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Investigations of Transformer Losses due to Unbalanced Loading in a Power Distribution Network

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ABSTRACT

The power sector has continued to experience three-phase unbalanced loading condition which is a familiar problem for power sector Engineers and therefore introduces extra burden in terms of power losses causing reduction in the loading capability of distribution transformers well below their nominal ratings. This research therefore focused on investigating the transformer losses as a result of unbalanced voltage and loading current of five selected substations of 11/0.415 kV GRA feeder in Benin City, Edo State, Nigeria using the classical analytical method on established formulas, the values of the unbalance voltages and current as well as the total power loss in each of the reported substations were calculated using the real time field data obtained during the period under investigation. The results show that the highest power loss was recorded in market square substation (0.2146 kW) while Ishegie substation recorded the lowest power loss of 0.00037 kW. Airewele substation recorded a zero voltage which shows stable and balanced voltage between phases. It is observed that all the investigated substations during the period under review recorded low power losses which confirm that the substations are doing well.

1. INTRODUCTION

Unbalanced loading in low power distribution networks has continued to pose a great threat to the power distribution systems as a result of uneven distribution of power systems thereby leading to poor power quality and undesirable operation of electrical equipment like induction motors, adjustable speed drives, power electronic circuits and system protection switchgear (Pullaguram *et al*., 2017).

Giridhar et al. (2007) stated that the presence of variation between the phase voltages can be attributed to the unsymmetrical impedances of transmission and distribution lines which can result to transformer losses.

Power losses could also occur as a result of uneven spread of single-phase loads across the three phases, single phase traction loads, weak rural power electric systems with long transmission lines and unidentified or unclear single phase to ground faults. Short, (2004) asserted that unbalanced loading is more common in low voltage (LV) feeders due to phase load inequality, especially where large single–phase loads are used. The network configuration and length also have effect on the voltage instability in the feeder. In low voltage residential feeders, majority of the consumers are on single–phase power supply. The voltage imbalance can be very high in these networks if the users are connected unequally among the three phases. George and Kingsford, (2016) asserted that non-technical losses relate to losses due to power theft and errors in billing systems, technical losses are inherent in the physical delivery of electrical energy which includes conductor and line losses as well as transformer losses. Results show that the cost of energy per year resulting from the harmonic loss was found to be GHc2,220,395.11 annually (US$ 555,098.78 annually). It was also found that the harmonic effect de-rates the total capacity of the transformers by 27%. Adesina and Abdulkareem, (2016) stated that from available literatures, it has been observed that the Nigeria power sector does not have dependable and reliable information about the behavior of technical and non-technical losses which is an important economic indicator for power distribution companies. It is also observed that majority of such literatures also used probabilistic and theoretical mathematical approach which makes the results inadequate.

Furthermore, from the utility's perspective, the load is expected to be of good design that has sufficient immunity to small disturbances in the power supply and would not harm the electrical power system and other loads. By improving its service for customers, the utility operators can reduce maintenance costs and penalties which arise when the power quality contract is breached, (Kennedy, 2000; Chandler, 2010). Therefore, the aim of the research was to investigate transformer losses due to unbalance loading in a power distribution network.

2. METHODOLOGY

2.1. Study Location

This study was carried out in five (5) selected 11/0.415 kV distribution substations emanating from the GRA 33/11 kV feeder in Benin City, Edo State, Nigeria. The substations are; Market Square, St. Mary Dedication School, Ogiemwonyi, Ishegie and Airewele.

2.2. Data Collection and Processing

Data were collected from the 11/0.415 kV distribution sub-stations under investigation by visiting each substation and taking hourly readings of the unbalanced voltage and current. The readings were recorded by the aid of Automatic Meter Reading (AMR) also known as power network analyzer. The AMR measures various parameters such as voltage, current, frequency etc. The data are automatically stored in both internal and external memory to enable access for further analysis. The data was collected over a period of one year. After recording the test data, they were subjected to various forms of sorting and transformation to suit the current purpose using Microsoft datasheet. The sorted data was further subjected to evaluations to finding the average voltage and current variations.

2.3. Method Used

Using direct calculation on established formulas depicted in Equations (1) and (2), the values of the unbalance voltages were calculated using the real time field data obtained (Giovanni *et al.*, 2015).

$$Voltage\ unbalance\ (\%) = 100x\frac{max\{|V_{irms} - V_{avg}|\}}{V_{avg}} \quad (1)$$

$$Average\ voltage\ V_{avg} = \sum V/3 \quad (2)$$

Where:

i = V_r, V_y or V_b (voltage in red, yellow and blue phase respectively)
Voltage unbalance % = voltage unbalance index in percent
V_{irms} = rms single-phase voltage
V_{avg} = average among the three single-phase voltages

In distribution system, current flowing through transformers, conductors and cables will cause power losses as given in Equation (3). These power losses are commonly known as copper losses or load dependent losses (Sahito *et al.*, 2015).

$$Copper\ losses = I^2R \quad (3)$$

Where I is the load current and R is resistance of the transformer winding.

Another type of copper loss which is generated as a result unbalanced currents flowing in three phases of the transformer is represented as follows:
Let the secondary load currents flowing in each of the phases be given as I_R, I_Y, and I_B. Therefore, total load current is given as (Egwaile, *et al.*, 2013):

$$I_T = I_R + I_Y + I_B \quad (4)$$

Copper losses in each phase = $I^2_R R$ {red phase}, $I^2_Y R$ {yellow phase}, I^2_B R {blue phase}. Therefore:

$$Copper\ loss = I^2_R R + I^2_Y R + I^2_B R = R(I^2_R + I^2_Y + I^2_B) \quad (5)$$

If the load on the transformer is balanced then:

$I_R = I_Y = I_B = I$

Therefore Equation 5 becomes:

$$Copper\ loss = R(I^2 + I^2 + I^2) = 3\ I^2R \quad (6)$$

Equation 6 gives the total copper losses in a transformer under balanced load condition while Equation 5 gives the total copper losses for unbalanced load. Subtracting Equation 6 from 5 yields:

$$Total\ power\ loss\ unbalanced\ load = R(I^2_R + I^2_Y + I^2_B) - 3\ I^2R = R\{(I^2_R + I^2_Y + I^2_B) - 3\ I^2\} \quad (7)$$

$$Current\ unbalance\ (\%) = 100x\frac{max\{|I_{I,rms} - I_{avg}|\}}{I_{avg}} \quad (8)$$

$$The\ average\ current\ I_{avg} = \sum I/3 \quad (9)$$

Where:

Current unbalance (%) = current unbalance index in percent
I_{irms} = rms single-phase current
I_{avg} = average among the three single-phase current

Applying Equations 1 to 9 to the overall average values of Tables 1 to 5 gives the calculated results as shown in Table 6.

3. RESULTS AND DISCUSSION

The data presented in Tables 1 to 5 shows the recorded monthly average unbalanced voltage and load current in all connected 11/0.415 kV substations under investigation while Table 6 shows the results of the classical analysis of the calculated percentage unbalanced voltage, current as well as the total power loss in each of the reported substations. The analysis in Table 6 shows that the percentage voltage unbalanced for St. Mary Dedication school was 6.85% showing a high voltage confirming a high voltage variation between phases while Airewele Substation recorded a voltage of zero unbalance voltage which shows a stable and balanced voltage between phases. For the unbalanced loading current, Ogiemwonyi substation had the highest value of unbalanced loading current of 7.6% and Ishegie substation had the lowest unbalanced loading current value of 0.42%. The highest power loss was recorded in market square substation (0.2146 kW) while Ishegie substation recorded the lowest power loss of 0.00037kW.

Table 1: 2019 monthly average load profile results for 300 kVA Market square substation

Month	Voltage (V_r)	Voltage (V_y)	Voltage (V_b)	Current I_r (A)	Current (I_y) (A)	Current (I_b) (A)
January	212.5	225.4	226.1	414.8	397.5	368.2
February	217.5	224.6	224.6	473.5	464.6	574.4
March	222.9	224.2	222.3	400.3	399.3	383.1
April	217.3	225.3	224.3	507.6	447.6	409.6
May	220.0	224.3	225.1	492.1	460.7	390.4
June	233.2	221.0	225.2	490.6	424.4	455.5
July	218.0	224.1	233.6	467.4	499.0	511.1
August	219.2	229.2	223.4	550.9	572.8	558.4
September	216.4	220.3	220.4	542.1	570.4	500.2
October	220.9	218.7	216.2	556.0	564.9	548.3
November	216.0	214.5	221.3	563.9	577.0	552.3
December	231.8	218.6	215.5	364.3	375.8	330.7
Average per substation	220.4	222.5	223.1	485.2	479.5	465.1

(V_r, V_y, V_b) = voltages in the red, yellow and blue phase respectively, (I_r, I_y, I_b) = Current in the red, yellow and blue phase respectively

Table 2: 2019 monthly average load profile results for 300 kVA St. Mary Dedication school substation.

Month	Voltage (V_r)	Voltage (V_y)	Voltage (V_b)	Current I_r (A)	Current (I_y) (A)	Current (I_b) (A)
January	219.0	217.4	213.5	415.9	430.2	339.0
February	215.3	221.0	219.2	509.0	489.3	557.0
March	220.3	218.3	226.4	552.9	572.6	551.8
April	222.3	217.0	222.1	576.6	544.1	554.1
May	219.6	218.1	220.3	579.5	567.6	572.8
June	226.3	221.9	230.2	572.2	547.3	525.3
July	218.7	224.5	220.9	543.1	567.8	567.0
August	226.2	227.8	224.9	588.1	634.6	561.7
September	220.7	229.0	219.4	596.9	574.3	584.8
October	219.6	223.5	227.9	577.3	564.1	570.5
November	222.6	224.0	236.0	568.6	564.8	571.8
December	219.3	227.2	221.3	565.6	572.6	567.7
Average per substation	220.8	222.4	223.5	553.8	552.4	543.6

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Table 3: 2019 monthly average load profile results for 100 kVA Ogiemwonyi substation

Months	Voltage (V_r)	Voltage (V_y)	Voltage (V_b)	Current I_r (A)	Current (I_y) (A)	Current (I_b) (A)
January	236.1	230.7	236.4	96.0	54.8	59.6
February	227.5	235.6	229.7	76.5	89.1	78.4
March	212.9	218.3	219.3	73.6	80.8	74.0
April	222.0	227.6	223.3	86.1	76.5	59.0
May	229.2	226.6	231.8	82.5	75.1	66.3
June	239.9	239.3	239.0	81.3	69.8	82.0
July	235.8	238.1	241.0	84.0	74.6	67.3
August	241.3	240.8	237.2	81.4	88.1	69.0
September	234.0	237.6	231.6	83.5	67.9	80.6
October	237.7	238.1	233.7	77.3	80.5	69.7
November	238.3	236.0	239.3	82.5	84.4	77.3
December	241.0	238.2	234.4	78.8	76.0	62.8
Average per substation	232.9	233.9	233.0	81.9	76.4	70.5

Table 4: 2019 monthly average load profile results for 100 kVA Ishegie substation

Months	Voltage (V_r)	Voltage (V_y)	Voltage (V_b)	Current I_r (A)	Current (I_y) (A)	Current (I_b) (A)
January	238.1	243.0	232.5	66.3	70.0	70.8
February	228.4	228.9	217.2	77.1	66.0	69.7
March	234.9	236.9	239.6	70.4	76.0	60.1
April	231.4	232.7	237.2	59.5	69.5	69.6
May	235.4	232.1	233.8	66.4	65.5	58.0
June	226.9	234.5	229.9	56.2	67.3	69.2
July	227.3	233.3	235.1	72.8	58.5	73.0
August	233.4	229.8	235.3	76.6	83.6	81.2
September	225.9	232.1	237.2	71.4	72.1	63.5
October	224.7	223.6	233.2	75.0	72.4	79.0
November	234.4	236.3	232.6	88.3	72.2	79.1
December	234.7	230.1	227.9	84.1	81.9	83.0
Average per substation	231.2	232.7	232.6	72.0	71.2	71.3

Table 5: 2019 monthly average load profile results for 200 kVA Airewele substation

Months	Voltage (V_r)	Voltage (V_y)	Voltage (V_b)	Current I_r (A)	Current (I_y) (A)	Current (I_b) (A)
January	237.0	231.9	235.4	406.0	362.9	368.2
February	235.3	237.8	236.4	377.1	384.1	383.4
March	238.3	236.1	235.4	380.6	369.2	365.9
April	233.6	230.3	238.0	373.9	370.2	373.7
May	237.4	235.5	235.5	370.8	384.3	382.1
June	234.3	234.3	235.3	383.4	381.5	372.8
July	230.9	236.7	237.1	381.0	377.9	380.1
August	234.4	237.0	234.0	367.5	385.0	370.3
September	237.4	240.0	233.3	367.1	378.8	383.6
October	239.0	239.0	238.4	385.6	388.2	375.2
November	239.4	235.3	241.7	406.1	382.8	369.8
December	241.0	237.5	234.4	384.3	384.3	378.5
Average per substation	236.5	235.9	236.2	381.9	379.1	375.3

Table 6: Calculated percentage unbalanced voltage, current and power loss

substations	Transformer ratings (kVA)	Voltage unbalance in percentage (%)	Current unbalance in percentage (%)	Total power loss (kW)
Market square	300	0.72	2.41	0.21460
St. Mary Dedication school	300	6.85	1.14	0.06115
Ogiemwonyi	100	0.17	7.60	0.06501
Ishegie	100	0.43	0.42	0.00037
Airewele	200	0.00	0.92	0.02190

In this study, the results revealed that St. Mary Dedication school and Ogiemwonyi substations had huge voltage and current unbalance variations respectively which may be due to uneven distribution of load across the phases as against 3.0% limit acceptable for both utility and industrial use of electrical power system (Lalitha *et al*., 2015). However, there is relatively low power loss in the entire substations being investigated confirming that the systems are healthy and also considering the fact that they are all privately owned substations as compared to the high power losses encountered in most public substations as reported in (Egwaile *et al*., 2013).

4. CONCLUSION

The result of this study clearly shows that the substations investigated are healthy and doing well. It therefore informs that the three phases of the transformer's load must be evenly distributed to the consumers for the transformer to continue to maintain the desired purpose in terms of maximum reliability.

5. ACKNOWLEDGMENT

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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