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Harmonic Analysis in a 33kV Distribution Network: A Case Study of Island Business District

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ABSTRACT

Distribution Line Network harmonic investigation has become an important issue in electric power systems since the increased use of power electronic devices and equipment sensitive to harmonics, which in turn, has increased the number of adverse harmonic-related events. Power quality problem and the means of keeping it under control is a growing concern. Due to the connection of nonlinear loads in a 33kV distribution network, power quality issues have been raised and have resulted to widespread waveform distortion. This paper makes use of the Busbar voltage solutions obtained from a power flow study on the Eko Electricity Distribution Company's 33kV network and they are used as the base data for the harmonic analysis. A distribution line model was formulated. MATLAB/Simulink was used to simulate this modelled network for each distribution lines of the power system network considered. This simulation was achieved through the application of sending and receiving end busbar voltages already obtained from the power flow study. The harmonics observed on each distribution line at various scenarios of load/feeder restoration and their characteristic impedance magnitudes/frequency are all presented. Necessary discussions on the harmonic results are also presented.

Keywords: Distribution Line, Power Quality, Harmonics

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1. INTRODUCTION

The late 80's and early 90's saw the emergence of power electronic loads. Power electronic loads offer the advantages of efficiency and controllability. However, they draw non-sinusoidal currents from AC power systems, and these currents react with system impedances to create voltage harmonics and in some cases, resonance. Studies have shown that harmonic distortion levels in distribution systems are rising as power electronic devices continue to proliferate [1]. Distribution Line network harmonic investigation has become an important issue in electric power systems since the increased use of these devices and equipment sensitive to harmonics, which has increased the number of undesirable harmonic-related conditions. The Power quality problem, and the means of keeping it under control, is a growing concern [2]. Power quality means the physical characteristics of the electrical supply provided under normal operating conditions that do not disturb the customer's processes [3].

Power Quality has no fully accepted definition, but surely the response involves the waveforms of current and voltage in an ac system, the presence of harmonic signals in bus voltages and load currents, the presence of spikes and momentary low voltages, and other issues of distortion [4]. Perhaps the best definition of power quality is [5], "the provision of voltages and system design so that the user of electric power can utilize electric energy from the distribution system successfully, without interference or interruption". The non-linear characteristics of power electronic loads cause harmonic currents, which result in additional losses in distribution system equipment, interference with communication systems, and misoperation of control [2].

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Harmonics are components of a periodic wave having a frequency that is an integral multiple of the fundamental power line frequency. Harmonics, therefore, are the multiple of the fundamental frequency. Traditional harmonic producing loads are the rotating machines and transformers in electric power systems. Because of uneven distribution of flux in the air gap of the rotating machine, non-sinusoidal voltages and currents are generated by rotating machines such as synchronous machines. Overloaded transformers generate harmonic currents. Transformer excitation currents will be non-sinusoidal because of core-saturation, magnetic imbalance or DC magnetization resulting in harmonic currents [6, 7]. The increasing usage of non-linear loads on electrical power systems is causing greater concern for the possible loss of transformer life[8,9].

Small power equipments such as televisions, computers, Adjustable Speed Drives (ASD), Uninterrupted Power Supply (UPS) systems, electronic ballasts and office equipments such as printers and fax machines draw non-sinusoidal voltages and currents. The current harmonics consumed by these loads flowing through the line impedances cause distorted voltages and, the significant harmonics are extended to the rest of the network [10]. Individual effects of this type of equipment to harmonic distortion may be negligible, but the combined effects of a larger number of these to harmonic distortion in power systems can be substantial. The network was modelled and simulated using the MATLAB/Simulink platform. Harmonic analysis in general can benefit from effective monitoring [11] of a power system network.

2. SOURCES OF HARMONICS

In order to understand the injection of harmonic currents in the power distribution network, it is necessary to discuss the general characteristics of nonlinear loads. Nonlinear loads inject harmonic currents or voltages into the distribution network even when fed by a sinusoidal voltage or current waveform. Nonlinear loads can be broadly divided into two categories [12]:

- Harmonic source type loads;
- Harmonic voltage source type loads.

The associated harmonic current passing through the system impedance causes voltage drops for each harmonic frequency based on Ohm's Law. The vector sum of all the individual voltage drops results in total voltage distortion, the magnitude of which depends on the system impedance, available system impedance, available system fault current levels of harmonic currents at each harmonic frequency [13].

The effects of harmonics can be summarized as follows:

- ❖ High fault current (stiff system)
- ❖ Distribution system impedance and distortion is low.
- ❖ Harmonic current draw is high.
- ❖ Low fault current (soft system)
- ❖ Distribution system impedance and distortion is high
- ❖ Harmonic current draw is low

For general purposes, the harmonic sources can be divided into three categories [14]:

1. A large number of distributed nonlinear components of small rating (i.e. mass products), consists mainly of: single phase diode bridge rectifiers, power supplies of low voltage appliances (SMPS in TV sets, PCs and other IT equipment), and gas discharge lamps.
2. Large static power converters (SPC) are used more extensively for controlling loads. There are many forms of SPC: rectifiers, inverters, cyclo-converters, single-phase, three-phase, twelve-pulse, six-pulse, but all have the same character. They are all nonlinear and they inject non-sinusoidal current into the power system.
3. Large and continuously varying nonlinear loads. This refers mainly to electric metal-melting arc furnaces with power ratings in the tens of megawatts and connected directly to the transmission network. The furnace arc impedance varies randomly and extremely asymmetrical, since the carbon electrodes in contact with iron have dissimilar impedances between the positive and negative flows of current. Resistance welding has the same characteristics, where the copper electrodes and the steel being welded have dissimilar impedances between the positive and negative flows of current.

2.1 Impact of Harmonics

Practically speaking, utilities frequently encounter the following harmonic-related problems [12]:

- Voltage distortion in distribution feeders;
- Increased RMS currents, heating and line losses;
- Overheating of power transformers, which requires higher K-factor transformers;
- Derating of distribution equipment;
- Overloading of phase and neutral conductors - neutral currents in a typical commercial office building may carry more than phase RMS currents;
- Overloading and fuse blowing of power factor correction capacitors;
- Tripping of voltage harmonic sensitive equipment;
- Failure of control electronics, micro-processors;
- Reduced accuracy of measuring instruments (such as watt-hour meters);
- Malfunction of solid-state fuses, breakers and relays;
- Reactive power and resonance problems;
- Reduced system stability and safe operating margins, etc.

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2.2 Harmonic Components

A method to represent any non-sinusoidal periodic function $u(t)$ using an infinite series of cosine and sine functions and coefficients as shown in equation (1) was first proposed by Baron Jean Fourier in 1822:

$$u(t) = A_o + \sum_{h=1}^{\infty}[A_o cos(h\omega_o t) + B_o sin(h\omega_o t)]$$

$$= A_o + \sum_{h=1}^{\infty} C_h cos(h\omega_o t + \Psi_h) \quad \text{.....(1)}$$

Where

$u(t)$ is a periodic function of frequency f_o, angular frequency $\omega_o = 2\pi f_o$, and period $T = \frac{1}{f_o} = 2\pi/\omega_o$.

$C_1 cos(h\omega_o t + \Psi_1)$ represents the fundamental component, and $C_h cos(h\omega_o t + \Psi_h)$ re[presents the h^{th} harmonic component of amplitude C_h, frequency $h\omega_o$ and phase Ψ_h relative to the fundamental.

Generally, for power systems, the fundamental frequency is either 50Hz or 60Hz. Power systems in Nigeria are typically operated at 50Hz and thus harmonic frequencies will appear as multiples of 50Hz (100Hz, 150Hz, 200Hz, etc.). The Fourier series coefficients C_1, C_2, …C_h and relative phases $\Psi_1, \Psi_2, \ldots \Psi_h$ make up the harmonic spectrum of the waveform and are found using equations (2) through (6):

$$A_o = \frac{1}{T}\int_0^T u(t)\,dt = \frac{1}{2\pi}\int_0^{2\pi} u(t)\,dx, where x = \omega_o t \text{.....(2)}$$

$$A_h = \frac{2}{T}\int_0^T u(t) cos(h\omega_o t)\,dt = \frac{1}{\pi}\int_0^{2\pi} u(t) cos(hx)\,dx \text{..(3)}$$

$$B_h = \frac{2}{T}\int_0^T u(t) sin(h\omega_o t)\,dt = \frac{1}{\pi}\int_0^{2\pi} u(t) sin(hx)\,dx \text{...(4)}$$

$$C_h = \sqrt{A_h^2 + B_h^2} \text{.....(5)}$$

$$\Psi_h = \tan^{-1}\frac{A_h}{B_h} \text{.....(6)}$$

Conversely, if the harmonic spectrum of a given current or voltage waveform *u(t)* is known the original waveform can be constructed using the Fourier series summation:

$$u_t = \sum_{h=1}^{\infty} U_h cos(h\omega_0 t + \Psi_h) \text{.....(7)}$$

where

Uh is the h^{th} harmonic peak current or voltage, Ψ_h is the hth harmonic phase, ω_0 is the fundamental angular frequency, $\omega = 2\pi f_o$ and f_o is the fundamental frequency, typically 50Hz.

3. HARMONIC SIMULATION

In order to study the net effects of harmonics in a power system, simulations were carried out taking the 33kV distribution network of Island Business Unit (IBU), Eko Electricity Distribution Plc (EKEDP) grid, as a case study and the network is shown in fig. 1.

In power systems, transmission or distribution lines are modelled using any of these networks: π - network, T – network and π & T networks, depending on the distance of the line.

Since the longest distribution route length in this journal paper is 6.84KM, a π distribution line modelling approach was adopted using the MATLAB/Simulink environment. The π-modelled diagram or circuit suitable for the display of harmonics flowing between two buses is shown in fig. 2 below. It comprises the source, which is the input, as well as the output electrical parameters such as resistance, reactance, and susceptance. It also has two oscilloscopes placed at Fowler (FOW) and Alagbon (ALG) busbars (within the distribution network under consideration) to monitor the input and output voltage variation during simulation process. A reactor is connected for power control, while a current source is included to act as non-linear loads which generate harmonics.

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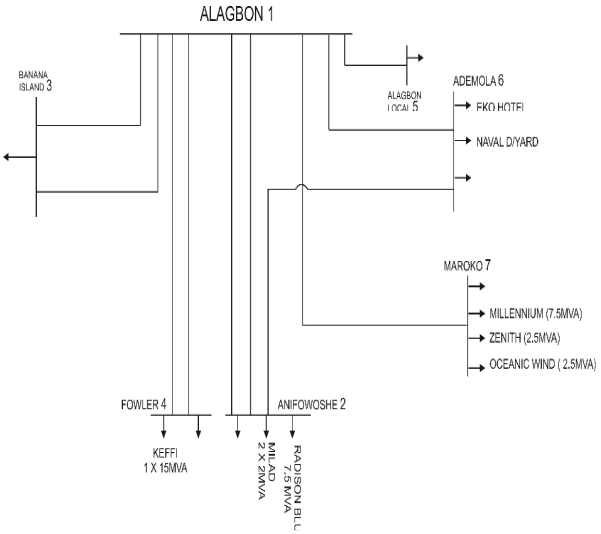


Figure 1: 33kV Network of Islands Business Unit, EKEDP

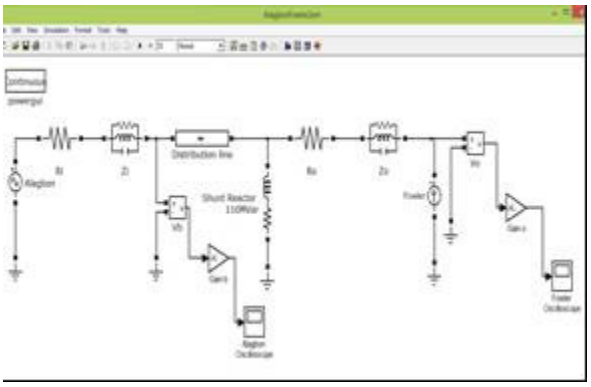
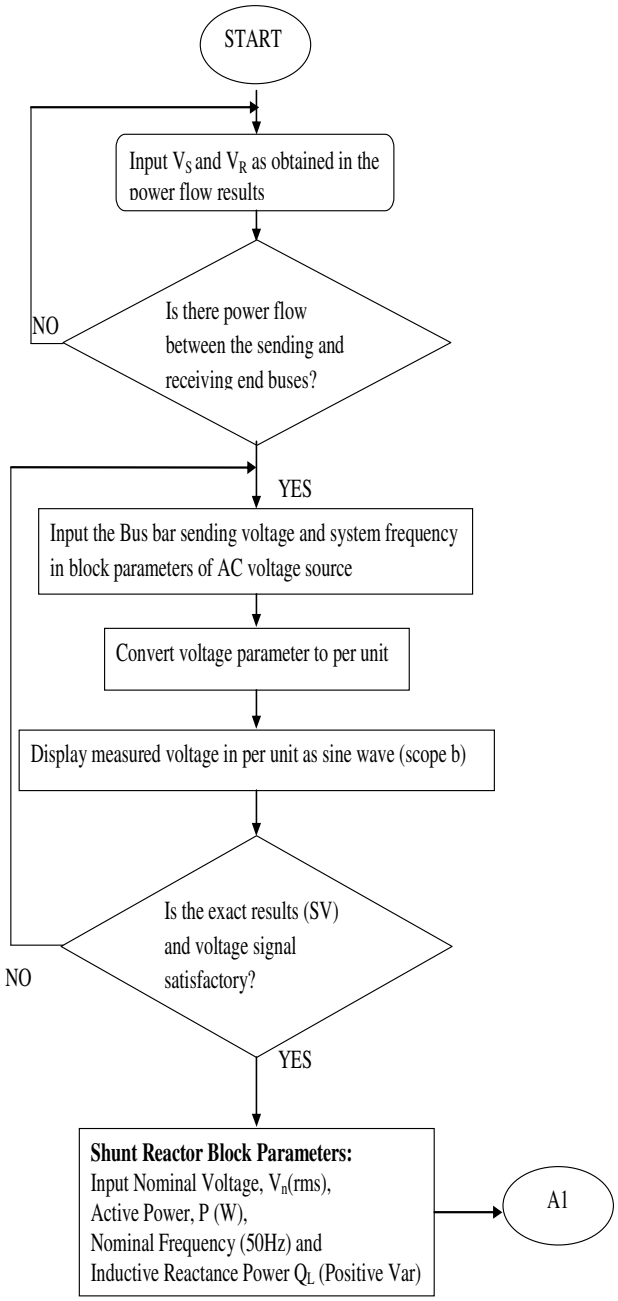


Figure 2: **Formulated Model of Distribution Line Alagbon – Fowler Busbars as example**

3.1 Development of Flowchart for Harmonic Evaluation on the Line between Two Buses

The Busbar voltage solution obtained from power flow study of fig.1 is further applied on the modelled π distribution network to get the harmonics on the line. It involves the use of two voltages at the ends of the distribution lines i.e. sending end voltage, V_S and the receiving voltages V_R.

The flow chart in figure 2 shows the procedure involved in obtaining harmonic flow on the line between two buses.



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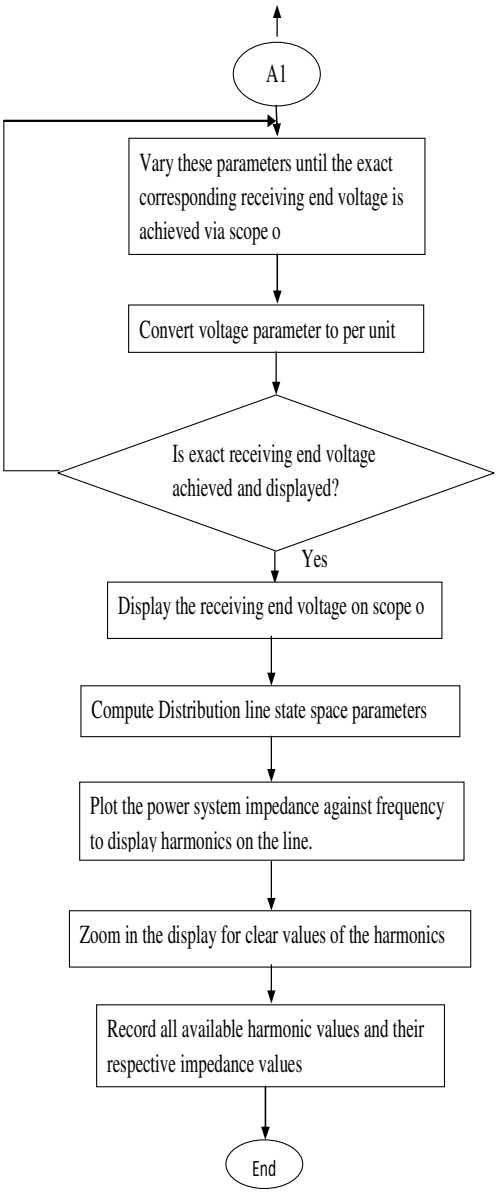


Figure 3: Development of flowchart for Harmonic Evaluation on Modelled π Distribition Lines between two Busbars

3.1 Harmonics Simulation Algorithms

The procedure involved in determining the Harmonic flow in the power systems Network using MATLAB simulation approach (Cascaded pi Distribution Model) are as follows:

1. Obtain a suitable Model Network as shown in Fig.1
2. For the line in consideration, insert system frequency and the sending end voltage obtained from power flow analysis results into the MATLAB block parameters of AC voltage source.
3. Display the Sending end Voltage (SV) signal on scope b (Input).
4. On MATLAB Shunt reactor (110Mvar) block parameters, input- Nominal Voltage V_n (rms)
5. Nominal Frequency (50Hz) Active Power P(w) Inductive reactive power Q_L (positive var)
6. Vary the parameter in 4 above (i.e. Nominal Voltage V_n) until an exact corresponding Receiving end Voltage (RV) is achieved via scope o
7. When step 5 is achieved, display the bus bar receiving end voltage signal (output) on scope o.
8. In the state-space model block, compute distribution line steady state parameters in magnitude and phase values. The parameters to be displayed will include values of:

a) **States**:

i. Current I_i through Z_i
ii. Voltage V_c across Z_i (RLC)
iii. Current I_i through Z_o
iv. Voltage V_c across Z_o
v. Current I_i through shunt Reactor 110MVar
vi. Input Voltage V_c at the beginning of Distribution line (Bus bar 1)
vii. Current I through the pi section (Distribution line)
viii. Output voltage V_c at the end of Distribution line (Bus bar 2)

b) **Measurements**:

Magnitude and phase values of:
i. Measured voltage V_o at scope o (output)
ii. Measured voltage V_b at scope b (Input)

c) Sources:

Magnitude and phase values of:
i. Bus bar voltage in volts
ii. Load on Bus bar in Amperes

1. Plot the power system impedance against frequency to display the harmonics on the distribution line.
2. From the plot, record harmonic frequencies and the corresponding harmonic impedance.
3. Repeat step 2-9 for other lines within the same time scenario. In these cases, the parameters (SE Voltage, RE Voltage and distance) may be different in values.
4. Prepare a table of Distribution line Harmonics and their impedance.
5. Go to "Next hour scenario"
6. Repeat steps 2-11
7. End

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3.2 Harmonic Simulation Results

Figures 3a to figure 3m are the harmonic analysis results for different cases and at different times of the day under consideration. The amplitude of Source voltage,V (33kV), Nominal frequency (50Hz), Shunt Reactor (110MVar), Active Power,P (110e6/300 W) and Inductive Reactive Power,Q_L (110e6 +Var), remain the same in all cases of the simulation, except for the case of Alagbon – Anifowoshe D/L at 23:00Hrs, whose amplitude of source voltage is 32.825kV. Tables 1 to 4 give summaries of the Distribution Line Harmonics and their Impedance for all cases under consideration.

At 02:00Hrs
Case 1: Alagbon (ALG) – Alagbon Local (ALG/L) Distribution Line (D/L)
Nominal Voltage, V (Vrms) = 39.5kV

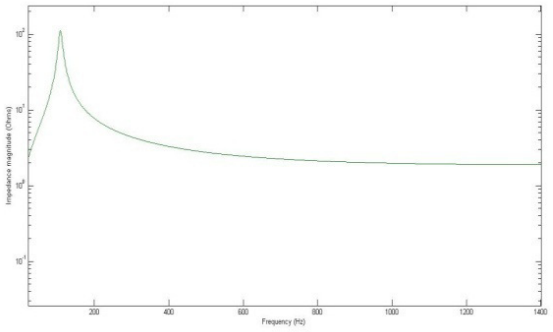


Figure 3a: Harmonic of the ALG - ALG/L D/L

Case 2: ALG – Fowler (FOW) D/L
Nominal Voltage, V (Vrms) = 91.13kV

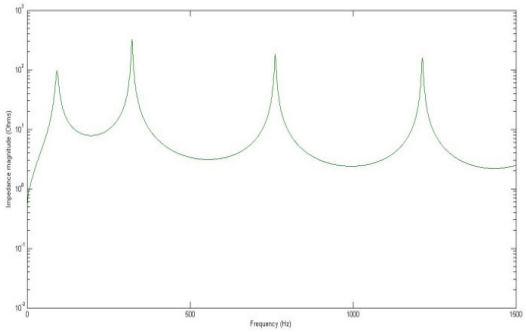


Figure 3b: Harmonics on ALG - FOW D/L

Table 1: Distribution Line Harmonics and their Impedance for cases of 02:00Hrs

D/L	Lnth (km)	SV (kV)	RV (kV)	Harmonics	Harmonic Imp. (Ω)
ALG-ADM	6.13	33	0	-	-
ALG-ALG/L	0.15	33	32.997	2^{nd}	$10^{1.881}$
ALG-ANI	6.84	33	0	-	-
ALG-FOW	3.00	33	32.881	2^{nd}, 6^{th}, 15^{th}, 24^{th}	$10^{2.0}$, $10^{2.51}$, $10^{2.27}$, $10^{2.2}$
ADM-MAR	1.80	0	0	-	-
ADM-ANI	2.40	0	0	-	-
ALG-BAN/I	5.00	33	0	-	-

At 09:00Hrs
Case 1: ALG – Ademola (ADM) D/L
Nominal Voltage, V (Vrms) = 117.5kV

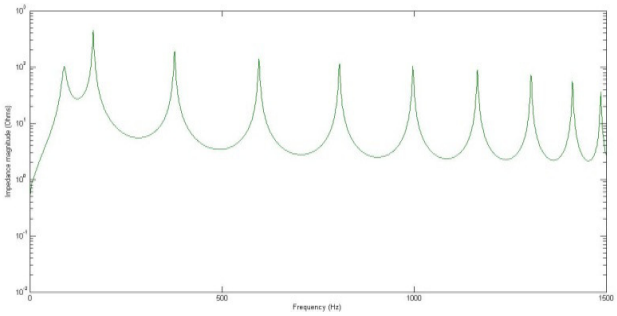


Figure 3c: Harmonics on ALG – ADM D/L

Case 2: ALG –ALG/LD/L
Nominal Voltage, V (Vrms) = 39.6kV

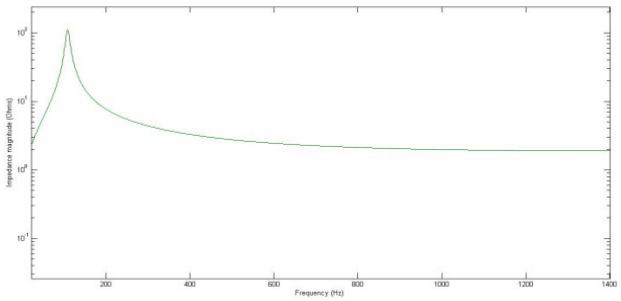


Figure 3d: Harmonics on ALG – ALG/L D/L

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Case 3: ALG – Anifowoshe (ANI) D/L
Nominal Voltage, V (Vrms) = 116.5kV

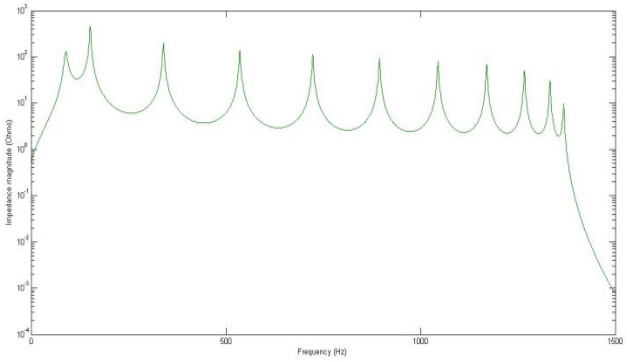


Figure 3e: Harmonics on ALG – ANI D/L

Case 4: Alagbon – Fowler D/L
Nominal Voltage, V (Vrms) = 91.1kV

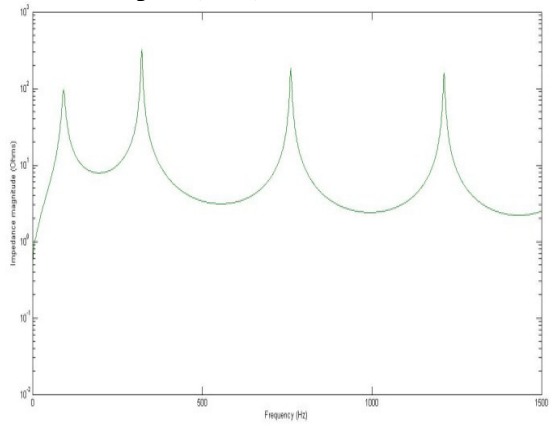


Figure 3f: Harmonics on ALG – FOW D/L

Case 5: ADM – ANI D/L
Nominal Voltage, V (Vrms) = 84kV

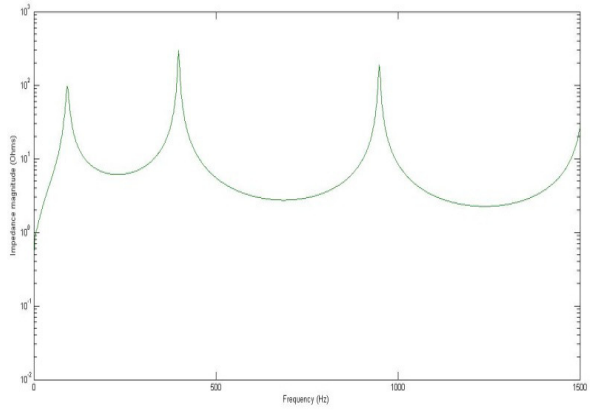


Figure 3g: Harmonics on ADM – ANI D/L

Case 6: ALG – Banana Island (BAN/I) D/L
Nominal Voltage, V (Vrms) = 114.4kV

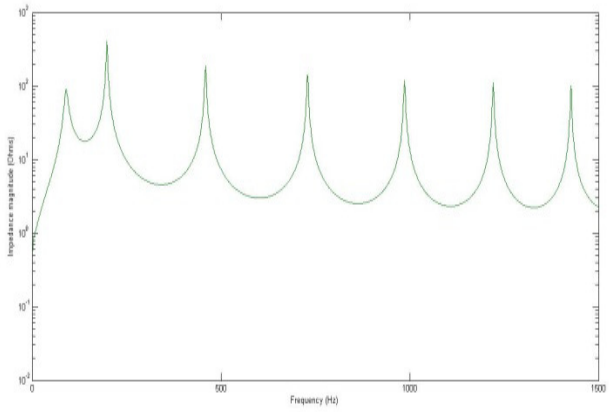


Figure 3h: Harmonics on ALG – BAN/I D/L

Table 2: Distribution Line Harmonics and their Impedance for Cases of 09:00Hrs

D/L	Length (km)	SV (kV)	RV (kV)	Harmonics	Harmonic Imp. (Ω)
ALG-ADM	6.13	33	32.711	2^{nd}, 3^{rd}, 8^{th}, 12^{th}, 16^{th}, 20^{th}, 23^{rd}, 26^{th}, 28^{th}, 29th	$10^{2.01}$, $10^{2.65}$, $10^{2.28}$, $10^{2.15}$, $10^{2.05}$, $10^{2.01}$, $10^{1.56}$, $10^{1.95}$, $10^{1.86}$, $10^{1.74}$
ALG-ALG/L	0.15	33	32.997	2^{nd}	$10^{2.05}$
ALG-ANI	6.84	33	32.645	2^{nd}, 3^{rd}, 7^{th}, 11^{th}, 14^{th}, 18^{th}, 21^{st},23^{rd}, 25^{th}, 26^{th}, 27^{th}	$10^{2.12}$, $10^{2.65}$, $10^{2.30}$, $10^{2.14}$, $10^{2.06}$, $10^{1.97}$, $10^{1.91}$, $10^{1.84}$, $10^{1.69}$, $10^{1.49}$, $10^{0.99}$
ALG-FOW	3.00	33	32.860	2^{nd}, 6^{th}, 15^{th}, 24^{th}	$10^{1.99}$, $10^{2.51}$, $10^{2.27}$,$10^{2.20}$
ADM-MAR	1.80	32.711	0	-	-
ADM-ANI	2.40	32.711	32.645	2^{nd}, 8^{th}, 19^{th}	$10^{1.98}$, $10^{2.47}$, $10^{2.28}$
ALG-BAN/I	5.00	33	32.942	2^{nd}, 3^{rd}, 9^{th}, 15^{th}, 20^{th}, 24^{th}, 29th	$10^{1.96}$, $10^{2.61}$, $10^{2.28}$, $10^{2.15}$, $10^{2.08}$, $10^{2.05}$, $10^{2.01}$

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At 21:00Hrs

Case 1: ALG – ADM D/L
Nominal Voltage, V (Vrms) = 117.7kV

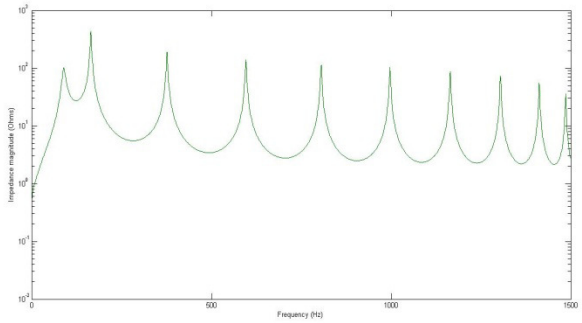


Figure 3i: Harmonics on ALG – ADM D/L

Case 2: ALG – ANI D/L
Nominal Voltage, V (Vrms) = 116.63kV

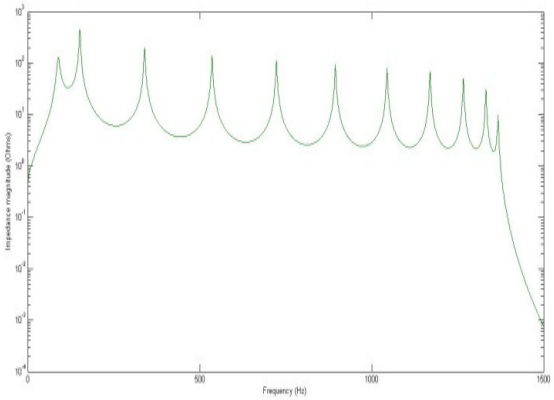


Figure 3j: Harmonics of the ALG – ANI D/L

Case 3: ALG – FOW D/L
Nominal Voltage, V (Vrms) = 91.1kV

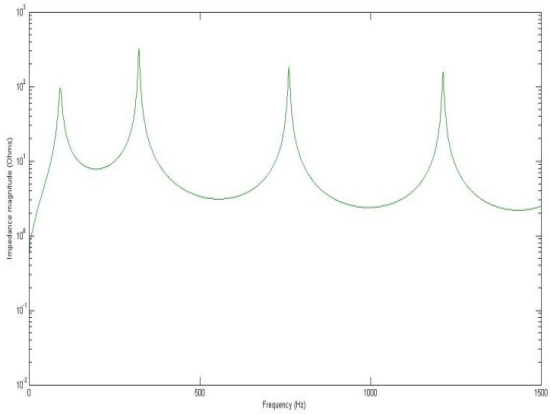


Figure 3k: Harmonics of the ALG – FOW D/L

Case 4: ADM – ANI D/L
Nominal Voltage, V (Vrms) = 83.9kV

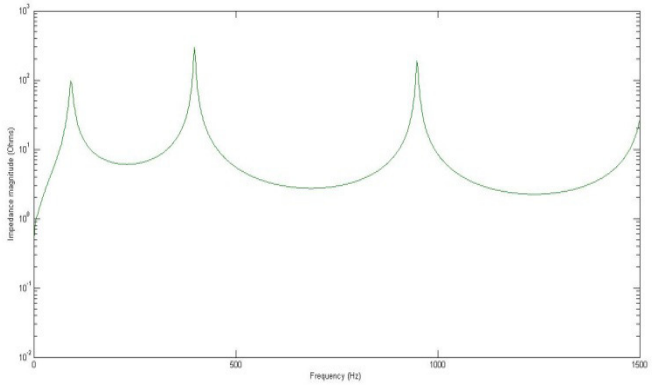


Figure 3l: Harmonics of the ALG – FOW D/L

Table 3: Distribution Line Harmonics and their Impedance for Cases of 21:00Hrs

D/L	Length (km)	SV (kV)	RV (kV)	Harmonics	Harmonic Imp. (Ω)
ALG-ADM	6.13	33	32.83	2^{nd}, 3^{rd}, 8^{th}, 12^{th}, 16^{th}, 20^{th}, 23^{rd}, 26^{th}, 28^{th}, 29^{th}	$10^{2.01}$,$10^{2.64}$, $10^{2.27}$, $10^{2.15}$, $10^{2.05}$, $10^{2.01}$, $10^{1.93}$, $10^{1.86}$, $10^{1.74}$, $10^{1.56}$
ALG-ALG/L	0.15	33	0	-	-
ALG-ANI	6.84	33	32.73	2^{nd}, 3^{rd}, 7^{th}, 11^{th}, 14^{th}, 18^{th}, 21^{st}, 23^{rd}, 25^{th}, 26^{th}, 27^{th}	$10^{2.12}$, $10^{2.66}$, $10^{2.37}$, $10^{2.14}$, $10^{2.06}$, $10^{1.97}$, $10^{1.91}$, $10^{1.84}$, $10^{1.69}$, $10^{1.49}$, $10^{0.99}$
ALG-FOW	3.00	33	32.87	2^{nd}, 6^{th}, 15^{th}, 24^{th}	$10^{1.99}$, $10^{2.51}$, $10^{2.27}$, $10^{2.20}$
ADM-MAR	1.80	32.83	0	-	-
ADM-ANI	2.40	32.83	32.73	2^{nd}, 8^{th}, 19^{th}	$10^{1.98}$, $10^{2.47}$, $10^{2.28}$
ALG-BAN/I	5.00	33	0	-	-

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At 23:00Hrs

Case 1: ALG – ANI D/L
Amplitude of Source voltage = 32.825kV
Nominal Voltage, V (Vrms) = 116.48kV

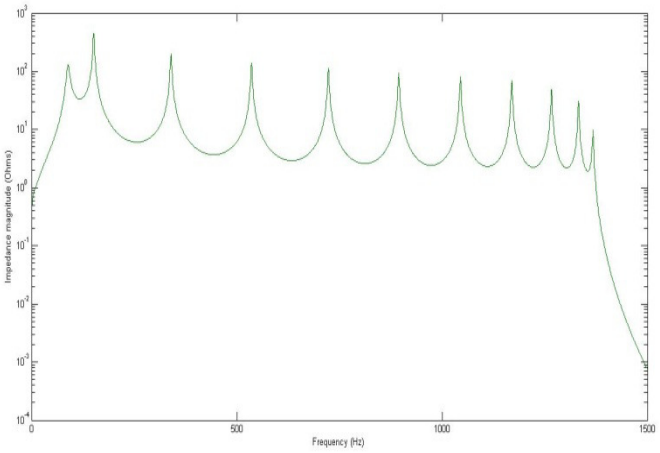


Figure 3m: Harmonics of the ALG – ANI D/L

Table 4: Distribution Line Harmonics and their Impedance for Cases of 23:00Hrs

D/L	Length (km)	SV (kV)	RV (kV)	Harmonics	Harmonic Imp. (Ω)
ALG-ADM	6.13	33	0	-	-
ALG-ALG/L	0.15	33	0	-	-
ALG-ANI	6.84	33	32.695	2^{nd}, 3^{rd}, 7^{th}, 11^{th}, 14^{th}, 18^{th}, 21^{st}, 23^{rd}, 25^{th}, 26^{th}, 27^{th}	$10^{2.12}$, $10^{2.65}$, $10^{2.30}$, $10^{2.14}$, $10^{2.06}$, $10^{1.97}$, $10^{1.91}$, $10^{1.84}$, $10^{1.69}$, $10^{1.49}$, $10^{0.99}$
ALG-FOW	3.00	33	0	-	$10^{1.99}$, $10^{2.51}$, $10^{2.27}$, $10^{2.20}$
ADM-MAR	1.80	32.83	0	-	-
ADM-ANI	2.40	32.83	0	-	$10^{1.98}$, $10^{2.47}$, $10^{2.28}$
ALG-BAN/I	5.00	33	0	-	

4. DISCUSSION OF RESULTS

At 02:00Hrs on 17th January 2014, there are 2 Distribution Lines with harmonics namely ALG – ALG/L and ALG – FOW D/Ls. Figures 3a and 3b are harmonic patterns of the Alagbon – Alagbon Local and ALG – FOW D/Ls. For ALG – ALG/L D/L, the 2^{nd} harmonic component is observed on the impedance magnitude versus frequency plotted (harmonic pattern), at a nominal voltage V (Vrms) level of 39.5kV, while the peak impedance magnitude is $10^{1.881}\Omega$. Whereas, for ALG – FOW D/L, a total of 4 harmonics occurred during simulation and the harmonic impedance values of the harmonics are shown in table 1. The peak impedance magnitude for this case occurs at a value of $10^{2.51}\Omega$

At 09:00Hrs, there are harmonics observed on ALG-ADM D/L, ALG-ALG/L D/L, ALG – ANI D/L, ALG – FOW D/L, ADM – ANI D/L and ALG – BAN/I D/L. ALG-ALG/L D/L has only 1 harmonic with peak impedance amplitude of $10^{2.05}\Omega$ and an intercept of $10^{0.40}\Omega$ at nominal voltage of 39.6kV. Furthermore, ALG – FOW D/L has 4 harmonics namely 2^{nd}, 6^{th}, 15^{th} and 24^{th} with peak impedance magnitude $10^{1.99}\Omega$, $10^{2.508}\Omega$, $10^{2.268}\Omega$ and $10^{2.198}\Omega$ respectively and all at a nominal voltage of 91.1kV. All other Distribution lines had multiple harmonics, except the ADM – MAR D/L, which apparently, showed no harmonics on the line since the voltage at the source (ADM Bus) was not transmitted to the receiving bus (MAR Bus). A summary is shown in table 2.
At 21:00Hrs, the number of harmonics on ALG – ADM D/L, ALG – ANI, ALG – FOW and ADM – ANI Distribution Lines are respectively, 10, 11, 4 and 3. Their respective Harmonic impedance magnitude values are shown in table 3, while the nature of their harmonic patterns are shown in figures 3 (i,j,k,l).

At 23:00Hrs, Harmonics only occurred in Alagbon – Anifowoshe Distribution Line and about 11 harmonics were observed on the line during this hour as shown in figure 3m. The Harmonic impedance amplitude for this case is summarized in table 4.

5. CONCLUSION

This paper has presented an overview of the Island Business Unit 33kV power Distribution network of Eko Electricity Distribution Plc. An algorithm was developed and used to evaluate the harmonics in each of the distribution lines of the network considered. This was done using MATLAB/Simulink platform. The various harmonics in the distribution lines of the network which were obtained as results are presented. Results were generally discussed and analysed for various scenario times of loading/restoration of 33kV feeders in the network.

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