Investigation of Voltage Unbalance in Low Voltage Electric Power Distribution Network under Steady State Mode

Ogunboyo Patrick Taiwo
Electrical, Electronic & Computer.
Engineering Discipline
University of KwaZulu-Natal,
Durban, South Africa
ogunboyopt@gmail.com

Remy Tiako
Electrical, Electronic & Computer.
Engineering Discipline
University of KwaZulu-Natal,
Durban, South Africa
Tiako@ukzn.ac.za

Innocent E. Davidson
Dept. of Electrical Power
Engineering
Durban University of Technology
Durban, South Africa
Innocentd@dut.ac.za

Abstract-With the ever increasing use of semiconductor devices and information technology (ICT) equipment in the industry's, homes and offices voltage quality are gaining meaningful attention to both industry and the electric utility. Poor voltage quality cause unusually large economic losses all over the world, since voltage quality problem is one of the major power quality disturbances. This report provides an investigative study on the typical 11/0.4 kV, low voltage electric power distribution network. The network was modelled with standard network parameters for low voltage typical electric power distribution network using MATLAB/Simulink Sim Power System tool box. Results obtained from simulation with distribution feeder length 0.5 km for unbalanced 3-phase loads are within the acceptable nominal voltage tolerance range of ± 5 % of the nominal voltage value at the customer's terminal. While this is admissible for customers close to the infeed terminal, it was established that an inadmissible poor voltage reaches the customers at the end of the distribution network for network lengths 0.8 km to 5 km. Voltages measured here were less than the standard allowable limit of 0.95 p.u, of nominal voltage value. The summary of the paper gives recommendations on effective methods for enhancing voltage profile and correcting the unbalanced voltage to an allowable standard.

Keywords-Low voltage, voltage unbalance, voltage profile, voltage quality, distribution network, power system.

I. INTRODUCTION

Voltage unbalance is a regularly faced power quality problem with low voltage electric power distribution networks [1]. Customer's sensitive load, such as: semiconductor devices, information, communication equipment, hospital equipment and factory automation equipment are highly susceptible to power supply disruptions, hence the ultimate need for high power quality and voltage stability [2]. Voltage unbalance leads to overheating of equipment, amplifying losses and overall decrease in effectiveness of the power system apparatus and customer apparatus. Poor voltage quality leads to huge economic losses all over the world. It is estimated that power quality problems cost industry and commerce close to €100 billion per annum in the European Union [3].

Voltage unbalance is considered to be one of the most undesirable power quality disturbances in low voltage electric power distribution system [3]. Voltage unbalance can be observed in individual end user loads as a result of two phase load imbalances, particularly, were very big single-phase devices are utilized [4]. Nevertheless, the voltage on the transmission side are well regulated and balanced, the voltage at the end user level can become unbalanced due to load variation on each phase and different impedances [5]. Single-phasing, which is the absolute loss of a phase is an extreme case of voltage unbalance condition for a three phase circuit. Electricity industry usually attempts to share customers' loads uniformly among the three-phases of delivery networks [6]. Amplification in voltage unbalance may lead to reduce the rating and over-heating of adjustable speed drives categories of devices [7]. Voltage unbalance may lead to the following unforeseen problems of electric distribution, giving examples as failure to work normally of power electronics converters, heaters, household components, elevators, office equipment and adjustable speed drives [6].

Unbalanced voltage in 3-phase secondary distribution network is a circumstance in which supplied voltages are not same or when three phase voltages are not measurably the same in amplitude or the phase shift between voltages of any two phases is not 120^0, or both three phase voltages differ in phase with normal phase difference of 120 degree between each phase and/or differ in amplitude. Various ways of defining, calculating and interpreting of voltage unbalance as proposed in [8, 9, 10]. IEEE approved practice for regulating electric power quality states voltage unbalance as ratio of the greatest possible change from the mean of the three phase voltages or currents, to the average of the three voltages or currents, expressed in percent, likewise it can be defined as the ratio of negative or zero sequence component to the positive sequence component [11]. The ANSI standard recommends that the electric supply system should be made and function to limit the maximum voltage unbalance to 3% under no load condition [12].

voltage unbalance can be illustrated, using formula given in (1):

$$LVU\% = \frac{Maximum\ deviation\ \ from\ average\,voltage}{average\,voltage} \times 100\% \qquad (1)$$

Mathematically, voltage unbalance can be written as in equation (2):

$$LVU\% = Max\frac{\left[\left|V_{ab}-V_{av}\right|,\left|V_{bc}-V_{av}\right|,\left|V_{ac}-V_{av}\right|\right]}{V_{av}}\times 100\% \qquad (2)$$

Where, average voltage is given as:

$$V_{av} = \frac{V_{ab}+V_{bc}+V_{ac}}{3} \qquad (3)$$

Voltage unbalance produces undesirable influence on the electric grid system and components; this is made possible due to the fact that a small unbalance in phase voltages can lead to large unbalance in the phase currents [3, 8]. In unbalanced situations, grid systems will adversely affect by losses and heating influences, and will experience instability compare to the event of balanced phases, the network is in suitable situations to react to unexpected and sudden load change [8]. The influence of voltage unbalance can also be hazardous to components in example as adjustable speed drives, elevators, heaters and power electronics converters.

Some of the common causes of unbalance voltages can be summarized as: heavy reactive single phase loads, such as: unequal impedance in conductors' mains power supply wiring; welders, open delta linked transformer banks; a blown fuse on a 3-phase bank of power factor enhancement capacitors; open phase on the primary of a three phase transformer on the distribution system; unbalanced distribution of single phase loads such as lighting; faults or grounds in the power transformer; unequal transformer tap settings; unbalanced incoming utility supply; and large single phase distribution transformer on the system.

Various researchers have put forward techniques for analyzing the unbalance of the electric power distribution networks. [9] presented a study on the unbalance issues of the 3-phase four-wire electric power distribution networks. [10] proposed a voltage unbalance critical evaluation and random assessment based on the ratings and positions of single phase grid-connected rooftop photovoltaic cells in a residential low voltage electric distribution system. [12] presented the main justifications of voltage unbalance which draws unstable currents from the distribution system is as a result of a not measurably the same distribution of single phase loads [13] proposed that unbalance currents will create unequal heating in cables and other parts of the distribution system, which might bring down the life span of the cables and other elements in the network. [14] discussed the ant colony optimization based technique to assign each customer to a phase in order to reduce the problems of current balancing in a three phase low voltage distribution network, to maximize the efficiency of the grid.

In this paper, an investigation of voltage unbalance was carried out on low voltage electric power distribution network 11/0.4 kV, 500 kVA, urban and rural network. The results are presented under steady state mode. The evaluation using MATLAB/Simulink modelling techniques is employed to investigate and to say what will happen on distribution network voltage unbalance and voltage variation for the different network lengths in low voltage electric power distribution network.

II. SYSTEM MODEL

A. Model of LV electric power distribution network

Voltage unbalanced in LV distribution network was modelled and simulated in MATLAB/Simulink using Sim Power System tool box. The LV electric power distribution system presented in this structure is on the fundamental principle of the acceptable system parameters followed by electricity industry. Figure 1 explains the suggested Simulink structure. The length of the LV electric power distribution lines ranges from 0.5 km to 5 km, the voltage levels and conductor type of the low voltage entry system comprise of 400 $V_{L\text{-}L}$, 220 $V_{L\text{-}N}$ through 11/0.4 kV, distribution transformer, based on all-aluminium conductors (AAC) standard. In the proposed Simulink model three phase load is unbalanced at 80% full load transformer rating.

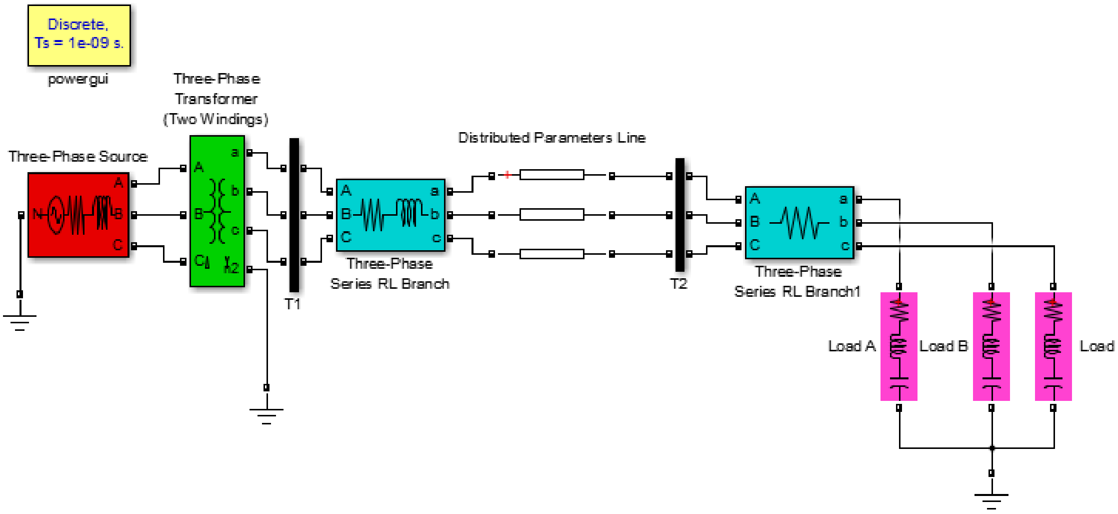

Fig. 1. Simulation model of 11/0.4 kV, LV electric power distribution network

B. *Network structure*

A low voltage (400 V) radial network residential urban/rural electric power distribution network was considered for low voltage unbalanced investigation. In this model, the transformer is delta/star connected, the phase loads are assumed to be unbalanced. The IEEE Recommendation practice for low voltage distribution power factor close to unity was used. The network supplies electricity to houses, shops and commercial organization. The feeder has three phase and four wire system with the length. The distance between each pole in low voltage electric power distribution network is 50 meters. From the electric pole, shops, offices and houses are provided from the phase. The technical information of the electric power distribution system is provided in Table 1

TABLE I. PARAMETERS OF LV DISTRIBUTION NETWORK

S/N	Material	Parameter
1	Distribution Transformer	11/0.4 kV, 500 kVA, Δ/Y grounded.
2	MV Feeder	Three Phase 11 kV radial, overhead lines.
3	LV Feeder	3–phase 4-wire, 400 V, overhead all-aluminium conductor 100 mm^2
4.	Unbalanced load	Phase A is 150 kW B is 110 kW and C 80 kW at 0.9 pf 80% transformer capacity rating

C. *Determination of electric power distribution network parameters and load*

To determine the voltage profile and current profile at each load point on the distribution network, a simulation was carried out on the modelled electric power distribution network using MATLAB/Simulink Sim Power Tool Box. This was done in order to estimate the voltage drop on three phase unbalance load on the network, hence the voltage profile, voltage deviation and percentage voltages deviation on the network was evaluated.

D. *Network parameters*

The line parameters resistance *R*, inductance *H*, and the capacitance *C*, were determined by computation.

The resistance, *R* of the line is determined by using equation (4):

$$R = \frac{\ell L}{A} \tag{4}$$

where ℓ is the resistivity of all-aluminum conductors and is given as 2.85 μΩ-cm, L is the length of each segment of the line, and *A* is the cross sectional area of the all- aluminum conductor used.

The inductance of each phase and capacitance can be calculated using equation (5) and (6)

$$L = 2\times10^{-7}\ln\left(\frac{GmD}{GmR}\right) H/m \tag{5}$$

$$C = \frac{2\pi\varepsilon}{\ln\left(\frac{GMD}{r}\right)} F/m \tag{6}$$

where, ε_o is 8.85×10^{-12}, the values of the geometric mean distance (GMD) and geometric mean radius (GMR) are calculated using equations (7) and (8) respectively.

$$GMD = \sqrt[3]{D_{ab} * D_{bc} * D_{ac}} \tag{7}$$

$$GMR = re^{-\frac{1}{4}} \tag{8}$$

where, r is the radius of the all-aluminium conductors and D_{ab} = 0.279 m, D_{bc} = 0.279 m, and D_{ac} = 0.559 m are distance between conductors of two phases of overhead LV electrical distribution network. For 100 mm^2 size all-aluminium conductors, it has 7/4.39 mm strands of conductors.

E. Determination of voltage deviation (E_{dev}, %) of the network

To determine the voltage deviation of the 11/0.4 kV distribution network. A three phase V-I measurement instrument in the Simulink model was used for voltage measurements between phase and neutral on the network. Readings obtained are presented in Tables 3 and 4 respectively.

The voltage deviation, (E_{dev}, %) was determined using equation (9):

$$E_{dev},\% = \frac{E_P - E_N}{E_N} * 100,\% \tag{9}$$

where E_P is the measured phase voltage, E_N is the normal voltage.

III. SIMULATION RESULT AND DISCUSIONS

Simulation results of three-phase unbalanced load and the analysis is shown in this part, include the voltage deviation, voltage drop and percentage voltage deviation.

A. Simulation of result of three-phase unbalanced load

The simulation result of the voltage unbalanced investigation of low voltage electric power 11/0.4 kV distribution network is presented in Figures 2 to 12, Table 2 shows the summary of the voltage profile and Figures 13 and 14 show the curves and the histogram of voltage profiles for unbalanced three phase load. Analysis of the results shows that the voltage profile for distribution length 0.5 km is 0.94 p.u , 0.95 p.u and 0.97 pu for phases A, B and C respectively. This implies that the voltage profile of phase B and C are within the voltage permissible limit of ± 5 % whereas phase A, voltage profile value of 0.94 p.u is 0.01 unit less than the minimum standard voltage permissible of 0.95 p.u nominal voltage, therefore is not good for customer use The remaining distribution network lengths of 0.8 km to 5 km, the voltage drop is far less than the standard allowable voltage range of 0.95 p.u and 1.05 p.u of the nominal voltage value, and so are not permissible for end users use Therefore the voltage profile at the beginning of the distribution feeder length decreased from 0.94 p.u to 0.17 p.u for phase A, 0.95 p.u to 0.22 p.u for phase B and 0.97 p.u to 0.28 p.u for phase C at the end of the distribution network feeder length.

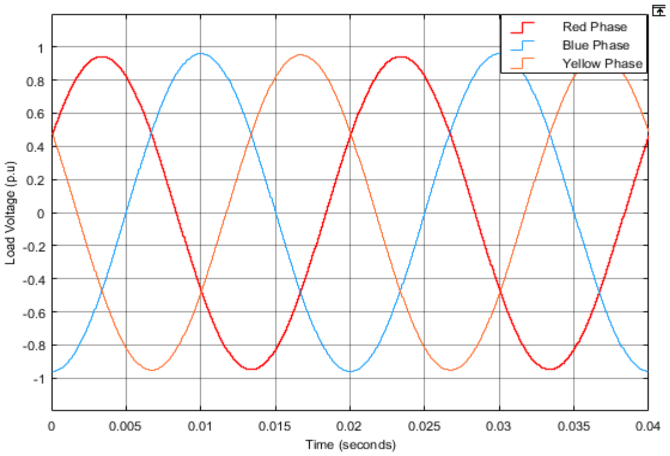

Fig. 2. Per-unit load voltage profile at 0.5 km for 3-phase unbalanced load

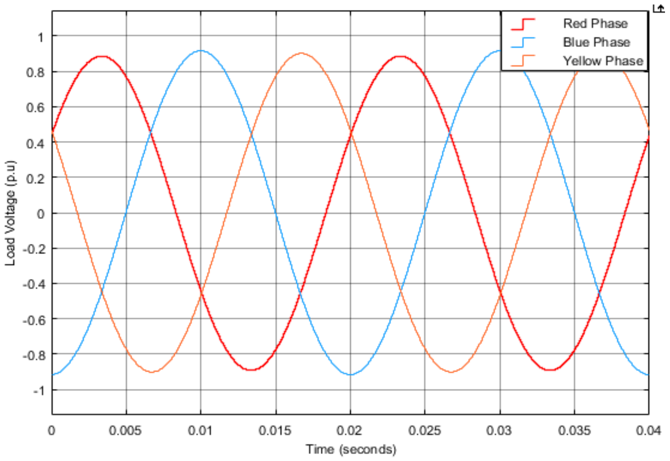

Fig. 3. Per-unit load voltage profile at 0.8 km for 3-phase unbalanced load

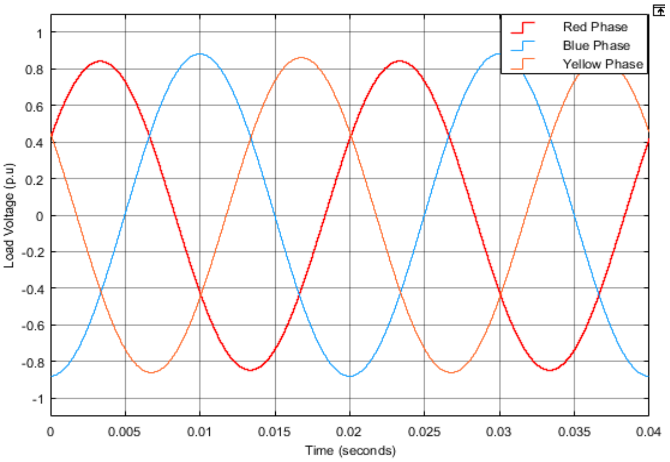

Fig. 4. Per-unit load voltage profile at 1.0 km for 3-phase unbalanced load

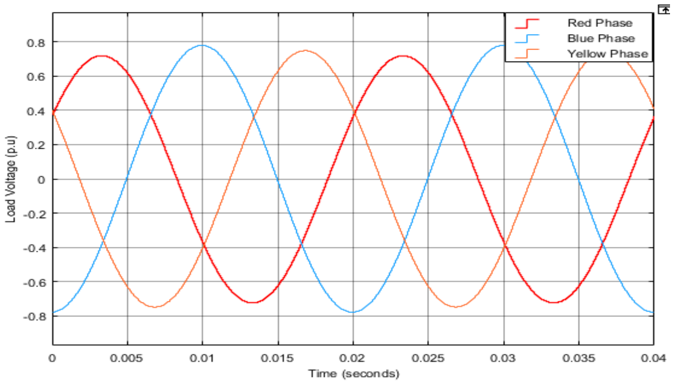

Fig. 5. Per-unit load voltage profile at 1.5 km for 3-phase unbalanced load

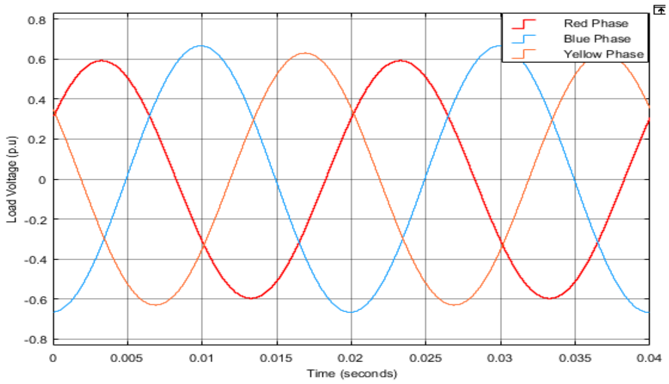

Fig. 6. Per-unit load voltage profile at 2.0 km for 3-phase unbalanced load

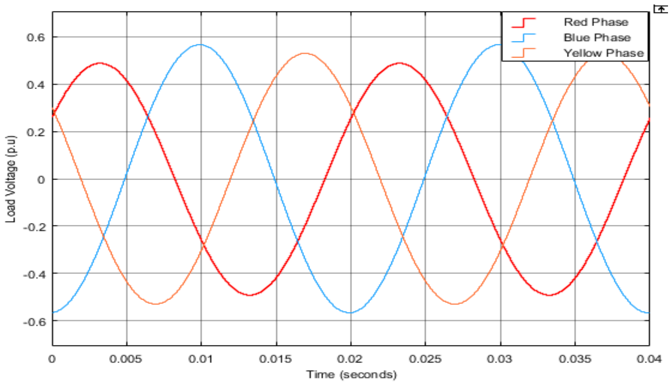

Fig. 7. Per-unit load voltage profile at 2.5 km for 3-phase unbalanced load

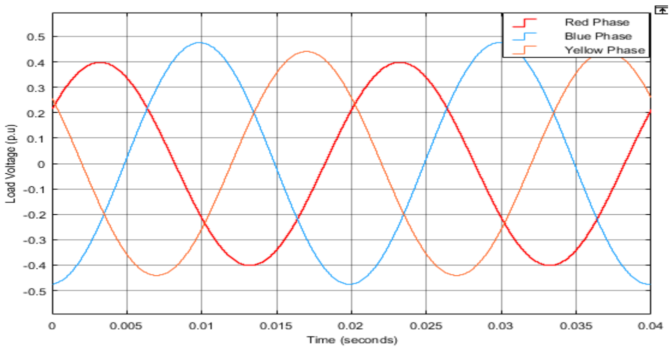

Fig. 8. Per-unit load voltage profile at 3.0 km for 3- phase unbalanced load

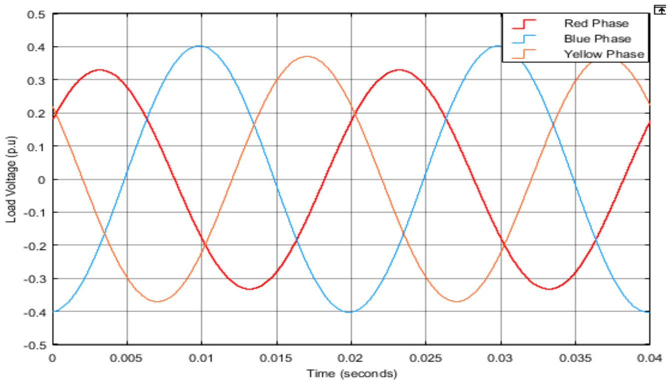

Fig. 9. Per-unit loadvoltage profile at 3.5 km for 3-phase unbalanced load

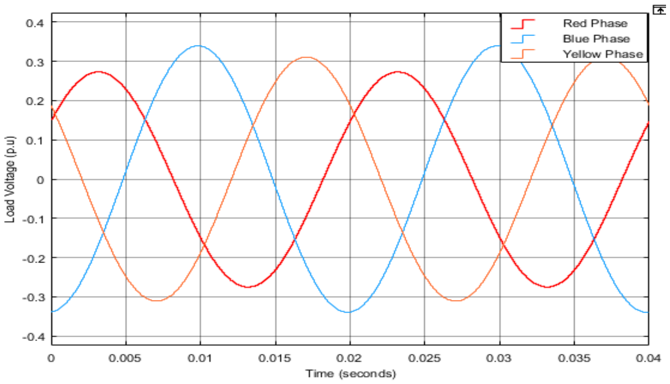

Fig. 10. Per-unit load voltage profile at 4.0 km for 3-phase unbalanced load

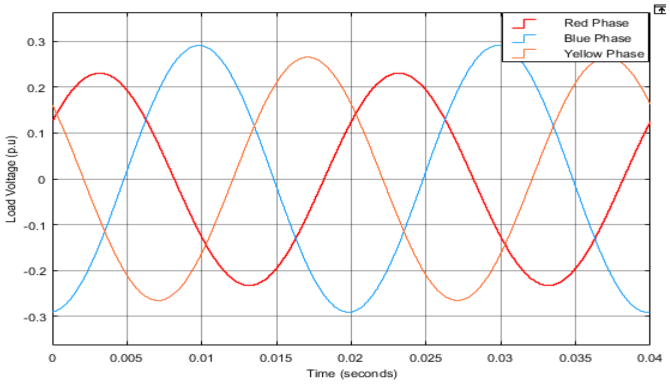

Fig. 11. Per-unit load voltage profile at 4.5 km for 3-phase unbalanced load

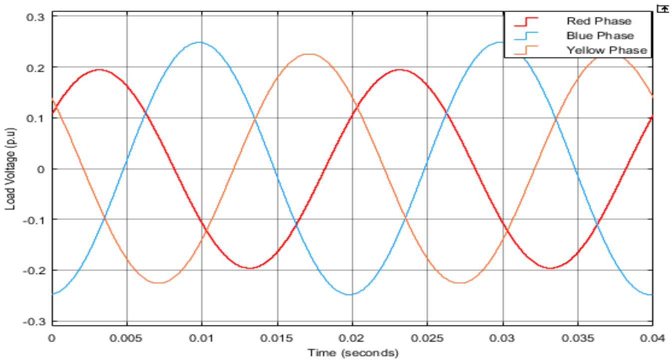

Fig. 12. Per-unit load voltage profile at 5 km for 3 phase unbalanced load

TABLE II. PER- UNIT MEASUREMENT OF VOLTAGE PROFILE FOR THREE-PHASE UNBALANCED LOAD

L, (km)	VP, Phase A (p.u)	VP, Phase B (p.u)	VP, Phase C (p.u)
0.5	0.94	0.95	0.97
0.8	0.87	0.90	0.93
1.0	0.82	0.87	0.90
1.5	0.68	0.75	0.80
2.0	0.56	0.63	0.70
2.5	0.45	0.52	0.60
3.0	0.36	0.43	0.51
3.5	0.29	0.36	0.44
4.0	0.24	0.30	0.37
4.5	0.21	0.25	0.32
5.0	0.17	0.22	0.28

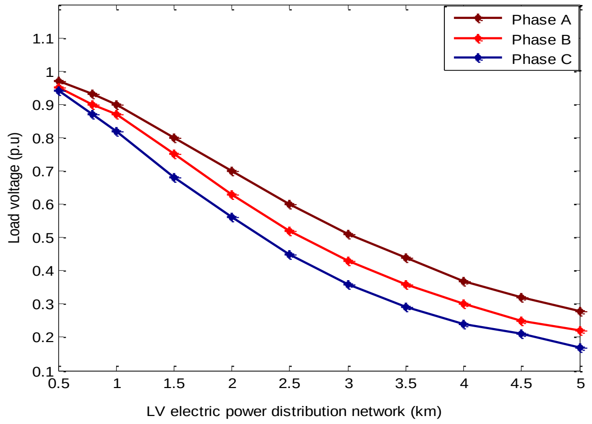

Fig. 13. Curve of voltage profile for three-phase unbalanced load

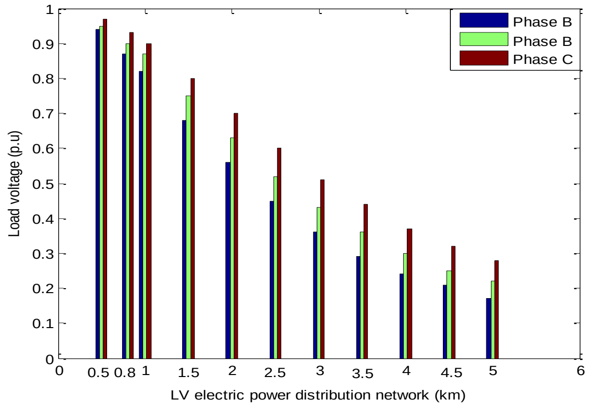

Fig. 14. Histogram of voltage profile for three-phase unbalanced load

B. *Voltage deviation for three-phase unbalanced load*

Table 3 shows the computation of voltage deviation for three phase unbalanced load and Figures 15, 16 and 17 show the pie charts of percentage voltage deviation of LV distribution network under study. Analysis shows that voltage deviation for 0.5 km feeder length of phases B is 5 % and C is 3 % fall within the normal permissible range which must be within ±5 % of nominal voltage value while that of phase A of 0.5 km length is 6 %, this is above -5 % of nominal voltage value, hence is not admissible for customer use. Whereas the voltage deviation of distribution length 0.8 km to 5 km does not fall within the normal permissible range, implying a poor voltage quality reaching end users: all values of *Edev, %*, for three phase of network feeder lengths of 0.8 km to 5 km are less than the minimum standard allowable of -5 % of nominal voltage values. Figures 18 and 19 show the summary of the percentage voltage deviation and voltage drop on three-phase unbalance load.

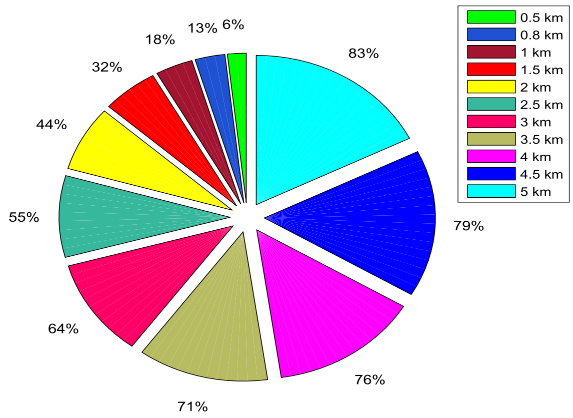

Fig. 15. Pie chart of percentage voltage deviation for three-phase unbalanced load phase A

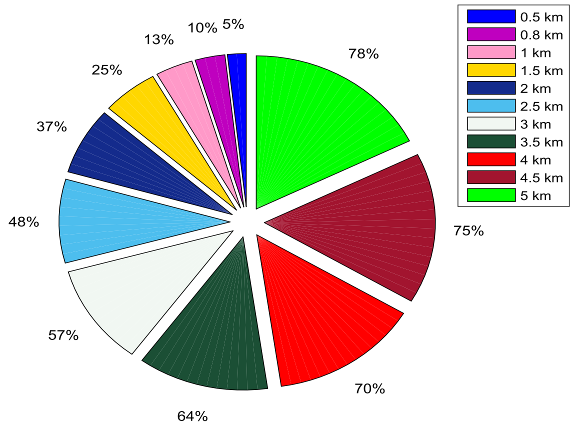

Fig. 16. Pie chart of percentage voltage deviation for three-phase unbalanced load, phase B

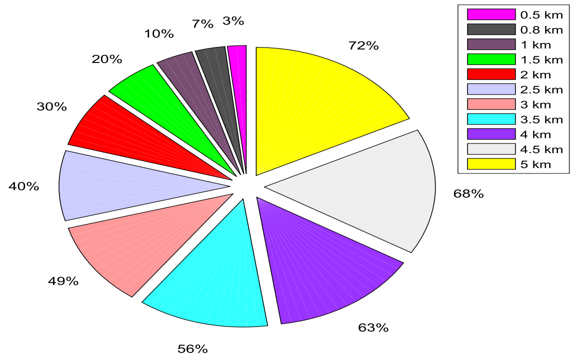

Fig. 17. Pie chart of percentage voltage deviation for three-phase unbalanced load Phase C

TABLE III. COMPUTATION OF VOLTAGE DEVIATION FOR THREE-PHASE UNBALANCED LOAD

L, km)	**ΔEdev, V,** Phase A	**ΔEdev,** , Phase B	**ΔEdev, V**, Phase C	**ΔE,V, A**	**ΔE,V,B**	**ΔE,V,C**	Edev,%, Phase A	Edev,%, Phase B	Edev,%, Phase C	**ΔEstd.min & max ., %**
0.5	0.06	0.05	0.03	13	11	6.6	6	5	3	±5
0.8	0.13	0.10	0.07	29	22	15	13	10	7	±5
1.0	0.18	0.13	0.10	40	29	22	18	13	10	±5
1.5	0.32	0.25	0.20	70	55	44	32	25	20	±5
2.0	0.44	0.37	0.30	97	81	66	44	37	30	±5
2.5	0.55	0.48	0.40	121	106	88	55	48	40	±5
3	0.64	0.57	0.49	141	125	108	64	57	49	±5
3.5	0.71	0.64	0.56	156	141	123	71	64	56	±5
4.0	0.76	0.70	0.63	167	154	139	76	70	63	±5
4.5	0.79	0.75	0.68	174	165	150	79	75	68	±5
5.0	0.83	0.78	0.72	183	172	158	83	78	72	±5

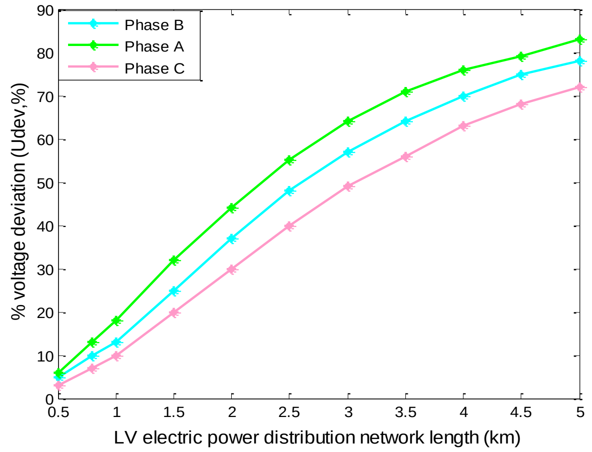

Fig. 18. Bar chart of % voltage deviation for three-phase unbalanced load

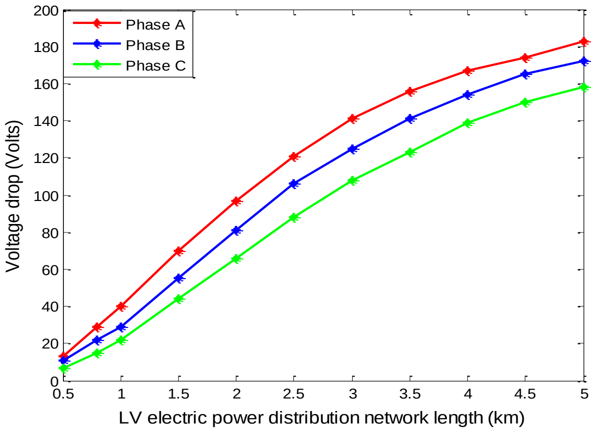

Fig. 19. Bar chart of voltage drop on three-phase unbalanced load.

IV. CONCLUSIONS

Based on the simulation result analysis of LV electric power distribution network standard parameters using MATLAB/Simulink Sim Power System tool box. It is shown that the voltage profile for 0.5 km distribution network length are admissible for customers from the beginning to the end of the feeder as designed with engineering standard and judgements. However, it is also established that the voltage profile for distribution network lengths of 0.8 km to 5 km from the beginning to the end of the feeder are less than standard minimum permissible limit of 0.95 p.u, hence voltage is inadmissible for customers use. Furthermore, it is also shown that a permissible voltage range can be attained with the utility companies must follow the minimum standard for distribution network feeder length of 0.5 km at 80 % transformer capacity rating with voltage booster connected to the bus of 11/0.4 kV transformer to boost supply voltage to 1.05 p.u nominal voltage. Finally, it was established that voltage imbalance in low voltage electric power distribution network will intensify or diminish based on the network length and the load on the phases. The proposed solutions to the problem of poor voltage profile in low voltage electric power distribution network are: [1] the utility companies must follow the minimum standard for distribution network length of 0.5 km to 0.8 km at 80% full load transformer rating and must provide voltage boosting at the feeder bus of 11/0.4 kV transformer to boost supply voltage to standard +5 % nominal voltage. This will eliminate the problem of critical voltage drops in the distribution system length. [2] In an event of extending the distribution length beyond the minimum standard of 0.5 km and 0.8 km, due to ever increasing demand by the electricity customers, the electricity industry should provide an efficient and effective means of voltage booster connected along the feeder length to enhance voltage profile from the beginning of the network to the end to standard permissible range. If implemented, the quality of electricity supply will improve and thereby reduce load shedding during peak load and winter period. It will similarly decrease incidents of malfunctioning of customers single and three phase sensitive loads. By extension, this will raise the general living standard of the customers deriving from the 11/0.4 kV electric power distribution network.

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