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The Effects of Unbalanced Load in Power Distribution Sub - Station Network

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ABSTRACT: *This study presents the effects of unbalanced load in power distribution sub-station network in Nigeria using, 33/11kV injection Ogbelaka substation source of power supply from Oba Palace 11kV feeder from Government Reservation Area, (GRA) 2x15MVA, whose source is from Benin Transmission substation switch yard 132/33kV, 60MVA step down transformers, with metering equipment and circuit breaker for energy accountability and the transformer protection respectively. Data were obtained included availability per day (hrs), Voltage in volt from the three phases and current in ampere from the three phases, power factor and frequency (Hz) were downloaded from the meter using computer software called ITRON ACE PILOT (Version 4.1.1 2010-2014) connected via an optical port for period of six month from March to August 2017. The results on voltage unbalance index, average load on each phase (A), balanced load loss (kW), unbalanced load loss (kW), savings in losses (kW), energy loss per day (kWh) and Energy Loss in Naira were determined. This study also shows that the various phase loads followed the same pattern and are not linear throughout the months of March, April, May, June, July and August 2017 amounting to 417.2, 486.6 and 467.3 amps. It was observed that slight value from unbalance voltage result to about 70 percentage increases in current unbalance. The causes and effects of unbalance load are highlighted in this study.*

Keywords: *Current; Losses; Revenue; Voltage, and Unbalance*

I. INTRODUCTION

Unbalanced load in power distribution sub-station network is technically referred to as voltage unbalance, which is defined by IEEE as the ratio of the negative or zero sequence components to the positive sequence component in simple terms. Deviation in voltage and current waveform from perfect sinusoidal wave is referred to as unbalance. Also, in term of magnitude or phase shift it is referred to as unbalance. It is the voltage variation in which the phase angle differences between the phases are not equal in power distribution network. This voltage unbalance phenomenon is associated with polyphase or three phase system; voltages are hardly exactly balanced between three phases. However when voltage becomes excessive, it can create problems in power distribution network such as heat, harmonic etc. Voltage unbalance is primary caused by unequal load on distribution lines and this can be explain as when the negative or zero sequence voltages in a power system result from unbalanced load causing negative or zero sequence currents to flow.

Voltage unbalance is caused by imperfect load distribution or unequal load, especially among the single phase; in addition voltage unbalance can arises from malfunctioning electrical equipment or even mismatch transformer taps and impedances, blown capacitor fuses, open delta transformers, open-delta regulators and inductive motor. Motor can cause voltage unbalance due to irregular impedance between phases from the motor rotor and stator winding. Voltage unbalance lead to current unbalance and current unbalance is associated with heat. Heat result to open circuit and fire outbreak in electronic devices. Heat effects from current unbalance in induction

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motor winding can result to partial and permanent damage to the motor. The winding resistance is mainly determined by the total length of the wire used, as well as the size of the wire. The temperature of the winding will affect the resistivity of the wire, therefore affecting the overall resistance and the copper loss. Load loss also called copper loss is associated with full-load current flow in the transformer windings. Copper loss is power lost in the primary and secondary windings of a transformer due to the ohmic resistance of the winding. Copper loss varies with square of the load current, based on Equation 1.

$$P=I^2 R \tag{1}$$

Michal, (2005) analyses on current unbalance caused by loads connected either to line or phase voltages. Follow-up voltage unbalance is calculated for receiving end of high voltage line. Mirabbasi et al, (2011), presents the effect of the unbalanced voltages on the motor performance, deficiencies like unbalanced voltages in the voltage source could result in problems like excessive losses, overvoltage, mechanical oscillations, and interference with control electronics. Motor itself can act as the sensor that detects abnormal conditions. The negative effects of unbalanced sinusoidal voltage which always present in the power supply voltage on the performance of induction motor in terms of line currents, power factor and efficiency were considered. Okakwu, (2015) made a comparison between the transformer copper losses calculated from the existing unbalanced load condition and the losses that would have resulted if the loads on the transformer were equally distributed between the phases. The result of these comparison shows that high levels of load unbalance produces greater losses in the distribution transformers when compared to balanced load. Therefore, copper losses of transformer vary considerably with the degree of load unbalance, hence reduction in the capacity of the transformer. Also Muljadi et al, (2000) considered an unbalanced load in power system network at the distribution lines, which result to unbalanced voltage conditions. If an induction generator is connected to an unbalanced voltage, the resulting stator current will be unbalanced. The unbalanced current creates unequal heating (hot spots) on the stator winding.

The heat increases the winding temperature, which degrades the insulation of the winding and the life expectancy of the winding. Unbalanced currents also create torque pulsation on the shaft resulting in audible noise and extra mechanical stress. While, Reese; (2011) analyses the effects of unbalanced loading, a method to generate the necessary individual load profiles for each phase is proposed and simulations on a typical non meshed distribution grid are presented. Mohammed, (2013), presents a study to analyze the operation of three phase distribution transformers with unbalance voltage conditions. Hossein 2017, make a remark on a three phase system the current unbalance is due to load unbalance while it is considered as the main cause of voltage unbalance. Also, Hossein (2017), study was on the duty of current balancing is solidarity of both of electricity suppliers and customers. The utilities must do it for voltage balancing by equally distribution of single- phase customers between three phases while three phase customers have no responsibility for doing it for theirs single phase loads. This study is on the Effects of Unbalanced Load in Power Distribution Sub-Station Network.

II. METHODOLOGY

Ogbelaka 500kVA, 11/0.415kV Distribution Substation System source of power supply is from Oba Palace 11kV feeder from Government Reservation Area, GRA 2x15MVA, 33/11kV injection substation, whose source is from Benin transmission substation switch yard 132/33kV, 60MVA step down transformers, with metering equipment and circuit breaker for energy accountability and the transformer protection respectively. The substation is as shown in Fig.1.

Fig. 1: Substations for Ogbelaka 500KVA, 11/0.415KV

Table 1: Ogbelaka 500KVA, 11/0.415KV Substation Metering Information

Customer's Information and Data		
1	Account Number	**41-84-88-0700-01**
2	Name of Customer	Yongxing Steel Factory (LINE1)
3	Address	Ogua Village Off Benin by-Pass
4	Tariff	**D3**
5	Meter Number	65009405
6	Meter Make	ITRON
7	Meter Model	SL7000
8	Total Installed Transformer Capacity	500 kVA, 11/0.415KV
9	Field CT Ratio	800/5A
10	Field PT Ratio	0.415kV
11	meter ratio	800/5A
12	M.F	1
13	Date of Meter Installation	April-2016

Data Collection and Presentation

Data obtained for every one hour daily included availability per day (hrs), voltage in volt and current in ampere from the three phases, power factor and frequency (Hz) were downloaded from the meter using computer software ITRON ACE PILOT (Version 4.1.1 2010-2014) connected via an optical port for period of six months from March to August 2017. These include daily, weekly and monthly data readings. The voltages and current from the three phases are represented with the following acronyms.

Voltage from red phase is represented as VRN (Volts),
Voltage from yellow phase is represented as VYN (Volts),
Voltage from blue phase is represented as VBN (Volts),
Current from red phase is represented as IPR (Amps),
Current from red phase is represented as IPY (Amps),
Current from red phase is represented as IPB (Amps).

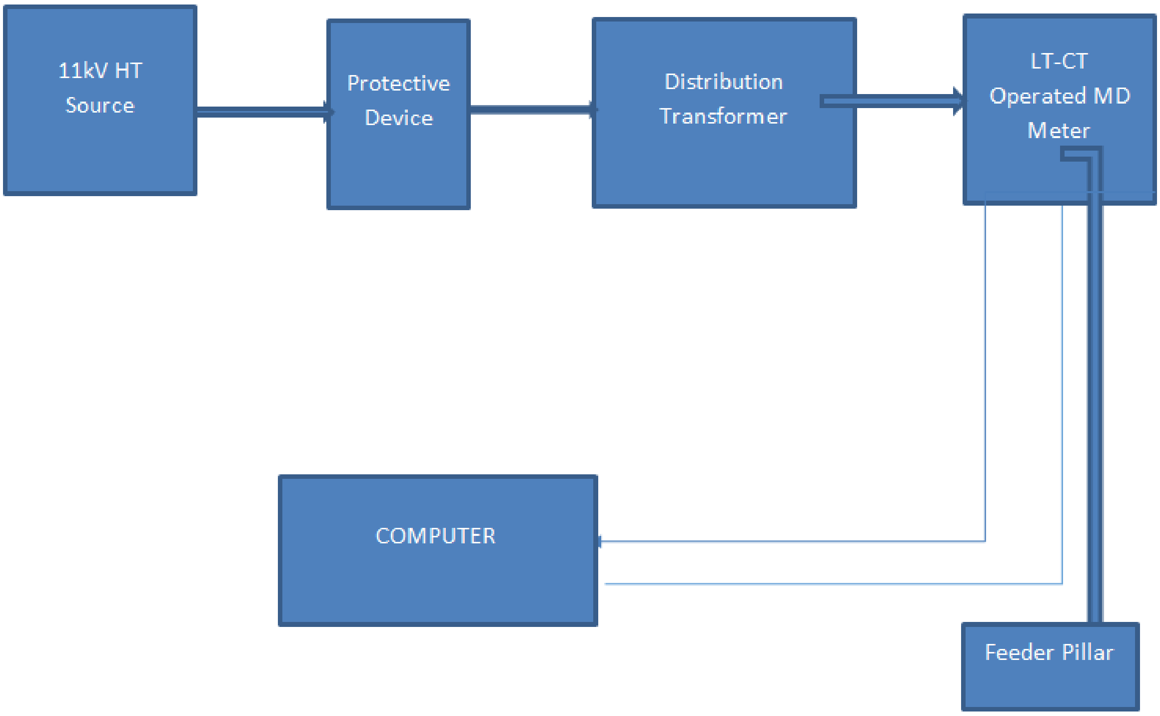

Fig.2: Block diagram of Ogbelaka (11/0.415kV) Distribution Substation

Data Presentation:

Table 2: Energy parameters obtained for a week in a Month of March 2017

Date	Name of days	Availability per	V_{RN} (Volts)	V_{YN} (Volts)	V_{BN} (Volts)	I_{PR} (Amps)	I_{PY} (Amps)	I_{PB} (Amps)	Power Factor (COSϕ)	Frequency (Hz)
1-Mar-17	Wednesday	14.3	231.3	226.8	231.6	410.5	578.6	371.4	0.92	50.01
2-Mar-17	Thursday	8.8	234.2	232.8	235.4	530.5	347.2	239.9	0.89	50.26
3-Mar-17	Friday	9.7	229.5	226.1	230.4	583.4	685.7	358.0	0.94	49.82
4-Mar-17	Saturday	12.3	228.0	224.1	228.1	549.2	645.7	329.9	0.94	50.59
5-Mar-17	Sunday	12.3	226.3	221.7	225.8	560.2	727.8	378.4	0.91	50.59
6-Mar-17	Monday	10.6	231.3	226.8	231.6	453.6	625.0	303.1	0.94	50.10
7-Mar-17	Tuesday	11.8	227.9	223.4	228.3	483.0	690.7	362.8	0.89	50.90
Total		11.4	229.2	225.7	230.2	510.1	614.39	334.8	0.919	50.32

Table 3 Energy Parameters obtained for Six Months from March to August 2017

Months	Availability per day (hrs)	V_{RN} (Volts)	V_{YN} (Volts)	V_{BN} (Volts)	I_{PR} (Amps)	I_{PY} (Amps)	I_{PB} (Amps)	Power Factor (COSϕ)	Frequency (Hz)
March	11.76	232.03	230.36	232.52	483.39	547.42	400	0.911	50.28
April	9.97	234.65	231.79	231.99	314.78	491.11	503.95	0.914	50.21
May	11.29	226.03	227.93	227.85	587.89	402.61	531.93	0.919	50.67
June	11.74	229.61	230.49	228.44	462.38	530.12	385.87	0.915	50.12
July	9.36	233.33	231.45	230.97	334.83	449.18	482.23	0.911	50.03
August	10.05	234.65	231.74	232.1	322.68	496.84	499.1	0.908	50.09
Total values	10.70	231.72	230.63	230.65	417.66	486.21	467.18	0.913	50.23

III. DATA ANALYSIS

Voltage unbalance can be determined as the maximum deviation from the average of the three-phase voltages divided by the average of the three-phase voltages, expressed in percent.

$Voltage\ Unbalance = Max\ Deviation\ from\ Average/Average\ Voitage$ (2)

From Table 2, the following voltages were obtained;

V_{RN} (Volts) = 229.2

V_{YN} (Volts) = 225.7

V_{BN} (Volts) = 230.2

$Total\ voltage\ sum\ for\ three\ phases = V_{RN} + V_{YN} + V_{BN}$

$\sum V = V_{RN} + V_{YN} + V_{BN}$ (3)

$\sum V = 229.2 + 225.7 + 230.2 = 685.1$

While the Average Voltage $\frac{\sum V}{3} = \frac{685.1}{3} = 228.4\ Voits$

$$\text{Maximum Deviation from Average Voltage} = 228.4 - 225.7 = 2.67$$

Recall Equation 2.

$Voltage\ Unbalance = \frac{\text{Maximum Deviation from Average Voltage}}{\text{Average Voltage}}\ x\ 100$ (4)

$Voltage\ Unbalance = \frac{2.67}{228.4}\ x\ 100 = 0.012\ Volts\ \ or\ \ 1.169\%$

Voltage unbalance data obtained from Table 2, for period of a week from 1st Wednesday to 7 Tuesday March 2017 is given as $0.012\ \ or\ \ 1.169\%$. The corresponding current unbalance using Equation 5 and parameters from Table 2 is given as

$Current\ Unbalance = \frac{\text{Maximum Deviation from Average Current}}{\text{Average Current}}\ x\ 100$ (5)

I_{PR} (Amps) = 510.1

I_{PY} (Amps) = 614.39

I_{PB} (Amps) = 334.8

$\sum I = 510.1 + 614.39 + 334.8 = 1459.29$

While the Average Current $\frac{\sum I}{3} = \frac{1459.29}{3} = 486.43$

$\text{Maximum Deviation from Average Current} = 486.43 - 334.8 = 151.63$

$Current\ Unbalance = \frac{151.63}{486.43}\ x\ 100 = 0.312\%\ \ or\ 31.2$ Amps

The average total energy parameters obtained for Six months from Table 3 are used to determine the average voltage, Average current, voltage unbalance and current unbalance.

Calculation for Average Voltage and Voltage Unbalance:

V_{RN} (Volts) = 231.72

V_{YN} (Volts) = 230.63

V_{BN} (Volts) = 230.65

$\sum V = 231.72 + 230.63 + 230.65 = 693$

While the Average Voltage $\frac{\sum V}{3} = \frac{693}{3} = 231$

$\text{Maximum Deviation from Average Voltage} = 231 - 231.72 = 0.72$

Recall Equation 4.

$Voltage\ Unbalance = \frac{\text{Maximum Deviation from Average Voltage}}{\text{Average Voltage}}\ x\ 100$

$Voltage\ Unbalance = \frac{0.72}{231}\ x\ 100 = 0.00312\ \ or\ \ 0.312\%$

Calculation for Average Current and Current Unbalance:

I_{PR} (Amps) = 417.66

I_{PY} (Amps) = 486.21

I_{PB} (Amps) = 467.18

$\sum I = 417.66 + 486.21 + 467.18 = 1371.05$

While the Average Current $\frac{\sum I}{3} = \frac{1371.05}{3} = 457.02$

Maximum Deviation from Average Current $= 486.21 - 457.02 = 29.19$

$Current\ Unbalance = \frac{29.19}{457.21}\ x\ 100 = 0.0638\ \%\ \ or\ 6.384$

Copper Losses due to Unbalance Load Current Analysis:

Average load current from the three phases $I_{\text{T}} = \frac{(I_R+I_Y+I_B)A}{3}$ (6)

Copper losses from balanced load current = $\frac{(I_T^2 R_R)+(I_T^2 R_Y)+(I_T^2 R_B)}{1000} kW$ (7)

Copper losses from unbalanced load current (kW) = $\frac{(I^2{}_R R_R + I^2{}_Y R_Y + I^2{}_B R_B)}{1000} kW$ (8)

Where:

I_R= Red phase Load in Amps (A)

I_Y= Yellow phase Load in Amps (A)

I_B= Blue phase Load in Amps (A)

V_R= Red phase Voltage in volts (V)

V_Y= Yellow phase Voltage in volts (V)

V_B= Blue phase Voltage in volts (V)

R_R= Red phase Resistance in ohms (Ω)

R_Y= Yellow phase Resistance in ohms (Ω)

R_B= Blue phase Resistance in ohms (Ω).

In doing this the winding resistance R per phase is assumed to be unity since this value is the same and constant for all phases of the transformer irrespective of loading. Next, balanced load condition was considered, which implies that the total load current will be shared equally among the phases of the transformer, under this condition Equation 3, holds where: $R_R = R_Y = R_B = R = 1$

For 1st March 2017 data from Table 2, were use for the analysis and similarly for other days, it is given as:

Average load current from the three phases $I_{\text{T}}(\text{A}) = \frac{(I_R+I_Y+I_B)}{3} A$

$= \frac{(410.5+578.6+371.4)}{3} = 435.5A$

Copper losses from balanced load current = $\frac{(I_T^2 R_R)+(I_T^2 R_Y)+(I_T^2 R_B)}{1000} kW$

Note: That R is the resistance of the transformer winding per each phase

$= \frac{(453.5^2 * 1)+(453.5^2 * 1)+(453.5^2 * 1)}{1000} = 617.0kW$

Copper losses from unbalanced load current (kW) $= \frac{(I^2{}_R R_R + I^2{}_Y R_Y + I^2{}_B R_B)}{1000} kW$

$= \frac{(410.5^2 * 1)+(578.6^2 * 1)+(371.4^2 * 1)}{1000} = 641.2kW$

The differential losses in (kW) = (Unbalanced Load Loss – Balanced Load Loss) kW

$= (641.2 - 617.0)kW = 24.2kW$

Energy Loss per Day (kWh) = differential Losses x Supply base on power Availability

$= 24.2 \times 14.3 = 346.5kWh$

Energy Loss in Naira = Energy Loss per Day x Energy Tariff

Using Energy Tariff form Three phase Residential customer = #34.4

Energy Loss in Naira $= 346.5 \times \#34.4 = \#11{,}919.6$

Based on the 1st day of March, 2017 data obtained.

IV. RESULT AND DISCUSSION

The three phase voltage and three phase current for different months from Table 3; are used to determine voltage unbalance and current unbalance for six months from 1st March to August 31th 2017 and it is presented in Table 4.

Table 4: Voltage and Current Unbalance in Percentage for Six Months

Months	Voltage Unbalance	Voltage Unbalance in percentage (%)	Current Unbalance	Current Unbalance in percentage (%)
March	0.0055	0.6	0.1478	14.78
April	0.0079	0.79	0.279	27.90
May	0.0055	0.55	0.2067	20.67
June	0.0046	0.462	0.160	16.02
July	0.00609	0.6093	0.207	20.67
August	0.0050	0.503	0.2659	26.59
Average Total	0.005765	0.58572	0.211067	21.105

The average total value of the three phase's voltage and corresponding current from Table 3 are used to determined voltage unbalance and current unbalance. In addition, the average total voltage unbalance current unbalance and the corresponding percentage were determined for a period of six shows in Table 4.

However, the copper losses due to unbalance load current analysis was determined, using the parameters from Table 2, Average load current from the three phases, balanced load current and unbalance load current.

Energy Loss per Day was determined from differential losses deduced from the different between balance load loss and unbalance load loss, which is multiplier by power supply availability. The resultant energy loss per day is multiplier by energy tariff using the recommended energy tariff form of three phase Residential customer of #34.4. Energy Loss in Naira is #11, 919.6 per day determined from Table 2 and the other corresponding parameters for six months from Table 3 are presented in Table 5.

The corresponding result determined from Table 3, after the analysis are presented in Table 5. they are total monthly unbalanced load loss (KWH), total monthly balanced load loss (KW), total monthly differential losses (kW), total monthly availability (hrs), total monthly energy loss (kWh) and total monthly energy loss in Naira @ #34,40 per KWH.

Total monthly energy loss in Naira for period of six months is # 2,412,197.1 due to copper losses from power transformer.

Table 5: Total Load Losses from the March to August 2017

1	March	22,554.90	21,358.90	1,196.00	364.5	13,718.20	471,904.60
2	April	18,416.80	17,315.60	1,101.20	299	10,659.60	366,690.20
3	May	25,421.30	24,097.40	1,323.90	349.9	14,065.30	483,846.60
4	June	21,051.90	19,910.50	1,141.40	352.2	13,038.30	448,517.60
5	July	17,655.20	16,903.60	751.6	289.8	7,419.50	255,230.20
6	August	19,286.40	18,148.70	1,137.70	311.4	11,221.20	386,008.00
	Total	124,386.50	117,734.70	6,651.80	1,966.80	70,122.00	2,412,197.1 Copper losses

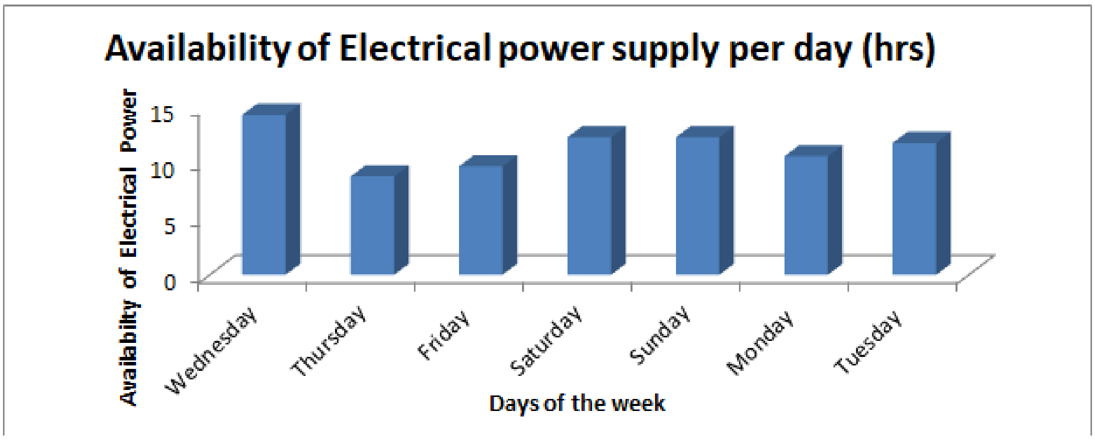

Fig. 2: Availability of Electrical Power supply Per Day (hrs)

The availability of electricity power supply to Ogbelaka environment for a week is presented in Fig. 2. It was observed that highest electricity power supply per day was witnessed on Wednesday, followed by Saturday and Sunday with the same capacity of electricity power supply. While Fig. 3, shown the availability of electricity power supply to Ogbelaka environment for six months duration from March to August, 2017. It was observed that the month of March witnessed the highest availability of electricity power supply to Ogbelaka environment followed by June and May etc.

Therefore, the availability of electricity to Ogbelaka is not linear, which implies that power supply to this environ is not constant. Mean while the same electricity generating capacity are still in place.

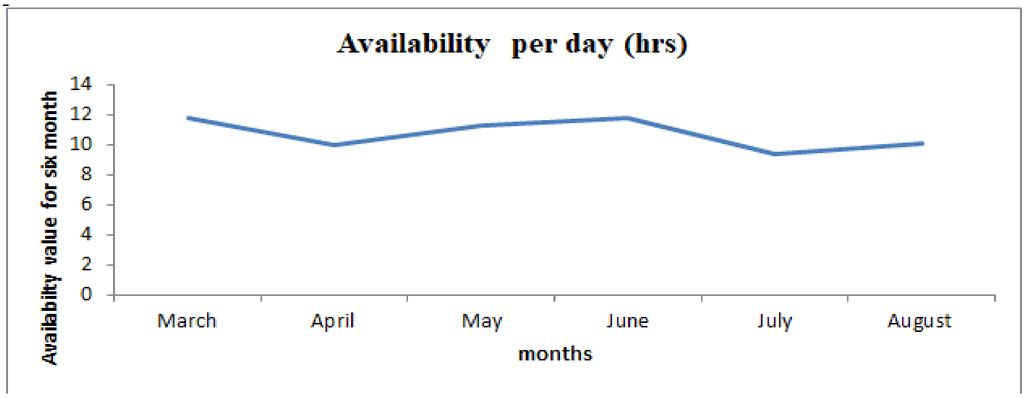

Fig. 3: Availability of Electrical Power supply for Six Months from March to August

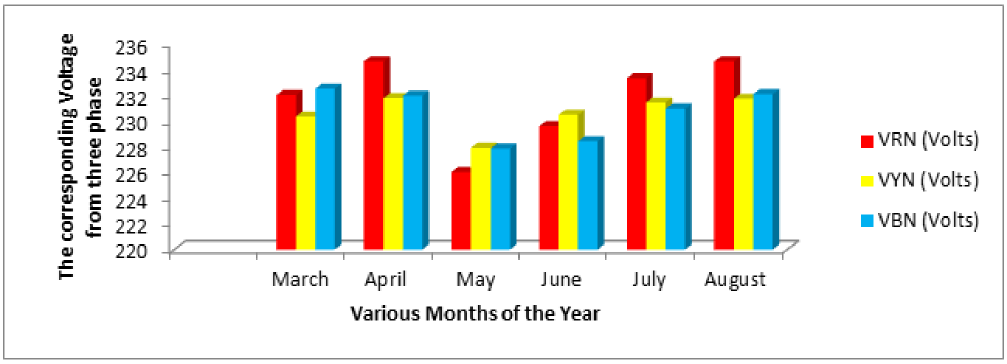

Fig.4: The Corresponding Voltage from Three Phases for Period of Six Months

The three phase's voltages measured in volt are presented in Fig.4 with their level of voltage indicated for six months from March to August 2017. It was observed that the voltage witnessed from the three phases (red-phase, yellow-phase and blue-phase) are not the same level of voltage. While, the corresponding current is presented in Fig.5, It was observed that the three phases (red-phase, yellow-phase and blue-phase) current witnessed undulating output values due voltage and load variation.

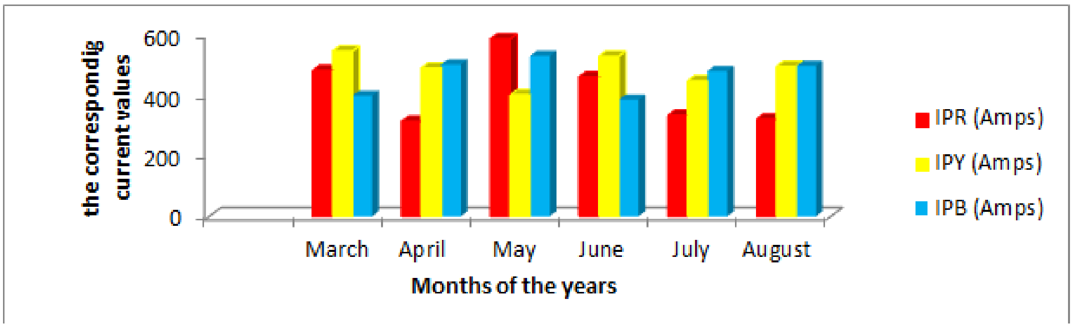

Fig.5: The corresponding Current from three phases (red-phase, yellow-phase and blue-phase) for period of six Months

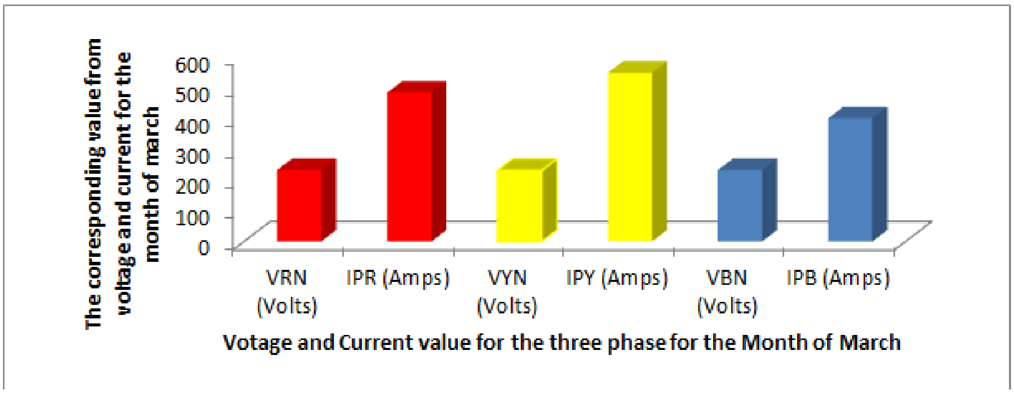

Fig.6: The comparison between each phase voltage and current for a period of six Months

In Fig.6, it was observed that unbalance voltage resulted to 50 to70 percentage increase in current variation in the month of March and the variation witnessed is not linear within the three phases (red-phase, yellow-phase and blue-phase) power distribution network. However, similar saturation was observed for six months from March to August.

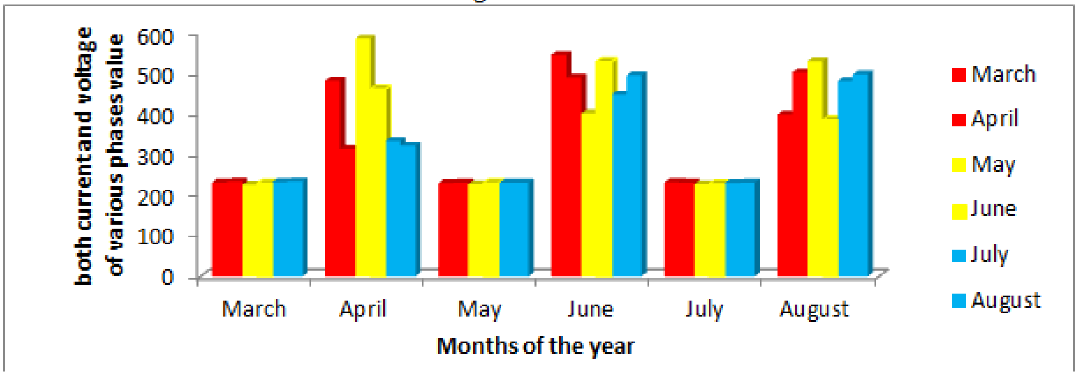

Fig.7: The three Phase (Red-Phase, Yellow-Phase and Blue-Phase) Comparison for Period of Six Months

Fig.7 presents the comparison of the three phases (red-phase, yellow-phase and blue-phase) for a period of six months; it was observed that the month of June witnessed highest voltage

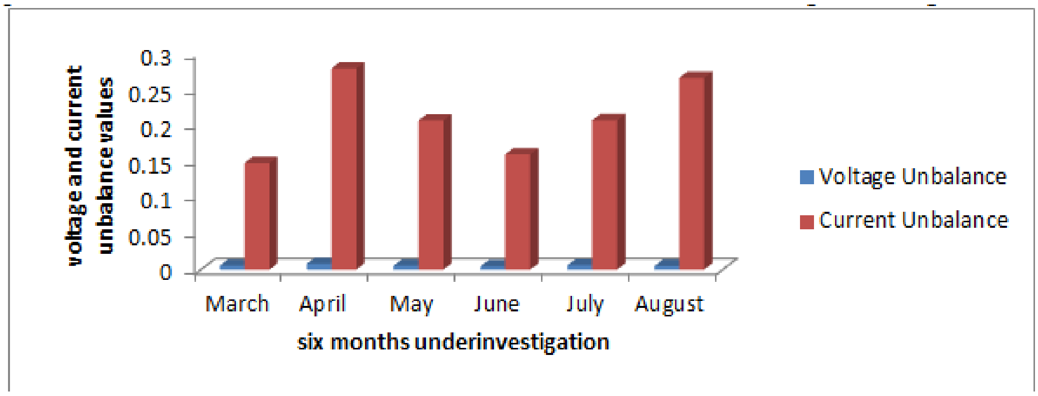

Fig.8: Unbalance Current Resulted from Unbalance Voltage

The difference between voltage unbalance and current unbalance was presented in Fig. 8. It was observed that slight value from unbalance voltage result to about 70 percentage increase in current unbalance from Table 3. This is to validate the theory that slight voltage variation leads to high increase of current in power system. This high value from current unbalance can lead to overheating in cables, induction motor etc.

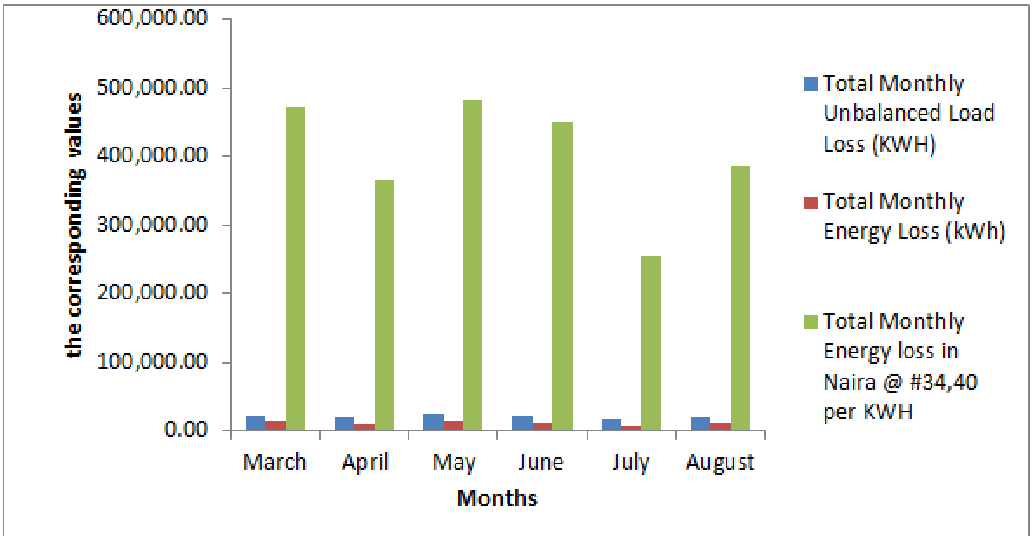

Fig. 9: Comparison between Unbalance Losses with the Corresponding Differential Losses and Energy losses.

The comparison between the energy losses and the equivalent amount in Naira is presented in Fig. 9.

Causes of Unbalance Voltage and Current:

The causes of unbalance voltage and current in power system are as follows;

(1) Unequal distribution of three phases among electrical load in electrical power system can result to unbalance voltage and current

(2) Blown out of electrical fuses in one phase of a three phase electrical power supply can result to unbalance voltage and current

(3) Unequal impedance in the power transmission or distribution system can cause differentiating electrical current in three phases

(4) Any large single phase load connected to only one phase can cause more current flow resulting to voltage drop on the line

(5) Switching of three phase heavy load result in current and voltage surge which can cause unbalance in the electrical system

(6) Three phase electrical equipment such as induction motor with unbalance windings with unequal reactance of three phases can result in varying the current flowing in the three phases and lead to system unbalance;

- Based on continuous operation leads to degradation and unbalance from different phase angle of current waveform
- A current leakage or motor body provide floating earth and probably causing fluctuating current

Effect of unbalance voltage and current:

The Effect of unbalance voltage and current in power system are as follows;

(1) Reduce the induction motor life span due to heating. In addition, the increase in the operational temperature, decomposes the grease or oil in the bearing

(2) Torque (the speed) produced by the motor can becomes vibrating, can affect the gear box or the entire equipment leading to excessive noise

(3) Unbalance voltage cause de rating of the power cable and thus increase I^2R losses in the cable. This loss along the power cable can result to losses in revenue collect from power operator.

(4) Inverter and UPS have low efficiency from unbalance voltage and inject more harmonic current in the power system.

(5) Negative electrical phase sequence current flow due to unbalance voltage, it can result in tripping or permanent damage of electrical equipments

Effects of unbalanced load on BEDC revenue:

The Effect of unbalance load on the transformer on BEDC revenue are as follows;

- Unbalanced load in a distribution substation has a negative effect on the revenue of BEDC, as the losses goes through the neutral to earth in star connection and remains as circulatory current in delta connection of transformer.
- This generates a great deal of heat in form of I^2R (copper loss), where R is the resistance of the copper windings in the transformer resulting losses in KW, Equation (5).

Thereafter, the number of hours (supply availability) in which there was power supply is considered to get the overall loss in KWH. Relating the loss in Naira value was using the Residential tariff, R_2T which is ₦31.27 per kWh of energy.

V. CONCLUSIONS

In this study, analysis of unbalance load and its effects on the revenue of BEDC a case study of Ogbelaka 500KVA, 11/0.414kV distribution substation is presented. Data were sort from the metering installation at Ogbelaka substation. Based on the data obtained it was observed that the power system possess different phase loads (unbalanced) on phase R, Y and B with average load of 587.9, 402.6, 531.9 amps in the month of May 2017 which is about 84%, 58%, 76% of the transformer loading capacity and if more loads are added continuously in this manner phase R protective device will operate even before phases Y and B reaches maximum capacity. This study also shows that the various phase loads followed the same pattern and are not linear throughout the months of March, April, May, June, July and August 2017 amounting to 417.2, 486.6 and 467.3 amps averagely which means that the phase R needs to be balanced with phase B and C to obtain a balanced loading system of 457.0 amps on each of the three phases which will bring the transformer loading capacity to 65.67% and can accommodate more loads, hence the need for a relief substation would be solved and lead to increased system capacity and more revenue for BEDC.

VI. REFERENCES

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