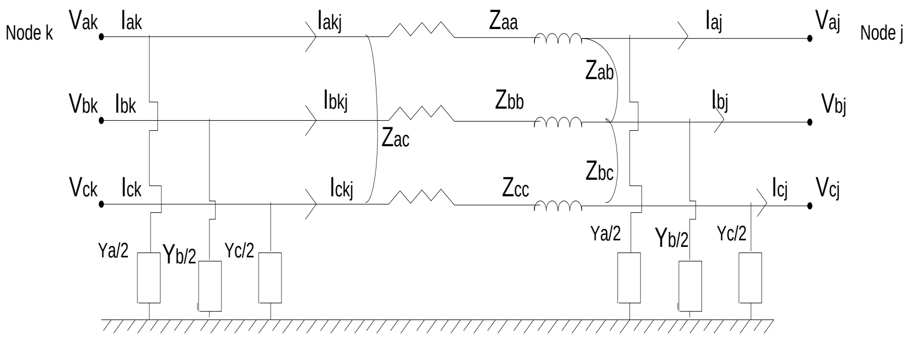

Figure 1. Representation of line model between bus *k* and *j*

The conductor phases' mutual inductances and the earth's impact were all captured by the non-diagonal elements of (3) using Carson's equations [19], reduced by Kron's reduction technique [20, 21] to a 3 × 3 matrix. Similarly, the self and mutual reactances of the lines captured the phase conductor sizes and spacing, and so their values are not identical owing to discrepancies in the distribution network's conductor sizes and spacing.

Since $Z_{abc} = Y_{abc}^{-1}$ (3) becomes

$$\begin{bmatrix} I_{akj} \\ I_{bkj} \\ I_{ckj} \end{bmatrix} = \begin{bmatrix} Y_{aa} & Y_{ab} & Y_{ac} \\ Y_{ba} & Y_{bb} & Y_{bc} \\ Y_{ca} & Y_{cb} & Y_{cc} \end{bmatrix}\begin{bmatrix} V_{ak} \\ V_{bk} \\ V_{ck} \end{bmatrix} - \begin{bmatrix} Y_{aa} & Y_{ab} & Y_{ac} \\ Y_{ba} & Y_{bb} & Y_{bc} \\ Y_{ca} & Y_{cb} & Y_{cc} \end{bmatrix}\begin{bmatrix} V_{aj} \\ V_{bj} \\ V_{cj} \end{bmatrix} \quad (4)$$

Substituting Eq. 4 into (1) and 2, this gives (5).

$$\begin{bmatrix} I_{ak} \\ I_{bk} \\ I_{ck} \end{bmatrix} = \left(\frac{1}{2} \begin{bmatrix} y_{aa} & y_{ab} & y_{ac} \\ y_{ba} & y_{bb} & y_{bc} \\ y_{ca} & y_{cb} & y_{cc} \end{bmatrix} + \begin{bmatrix} Y_{aa} & Y_{ab} & Y_{ac} \\ Y_{ba} & Y_{bb} & Y_{bc} \\ Y_{ca} & Y_{cb} & Y_{cc} \end{bmatrix} \right) \begin{bmatrix} V_{ak} \\ V_{bk} \\ V_{ck} \end{bmatrix} - \begin{bmatrix} Y_{aa} & Y_{ab} & Y_{ac} \\ Y_{ba} & Y_{bb} & Y_{bc} \\ Y_{ca} & Y_{cb} & Y_{cc} \end{bmatrix} \begin{bmatrix} V_{aj} \\ V_{bj} \\ V_{cj} \end{bmatrix} \quad (5)$$

In condensed form, (5) can be expressed as in (6).

$$I_{abck} = \left(\frac{1}{2} y_{sh-abc} + Y_{abc} \right) V_{abck} - \left(Y_{abc} V_{abcj} \right) \quad (6)$$

$$\begin{bmatrix} I_{aj} \\ I_{bj} \\ I_{cj} \end{bmatrix} = - \begin{bmatrix} Y_{aa} & Y_{ab} & Y_{ac} \\ Y_{ba} & Y_{bb} & Y_{bc} \\ Y_{ca} & Y_{cb} & Y_{cc} \end{bmatrix} \begin{bmatrix} V_{ak} \\ V_{bk} \\ V_{ck} \end{bmatrix} + \left(\begin{bmatrix} Y_{aa} & Y_{ab} & Y_{ac} \\ Y_{ba} & Y_{bb} & Y_{bc} \\ Y_{ca} & Y_{cb} & Y_{cc} \end{bmatrix} + \frac{1}{2} \begin{bmatrix} y_{aa} & y_{ab} & y_{ac} \\ y_{ba} & y_{bb} & y_{bc} \\ y_{ca} & y_{cb} & y_{cc} \end{bmatrix} \right) \begin{bmatrix} V_{aj} \\ V_{bj} \\ V_{cj} \end{bmatrix} \quad (7)$$

In condensed form, (7) can be expressed as (8).

$$I_{abcj} = -\left(Y_{abc} \right) V_{abck} + \left(\frac{1}{2} Y_{sh\_abc} + Y_{abc} \right) V_{abcj} \quad (8)$$

Therefore, a three-phase line's series impedance and shunt capacitance, when mutual inductive coupling between the phases is taken into consideration, are 3 × 3 complex matrices.

Where

$$Y_{abc} = \begin{bmatrix} Y_{aa} & Y_{ab} & Y_{ac} \\ Y_{ba} & Y_{bb} & Y_{bc} \\ Y_{ca} & Y_{cb} & Y_{cc} \end{bmatrix} \quad (9)$$

$$y_{sh\_abc} = \begin{bmatrix} y_{aa} & y_{ab} & y_{ac} \\ y_{ba} & y_{bb} & y_{bc} \\ y_{ca} & y_{cb} & y_{cc} \end{bmatrix} \quad (10)$$

Hence, the admittance matrix Y_{kj} for a three-branch between buses *k* and *j* will be a 6 × 6 matrix, given as (11).

$$Y_{abckj} = \begin{bmatrix} \frac{1}{2} y_{sh\_abckj} + Y_{abckj} & -Y_{abckj} \\ -Y_{abckj} & \frac{1}{2} y_{sh\_abckj} + Y_{abckj} \end{bmatrix} \quad (11)$$

From (8), it can be deduced that the currents and voltages of a three-phase model are 3 × 1 vectors and the relationship between sending end current I_{abck} and voltage V_{abck} to receiving end current I_{abcj} and voltage V_{abcj} is

$$\begin{bmatrix} I_{abck} \\ I_{abcj} \end{bmatrix} = Y_{abckj} \begin{bmatrix} V_{abck} \\ V_{abcj} \end{bmatrix} \quad (12)$$

In expanded form, Y_{abckj}, can be expressed as

$$Y_{abckj} = \begin{bmatrix} Y_{ak,ak} & Y_{ak,bk} & Y_{ak,ck} & Y_{ak,aj} & Y_{ak,bj} & Y_{ak,cj} \\ Y_{bk,ak} & Y_{bk,bk} & Y_{bk,ck} & Y_{bk,aj} & Y_{bk,bj} & Y_{bk,cj} \\ Y_{ck,ak} & Y_{ck,bk} & Y_{ck,ck} & Y_{ck,aj} & Y_{ck,bj} & Y_{ck,cj} \\ Y_{aj,ak} & Y_{aj,ak} & Y_{aj,ak} & Y_{aj,aj} & Y_{aj,bj} & Y_{aj,cj} \\ Y_{bj,ak} & Y_{bj,ak} & Y_{bj,ak} & Y_{bj,aj} & Y_{bj,bj} & Y_{bj,cj} \\ Y_{cj,ak} & Y_{cj,ak} & Y_{cj,ak} & Y_{cj,aj} & Y_{cj,bj} & Y_{cj,cj} \end{bmatrix} \quad (13)$$

2.2. Load Modeling

In comparison to transmission networks, distribution networks have a variety of balanced and unbalanced load types based on the number of phases (1 or 3-phase) and connection types (delta or star). Furthermore, for realistic load models, constant power, constant current, constant admittance, or any combination of these must be conducted in terms of electricity consumption characteristics. Because the Nigerian distribution networks under consideration only serve home customers and a few business customers, the loads were modeled as constant power.

2.3. Power Flow Analysis

To tackle the networks' three-phase power flow problems, the three-phase power flow analysis, which is based on the Newton-Raphson power flow approach provided by [22], was used. The power flow problems were formulated using the three-phase bus admittance matrix of the networks as modeled above. The flow chart for the three-phase power flow solutions of the networks is shown in Figure 2.

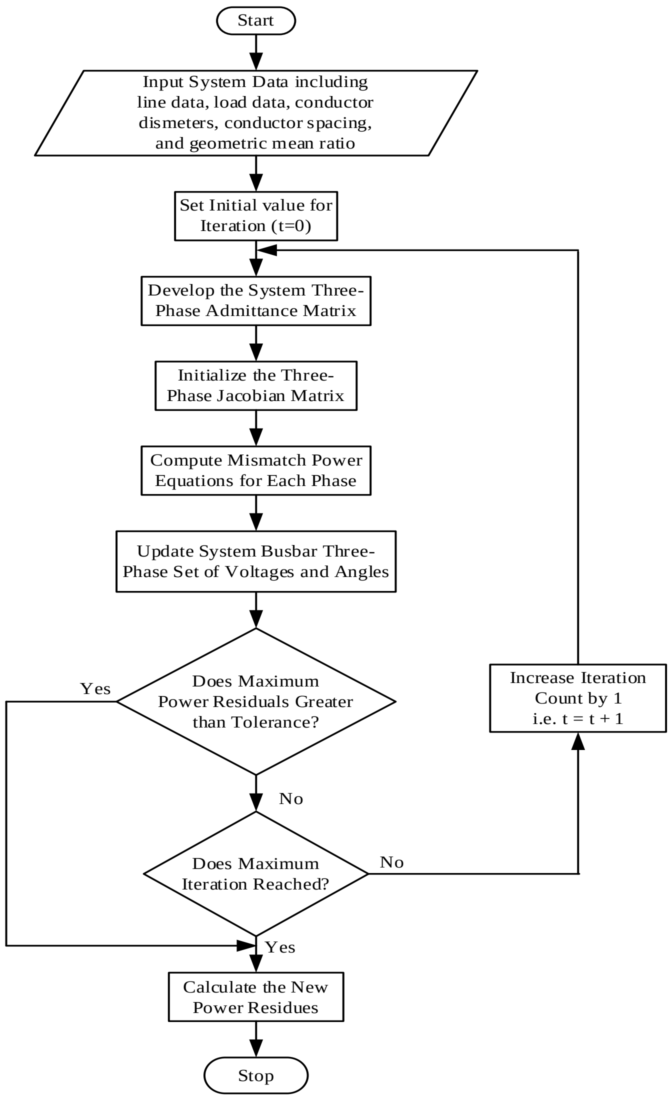

Figure 2. Flow chart for the three-phase Newton-Raphson power flow solution

2.4. Description of the Olusanya 54-Bus Network

It is a typical Nigerian distribution system that radiates from the Oluyole 15 MVA, 33/11 kV injection substation of the Ibadan Electricity Distribution Company of Nigeria (IBEDC). This distribution network has

54 buses. Different conductor diameters per segment and, in most cases, per phase characterize the feeder. Furthermore, the branches are not transposed, the interconnected end-users' loads are unevenly distributed on each phase, and conductor spacing is uneven. As a result, the network is highly unbalanced. This network's single-line diagram is shown in Figure 3. The load, line, and other statistics for this distribution network, including phase conductor diameters, conductor spacing, and geometric mean radii of phase conductors, were obtained from IBEDC.

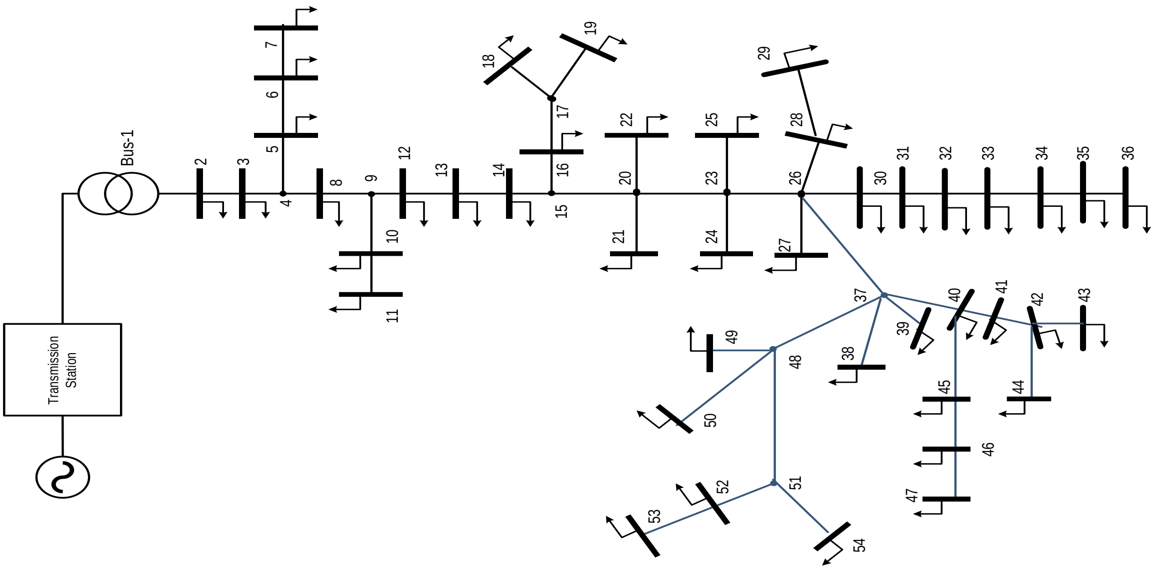

Figure 3. The Olusanya 54-bus network

2.5. Description of the Ajinde 11 kV Feeder

It is a typical Nigerian distribution system that also originates from the Oluyole 15 MVA, 33/11 kV injection sub-station of the IBEDC, Nigeria. The network has 62-bus. This feeder, like the Olusanya 54-bus network, is distinguished by differing conductor diameters per segment and, in many cases, each phase. Furthermore, the lines are untransposed, the linked connected loads are equally distributed among each phase, and conductor spacing is uneven. Consequently, this network is extremely unbalanced. This network diagram is shown in Figure 4. IBEDC also provided the necessary data for this distribution network, which included load, line, phase conductor diameters, conductor spacing, and geometric mean radii of phase conductors. The three-phase power flow problems of this highly unbalanced distribution network were also solved using the Newton-Raphson based three-phase power flow solution.

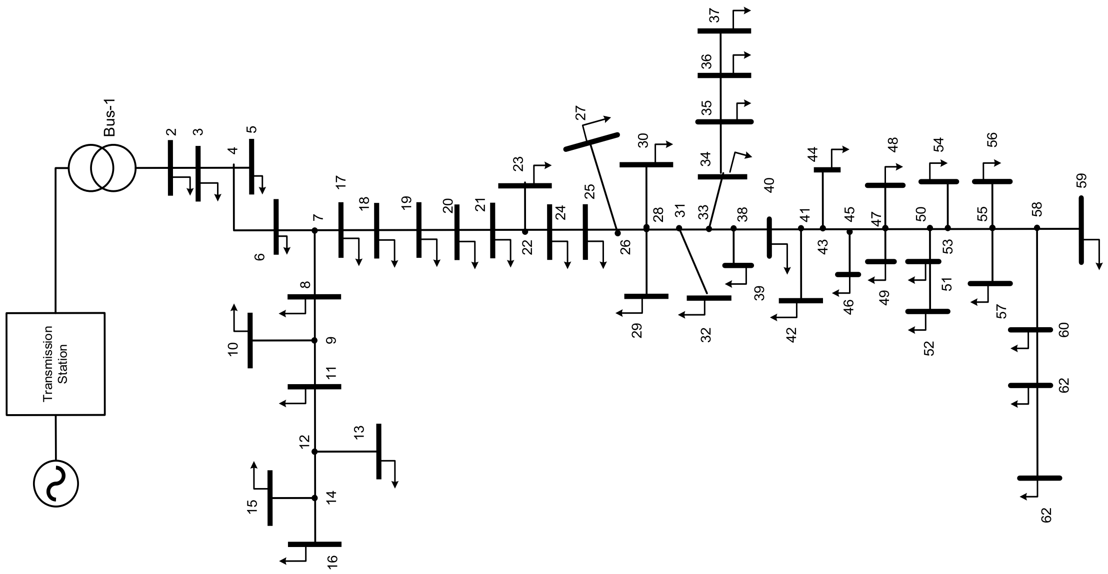

Figure 4. The Ajinde 62-bus network

3. RESULTS AND DISCUSSION

For the simulations, the base MVA was set at 100, and 11 kV was chosen as the base voltage with a maximum of 10 iterations. The simulation results for the power flow solutions are presented under two subsections; the Olusanya 54-bus and the Ajinde 62-bus sections.

3.1. The Olusanya 54-Bus Network

This subsection begins with the simulation results for the voltage profile of the Olusnaya 54-bus network, followed by the simulation results of the network's real power loss, and then as the network's reactive power loss.

3.1.1. Voltage profile

The power flow solution converged in three iterations with a precision of 10^{-10}. For visual inspection and easy observation, the voltage profile for each of the phases is illustrated in Figure 5. Observation of the voltage profiles as presented in Figure 5 shows that the voltage profile of phase B is much better than the voltage profiles of phases A and C. However, the worst voltage profile was that of phase C, as almost all the voltage magnitudes in this phase were significantly below the lower acceptable voltage limit. The least voltage magnitude on phase A occurred at bus 53 and it was 0.9581 p.u. The least voltage magnitude on phase B occurred at bus 53 also, and it was 0.9658 p.u. Similarly, the least voltage magnitude in phase C occurred at bus 53 and it was 0.9154 p.u. This implies that phases A and B have their voltage profiles well within the acceptable voltage limits, as all their bus voltage magnitudes fall well within the acceptable voltage limits.

However, the phase C voltage profile violated the acceptable voltage limits. This can be easily observed in Figure 5, as starting from bus 20 to bus 54, the voltage magnitudes were below 0.950 p.u., which is the acceptable lower voltage limit. This means that about 35% of the buses in phase C have voltage magnitudes above 0.950 p.u. The reason for this is that phase C was heavily loaded as the total real and reactive loads on it were 4.80 MW and 3.98 MVAr, respectively, as compared with phase A, which were 1.03 MW and 2.30 MVAr, respectively, and phase B, which were 1.56 MW and 1.65 MVAr, respectively. The results showed that the magnitudes of the bus voltage differ significantly across the three phases and that only phase C requires voltage profile enhancement through reactive power compensation, while the voltage profiles of phases A and B are within standard voltage limits and therefore acceptable.

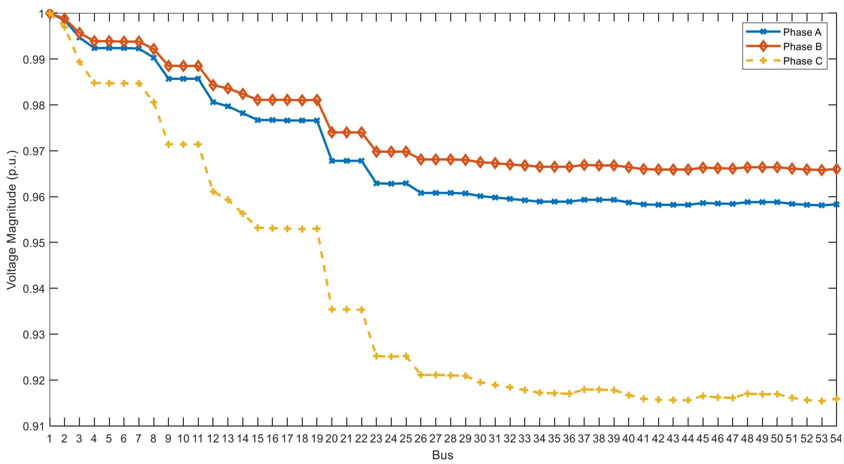

Figure 5. Voltage profile of the Olusanya 62-bus network

3.1.2. Real power loss

The real power losses in the lines of all the three phases are illustrated in Figure 6, with line 1-2 in phase C exhibiting the highest real power loss, followed by lines 2-3, 3-4, 4-8, 4-9, 9-12, etc., just to mention a few cases. The highest real power losses were observed on all the lines in phase C when compared with phases A and B. Similarly, all the lines in phase B exhibited higher real power losses when compared with all the lines in phase A. In other words, all the lines in phase A exhibited the least real power losses. The overall real power loss in C was 45.82 kW as compared with phases A and B, which were 2.67 and 26.00 kW, respectively. Phase C contributed significantly to the total network real power loss of 74.50 kW, which was about 61.5% of the total network power loss. This implies that only phase C of the network was problematic and consequently needs to be addressed, and not phases A and B, which per se were fairly good. The simulation results actually showed the efficacy of three-phase power flow analysis in accurately evaluating the performance of highly imbalanced radial distribution networks.

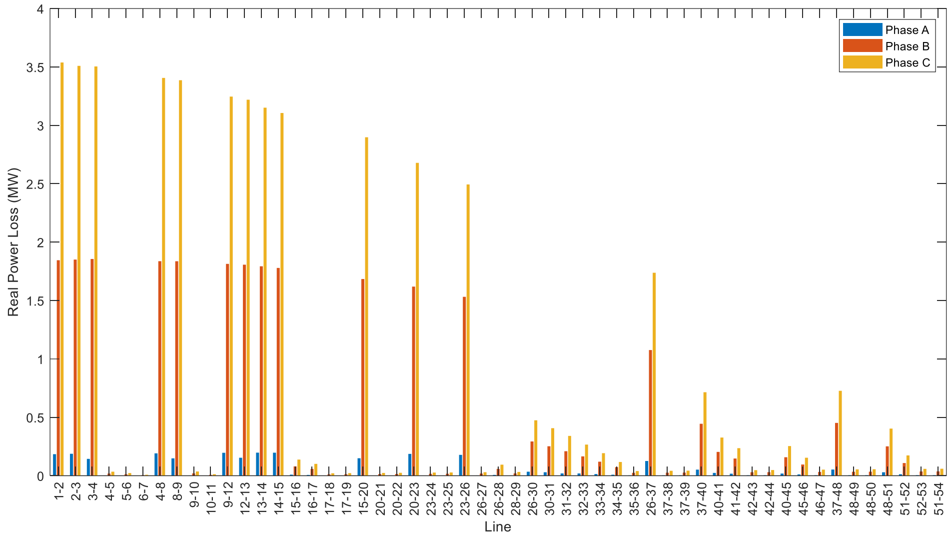

Figure 6. Real power losses of the Olusanya 62-bus network

3.1.3. Reactive power

Figure 7 illustrates the reactive power losses in all the lines of the network for phases A, B, and C. Like the real power losses as illustrated in Figure 6, Phase C still exhibited the highest reactive power losses as obviously revealed by lines 1-2, 2-3, 3-4, 4-8, 8-9, 9-12, 12-13, 13-14, 14-15, 15-20, 20-23, 23-26, etc., just to name a few cases, as presented in Figure 7. Phase A reactive power losses in all the lines were higher than those of phase B. In other words, all the lines in phase B exhibited the least reactive power losses as compared with those in phases A and C. The total reactive power loss in phase C was 36.64 kVAr, which was about 39.3% of the network's total reactive power loss, which was 93.3 kVAr. Reactive power loss contributions by phases A and B were 30.12 and 26.54 kVAr, corresponding to 32.3 and 28.4%, respectively. It was observed that phase B contributed the least amount of reactive power loss to the total reactive power loss in the network. This means that in the process of solving the problem of reactive power losses in the network, phase C should be given more attention, followed by phases A and B.

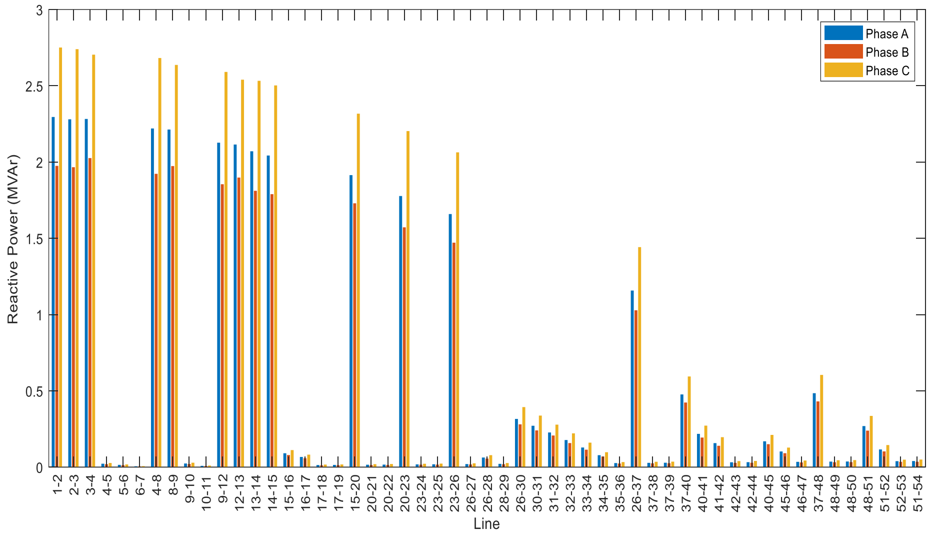

Figure 7. Reactive power losses of the Olusanya 62-bus network

Table 1 summarizes the simulation results of the three-phase power flow solution of the Olusanya 54-bus radial distribution network in a nutshell, allowing for a better understanding and appreciation of the application of three-phase power flow analysis to highly unbalanced radial distribution networks. Table 1 further confirms the assertion that the behavior of each of the three phases of a severely imbalanced radial distribution system is not equal.

Table 1. Summary of the simulation results of the Olusanya 54-bus network

Description	Phase A	Phase B	Phase C
Minimum voltage (p.u.)	0.9581	0.9658	0.9154
Total real power loss (kW)	2.67	26.00	45.82
Total reactive power loss (kVAr)	30.12	26.54	36.64
Total active power demand (MW)	1.03	1.56	4.80
Total reactive power demand (MVAr)	2.30	1.65	3.98
Total feeder capacity (MVA)	2.52	2.27	6.24

3.2. The Ajinde 62-Bus Network

The simulation results for the Ajinde 62-bus network's voltage profile are presented first, then those for the network's real power loss, and finally those for the network's reactive power loss.

3.2.1. Voltage profile

The power flow solution of this network converges in five iterations with an accuracy of 10^{-10}. Figure 8 illustrates the voltage profiles of all the three phases. A close analysis of Figure 8 revealed that phase B's voltage profile was lower than phases A and C's voltage profiles. This was a result of the fact that buses 57 through 62 in phase B have voltage magnitudes slightly lower than the acceptable lower voltage limit, while all the buses in phases A and C have voltage magnitudes very well within the acceptable voltage limits. The least voltage magnitude of 0.9812 p.u. was observed on bus 62 in phase A. Furthermore, the least voltage magnitude of 0.9491 p.u. was observed on bus 62 as well, in phase B. Similarly, the least voltage magnitude of 0.9843 p.u. was observed on bus 62 in phase C. Based on these simulation results and as corroborated by Figure 8, it was observed that phase C had the best voltage profile, followed by phase A and then phase B. This was as a result of the fact that phase B was highly loaded with real and reactive loads of 2.24 MW and 1.40 MVAr, respectively, as compared with those of phase A, which were 2.04 MW and 1.27 MVAr, respectively, and phase C, which were 1.93 MW and 1.21 MVAr, respectively. In addition, as shown in Figure 8, only phases A and C have voltage profiles that are well within the acceptable voltage limits, whereas phase B's voltage profile is not, necessitating voltage profile enhancement in this phase only and thus resulting in a low cost in enhancing the network voltage profile since only a phase is involved. Because the voltage profiles of the three phases were significantly distinct, the simulation results of the three-phase power flow analysis clearly indicate the genuine network state.

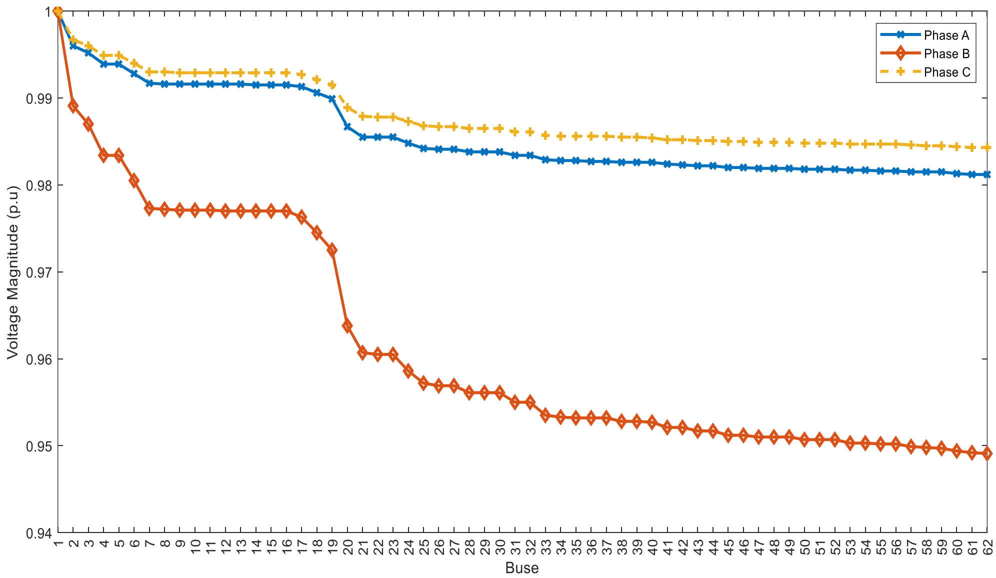

Figure 8. Voltage profile of the Ajinde 62-bus system

3.2.2. Real power

Figure 9 depicts the real power losses in all three phases of the network's lines. A careful examination of Figure 9 reveals that phase B has the highest power losses in all lines, as indicated by lines 1-2, 2-3, 3-4, 4-6, 6-7, 7-8, etc., just to name a few cases. When compared to phase A, phase C had higher real power losses in all lines. In other words, all the lines in phase A have the least real power losses. The overall real power loss in phase B was 33.42 kW, while those in phases A and C were 3.84 and 6.60 kW, respectively. Phase B contributed largely to the total real power loss in the network, which was 43.87 kW, which was about 76.2% of the total real power loss. Phases A and C exhibited real power loss contributions of about 8.75 and 15.04%, respectively, to the network's total real power loss. Figure 9 clearly indicated that phase B of the network was seriously suffering from real power loss and thus needed to be addressed.

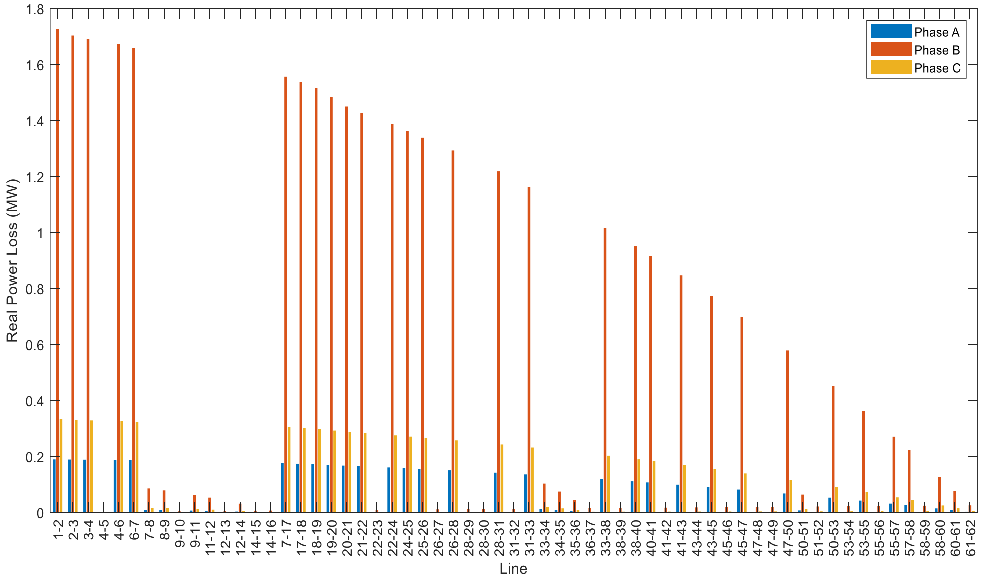

Figure 9. Real power losses of the Ajinde 62-bus network

3.2.3. Reactive power

Figure 10 illustrates the reactive power losses along the lines in phases A, B, and C. The reactive power losses in all the lines of phase A were extremely high, followed by those of phase B, as indicated by lines 1-2, 2-3, 3-4, 4-6, etc., just to name a few cases, as illustrated in Figure 10. However, all the lines in phase C exhibited extremely low reactive power losses. The total reactive power loss in phase A was 17.34 kVAr, that in phase B was 16.55 kVAr, and that in phase C was 3.72 kVAr. Phase A contributed about 46.1% of the network's total reactive power loss of 37.61 kVAr. Phases B and C contributed about 44 and 9.89%, respectively, to the total reactive power loss in the network. The simulation results of the three-phase power flow analysis demonstrated that the reactive power losses in all the lines of the three phases and the total reactive power losses in all the three phases were not equal and that phases A and B were the only phases that required compensation so as to drastically reduce the losses exhibited in all the lines of these two phases so as to improve the efficiency of the network significantly.

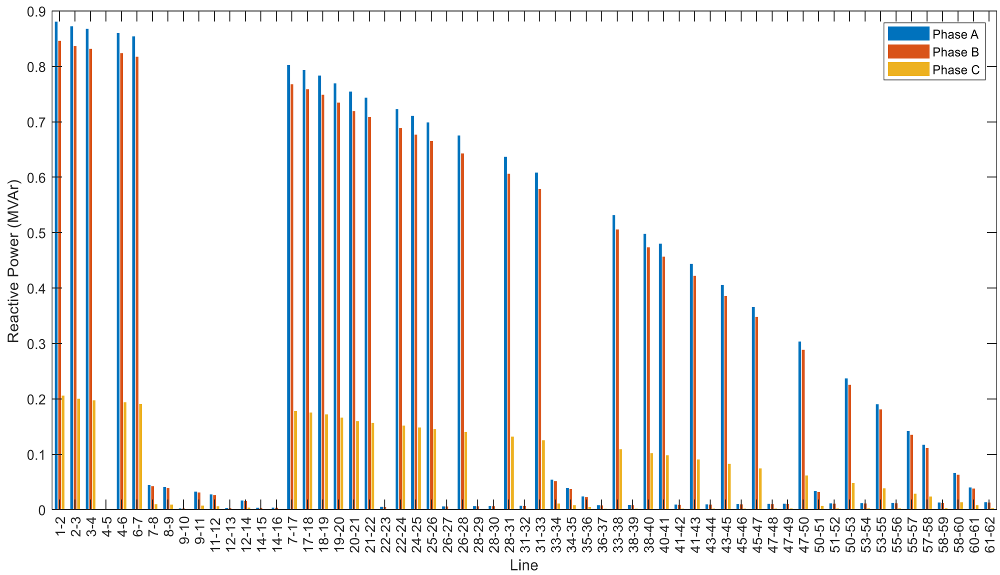

Figure 10. Reactive power losses of the Ajinde 62-bus network

For easier understanding, Table 2 gives the summary of the simulation results of the three-phase power flow solution of the Ajinde 62-bus radial distribution network. Also, Table 2 shows that the behaviors of the three phases of the network are not equal.

Table 2. Summary of the simulation results of the Ajinde 62-bus network

Description	Phase A	Phase B	Phase C
Minimum voltage (p.u.)	0.9812	0.9491	0.9843
Total real power loss (kW)	3.84	33.42	6.60
Total reactive power loss (kVAr)	30.12	26.54	36.64
Total active power demand (MW)	2.04	2.24	1.93
Total reactive power demand (MVAr)	1.27	1.40	1.21
Total feeder capacity (MVA)	2.40	2.64	2.28

3.3. Comparison of Results with the Single-Phase Power Method

The power flow solutions for the single-phase power flow algorithm and the three-phase power flow algorithm for the Olusanya 54-bus and Ajinde 62-bus radial distribution networks are compared in the ensuing subsections.

3.3.1. The Olusanya 54-Bus Network

Figure 11 compares the voltage profiles of each phase in the Olusanya 54-bus radial distribution network to those obtained using the single-phase power flow algorithm. In stark contrast to the voltage profile obtained using the single-phase power flow technique, phases A, B, and C's voltage profiles are not equal. Figure 11 makes it abundantly evident that the network voltage profile obtained using the single-phase power flow technique does not adequately capture the features of the distribution network under examination.

Figure 12 illustrates the real and reactive power loss comparison of the Olusanya 54-bus radial distribution network. It is evident from Figure 12 that the real and reactive power losses of the system obtained using the single-phase power flow algorithm do not actually reflect the exact real and reactive power losses in the network. Furthermore, the real and reactive power losses for the single phase were far lesser than the real and reactive power losses in each of the three phases obtained using the three-phase power flow algorithm proposed in this study. Hence, the single-phase power model of the network failed to reveal the actual nature of the network.

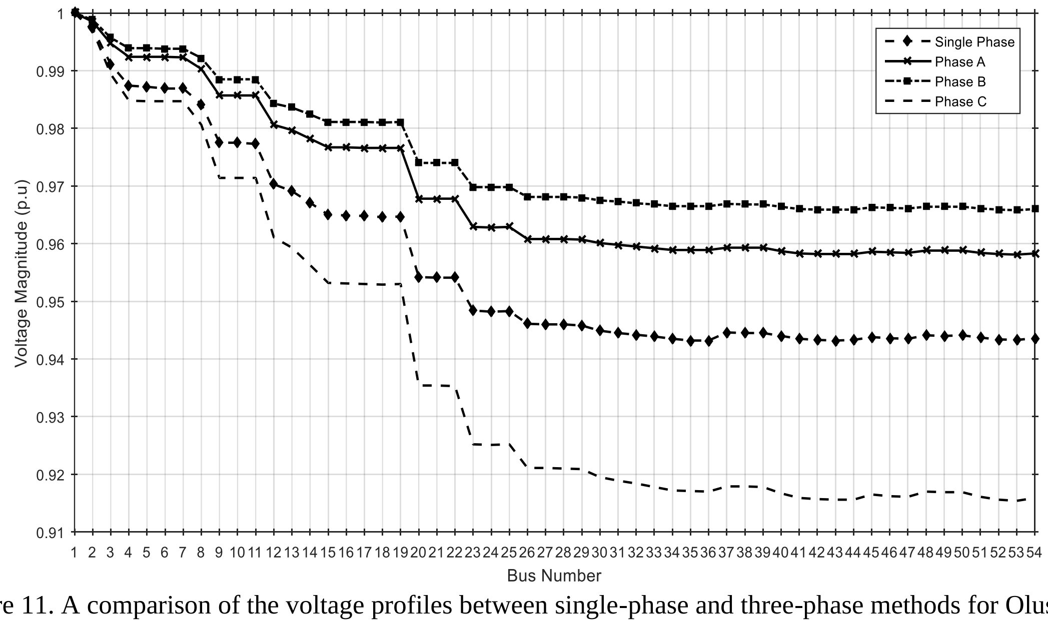

Figure 11. A comparison of the voltage profiles between single-phase and three-phase methods for Olusanya 54-bus network

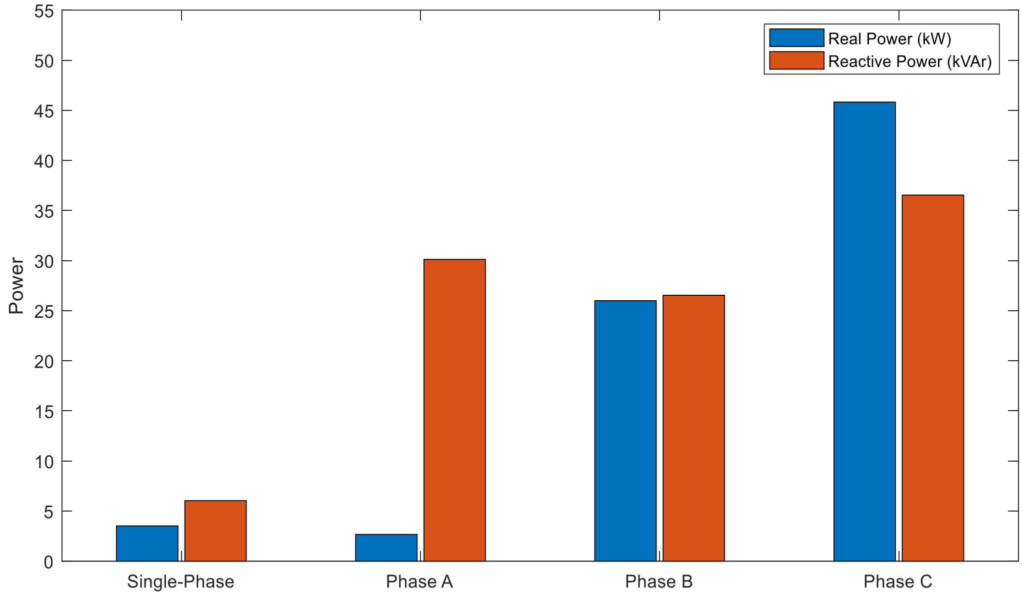

Figure 12. A comparison of the power losses between single-phase and three-phase methods for Olusanya 54-bus network

3.3.2. The Ajinde 62-Bus Network

The voltage profiles for each phase in the Ajinde 62-bus network are contrasted with the results from the single-phase power flow algorithm in Figure 13. Phases A, B, and C have voltage profiles that are very different from the single-phase power flow technique's voltage profile. The network voltage profile obtained using the single-phase power flow technique is clearly insufficient to capture the characteristics of the distribution network, as shown in Figure 13.

The Ajinde 62-bus radial distribution network's real and reactive power loss comparison is shown in Figure 14. Figure 14 makes it clear that the real and reactive power losses obtained for the network using the single-phase power flow algorithm are not an accurate representation of the real and reactive power losses in the network. Additionally, the real and reactive power losses for the single-phase algorithm were significantly lower than those for each of the phases computed using the three-phase power flow algorithm presented in this work. Consequently, the network's single-phase power model was unable to accurately depict the network's true unbalanced nature.

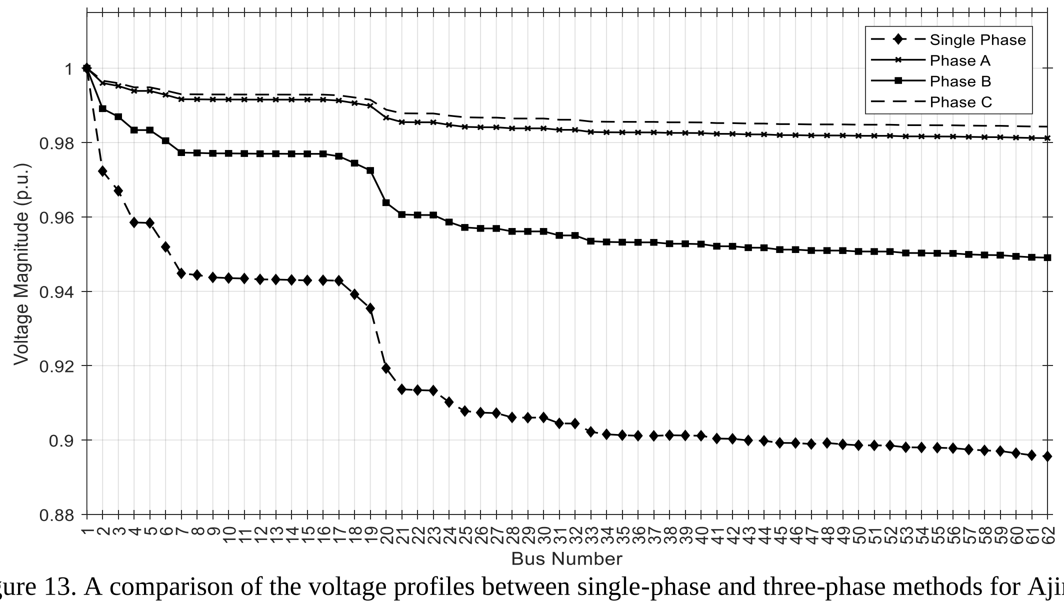

Figure 13. A comparison of the voltage profiles between single-phase and three-phase methods for Ajinde 62-bus network

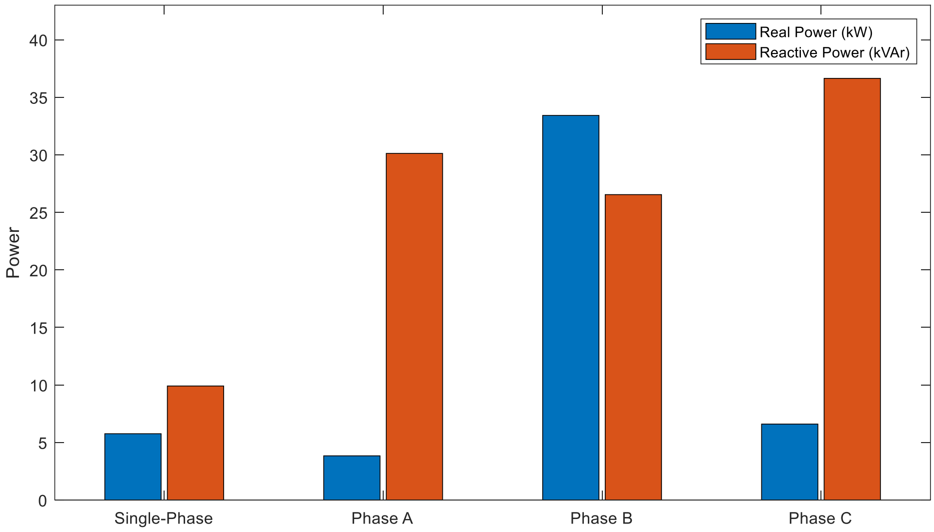

Figure 14. A comparison of the power losses between single-phase and three-phase methods for Ajinde 62-bus network

4. CONCLUSION

The paper has demonstrated the effectiveness of the application of three-phase power flow analysis on highly unbalanced radial distribution networks using two practical Nigerian distribution networks as case studies. The simulation results revealed that the three-phases of the Nigerian distribution networks under study behaved differently in terms of voltage profile and real and reactive power losses, as the networks were extremely unbalanced. However, single-phase power flow technique failed to show the true reflection of the two networks under study. Therefore, the three-phase power flow analysis accurately reflects the actual characteristics of the networks and should always be deployed in evaluating highly unbalanced radial distribution networks for network planning and future expansion.

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BIOGRAPHY OF AUTHORS

Samson Oladayo Ayanlade earned a Bachelor of Technology (B.Tech.) in Electronic and Electrical Engineering from Ladoke Akintola University of Technology in Ogbomoso, Oyo State, Nigeria in 2012 and an M.Sc. in Electronic and Electrical Engineering from the same institution in 2013. He was awarded a bachelor's degree in power system engineering by Obafemi Awolowo University, Ile-Ife, Osun State, Nigeria, in 2019. He is a doctoral candidate at Obafemi Awolowo University in Ile-Ife, Osun State, Nigeria. His studies focus on power system optimization, power system stability, and other related topics. He can be contacted at samson.ayanlade@lcu.edu.ng/ayanladeoladayo@gmail.com.

Abdulrasaq Jimoh graduated from the University of Ilorin with a bachelor's degree in electrical engineering in 2002 and a master's degree in electrical power system engineering from the University of Lagos in 2010. He is a member of the Nigerian Society of Engineers as well as a registered engineer with the Nigerian Council for Engineering Regulation. He is now working as a business manager at IBEDC while also studying for a Master of Philosophy at Obafemi Awolowo University in Ile-Ife, Nigeria. Voltage control and enhancement in distribution systems, as well as distribution system economics, are among his research interests. He may be reached at the following email address: jimohabdulrasaq@gmail.com.

Funso Kehinde Ariyo earned a B.Sc. in Electronic and Electrical Engineering, as well as a Master of Science and Ph.D. in Power System Engineering from Obafemi Awolowo University in Ile-Ife, Osun State, Nigeria. He is presently a senior lecturer in the Department of Electronic and Electrical Engineering at Obafemi Awolowo University, Nigeria. His research interests include, among other things, power system analysis, and modeling. He may be contacted at funsoariyo@yahoo.com.

Adedire Babatunde was awarded a Bachelor of Science (B.Sc.) in Electrical and Electronic Engineering by Olabisi Onabanjo University, Ago-Iwoye, Ogun State, Nigeria. He is currently employed at Applied Engineering Technology Initiative as a graduate trainee. System control and optimization are two of his main areas. He can be contacted at email: adedire95@gmail.com.

Abdulsamad Bolakale Jimoh, a final-year electrical and electronic engineering student at the University of Ilorin in Kwara State, Nigeria, was born in 1999. Energy management and power economics are two of his research interests. You can reach him at jimohabdulsamad@gmail.com.

Fatina Mosunmola Aremu was born in 2001 and is a final year student in the department of Electrical and Computer Engineering at Kwara State University, Malete, Kwara State, Nigeria. Her research interests include industrial power demand and energy loss mitigation. She can be contacted by email at aremufatina@gmail.com.