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Impact of Tap Changing Transformers on the Loss Minimization of Electrical Power Distribution System

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ABSTRACT

The tap changing transformer is one of the important methods of voltage control. It works on the principle of regulating the secondary voltage based on the concept of changing the number of turns on the primary or secondary side of the transformer. An increase in the primary turns result in a corresponding increase in the magnitude of emf per turn, and hence an increase in the secondary output voltage.

This paper establishes the impact of tap changing transformers on the loss minimization of electrical power distribution feeders using ten selected feeders each of Kaduna and Port-Harcourt distribution systems as case studies. The loaded primary radial feeders were divided into load sections with a tap changing transformer at the beginning of the distribution network. The mathematical formulation for the minimization of power loss tap changer problem was done to find the tap setting of the substation transformer that would give minimum distribution loss while satisfying the operating constraints under a certain load pattern. These operating constraints are voltage drop, current capacity and radial operating structure of the system.

The maximum load at the nodes and distances between nodes were obtained from the network layout of the Power Distribution Centre. The voltage drops and power losses were computed for each feeder by considering the tap changing using appropriate mathematical notations. The power losses on each feeder were examined until the minimum voltage drop was obtained. At the minimum voltage drop, the corresponding tap position considered to be optimum tapping position was noted and the corresponding power loss obtained. The results of the paper showed that the active power losses on the ten selected feeders of Port-Harcourt distribution system had reduced from 2.4MW per feeder to 1.6MW per feeder representing a percentage reduction of 33% after the adoption of the tap changing transformer in the distribution system. The reactive power losses had equally reduced from 1.28MVAr per feeder to 0.6MVAr per feeder representing a reduction of 86%.

For Kaduna distribution system, the active power loss per feeder has reduced from 3.28MW per feeder to 2.47MW per feeder after the tap changing thus representing a percentage reduction of 25%. The reactive power loss per feeder also reduced from 22.4MVAr to 15.0MVAr representing a percentage reduction of 32%. Analysis of the result will assist power system engineers to propose adequate and appropriate maintenance strategies for electric power distribution systems.

Keywords: Tap Changer, Transformers, Loss Minimization, On-Load, Off-Load, Voltage Regulation, Insulation, Distribution System

I. INTRODUCTION

The tap changing transformer is an important voltage control method. The principle of operation is based on the concept of changing the number of turns on the primary or secondary side of the transformer. An increase in the primary turns results in a corresponding increase in the magnitude of emf per turn, and hence an increase on the secondary output voltage [3], [7].

Application of tap changing transformers on primary feeders is a form of compensation technique for loss reduction that captures both the primary and secondary distribution system together [1], [6].

The use of tap changing transformer has the advantage of being able to regulate the voltage at a bus. With this approach, the appropriate tap settings required to compensate for the voltage drops in the distribution system (both primary and secondary system) are determined and hence, the power loss is equally minimized[11],[12].

II. METHODS AND MATERIAL

A. Tap Changing Transformer

Standard distribution transformers have taps arranged in 2 ½ % step so that the rated secondary voltage can be obtained when the primary supply voltage is 0, 2 ½, 5, 7½ % below the nominal primary voltage rating. The 2 ½ % steps can be used on transformers with automatic tap changing equipment. The two types of tap changing include [9], [13]:

I. Off-load and
II. On-load.

The off-load tap changer is the cheapest method of changing the turns ratio of the transformer because the taps are changed when the transformer is disconnected. Therefore the required insulation for the contacts of the tap-changer is minimal. This method does not ensure constancy of service thus it is not suitable for on-load voltage regulation.

The on-load tap-changer regulates power system voltage while the transformer is still delivering load. It consists of a motor operated changer housed in an oil-filled compartment. Insulation requirement is higher, thus it is more expensive compared to the later.

B. Voltage Regulation on Distribution Transformer

When a power transformer is loaded at a particular power factor, the secondary terminal voltage tends to fail. Hence, to keep the output voltage constant at the required value, the need to increase the primary input voltage becomes crucial. The rise in voltage from no-load to full-load at a given power factor expressed as a percentage of the rated voltage gives the voltage regulation of transformer [2], [8]. [5].

For a distribution system power transformer, the voltage regulation is done at the secondary terminals using the step-voltage regulators that are attached to the secondary side of the transformer [4],[10].

Once a load flow solution is obtained, the voltage regulation of any feeder is expressed as follows:

$$V_{reg} = \frac{V_s - V_r}{V_r} \times 100\%$$

Where

V_s: is sending -end voltage

V_r: is receiving-end voltage

C. Optimisation Model for Loss Reduction

For the minimization of power loss tap changer problem, the mathematical formulation is expressed as:

$$\text{Minimize} f = \text{Min} f\left(P_{T,LOSS}\right) \quad (1)$$

$$P_{F,LOSS} = \sum_{i=0}^{n-1} P_{Loss(i)} \quad (2)$$

Subject to the following constraints:

i. Radial network constraints: that is, the network must remain radial after reconfiguration.

ii. Power source limit constraint: that is, the total load of a certain partial network cannot exceed the capacity limit of the corresponding power source.

iii. Voltage constraint: that is, the voltage magnitude at each bus must lie within their permissible ranges to maintain power quality.

$$V_{min} \leq V_j \leq V_{max} \quad (3)$$

$$V_{drop(max)} \leq \pm 10\% \quad (4)$$

Where:

I : Specific branches between two nodes on the feeders;

j : specifies nodes (buses) on the feeders;

$P_{T,LOSS}$: is the real power loss of the system;

$P_{LOSS(i)}$: is the real power loss in the branch i;

V_j : is the voltage magnitude of bus j;

V_{min} : is the bus minimum voltage;

V_{max} : is the bus maximum voltage;

n : is the total number of nodes on the feeder and the laterals.

For the component model in Figure 1 below;

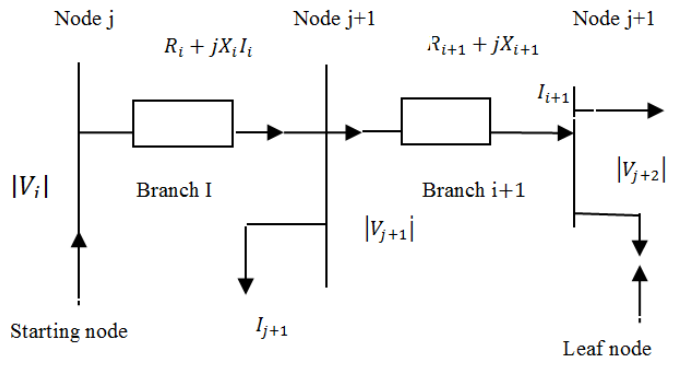

Figure i: Component Model Representation

From the figure above, V_j is the nodal voltage, I_i is the branch current while I_j is the load current in node j. Applying current analysis,

$$I_i = I_{i+1} + I_{j+1} \quad (5)$$

Where;

I_i : is the current in branch i in Ampere

I_{i+1}: is the current in branch $i+1$ in Amperes

I_{j+1}: is the nodal injection current in node $j+1$ in Ampere

Assume an initial voltage of 1 $p.u$ at all nodes on feeder and lateral, that is V_j= 1p.u. for j = 1, 2, 3… n where n is the total number of nodes on feeder and laterals.

Starting from the root and moving towards the feeder and laterals, the node current injection at node j is computed as equation as:

$$I_j = \frac{S_j}{V_j} \quad (6)$$

Where:

I_j : is the nodal current injection at node j in Amperes.

S_j : is the load power at node j in MVA.

V_j : is the assumed nodal voltage at node j in kV.

Hence, the load power at node j is given by:

$$S_j = P_j + jQ_j \quad (7)$$

Where:

$P_j = S_j \cos\theta$ is the active load power at node j in MW

$Q_j = S_j \sin\theta$ is the reactive load power at node j in MVAR

$\cos\theta = 0.7$ is the assumed power factor for the distribution system.

The nodal voltage at node j is:

$$V_j = V_{j+1} + Z_iI_i \quad (8)$$

Where:

V_j: is the voltage drop at node j in kV

V_{j+1}: is the voltage value at node j+1 in kV taking into account the voltage drop

$Z_i = R_i + X_i$: is the impedance of branch i in Ω/km/phase

I_i : is the current in branch i in Amps.

From equation (8), the voltage drop between the nodes j and j+1 is

$$V_{drop(j,j+1)} = V_j - V_{j+1} = Z_iI_i \quad (9)$$

For optimal power loss, equation (8) must be less than or equal to $\pm 10V$.

The total active power loss and the corresponding total reactive power loss of the distribution system before tap changing are computed as

$$P_{LT} = \sum_{i=1}^{n} I_i^2 R_i \quad (10)$$

and

$$Q_{LT} = \sum_{i=1}^{n} I_i^2 X_i \quad (11)$$

Where:

P_{LT}: is the total active power loss in MW

Q_{LT} : is the total reactive power loss in MVAR

I_i : is the magnitude of current in branch j in Amps.

R_i : is the resistance of branch i in Ω/km/phase

X_i: is the reactance of branch i in Ω/km/phase

The total power loss of the distribution system is given as:

$$S = \sqrt{P_{LT}^2 + Q_{LT}^2}\ MVA \quad (12)$$

For a tap-changing transformer with "s" steps and with the tap variation of $\pm 10\%$ of the voltage selection as indicated in equation (8)

The total voltage variation (TVV) is given by:

$$TVV = 10\% \quad (13)$$
$$TVV = 20\%$$
$$TVV = 0.2$$

Therefore, the per-unit voltage change per step is given by:

$$\Delta V_{(per\ step)} = \frac{0.2}{S} \quad (14)$$

Given that the base voltage of the distribution system is V_{base} then, the exact voltage change per-unit step is given as:

$$\Delta V_{(per\ step)} = \frac{0.2V_{base}}{S} \quad (15)$$

Thus, for a distribution system with base voltage V_{base} and with the tap changer on the secondary side, equation (15) gives the voltage change for each tap change.

The percentage voltage regulation provided by each of the taps of the regulating transformer is computed as:

$$\%V_{regulation} = \frac{V_R - V_{base}}{V_{base}} \times 100 \quad (16)$$

Where

V_R: is the regulated voltage in kV.

If "t" denotes the tap position on the primary side of the regulating transformer, then, the regulated voltage at a given tap position "t" is given by:

$$V_R - V_{base} = \pm 0.2t\frac{V_{base}}{S} \quad (17)$$

and

$$V_{R(per\ unit)} = 1 \pm 0.2\frac{t}{S} \quad (18)$$

Subject to the assumption that the regulating transformer has on-load tap-changer (OLTC) with variable taps in 15 steps in addition to the earlier assumption of ±10% voltage selection of the tap variation, then, S is considered to be 15. Hence, equation (18) becomes:

$$V_R = (1 \pm 0.0133t)V_{base} \quad (19)$$

Equation (17) with the application of equation (19) becomes:

$$\%V_{reg} = \pm 1.33t\% \quad (20)$$

Where "t" is the tap position, varying from 1 to 15

Expressing equation (19) in terms of T, the tap position expressed as a percentage of the regulated voltage, equation (19) becomes:

$$V_R = (1 \pm 0.01T)V_{base} \quad (21)$$

Where T = 1.33t with the positive sign signifying an upward regulation while the negative sign implies a downward regulation.

Equation (21) gives the regulated voltage at the source.

Hence, the total voltage change for the tap changer is given by:

$$\Delta V = 0.01TV_{base} \quad (22)$$

For the primary distribution system, V_{base} is 11kV.

Therefore, the voltage increment from the base value for any tap setting is given by equation (24).

$$\Delta V = 0.01T \times 11 \quad (23)$$

$$\Delta V = 0.11T\ kV \quad (24)$$

Hence

$$V_{j(T)} = V_j + 0.11T \quad (25)$$

The voltage drop on the radial distribution network is the algebraic sum of the individual voltage drops of the nodes.

Thus,

$$\Delta V_{total} = \sum_{i=1}^{n} \frac{P_j R_{0j} + Q_j X_{0j}}{V_{j(T)}} \quad (26)$$

After the regulation, the regulated voltage at the source node becomes the updated nodal voltage. Hence, the nodal current injection at the node j at the rated voltage becomes:

$$I_{j(T)} = \frac{S_j^*}{V_j T} \quad (27)$$

$$I_{j(T)} = \frac{S_j^*}{1 \pm 0.01TV_{base}} \quad (28)$$

From equation (28), the total active power loss and the corresponding reactive power loss at this new tap position T for the distribution are given by equations (29) and (30) respectively as:

$$P_{Lt(T)} = \sum_{i=1}^{n} {I_{i(T)}}^2 R_i \qquad (29)$$

$$Q_{Lt(T)} = \sum_{i=1}^{n} {I_{i(T)}}^2 X_i \qquad (30)$$

Where:

$P_{Lt(T)}$: is the total active power loss after regulation in MW

$Q_{Lt(T)}$: is the total reactive power loss after regulation in MVAR

$I_{i(T)}$: is the magnitude of current in branch j in Amps after regulation.

The total apparent power loss of the distribution after regulation is given as:

$$S_T = \sqrt{{P_{LT}}^2 + {Q_{LT}}^2} \text{ MVA} \qquad (31)$$

For the purpose of this work, in determining the optimal tap-setting of the distribution transformer for loss minimization, the following assumptions were made;

i. The constant impedance transformer model was used, that is, the transformer impedance does not vary with the position of the tap.

ii. The transformer has an on-load tap-changer (OLTC) with variable taps in 15 steps.

iii .The radial network with single source is considered.

III. RESULTS AND DISCUSSION

A. Kaduna Distribution System

The relationship between the Voltage drop and the feeder names before the tap changing for Kaduna distribution system is as illustrated in Figure 1.Dawaki feeder of Kaduna distribution system had the highest voltage drop of 3.5 kV before the tap changing, out of all the ten selected feeders for the study, even though, the voltage for this feeder at this instant is 4.5 kV with active and reactive power losses of 7.6MW and 2.8 MVAr respectively. The least voltage drop of 1.1 kV was recorded on Arewa feeder with a voltage of 2.7 kV. At this instance, the real and reactive power for Arewa distribution feeder is 3.8 MW and 1.1 MVAr respectively.

The active power loss fluctuated among the ten selected feeders in Kaduna distribution system as shown in Figure 2. The highest active power loss of 7.6MW was recorded on Dawaki feeder before tap changing probably because this 7.6MW active power loss corresponds to a real power loss of 2.8MVAr even though this is not the highest or least power reactive power loss as shown in Figure 3. FDR3, FDR2 and FDR1 had active power losses of 2.5MW, 3.2MW and 1.6MW respectively before tap changing while the reactive power losses of these feeders are 1.5, 2.3 and 1.6MVAR respectively.

Kujama feeders of Kaduna distribution feeders recoded the highest reactive power loss of 3.2MVAr while Arewa feeder having the least reactive power loss of 1.1MVAr before tap changing, even though the reactive power losses fluctuated among the ten selected feeders used in the analysis. This could be due to the MVA loads of the feeders which also fluctuated with the highest load of 5.9MVAr on St. Gorald feeder and a least load of 7.5MV recorded on FDR1 feeders. Thus, the total load on Kaduna distribution feeders before tap changing was 125.6MVA representing an average of 12.56MW load per feeder.

After the tap changing, the voltage drop on each of the selected feeders of Kaduna distribution system dropped appreciably as illustrated in Figure 4. The voltage on FDR3 has dropped from 4.3kV to 3.8kV because of the application of tap changer on the distribution system. This trend was noticed throughout the distribution feeders of Kaduna distribution system. The voltage drops on FDR2, FDR1 and Arewa feeders before the tap changing are 4.6kV, 5.3kV and 2.7kV respectively while after the tap changing the voltage on these feeders dropped appreciably to 1.5kV, 1.1kV and 0.8kV respectively.

Junction road feeders had the least voltage drop of 0.6KV after tap changing while the FDR3 feeder had the highest voltage drop of 3.8kV among the distribution feeders probably because of the MVA loading of the feeders. After the tap changing, the voltage of Kajama dropped appreciably from 2.1kV to 1.4kV. Similarly, the voltage on Danraki, Tundun Wada, St. Gorald and Junction road dropped from 3.5kV to 3.0kV, 1.7kV to 0.9kV, 2.3kV to 1.3kV, and 1.5kV to 0.6kV respectively. The relationship between the active power loss and the feeder names for Kaduna Distribution after tap changing is displayed in Figure 5. The active power losses reduced considerably for each of the feeders after the tap changing. The active power losses for FDR3, FDR2, FDR1 and Arewa feeders had reduced to 2.0MW, 2.6MW, 1.0MW and 3.1MW respectively after the action of the tap changers on the distribution feeders. Kujama, Danraki, Tundun Wada, and St. Gorald also had active power losses of 2.9MW, 6.5MW, 2.0MW and 2.4MW respectively after tap changing. Junction road and constitution road feeders had active power loss of 0.7MW and 1.5MW respectively after the action of tap changing, even though Junction road feeder had the least active power loss suggesting that the action of the tap changer was more effective on this feeder compared to other feeders. Danraki feeder recorded the highest active power loss of 6.5MW after tap changing suggesting a decrease in active power loss from 7.6MW to 6.5MW before and after the tap changing respectively.

Figure 6 illustrate the variation of reactive power for the various distribution feeders. The reactive power loss fluctuated for the selected distribution feeders. Thus, the reactive power losses for the FDR3, FDR2, FDR1 and Arewa feeders are 1.0MVAr, 1.6MVAr, 0.9MVAr and 0.4MVAr respectively while that of Kujama, Danraki, Tundum Wada and St. Gorald feeders are 2.7MVAr, 2.3MVAr, 2.3MVAr and 1.6MVAr respectively after the tap changing on the distribution feeders. Junction road feeders and constitution road feeder had reactive power losses of 0.9MVAr and 1.3MVAr respectively after the tap changing even though Arewa feeder had the least reactive power loss of 0.4MVAr due to the efficiency of the tap changer on this distribution feeder. Danraki and Tundun Wada recorded the highest reactive power loss of 2.3MVAr each after the tap changing even though, Danraki and Tundun Wada had a reactive power loss of 2.8MVAr and 3.1MVAr respectively before the tap changing.

The average active and reactive power losses on Kaduna distribution system is 2.47MW and 1.5MVAr after the tap changing respectively as compared to the corresponding values of 3.28MW and 2.24MVAr before the tap changing action.

B. Port-Harcourt Distribution System

Figure 7 shows the variation of the voltage drop with the feeder names before the tap changing. The voltage drops on the Airport, Port-Harcourt Town 1, Port-Harcourt Town 2 and Refinery 1 feeders are 3.5kV, 3.6kV, 0.7kV and 2.3kV respectively which correspond to the voltage levels of 3.3kV, 3.6kV, 6.4kV and 1.6kV respectively. The voltage drops fluctuated along the distribution feeders before the tap changing due to their MVA loadings. The voltage drops on Refinery2, Sheel1, Shell2 and Shell3 feeders are 4.9kV, 3.2kV, 3.7kV and 4.5kV respectively with MVA loading of 8.6MVA, 13.2MVA, 14.5MVA and 11.3MVA. Glass factory feeders and Michelin feeder had voltage drops of 1.1kV and 2.6kV corresponding to voltage levels of 5.7kV and 2.8vV due to their MVA loading of 10.4MVA and 15.7MVA respectively before the tap changing.

Figure 8 illustrate the variation of the active power loss with the feeder names before tap changing. The highest active power losses of 4.5MVA were recorded each on Port-Harcourt Town1 and Shell1 feeders probably because of the nature of customers attached to these feeders. Port-Harcourt Town 2 feeder had the least active power loss of 0.3MW before the tap changing due to the MVA loading of the distribution feeder. The average active power loss on this distribution system was 2.44MW. Shell 1, Shell 2, Shell 3, Glass factory and Michelin feeders had active power losses of 4.5MW, 1.2MW, 2.8MW, 0.6MW and 1.6MW respectively before the tap changing.

Figure 9 illustrate how the reactive power varies along the feeder names before tap changing for the distribution system. Airport, P0rt-Harcourt Town 1, Port-Harcourt Town 2, Refinery 1, Refinery 2, Shell1 and Shell 2 feeders have reactive power losses of 0.6MVAr, 2.3MVAr, 1.4MVAr and 2.6MVAr respectively before the tap changing due to their MVA loadings of 9.3MVA, 8.6MVA, 9.5MVA, 12.8MVA, 13.2MVA and 14.5MVA respectively while 1.8MVAr, 0.4MVAr and 13.4MVAr represent the reactive power losses of Shell 3, Glass factory and Michelin feeders respectively as a result of their MVA loadings.

After the tap changing, the voltage drop varies along the feeder names as illustrated in Figure 10. Airport feeder recorded a voltage drop of 2.6kV after tap changing due to its voltage level of 2.2kV. The voltage drop fluctuated along the feeder names due to their voltage levels. Shell 2 feeder had a least voltage drop of 0.1kV which appeared as the least in the range while Airport feeder recorded the highest voltage drop of 2.6kV. The voltage drop along Airport, Port-Harcourt Town 1, Port-Harcourt Town 2 and Refinery 1 feeder were 2.6kV, 2.1kV, 0.2kV and 1.6kV respectively. The feeders in this distribution system have an average voltage drop of 1.28KV per Feeder with an average voltage level of 2.69kV after the tap changing.

The active power loss for the selected feeders fluctuate throughout after the tap changing as displayed in Figure 11. The active power losses for Airport, Port-Harcourt Town 1, Port-Harcourt Town 2, Refinery 1, Refinery 2 and Shell 1 feeders are 2.5MW, 3.6MW, 0.1MW, 1.8MW, 1.3MW and 3.5MW respectively after the action of the tap changer as compared to the active power losses of 3.4MW, 4.5MW, 0.3MW, 2.6MW, 2.9MW and 4.5MW for Airport, Port-Harcourt Town1, Port-Harcourt Town2, Refinery1, Refinery2, and Shell 1 feeders before the introduction of a tap changer into the distribution feeder.

Glass factory and Port-Harcourt Town 2 feeders recorded the least active power losses of 0.1MW after the tap changing probably because of the adequate maintenance routines embarked upon in the Glass factory situated in this vicinity and perhaps because of the many industries situated in Port-Harcourt Town 2. An active power loss of 3.6MW was regarded on Port-Harcourt Town 1 feeder which appeared to be the highest active power losses compared to other feeders in this range after the introduction of a tap changer into the distribution feeders.

The relationship between the reactive power loss and the feeders' names is illustrated in Figure 12.

Refinery 1 feeder had the least reactive power loss of 0.1MVAr due to the power rating of the heavy machine used in the Refinery attached to this feeder. Shell 2 feeder recorded the highest power loss of 1.1MVAr as a result of prompt action of the tap changer on this feeder. The reactive power losses after the tap changing fluctuated among the feeders. The reactive power losses for Airport, Port-Harcourt Town 1, Port-Harcourt Town 1, Refinery1, Refinery2 and Michelin feeders after the adoption of the tap changer are 0.2MVAr, 0.8MVAr, 0.1MVAr, 0.9MVAr and 0.6MVAr respectively.

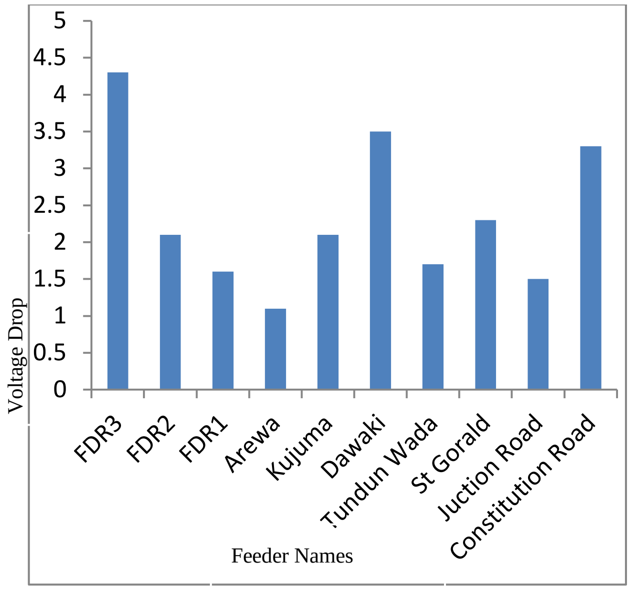

Figure 1: Voltage Drop before Tap changing for Kaduna distribution system

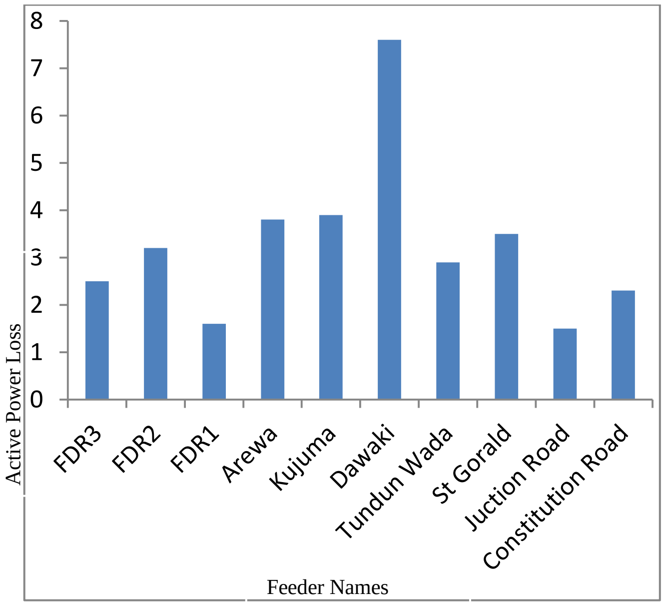

Figure 2: Active Power Loss before Tap changing for Kaduna distribution system

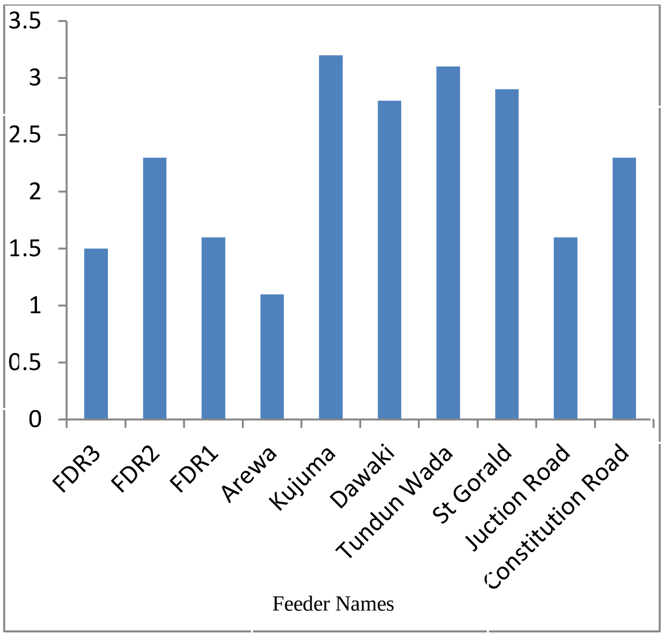

Figure 3: Reactive Power Loss before Tap changing for Kaduna distribution system

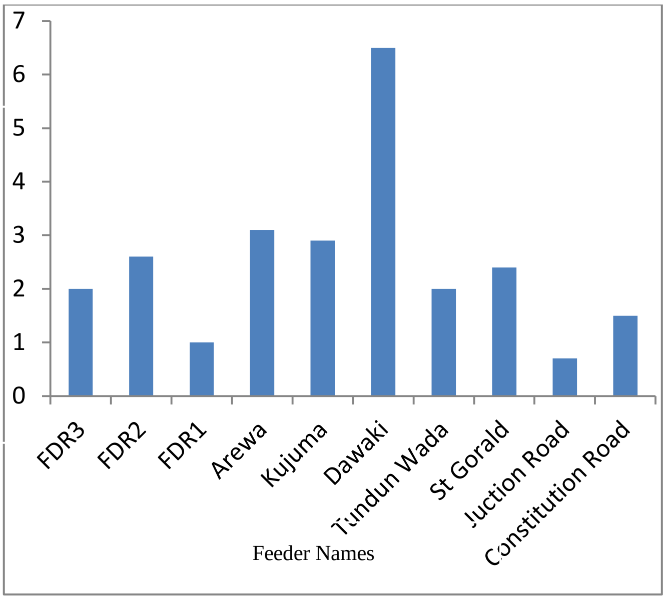

Figure 5: Active Power Loss after Tap changing for Kaduna distribution system

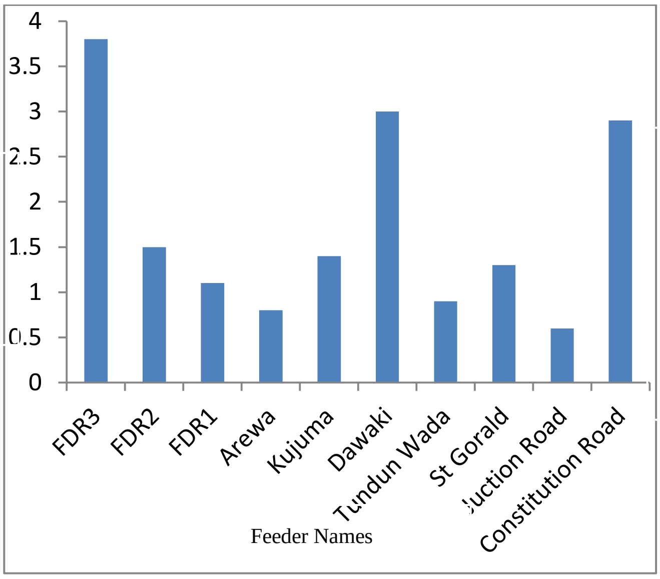

Figure 4: Voltage Drop after Tap changing for Kaduna distribution system

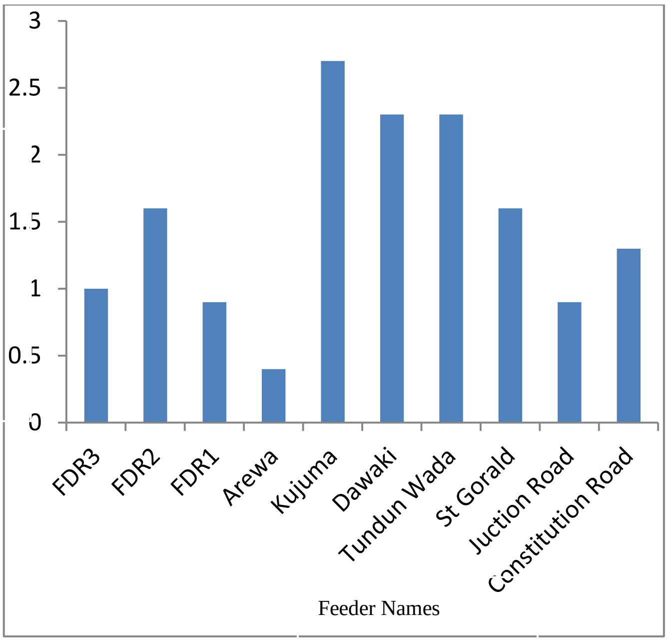

Figure 6: Reactive Power Loss after Tap changing for Kaduna distribution system

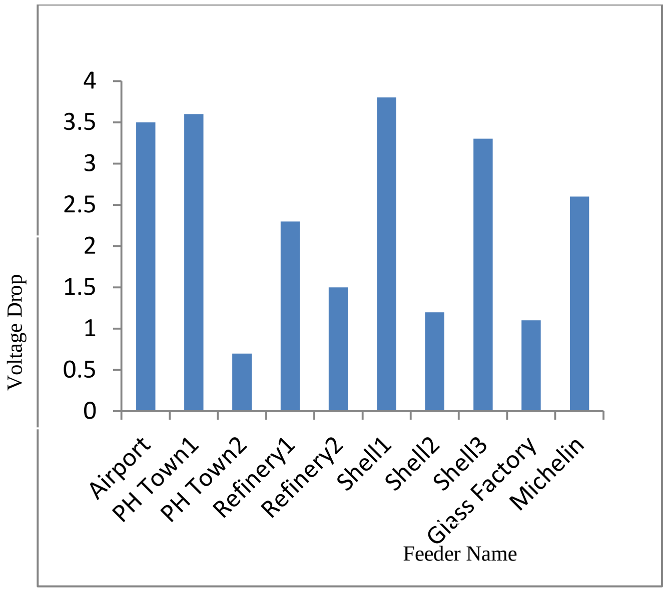

Figure 7: Voltage Drop before Tap changing for Port Harcourt distribution system

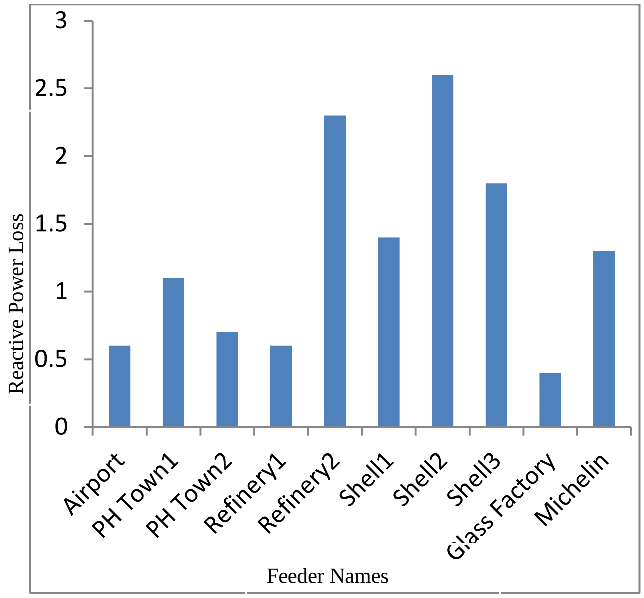

Figure 9: Reactive Power Loss before Tap changing for Port Harcourt distribution system

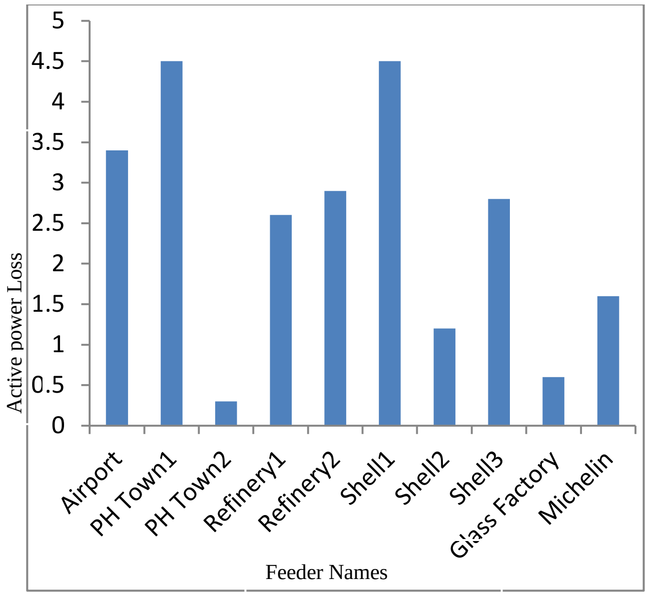

Figure 8: Active Power Loss before Tap changing for Port Harcourt distribution system

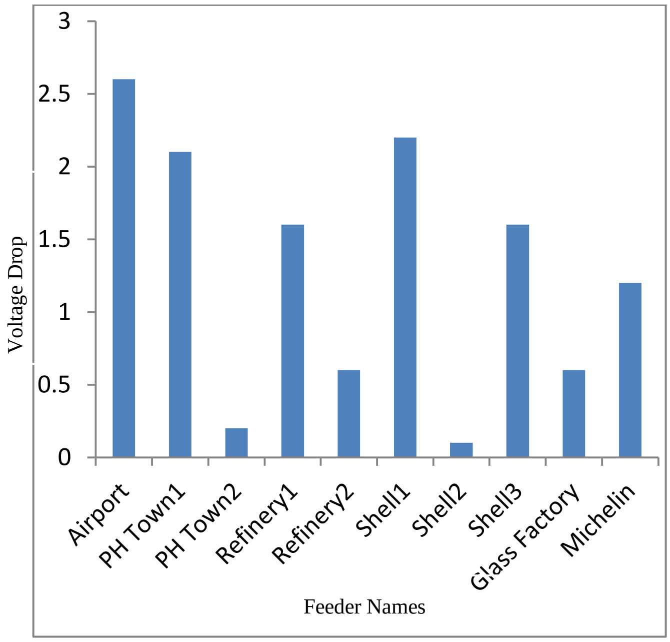

Figure 10: Voltage Drop after Tap changing for Port Harcourt distribution system

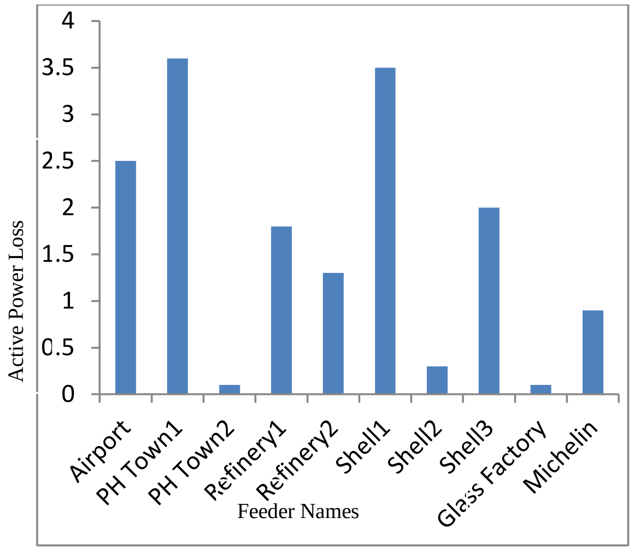

Figure 11: Active Power Loss after Tap changing for Port Harcourt distribution system

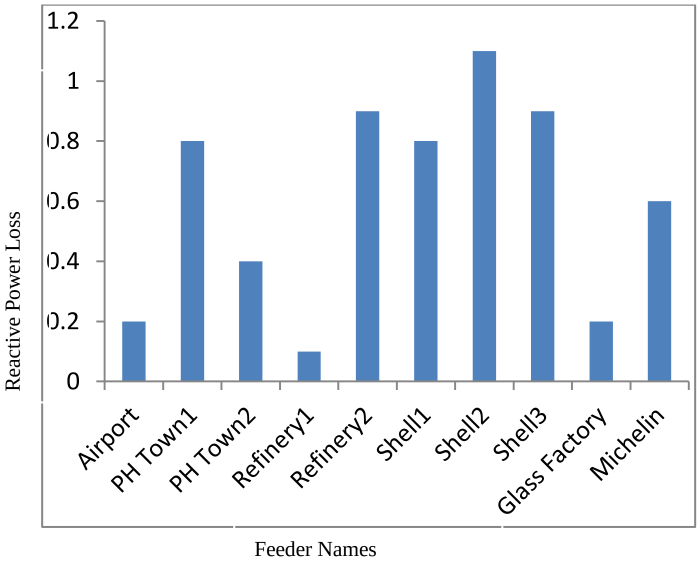

Figure 12: Reactive Power Loss after Tap changing for Port Harcourt distribution system.

IV. CONCLUSION

The impact of tap changing transformers on the loss minimization of electrical power distribution system has been presented. The average active and reactive power losses for Kaduna distribution system has reduced from 3.28MW and 2.24MVAr to 2.47MW and 1.5MVAr respectively after the action of the tap changing transformer. In addition, the active and reactive power losses on Port-Harcourt distribution system feeders had also reduced from 2.4MW to 1.6 MW per feeder and 1.28 MVAr to 0.6 MVAr respectively after the tap changing action. This represents a percentage reduction of 335% and 86% in the active power losses and reactive power losses respectively.

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