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Variations in phase conductor size and spacing on power losses on the Nigerian distribution network

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ABSTRACT

Most Nigerian distribution networks are examined on a single-phase basis, which fails to reflect the network's true features. Using three-phase power flow algorithms, this research explores the implications of variations in conductor sizes and spacing on power losses on a Nigerian network. Modified carson's equations were used to model the distribution lines to determine the network's impedance without presuming transposition of the lines. The conductor sizes and spacing were changed to see how they affected network power losses and how they contributed to the distribution network imbalance. The results showed that changing the conductor sizes of certain of the phases increased real power losses by 55.8 and 5.8%, respectively, in phases A and B. Phase C's was reduced by 13.04%. Furthermore, reactive power losses in phases A and B increased by 3.29 and 8.18%, respectively, whereas reactive losses in phase C dropped by 10.32%. Changing the conductor spacing in phases A, B, and C increased real power losses by 825.8, 136.2, and 13.2%, respectively, and reactive power losses by 72.86, 52.30, and 31.89%. Distribution networks should not be evaluated on a single-phase basis since losses differ in each of the three phases. Conductor size and spacing reductions cause huge losses.

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1. INTRODUCTION

In Nigeria, distribution networks are plagued by discrepancies in conductor sizes and spacing. Inequality in the conductor sizes of Nigeria's radial distribution networks is one of the causes of considerable power losses in the networks. In some distribution lines, the sizes of the conductors on each phase and in each segment of a realistic distribution network in Nigeria are completely different from one another. As power is transferred to end consumers, power losses occur throughout the networks, resulting in a significant reduction in income occasioned by losses.

Furthermore, in Nigeria, distribution networks have irregularly spaced conductors, resulting in differences in mutual inductances among phase conductors. Power losses in most Nigerian radial distribution networks are caused by variations in mutual inductances between conductor phases. The distances between conductors and the earth's surface are also not equal. This further reduces the amount of power provided and hence the loss in revenue.

Unfortunately, Nigerian electrical utility companies are more focused on metering for money generation than finding answers to these challenges [1]. They are oblivious to the fact that solving these challenges would actually make it easier to generate income. They also refuse to invest in bettering their consumers' electrical power quality delivery. As a result, Nigeria's electrical supply is erratic and unreliable [2]. Although the nigerian electricity regulatory commission (NERC) has standard regulations for electricity installation and services, enforcement is lax.

Similarly, Nigerian researchers failed to evaluate the impact of different conductor sizes per phase and per segment, as well as spacing disparities, on power losses in the Nigerian network. They are more interested in employing erroneous single-phase power flow models to solve Nigerian unbalanced distribution network power flow problems rather than employing three-phase models, which reflect the practical nature of the networks [3]-[8]. As a result, the true status of the networks is unknown. Only a few Nigerian scholars employed three-phase power flow models to investigate the country's highly imbalanced distribution networks [9]. The three-phase power flow in a power distribution system differs significantly from the three-phase power flow in a transmission network. The distribution network is characterized by a radial structure, an unbalanced load, and a large number of nodes. As a result, rather than a transmission network, which is usually examined on a single-phase basis, the system should always be analyzed on a three-phase basis. Radial distribution networks have a high resistance to reactance ratio and operate in an imbalanced manner, which can result in substantial power loss and voltage instability [10]-[12].

Many three-phase power flow methodologies for handling power flow problems in unbalanced radial distribution networks have been published in the literature [13]. Girardi and Leite [14] presented two techniques for calculating three-phase power flow in distribution networks. The steady state and behavior of the components in the electricity distribution network, such as buses with dispersed generation and regulated voltage, were assumed in the computational study. The performance of the power flow solution was evaluated using a single sweep approach, known as backward/forward sweep power flow, which maintained the high speed of execution required for real-time applications in distribution automation tools. Kumar and Kumar [15] proposed a linear power flow for an imbalanced distribution system that considers resistance, voltage magnitude, reactance, and voltage angle. The suggested approach was built and evaluated on unbalanced radial distribution systems with 19 and 25 buses, and it was compared to traditional backward-forward sweep power flow analysis. Rahman *et al*. [16] developed a three-phase power flow technique based on the current mismatch variation of the Newton Raphson to examine the impact of large single-phase PV penetration and how energy storage devices might help offset the unfavorable effect. The authors proposed a three-phase detailed modeling of the grid's essential components that may be used with the three-phase power flow method. Reddy *et al.* [17] considered radial distribution networks and used a compensation-based power flow approach for weakly-meshed structures that uses a multiport compensation method and kirchhoff's laws. A straightforward two-step procedure was implored to solve the radial part, in which the currents of the branch were first computed by the backward-sweep method, and then the voltages at the buses were revised by the forward-sweep method. Babu *et al.* [18] utilized the modified forward/backward approach to simulate load distribution equipment such as regulators, transformers, and switches that have constant power, constant impedance, and constant current. It was simple to solve the algebraic algorithmic voltage magnitude expression. In practical numerical experiments, [19] investigated the analytical equations of the load, three-phase load connection, and three-phase transformer connection, and expanded single-phase newton-raphson power flow methodologies to three-phase power flow concerns. The research looks at Newton-based power flow methods for balanced and unbalanced distribution networks with a large topology, with the issue description and coordinate specification influencing the outcomes. Alinjak *et al.* [20] provided modeling of distribution network elements and their application in the backward/forward sweep (BFS) power flow technique. The BFS approach was improved by using a breadth-first search strategy for network renumbering and the construction of a modified incidence matrix. Bannykh and Pazderin [21] proposed a three-phase power flow model for distribution grid analysis based on distribution grid power flow calculations. The imbalanced condition of the distribution grids is taken into account by the three-phase model used.

This study deploys a three-phase power flow model [22], which shows the true reflection of radial distribution networks with very few assumptions on the modeling of the networks' components, to investigate the impact of variations in phase conductor sizes per phase and per segment, as well as variations in the conductor spacing, on the power losses of a practical, highly unbalanced Nigerian radial distribution network.

2. METHOD

This work proposes the application of a three-phase power flow approach to investigate the effect of variations in conductor sizes and spacing on power losses in a practical Nigerian 11 kV Olusanya distribution network. The three-phase power flow approach discussed in section 2.2 was implemented in MATLAB software to carry out the study.

2.1. Distribution networks line model

In the analysis of electrical transmission networks, two important assumptions are that the currents in the three phases are balanced and that the conductors must be transposed. However, neither of these assumptions holds true for distribution systems. The assumption of balanced three-phase currents is not applicable due to the preponderance of single-phase loads and uneven conductor diameters and spacing. Distribution lines are seldom transposed, and the conductor arrangement cannot be expected to represent an equilateral triangle. When these two assumptions are proven to be false, a more precise technique of estimating line impedance must be used. Carson's equations [23] may be used to build a generic description of a distribution system with *N* conductors, resulting in a *N*×*N* primitive impedance matrix. The primitive impedance matrices, including the self and mutual impedances of each branch, must be reduced to the same size for most applications. A 3×3 matrix in the phase frame, consisting of the self and mutual equivalent impedances for the three phases, is a useful representation. Kron's reduction [24], based on Kirchhoff's principles, is the traditional approach for forming this matrix. A four-wire grounded wye overhead distribution line, such as the one illustrated in Figure 1, produces a four-wire impedance matrix [25]. The equations that go with it are as:

$$\begin{bmatrix} V_i^a \\ V_i^b \\ V_i^c \\ V_i^n \end{bmatrix} = \begin{bmatrix} V_i^a \\ V_i^b \\ V_i^c \\ V_i^n \end{bmatrix} + \begin{bmatrix} Z_{ij}^{aa} & Z_{ij}^{ab} & Z_{ij}^{ac} & Z_{ij}^{an} \\ Z_{ij}^{ba} & Z_{ij}^{bb} & Z_{ij}^{bc} & Z_{ij}^{bn} \\ Z_{ij}^{ca} & Z_{ij}^{cb} & Z_{ij}^{cc} & Z_{ij}^{cn} \\ Z_{ij}^{na} & Z_{ij}^{nb} & Z_{ij}^{nc} & Z_{ij}^{nn} \end{bmatrix} \begin{bmatrix} I_{ij}^a \\ I_{ij}^b \\ I_{ij}^c \\ I_{ij}^n \end{bmatrix} \quad (1)$$

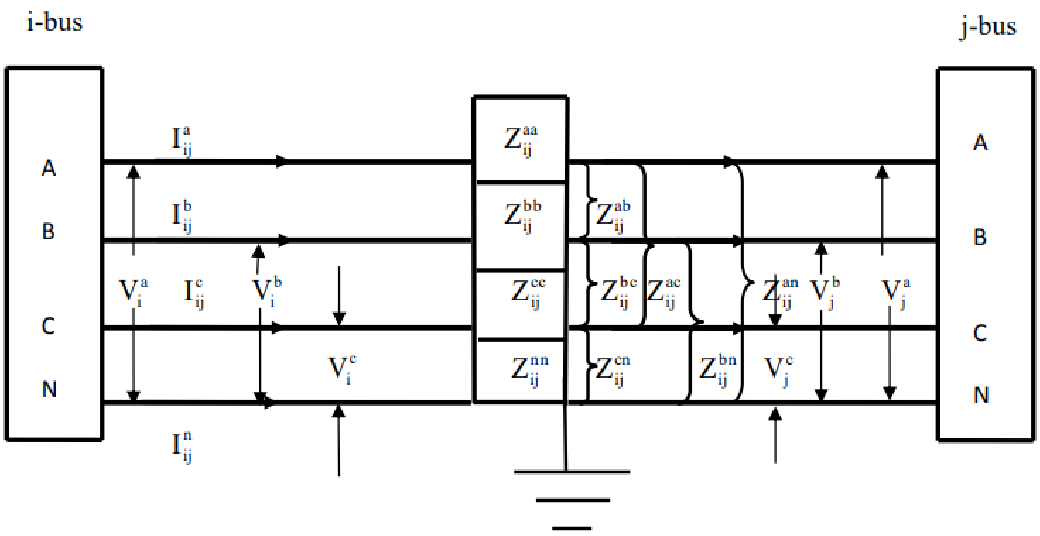

Figure 1. Model of the three-phase four-wire distribution line

It can also view in matrix form as

$$\begin{bmatrix} V_i^{abc} \\ V_i^n \end{bmatrix} = \begin{bmatrix} V_j^{abc} \\ V_j^n \end{bmatrix} + \begin{bmatrix} Z_{ij}^{abc} & Z_{ij}^n \\ Z_{ij}^{n^T} & Z_{ij}^{nn} \end{bmatrix} \begin{bmatrix} I_{ij}^{abc} \\ I_{ij}^n \end{bmatrix} \quad (2)$$

If neutral is grounded, the voltages V_i^n and V_j^n are considered to be equal. Then from the first row of (2), the value of I_{ij}^n can be obtained as

$$I_{ij}^n = -Z_{ij}^{nn^{-1}} Z_{ij}^{n^T} I_{ij}^{abc} \quad (3)$$

Substituting (3) into (2), the Kron's reduction of voltage equation reduces to

$$V_i^{abc} = V_j^{abc} + Ze_{ij}^{abc} I_{ij}^{abc} \tag{4}$$

where,

$$Ze_{ij}^{abc} = Z_{ij}^{abc} - Z_{ij}^{n} Z_{ij}^{nn^{-1}} Z_{ij}^{n^T} = \begin{bmatrix} Ze_{ij}^{aa} & Ze_{ij}^{ab} & Ze_{ij}^{ac} \\ Ze_{ij}^{ba} & Ze_{ij}^{bb} & Ze_{ij}^{bc} \\ Ze_{ij}^{ca} & Ze_{ij}^{cb} & Ze_{ij}^{cc} \end{bmatrix} \tag{5}$$

2.2. Three-phase power flow analysis for radial distribution system

For a three-phase radial distribution system, the current at bus j is given as [26]:

$$I_{abcj} = Y_{abckj} V_{abckj} - Y_{abcjm} V_{abcjm} - Y_{abcjp} V_{abcjp} \tag{6}$$

In expanded form, (6) becomes

$$\begin{aligned} I_{abcj} &= \begin{bmatrix} \frac{1}{2} Ysh_{abckj} + Y_{abckj} & -Y_{abckj} \\ -Y_{abckj} & \frac{1}{2} Ysh_{abckj} + Y_{abckj} \end{bmatrix} V_{abckj} \\ &- \begin{bmatrix} \frac{1}{2} Ysh_{abckj} + Y_{abckj} & -Y_{abckj} \\ -Y_{abckj} & \frac{1}{2} Ysh_{abckj} + Y_{abckj} \end{bmatrix} V_{abcjm} \\ &- \begin{bmatrix} \frac{1}{2} Ysh_{abckj} + Y_{abckj} & -Y_{abckj} \\ -Y_{abckj} & \frac{1}{2} Ysh_{abckj} + Y_{abckj} \end{bmatrix} V_{abcjp} \end{aligned} \tag{7}$$

$$I_{qj} = \sum_{q=a,b,c}^{c} \quad \sum_{k,m=1}^{n} Y_{qkj} V_{qkj} \tag{8}$$

The complex power equations are given as:

$$\begin{aligned} S_{qk} &= V_{qk} \left(\sum_{q=a,b,c}^{c} \sum_{k,j=1}^{n} Y_{qkj} V_{qkj} \right)^* = \sum_{q=a,b,c}^{c} \sum_{k,j=1}^{n} V_{qk} (V_{qj})^* (Y_{qkj})^* \\ S_{qj} &= V_{qj} \left(\sum_{q=a,b,c}^{c} \sum_{k,j=1}^{n} Y_{qkj} V_{qjk} \right)^* = \sum_{q=a,b,c}^{c} \sum_{k,j=1}^{n} V_{qj} (V_{qj})^* (Y_{qjk})^* \end{aligned} \tag{9}$$

Expressing the voltages in polar form and applying Euler's formula, (9) yields

$$\begin{aligned} S_{qk} &= \sum_{q=a,b,c}^{c} \sum_{k,j=1}^{n} \left(|V_{qk}| e^{j\delta_{qk}}\right)\left(|V_{qj}| e^{-j\delta_{qj}}\right)\left(Y_{qkj}\right) \\ S_{qj} &= \sum_{q=a,b,c}^{c} \sum_{j,k=1}^{n} \left(|V_{qj}| e^{j\delta_{qj}}\right)\left(|V_{qk}| e^{-j\delta_{qk}}\right)\left(Y_{qjk}\right) \end{aligned} \tag{10}$$

$$\begin{aligned} S_{qk} &= \sum_{q=a,b,c}^{c} \sum_{k,j=1}^{n} |V_{qk}||V_{qj}| \left(\cos \delta_{qkj} + j \sin \delta_{qkj}\right)\left(Y_{qkj}\right) \\ S_{qj} &= \sum_{q=a,b,c}^{c} \sum_{j,k=1}^{n} |V_{qj}||V_{qj}| \left(\cos \delta_{qjk} + j \sin \delta_{qjk}\right)\left(Y_{qjk}\right) \end{aligned} \tag{11}$$

where,

$$\delta_{qkj} = \delta_{qk} - \delta_{qj}$$
$$\delta_{qjk} = \delta_{qj} - \delta_{qk} \qquad (12)$$
$$Y_{qkj} = G_{qkj} + jB_{qkj}$$

Substitute (11) into (12) and dividing into real and imaginary parts results in (13).

$$P_{qk} = \sum_{q=a,b,c}^{c} \sum_{k,j=1}^{n} |V_{qk}||V_{qj}| \left(Y_{q_{kj}} cos(\delta_{qk} - \delta_{qj}) + Y_{qkj} sin(\delta_{qk} - \delta_{qj})\right)$$
$$Q_{qk} = \sum_{q=a,b,c}^{c} \sum_{k,j=1}^{n} |V_{qk}||V_{qj}| \left(Y_{q_{kj}} sin(\delta_{qk} - \delta_{qj}) - Y_{qkj} cos(\delta_{qk} - \delta_{qj})\right)$$
$$P_{qj} = \sum_{q=a,b,c}^{c} \sum_{j,k=1}^{n} |V_{qj}||V_{qk}| \left(Y_{q_{jk}} cos(\delta_{qj} - \delta_{qk}) + Y_{qjk} sin(\delta_{qj} - \delta_{qk})\right) \qquad (13)$$
$$Q_{qj} = \sum_{q=a,b,c}^{c} \sum_{j,k=1}^{n} |V_{qj}||V_{qk}| \left(Y_{q_{jk}} sin(\delta_{qj} - \delta_{qk}) - Y_{qjk} cos(\delta_{qj} - \delta_{qk})\right)$$

The power mismatch equations with generator internal buses are presented as:

$$\Delta P_{abck} = P_{abc(gen)k} - P_{abc(load)k} - P_{abc(calculated)k}$$
$$= P_{abc(scheduled)k} - P_{abc(calculated)k} = 0$$
$$\Delta Q_{abck} = Q_{abc(gen)k} - Q_{abc(load)k} - Q_{abc(calculated)k} \qquad (14)$$
$$= Q_{abc(scheduled)k} - Q_{abc(calculated)k} = 0$$

$$\Delta P_{abck} = P_{abc(scheduled)k} - \sum_{a,b,c=1}^{3} \sum_{k,j=1}^{n} (V_{abck})^2 Y_{abckk} + V_{abck} Y_{abckj} V_{abcj} cos(\delta_k - \delta_j - \theta_{kj}) = 0 \qquad (15)$$
$$\Delta Q_{abck} = Q_{abc(scheduled)k} - \sum_{a,b,c=1}^{3} \sum_{k,j=1}^{n} V_{abck} Y_{abckj} V_{abcj} sin(\delta_k - \delta_j - \theta_{kj}) = 0$$

The new estimates for the three phase voltages and phase angles are given by (17) and (18).

$$V_{abck}^{(n+1)} = V_{abck}^{(n)} + \Delta V_{abck}^{(n)} \qquad (16)$$

$$\delta_{abck}^{(n+1)} = \delta_{abck}^{(n)} + \Delta \delta_{abck}^{(n)} \qquad (17)$$

2.3. Description of olusanya 11 kV feeder

The Olusanya 11 kV distribution network is a 54-bus practical Nigerian distribution network that radiates from ibadan electricity distribution company's oluyole 15MVA, 33/11 kV injection substation in Ibadan, Nigeria. The feeder is characterized by different conductor sizes per section and most often per phase. In addition, the lines are untransposed and the connected end-users' loads are unevenly distributed per phase, as well as unequal conductor spacing. This makes the network highly imbalanced. The single-line diagram of this network is illustrated in Figure 2. The load and the line data of this distribution network are obtained from the ibadan electricity distribution company of nigeria (IBEDC). The three-phase power flow strategy given in the preceding part is applied to this network to solve the power flow problems of this imbalanced distribution network.

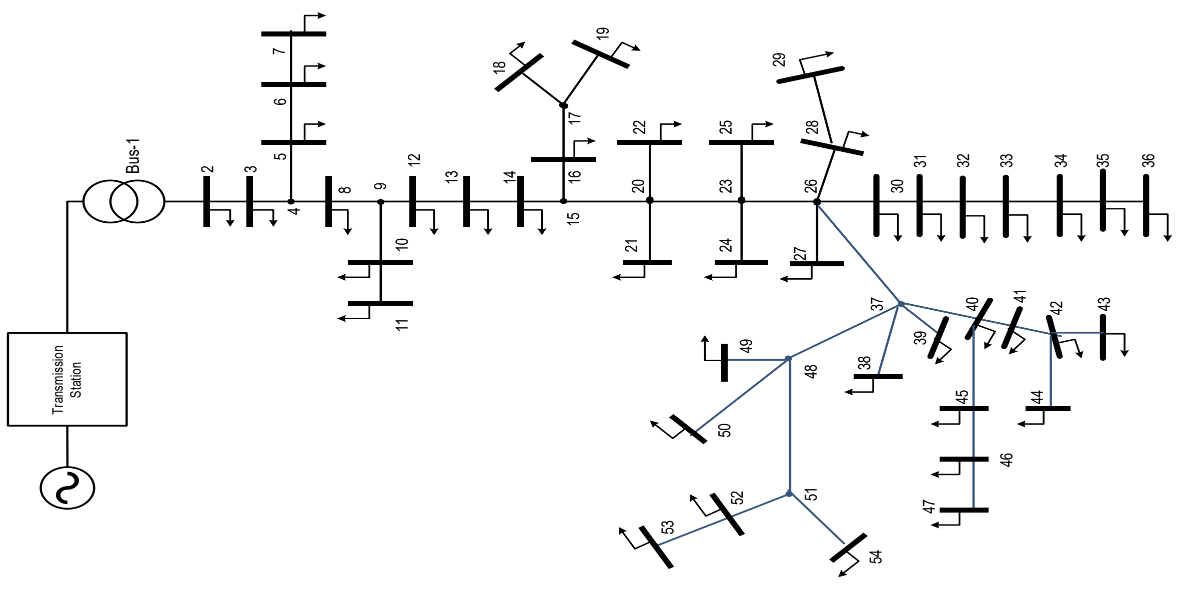

Figure 2. Single-line diagram of Olusanya 11 kV feeder

3. RESULTS AND DISCUSSION

Variations in conductor size and spacing were studied to discover what influence they had on the system. The investigations were based on the effect of variations in the conductor size and spacing on the network power losses in all the lines, as well as the overall network power loss.

3.1. Effect of variation in conductor sizes

Of 53 lines, the sizes of 24 lines in all three phases were reduced at various phases. Some are from 150 to 50 mm^2, while others are from 150 to 100 mm^2. The results of the effects of variations in the conductor size on the active power losses on all the phases are presented in Table 1 (in appendix). Similarly, the results of the effects of variations in conductor size on the reactive power losses on all the phases are shown in Table 2 (in appendix). In Tables 1 and 2, the lines in bold face are those whose conductor sizes were reduced. It was observed from Tables 1 and 2 that there were insignificant real and reactive power losses on the lines whose sizes were not varied.

However, there is a significant rise in the real and reactive power losses of the lines whose conductor sizes were reduced. For instance, in Table 1, the active power losses on phases A and C of the line 3-4, which were 0.144 and 3.50 kW, respectively, were tremendously increased to 0.54, and 4.17 kW, respectively. The reason for this is that reducing the size of the conductor per phase increases the resistance of the conductor per phase because resistance is inversely proportional to conductor size, resulting in an increase in active power losses (I^2R) on these phases. Nevertheless, the real power loss on phase B of line 3-4, which is 1.86 kW, was reduced to 0.71 kW. This is so because phase B is sandwiched between phases A and C, and the increase in the mutual inductances between the two phases (A and B) as well as the B and C phases is responsible for the decrease in real power loss in phase B. This phenomenon was observed in all the phases of the lines, whose sizes were varied. The overall real power losses on phases A and B, which were initially 2.67 and 45.82 kW, respectively, were increased to 4.16 and 48.48 kW, corresponding to 55.8 and 5.8%, respectively. While that of phase C, which was 26.00 kW, was reduced to 22.61 kW, corresponding to 13.04%.

Similarly, the reactive power on phases A and B of the line 3-4, which are 2.28 and 2.03 kVar, respectively, was slightly increased to 2.48 and 2.03 kVar, respectively. However, the reactive power loss on phase C of the line, which was 2.70 kVar, was reduced to 1.13 kVar. Concerning the reactive power losses on phase C of the rest of the other lines, a slight decrease was noticed in the reactive power losses when the sizes of the conductors of the selected lines were reduced. However, the overall reactive power losses on phases A and B, which were 30.12 and 26.54 kVar, were increased to 31.11 and 28.71 kVar, respectively, corresponding to 3.29 and 8.18%, whereas the overall reactive power loss on phase C, which was 36.64 kVar, was reduced to 32.86 kVar, corresponding to a 10.32% decrease in reactive power loss. This is due to the fact that only a few conductor spacings were reduced in phase C as compared to the other two phases.

3.2. Effect of variation in conductor spacing

Simulations were also performed when the conductor spacing was varied. The effect of variations in conductor spacing on the real and reactive power losses in all the lines and the overall power loss was investigated, and the results are presented in Tables 3 and 4 (in appendix), respectively. In Tables 3 and 4, the lines in bold faces are those whose conductor spacing was varied. From Table 3, it was observed that almost all the lines exhibit increases in real power losses, while only a few lines exhibit decreases in real power losses.

The overall real power losses on the three phases (A, B, and C), which stood at 2.67, 26.00, and 45.82 kW, respectively, were increased to 24.72, 61.40, and 51.88 kW. Similarly, the same phenomena also occur as far as the reactive power loss is concerned, as presented in Table 3. Also, the overall reactive power losses on phases A, B, and C, which stood at 30.12, 26.54, and 36.63 kW, respectively, were increased to 52.065, 40.42, and 48.31 kW, corresponding to 72.86, 52.30, and 31.89%, respectively. The tremendous increase in the overall real and reactive power losses in all the three phases is as a result of an increase in the mutual inductances between any of the two conductors in any of the three phases as a result of a decrease in conductor spacing.

4. CONCLUSION

This study has presented and applied the three-phase power flow technique, which is based on phase frame theory, to the Olusanya 54-bus network, which is a practical Nigerian radial distribution network, to investigate the effect of variations in conductor sizes and spacing on the network. The results reveal that variations in conductor diameters and spacing cause the radial distribution network to be unbalanced, resulting in increased network power losses. Therefore, three-phase power flow is a valuable tool for analyzing and planning how electric power distribution networks operate, as opposed to single-phase power flow, which makes multiple assumptions and so limits the method's accuracy.

APPENDIX

Table 1. Real power loss with variations in conductor size

	Base case (W)			Conductor size (W)		
Line	Pa	Pb	Pc	Pa	Pb	Pc
1-2	1.844.467	1.845.082	3.538.174	1.847.227	1.842.538	3.532.323
2-3	187.864	1.850.753	3.509.168	188.124	1.848.176	3.503.386
3-4	1.442.146	1.855.674	3.504.239	**5.397.493**	**7.139.645**	**4.174.688**
4-5	2.089.382	1.867.119	3.449.276	2.097.731	1.863.352	3.453.871
5-6	106.145	1.223.237	2.279.243	**6.619.641**	**1.065.226**	**2.613.399**
6-7	0.391111	4.506.794	8.396.864	**2.438.698**	**3.924.737**	**9.628.007**
4-8	1.915.375	1.836.828	3.405.982	1.924.257	1.831.284	3.406.623
8-9	1.485.838	1.836.343	3.386.142	**777.439**	**1.872.451**	**3.843.185**
9-10	2.295.662	2.023.723	3.638.891	4.763.089	2.070.157	3.687.846
10-11	0.814649	71.812	1.291.171	**1.186.305**	**4.485.151**	**1.435.995**
9-12	1.963.712	1.813.702	3.246.042	**2.596.588**	**1.442.881**	**3.475.144**
12-13	1.538.868	1.806.814	3.219.311	**2.561.614**	**9.234.864**	**3909.17**
13-14	1.975.295	1.793.175	3.151.203	1.990.594	1789.97	3.157.495
14-15	1.971.189	1.779.041	3.105.598	1.986.365	1.775.847	3111.83
15-16	9.196.484	7.982.496	1.382.676	**1.231.428**	**6.366.132**	**1.464.782**
16-17	6.745.334	5.854.226	101.386	679.569	5.847.127	1.016.589
17-18	137.992	1.197.537	2.073.639	**0.157066**	**7.325.478**	**2.378.822**
17-19	1.152.042	1.264.305	220.793	**2.084.106**	**102.787**	**2.322.743**
15-20	1.495.877	1.684.178	2.897.857	**2.565.685**	**1.342.644**	**3.045.769**
20-21	1.658.438	1.423.091	237.534	1.680.506	1.418.946	238.392
20-22	1.737.429	1.490.882	2.488.429	1.760.547	1.486.539	2.497.418
20-23	186.782	1.619.332	2.678.689	1.893.019	1.614.554	2.688.251
23-24	1.543.996	1.644.289	270.875	**7.920.167**	**1.495.161**	**3.152.743**
23-25	2.005.596	1.711.916	2.797.133	2.032.125	1.706.941	2.807.345
23-26	1.785.513	1.531.761	2.493.867	1.809.304	1.527.257	2.502.871
26-27	2.179.282	1.856.747	3.007.382	2.208.052	1.851.356	301.841
26-28	6.860.639	5.845.618	946.761	6.951.216	5.828.645	9.502.327
28-29	2.341.144	1.994.606	3.229.677	237.205	1.988.815	3.241.522
26-30	3.436.244	2.933.484	4.745.084	3.481.699	2.924.923	4.762.408
30-31	295.879	2.522.606	4.070.662	2.997.867	2.515.244	408.554
31-32	1.977.683	2.097.434	3.408.341	**9.983.253**	**191.596**	**3.972.927**
32-33	1.944.369	1.655.859	2.665.291	1.970.372	1.650.997	2.675.156
33-34	141.139	1.201.133	1.930.698	143.025	1.197.607	193.785
34-35	8.604.047	7.319.172	1.175.618	8.718.964	7.297.694	1.179.976

Table 1. Real power loss with variations in conductor size (continue)

	Base case (W)			Conductor size (W)		
Line	Pa	Pb	Line	Pa	Pb	Line
35-36	2.922.426	2.485.905	3.992.366	2.961.456	247.861	4.007.166
26-37	1.259.897	1.075.979	1.737.731	1.276.604	1.072.812	1.744.022
37-38	3.081.102	2.621.736	4.218.034	3.121.721	261.413	4.233.554
37-39	3.162.195	2.690.748	4.329.018	**3.664.959**	**1.413.906**	**5.396.689**
37-40	5.221.094	4.446.965	7.147.327	5.290.382	4.433.903	7.173.269
40-41	2.396.133	2.038.836	3.269.674	**2.761.736**	**1.072.921**	**407.706**
41-42	1.731.986	1.472.755	2.359.022	**1.989.901**	**7.753.138**	**2.942.325**
42-43	349.771	2.973.647	4.761.168	**4.014.411**	**1.565.628**	**5.938.945**
42-44	3.579.017	3.042.741	4.871.947	3.628.858	3.032.692	4.891.411
40-45	1.859.745	1.582.111	2.538.639	1.884.258	1.577.521	2.547.991
45-46	1.129.357	9.605.396	1.540.415	1.144.239	9.577.534	1.546.091
46-47	3.820.096	3.248.462	5.207.219	3.870.424	3.239.041	5.226.414
37-48	5.309.849	4.522.337	7.269.992	**8.751.785**	**2.526.284**	**814.338**
48-49	3.978.541	3.384.055	5.433.203	**6.532.353**	**189.129**	**6.087.174**
48-50	4.059.736	3.453.118	5.544.084	**6.665.666**	**1.929.888**	**6.211.402**
48-51	2.955.651	2.515.293	4.035.369	**4.851.595**	**1.405.924**	**4.521.327**
51-52	1.276.437	1.085.549	1.738.964	**2.088.604**	**6.070.374**	**194.876**
52-53	431.171	366.561	5.867.775	**7.044.009**	**2.050.252**	**6.576.319**
51-54	4.390.001	3.732.932	5.981.721	**7.184.763**	**2.087.329**	**670.321**

Table 2. Reactive power loss with variations in conductor size

	Base case (VAR)			Conductor size (VAR)		
Line	Qa	Qb	Line	Qa	Qb	Line
1-2	2295.47	1.975.033	2.750.878	2.291.648	1.971.314	2.746.591
2-3	2280.26	1.966.228	2.740.116	2.276.474	1.962.524	2.735.843
3-4	2282.56	2.026.144	2.704.118	**2.475.643**	**2033.48**	**1.127.663**
4-5	2.246.348	1.931.301	2.719.335	2.247.168	1.929.871	2.720.045
5-6	1.485.429	1.311.571	1.767.267	**1.736.069**	**2.412.509**	**1.544.323**
6-7	5.472.462	4.832.023	651.089	6.395.925	8.888.162	5.689.596
4-8	2.220.211	1.922.823	2.682.109	2.218.495	1918.98	2.679.871
8-9	2.213.207	1.973.716	2.636.814	**2.861.734**	**3.362.799**	**2.229.348**
9-10	2.379.978	2.059.966	2.898.542	2.518.511	1.809.706	2.820.133
10-11	8.444.865	7.309.492	1.028.505	**9.457.548**	**7.668.369**	**6.639.777**
9-12	2.127.068	1.854.576	2.590.827	**2.139.198**	**1.927.068**	**2.518.451**
12-13	2.114.913	1.898.393	2.539.938	**2.065.522**	**2.224.522**	**2.083.599**
13-14	2070.65	1.811.557	2.532.654	2.070.209	1810.16	2.533.546
14-15	2042.81	1789.42	2.502.372	2.042.378	1.788.045	2.503.256
15-16	9.099.259	7.947.873	1.117.288	**9.815.989**	**8.020.228**	**7.795.153**
16-17	6.672.299	5.828.202	8.193.148	6.675.306	5.827.978	8.201.404
17-18	1.364.713	1.192.106	1.675.833	**1.438.595**	**1.228.472**	**1.161.992**
17-19	1.453.984	1.304.481	1.755.198	**1.565.424**	**1.309.828**	**1.249.509**
15-20	1.914.302	1.729.645	2.317.227	**2046.01**	**1.684.574**	**1.632.866**
20-21	1.573.043	1.386.044	1.946.731	1.573.005	1.386.282	1.949.696
20-22	1.647.943	1.452.051	2.039.434	1.647.903	14.523	204.254
20-23	1.777.336	1.572.074	2.203.131	1.777.202	1.572.251	2.206.371
23-24	1.801.646	1.638.798	2.202.215	**2.146.874**	**3.079.796**	**1.959.203**
23-25	1.859.387	1.646.458	2.311.344	185.935	1.646.784	2.314.884
23-26	1.659.094	1.471.516	2.063.636	1.658.989	1.471.734	2.066.708
26-27	2.002.297	1.776.554	2.493.472	200.226	1.776.925	24.973
26-28	6.303.558	5.593.016	784.994	6.303.442	5.594.185	7.861.991
28-29	2.150.422	1.908.123	2.678.099	2.150.382	1.908.523	2.682.211
26-30	3.160.181	2.805.645	3.936.277	3.160.069	2.806.178	3.942.252
30-31	2.712.149	2.408.911	3.379.937	2.712.052	2.409.376	3.385.069
31-32	2.272.559	2.073.976	2.785.719	**2.714.111**	**3.906.719**	**2.482.958**
32-33	1.776.577	1.578.694	2.215.175	1.776.516	1.579.046	2.218.614
33-34	1.287.235	1.144.143	1.605.491	1.287.193	1.144.401	1.607.986
34-35	7.839.079	6.968.534	9.778.735	7.838.822	6.970.118	9.793.938
35-36	2.662.193	2.366.618	3.321.003	2.662.106	2.367.156	3.326.167
26-37	1.157.664	1.028.256	1.442.412	1.157.585	1.028.413	1.444.558
37-38	2.811.766	2.498.579	3.506.318	2.811.718	2.499.123	3.511.711
37-39	2.885.754	2.564.335	3.598.591	**2.856.893**	**3.262.133**	**294.023**
37-40	4.765.466	4.236.348	5.943.704	4.765.143	4.237.003	5.952.573
40-41	2.180.894	1.939.549	2.721.366	**2.158.824**	**2.468.481**	**222.5**
41-42	1.573.811	1.399.937	1.964.331	**155.806**	**1.782.043**	**1.606.501**
42-43	317.662	2.825.884	3.965.196	**314.493**	**3.597.389**	**3.243.174**
42-44	3.250.511	289.159	4.057.407	3.250.836	2.891.726	4.063.868
40-45	1.693.104	1.505.484	2.112.465	1.693.075	1.505.815	2.115.715
45-46	1.027.456	9.136.969	1.282.092	1.027.439	913.899	1.284.066
46-47	3.473.487	3.089.172	4.334.734	347.343	3.089.858	4.341.407

Table 2. Reactive power loss with variations in conductor size (continue)

Line	Base case (VAR) Qa	Qb	Line	Conductor size (VAR) Qa	Qb	Line
37-48	4.847.057	430.862	604.522	**4.871.281**	**4.837.582**	**4.138.414**
48-49	3.623.176	3.221.124	4.520.076	**3.641.699**	**3.617.701**	**3.095.218**
48-50	3.697.118	3.286.861	4.612.323	**3.716.019**	**3.691.532**	**3.158.385**
48-51	2.691.428	2.393.396	3.358.143	**2.705.127**	**2.688.274**	**2.299.782**
51-52	1.160.126	1.031.954	1.447.966	**1.166.117**	**115.944**	**9.919.066**
52-53	3.915.103	3.483.014	4.887.223	**3.935.469**	**3.913.867**	**3.348.387**
51-54	3.990.378	3.549.164	4.980.139	**4.011.002**	**3.987.468**	**3.411.418**

Table 3. Real power loss with variation in conductor spacing

Line	Base case (VAR) Qa	Qb	Line	Conductor size (VAR) Qa	Qb	Line
1-2	1.844.467	1.845.082	3.538.174	**1.844.931**	**1.845.165**	**3.538.265**
2-3	187.864	1.850.753	3.509.168	2.799.556	4335.37	5.381.789
3-4	1.442.146	1.855.674	3.504.239	1.962.566	1.840.724	3.473.138
4-5	2.089.382	1.867.119	3.449.276	**5.655.415**	**1.032.639**	**3.367.626**
5-6	106.145	1.223.237	2.279.243	1.399.137	1.212.851	2.258.862
6-7	0.391111	4.506.794	8.396.864	0.515519	4.468.525	8.321.776
4-8	1.915.375	1.836.828	3.405.982	1.961.348	1.821.167	3.404.657
8-9	1.485.838	1.836.343	3.386.142	1.992.097	1.820.841	3.355.922
9-10	2.295.662	2.023.723	3.638.891	2.344.665	2.005.809	3.637.428
10-11	0.814649	71.812	1.291.171	**2.151.283**	**3.902.277**	**1.261.043**
9-12	1.963.712	1.813.702	3.246.042	**5.395.996**	**9.862.039**	**3.169.374**
12-13	1.538.868	1.806.814	3.219.311	**5.350.461**	**9737.91**	**3.117.195**
13-14	1.975.295	1.793.175	3.151.203	8.884.072	2.523.214	3.642.947
14-15	1.971.189	1.779.041	3.105.598	**2.423.928**	**3807.08**	**4.562.016**
15-16	9.196.484	7.982.496	1.382.676	**1.315.341**	**1.911.202**	**2.246.639**
16-17	6.745.334	5.854.226	101.386	6.903.305	5.803.425	1.013.617
17-18	137.992	1.197.537	2.073.639	1.412.233	1.187.145	2.073.142
17-19	1.152.042	1.264.305	220.793	1.490.659	125.306	2.188.352
15-20	1.495.877	1.684.178	2.897.857	**4.924.652**	**8.866.942**	**2.807.817**
20-21	1.658.438	1.423.091	237.534	**4.137.469**	**7.374.824**	**2.323.072**
20-22	1.737.429	1.490.882	2.488.429	**4.334.513**	**7.726.018**	**2.433.674**
20-23	186.782	1.619.332	2.678.689	1.915.295	1.605.178	2.678.577
23-24	1.543.996	1.644.289	270.875	**2.728.576**	**4.011.892**	**4.509.066**
23-25	2.005.596	1.711.916	2.797.133	**2.842.013**	**4.178.991**	**4.696.901**
23-26	1.785.513	1.531.761	2.493.867	**2.543.617**	**3733.55**	**4.193.325**
26-27	2.179.282	1.856.747	3.007.382	**3.109.753**	**4.516.639**	**5.074.408**
26-28	6.860.639	5.845.618	946.761	**1.681.932**	**2.964.096**	**9.262.118**
28-29	2.341.144	1.994.606	3.229.677	2.424.705	1.967.948	3.228.823
26-30	3.436.244	2.933.484	4.745.084	**8.434.216**	**1.486.555**	**4.642.113**
30-31	295.879	2.522.606	4.070.662	3.065.071	2.488.961	4.069.652
31-32	1.977.683	2.097.434	3.408.341	**601.974**	**1.059.822**	**330.556**
32-33	1.944.369	1.655.859	2.665.291	2.014.218	163.376	2.664.645
33-34	141.139	1.201.133	1.930.698	**3.445.963**	**6.061.994**	**1.889.035**
34-35	8.604.047	7.319.172	1.175.618	8.913.386	7.221.562	1.175.341
35-36	2.922.426	2.485.905	3.992.366	**7.129.782**	**1.253.902**	**3.906.288**
26-37	1.259.897	1.075.979	1.737.731	1.304.922	1.061.567	1.737.222
37-38	3.081.102	2.621.736	4.218.034	**7.524.823**	**1.323.884**	**4.126.861**
37-39	3.162.195	2.690.748	4.329.018	**4.508.264**	**655.937**	**7.332.216**
37-40	5.221.094	4.446.965	7.147.327	540.696	4.387.463	7.145.407
40-41	2.396.133	2.038.836	3.269.674	**3.417.539**	**4.972.832**	**5.547.651**
41-42	1.731.986	1.472.755	2.359.022	1.797.142	1.451.708	2.358.275
42-43	349.771	2.973.647	4.761.168	**4.991.267**	**7.251.164**	**8.085.983**
42-44	3.579.017	3.042.741	4.871.947	**5.107.134**	**7.419.744**	**8.273.993**
40-45	1.859.745	1.582.111	2.538.639	**2.650.989**	**3.859.736**	**4.306.116**
45-46	1.129.357	9.605.396	1.540.415	**1.610.475**	**2.342.821**	**2.613.738**
46-47	3.820.096	3.248.462	5.207.219	**5.449.186**	**7.921.796**	**8.837.768**
37-48	5.309.849	4.522.337	7.269.992	**8.987.914**	**8.793.218**	**7.695.034**
48-49	3.978.541	3.384.055	5.433.203	**6.721.362**	**6.572.572**	**5.752.007**
48-50	4.059.736	3.453.118	5.544.084	**6.858.533**	**6.706.705**	**5.869.394**
48-51	2.955.651	2.515.293	4.035.369	**4.993.637**	**4.882.637**	**4.272.334**
51-52	1.276.437	1.085.549	1.738.964	2.055.158	6.006.621	1.941.123
52-53	431.171	366.561	5.867.775	6.931.097	2.028.714	6.550.539
51-54	4.390.001	3.732.932	5.981.721	7.069.735	2.065.409	6.676.945

Table 4. Reactive power loss with variation in conductor spacing

	Base case (VAR)			Conductor spacing (VAR)		
Line	Qa	Qb	Line	Qa	Qb	Line
1-2	**2295.47**	**1.975.033**	**2.750.878**	**2.295.527**	**1.975.052**	**2.750.967**
2-3	**2280.26**	**1.966.228**	**2.740.116**	**2.333.067**	**3.195.157**	**4.942.307**
3-4	**2282.56**	**2.026.144**	**2.704.118**	**2.259.293**	**1.942.369**	**2.722.521**
4-5	2.246.348	1.931.301	2.719.335	**8.617.319**	**3.463.937**	**2.410.822**
5-6	1.485.429	1.311.571	1.767.267	1.469.973	1.256.988	1.778.994
6-7	5.472.462	4.832.023	651.089	5.415.521	4.630.929	655.409
4-8	2.220.211	1.922.823	2.682.109	2217.71	1.910.177	2.678.263
8-9	2.213.207	1.973.716	2.636.814	2.190.535	1.891.886	2.654.356
9-10	2.379.978	2.059.966	2.898.542	2.377.158	2.046.317	2.894.208
10-11	8.444.865	7.309.492	1.028.505	**3.258.916**	**1.331.025**	**9.111.352**
9-12	2.127.068	1.854.576	2.590.827	**8.251.196**	**3.328.609**	**2.294.531**
12-13	2.114.913	1.898.393	2.539.938	**8.146.891**	**3.322.074**	**2.266.644**
13-14	2070.65	1.811.557	2.532.654	**1.212.039**	**3.136.342**	**6.184.229**
14-15	2042.81	1789.42	2.502.372	**4.654.123**	**6474.33**	**7.184.102**
15-16	9.099.259	7.947.873	1.117.288	**9.327.941**	**124.662**	**2.027.449**
16-17	6.672.299	5.828.202	8.193.148	6.663.495	5.787.033	8.181.079
17-18	1.364.713	1.192.106	1.675.833	1.362.912	1.183.685	1.673.364
17-19	1.453.984	1.304.481	1.755.198	1.438.641	1.249.437	1.766.326
15-20	1.914.302	1.729.645	2.317.227	**7.419.036**	**3.105.742**	**2065.79**
20-21	1.573.043	1.386.044	1.946.731	**6.166.642**	**2.639.909**	**1.721.264**
20-22	1.647.943	1.452.051	2.039.434	**6.460.307**	**2.765.657**	**1.803.229**
20-23	1.777.336	1.572.074	2.203.131	1.774.766	1.560.295	2.199.882
23-24	1.801.646	1.638.798	2.202.215	**1.833.958**	**2.421.201**	**4.078.866**
23-25	1.859.387	1.646.458	2.311.344	**1.910.402**	**2.522.204**	**4.248.899**
23-26	1.659.094	1.471.516	2.063.636	**1.704.132**	**2.246.898**	**3.789.995**
26-27	2.002.297	1.776.554	2.493.472	**2.056.009**	**2.701.436**	**4.569.759**
26-28	6.303.558	5.593.016	784.994	**2.482.229**	**1.077.594**	**693.131**
28-29	2.150.422	1.908.123	2.678.099	2.145.809	1.887.073	2.672.075
26-30	3.160.181	2.805.645	3.936.277	**1.245.035**	**5.405.019**	**3.475.503**
30-31	2.712.149	2.408.911	3.379.937	2.706.301	2.382.254	337.235
31-32	2.272.559	2.073.976	2.785.719	**8.876.804**	**3.863.104**	**2.477.894**
32-33	1.776.577	1.578.694	2.215.175	1.772.734	1.561.201	2.210.201
33-34	1.287.235	1.144.143	1.605.491	**5.077.622**	**2.213.574**	**1.417.333**
34-35	7.839.079	6.968.534	9.778.735	7.822.072	6.891.217	9.756.791
35-36	2.662.193	2.366.618	3.321.003	**1.050.297**	**4.581.539**	**2.931.732**
26-37	1.157.664	1.028.256	1.442.412	1155.15	1.016.888	1.439.132
37-38	2.811.766	2.498.579	3.506.318	**1.108.945**	**483.074**	**3.095.449**
37-39	2.885.754	2.564.335	3.598.591	**2.963.957**	**3.887.586**	**6.604.814**
37-40	4.765.466	4.236.348	5.943.704	4.755.207	418.962	5.930.332
40-41	2.180.894	1.939.549	2.721.366	**2.240.118**	**2.935.293**	**4.996.584**
41-42	1.573.811	1.399.937	1.964.331	1.570.198	1.383.521	1.959.607
42-43	317.662	2.825.884	3.965.196	**3.262.729**	**4.271.837**	**7.278.365**
42-44	3.250.511	289.159	4.057.407	**3.338.631**	**4.371.282**	**7.447.696**
40-45	1.693.104	1.505.484	2.112.465	**173.915**	**2.279.494**	**3.879.289**
45-46	1.027.456	9.136.969	1.282.092	**1.055.359**	**1.382.802**	**2.353.938**
46-47	3.473.487	3.089.172	4.334.734	**356.771**	**4.673.425**	**7.957.344**
37-48	4.847.057	430.862	604.522	**4.694.753**	**8.666.043**	**3.772.755**
48-49	3.623.176	3.221.124	4.520.076	**3.509.446**	**6.482.936**	**2.821.572**
48-50	3.697.118	3.286.861	4.612.323	**3.581.068**	**6.615.241**	**2.879.155**
48-51	2.691.428	2.393.396	3.358.143	**260.769**	**4.817.322**	**2.096.399**
51-52	1.160.126	1.031.954	1.447.966	1.164.918	1.145.736	9.887.047
52-53	3.915.103	3.483.014	4.887.223	393.142	3.867.604	3.337.577
51-54	3.990.378	3.549.164	4.980.139	400.688	3.940.341	3.400.404

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