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Harmonic Analysis of 132/33/11 KV Distribution Network Using Etap

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ABSTRACT- The harmonic analysis of the 132/33/11 kV distribution network in Port Harcourt was the main subject of this paper. Using the harmonic voltage, Total Harmonic Distortion (THD) of the buses was computed. The Port Harcourt 132/33/11kV distribution network was modelled and simulated using the harmonic load flow analysis tool built into the ETAP 19.0 software. The THD results are presented to demonstrate the level of distortion in the network. Figure 3 shows a simulation of a harmonic load flow with the harmonic source connected to the network, and Table 2 indicates buses whose THD values have surpassed the harmonic standards specified by IEC 61000-3-6:2008. The harmonic voltage distortion of the buses is shown in Table 3. Buses that are marked with an asterisk signify severe harmonic distortion that has to be corrected right away. Buses 1, 3, 4, 6, and 7 all have THDs that are acceptable. Figure 6 shows the harmonic distortion waveforms for buses 1, 2, 3, 4, and 5. The least distorted waveform is on Bus 1, which is furthest away from the harmonic source. The flow of harmonic voltage was impacted by the open switches that connected buses 2 and 3, as well as 3 and 4. Installation of three (3) single tuned harmonic filters whose frequencies were set to eliminate 5^{th}, 7^{th}, and 11^{th} order harmonics has proven to be effective in eliminating the harmonics and thus producing a smooth sinusoidal voltage waveform shown in fig. 8.

Keywords: THD, harmonic waveform, harmonic source, fundamental component

I. INTRODUCTION

Waveform distortion in power system applications is brought on by non-linear system elements. In wind and solar power facilities, examples that are widely utilized include High Voltage Direct Current (HVDC), Variable Speed Drives (VSD), and frequency converters (HVDC). The resulting non-sinusoidal recurring waveform, which has the potential to substantially interrupt the power supply, consists of an undesirable harmonic component and a fundamental component. Due to the enormous increase in the use of power electronics over the past few decades, harmonics and their limiting have become a key problem and research field [1].

Parts of the electricity system may malfunction as a result of harmonics. One method for assessing the power quality of a power system is harmonic distortion. A technique for managing and decreasing harmonic incidence is provided by IEEE standard 519-1992. The definition of the measurement index for harmonic distortion known as the total harmonic distortion (THD), which is applied to both current and voltage, is the root mean square (rms) value of the highest harmonic voltage divided by the rms value of the fundamental harmonic voltage multiplied by 100%. A current's THD might range from a few percent to more than 100%. Standard THDs for voltage are less than 5%, and are considered to be acceptable; values over 10% are not approved because they would be more hazardous [2].

II. REVIEW OF RELATED WORKS

Harmonic current and Voltage Distortion

According to [3], distortions of both current and voltage occur frequently in power systems and they gave expressions for supply voltage, assuming a pure sinusoidal voltage at the fundamental frequency:

$$v_s = \sqrt{2}V_s \sin w_1 t \qquad (2.1)$$

A distorted line current,

$$i_s = i_{s1} + \sum_{h=2}^{\infty} i_{sh} \qquad (2.2)$$

where, i_{s1} is the fundamental component while i_{sh} is the sum of all the harmonic components. The subscript h stands for the harmonic order and is defined as h=2, …..,∞.

The expression for the RMS value of the current is given as:

$$I_s = \sqrt{\frac{1}{T_1}\int_0^{T_1} i_s^2\,(t)dt} \qquad (2.3)$$

In terms of its Fourier components, the RMS expression of current is given as

$$I_s = \sqrt{I_{s1}^2 + \sum_{h=2}^{\infty} I_{sh}^2} \qquad (2.4)$$

The sum of current harmonics gives the distortion component of the current and it can be expressed as

$$i_{dis} = i_s - i_{s1} = \sum_{h\neq 2} i_{sh} \qquad (2.5)$$

Harmonic Classification

Harmonics can be categorized as characteristic, non-characteristic, or inter-harmonic. There are no triple harmonics; only odd harmonics are characteristic. Due to half-wave symmetry in the majority of power system components, even harmonics are rare. Triple harmonics can be disregarded when studying the harmonic spectrum of a VSD with ungrounded wye-wye transformers since they have zero-sequence characteristics. Even and triple harmonics are regarded as uncommon harmonics [4].

Inter-harmonics are harmonics that are non-integer multiples of the basic frequency. Inter-harmonics, which have harmonic frequencies lower than the basic, are produced by some power electronics equipment, which include current source converter driven synchronous machines and fractional-slot concentrated-winding synchronous machines, in addition to some types of loads, such as arc furnaces [5].

Power and Displacement Factor for Non-Sinusoidal Quantities

Power factor (PF) will be briefly reviewed at this point because it is an essential indicator of power quality and one of the inputs needed to build harmonic filters.

According to [6], the expression for time-averaged electric power is given as:

$$P = \frac{1}{T_1}\int_0^{T_1} p(t)dt = \frac{1}{T_1}\int_0^{T_1} v_s\,(t) i_s(t)dt \qquad (2.6)$$

Power factor (PF) is defined as the ratio of true power to the apparent power.

$$PF = \frac{P}{S} \qquad (2.7)$$

Where, S represents the apparent power and itsgiven as:

$$S = V_s I_s \qquad (2.8)$$

The power factor can also be written as:

$$PF = \frac{V_s I_{s1} \cos\theta_1}{V_s I_s} = \frac{I_{s1}}{I_s}\cos\theta_1 \qquad (2.9)$$

In linear circuit with sinusoidal waveforms,

$$\frac{I_{s1}}{I_s} = 1, \qquad (2.10)$$

$$PF = \cos\theta_1 = DPF \qquad (2.11)$$

DPF represents the displacement power factor. Equation 2.10 can also be restated as:

$$PF = \frac{I_{s1}}{I_s} = DPF \qquad (2.12)$$

for non-sinusoidal waveforms.

According to [6], there is an inverse relationship between harmonic distortion and power factor. $\frac{I_{s1}}{I_s}$decreases for a given load angle when there is a significant harmonic distortion, which lowers the power factor.

Harmonic Standards

According to [7], harmonic standard defines the permissible voltage and/or current distortion. One of the most widely used harmonic standards is the IEC 61000 series. It defines compliance standards for industrial distribution systems with voltages up to 35 kV and frequencies of 50Hz or 60Hz. Another well-known standard is IEEE Recommended Practice 519, which defines compliance requirements and give guidelines for harmonic management in electric power systems [8]. According to [9], EN50160 is another standard which defines the voltage quality a consumer might anticipate at the time of connection.

Harmonic Filters

There are two types of harmonic filters: active and passive. In addition to the passive components (resistors, inductors, and capacitors), which are the only components used in passive filters, active filters also include power electrical devices. In low power applications, some of the limitations of passive filters are successfully solved by the use of active filters. Passive filters are however frequently employed in high power applications. This is due to the fact that active designs cannot yet achieve their high cost-benefit ratio. Passive filters come in two varieties: series filters (high impedance at tuning frequency), like the line reactor in a power electronics converter, and shunt filters (low impedance at tuning frequency), like single-tuned LC filters.To get rid of a certain harmonic, series filters are set to have a high impedance at the target frequency. If there are several undesired harmonics, series filters can be cascaded so that each filter is tuned to a distinct harmonic order. Series filters have a number of disadvantages that contribute to their limited use, including the need for reactive power and the

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requirement that they resist their maximum current and voltage ratings [10].

III. MATERIALS AND METHODS

According to [11], the expression for the total harmonic distortion (THD) for voltage or current is give as:

$$\mathrm{THD} = \frac{100\sqrt{\sum_{h=2}^{k} U_{hrms}^2}}{U_{1rms}} \qquad (3.1)$$

Where U_{1rms} and U_{hrms} are the fundamental harmonic voltage and h^{th} (higher order) harmonic voltage components respectively.

According to [12], the rms value of the harmonic voltage is expressed in terms of the h^{th} harmonic voltage component as shown in the equation below:

$$U_{rms} = \sqrt{\sum_{h=1}^{\infty}\left(\frac{1}{\sqrt{2}}U_h\right)^2} \qquad (3.2)$$

Where, U_{rms} and U_h represent the rms and maximum h^{th} harmonic voltage component.

In essence, the level of waveform distortion can also be measured using rms voltage or current. According to [13],THD_u; the total harmonic distortion of voltage or current waveform (which can also be written as THD_V or THD_i) is calculated thus:

$$THD_u = \sqrt{\sum_{h=2}^{\infty}(U_h)^2} = \sqrt{\left(\frac{U_{rms}}{U_{1rms}}\right)^2 - 1} \qquad (3.3)$$

U_{1rms}: the rms fundamental voltage or current, whereas THD_U: denotes voltage or current total harmonic distortion, which can also be expressed as THD_V and THD_I, respectively according to [14].

Network Description

The study case is Port Harcourt Town 132/33/11 kV Substation consisting of four (4) number power transformers of 132/33kV which are 2x30MVA, 1x45MVA and 1x60MVA and 12 feeders. The single line diagram was modelled using ETAP 19.0 software and the simulation was done using the harmonic analysis tool embedded in the ETAP software.

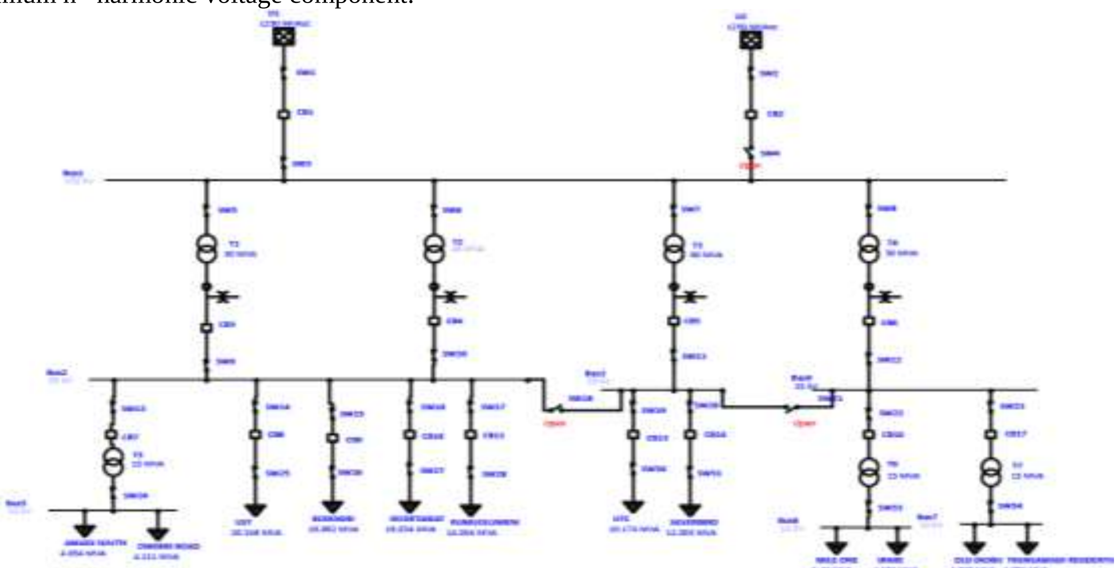

Figure 1: The Single Line Diagram of Port Harcourt Town 132/33/11 kV Substation

IV. RESULTS AND DISCUSSION

Table 1: Bus operating voltage before and after compensation

Equipment	Rated Value (kV)	Recorded Voltage Before SVC Compensation (%)	Recorded Voltage After SVC Compensation (%)
Bus1	132	100	100
Bus2	33	92.75	98.95
Bus3	33	97.47	99.66
Bus4	33	95.51	99.67

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Bus5	11	89.53	99.79
Bus6	11	92.03	96.04
Bus7	11	92.05	96.06

Table 1 shows the load flow result of the study case and the simulation before and after static var compensator(SVC) compensation was carried out using ETAP 19.0 software. The results show that buses 2, 5, 6, and 7 do not comply with the Transmission Company of Nigeria's 95%–105% statutory bus voltage limit condition (TCN). However, after SVC was installed, there was significant voltage improvements of the weak buses as shown in table 1.

Coupling of harmonic source to the network

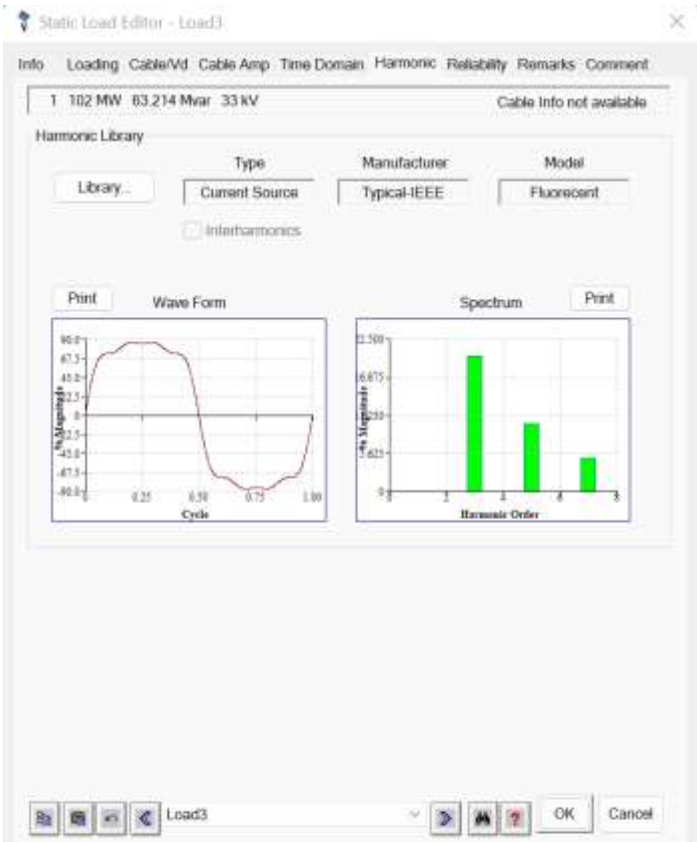

Figure 2: Harmonic source (static load)

In Figure 2, a static load of 120 MVA is depicted as the harmonic source is connected to bus 2, which serves as the network's point of common coupling (PCC) and is built in compliance with IEC 61000-3-6:2008 European standards. Using the harmonic analysis tool included with the ETAP 19.0 program, the impact of this harmonic source on the power network was examined and required mitigation technique will be taken to eliminate the distortions present. The result of this investigation was examined and presented.

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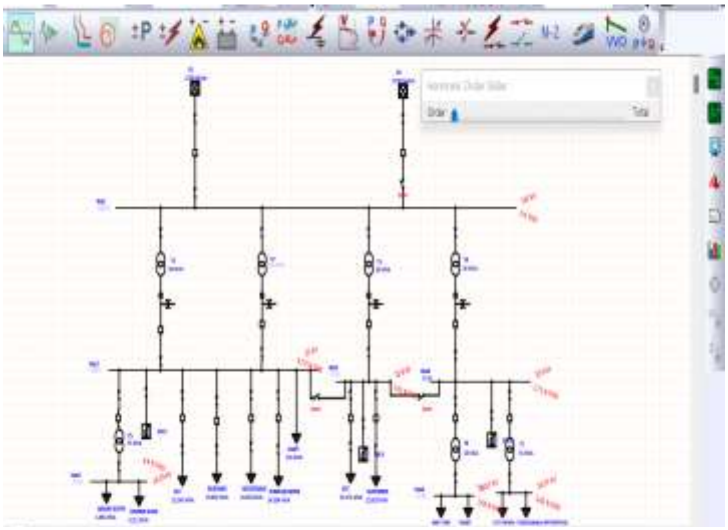

Performance of harmonic load flow analysis

Figure 3:Load flow simulation of harmonic source

Figure 3 depicts a harmonic load flow simulation of the study case without harmonic filter, used to measure the degree of network harmonic distortion and check for individual harmonic distortion (IHD) and total harmonic distortion limit violations (THD). The THD of bus 2 is 6.72%, the first harmonic is 31.92 kV, the third harmonic is non-existent, the fifth harmonic is 1.89 kV, and the seventh harmonic is 1.02 kV. Bus 2 is the point of common coupling.

Table 2: **Alert view of buses**

Table 2 displays the alert view following the completion of the harmonic analysis to examine the impact of the harmonic source on the power system network. After conducting a harmonic load flow analysis, the calculated THD and IHD values are contrasted with the preset limit conditions for THD and IHD. The alert message displays if any bus exceeds the limit or is within the permitted limit. From table 2, buses 2 and 5 have their THD limits exceeded.

Harmonic Load Flow Analysis Alert View - Output Report: HA4

Study Case: HA   Data Revision: Base   Filter: Zone / Area / Region
Configuration: Normal   Date: 12-01-2023

Critical

Device ID	Type	Condition	Rating Limit	Operating	% Operating	Harmonic
Bus5	Bus IHD	Exceeds Limit	3	5.68	189.37	5.00
Bus5	Bus THD	Exceeds Limit	5	6.4	127.89	Total
Bus2	Bus IHD	Exceeds Limit	3	5.91	197.13	5.00
Bus2	Bus IHD	Exceeds Limit	3	3.18	106.1	7.00
Bus2	Bus THD	Exceeds Limit	5	6.72	134.32	Total
Bus1	Bus IHD	Exceeds Limit	1.5	1.77	118.13	5.00

Marginal

Device ID	Type	Condition	Rating Limit	Operating	% Operating	Harmonic
Bus5	Bus IHD	Exceeds Limit	2.85	2.95	103.38	7.00

Determination of Harmonic Voltage Distortion

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Table 3: System Bus Information showing voltage distortion

Bus ID	**Nominal voltage (kV)**	**Fundamental voltage (%)**	**RMS voltage (%)**	**THD**
Bus 1	132	100	100	2.00
Bus 2	33	96.87	96.69	6.72
Bus 3	33	99.67	99.69	1.91
Bus 4	33	99.68	99.70	1.71
Bus 5	11	99.38	93.57	6.42
Bus 6	11	96.05	96.06	1.62
Bus 7	11	96.08	96.09	1.62

Table 3 shows harmonic voltage distortion of the buses after a harmonic load flow analysis was done. Buses 2 and 5 have critical harmonic distortion requiring urgent attention. Buses 1, 3, 4, 6, and 7 have their THD within acceptable limits.

Table 4: harmonic voltages (% of the fundamental voltage) without harmonic filter

	Without Harmonic Filter			
Bus ID	**Fundamental harmonic voltage (kV)**	**5^{th} order harmonic voltage (kV)**	**7^{th} order harmnic voltage (kV)**	**Total Harmonic Distortion (THD) %**
Bus 1	132	2.34	1.24	2
Bus 2	31.92	1.89	1.02	6.72
Bus 3	32.89	0.558	0.289	1.91
Bus 4	32.9	0.504	0.248	1.71
Bus 5	10.27	0.584	0.303	6.4
Bus 7	10.57	0.155	0.073	1.62

Table 4 shows the harmonic voltage (% of fundamental voltage) for fundamental, 5^{th}, and 7^{th} order harmonic frequency without harmonic filter. 3^{rd} order harmonics is absent. It can be observed from table 4 that the most distorted bus is bus 2 where the harmonic source was coupled, next to bus 5 which is seen to be closer to the harmonic source as a result of the open switch connecting bus 2 and bus 3.

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Harmonic voltage distortion waveforms of some buseswithout filter

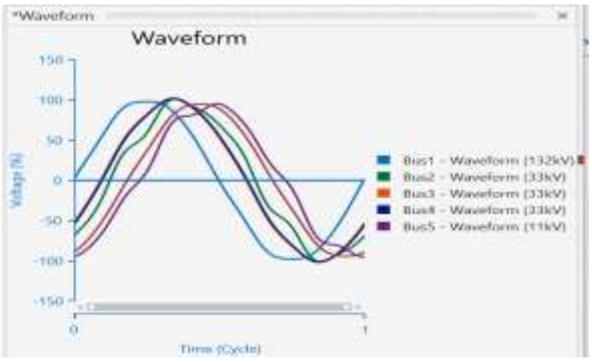

Figure 4: Harmonic waveforms of buses 1, 2, 3, 4, 5 without harmonic filter

Figure 4 shows the harmonic distortion waveforms for buses 1,2,3,4, and 5 without harmonic filter. The waveforms show a higher magnitude of 5^{th}, 7^{th}, 11^{th}, and 13^{th} order harmonics. The least distorted waveform is bus 1 which is farther away from the harmonic source. The most distorted waveform is bus 2; the point of common coupling, next to bus5, bus 3 and bus 4. The reason for this is because bus 5 is nearer bus 2 which has the harmonic source, than the other buses.

Harmonic voltage distortion spectrum of some buses without filter

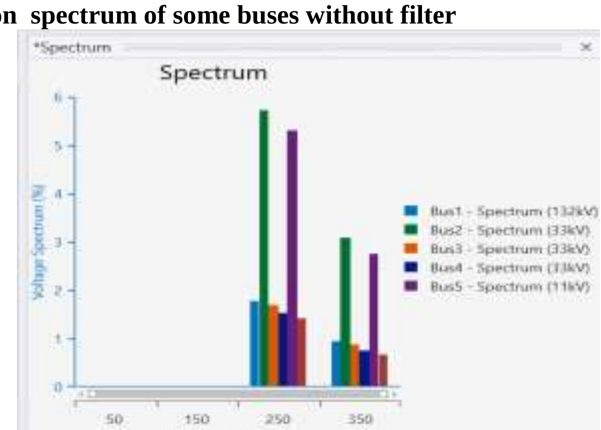

Fig. 5: voltage spectrum of the harmonic voltages of the buses

Fig. 5 presents the voltage spectrum of the harmonic voltages of the buses. The bus with the highest spectrum is bus 2 where the harmonic source is located, next to bus 5 which is closest to the harmonic source.

Reduction ofHarmonic Voltage Distortion Using Harmonic Filter

In order to reduce the total harmonic distortion (THD) of the voltage signals at the buses to the acceptable limits as stated in the harmonic standards, three (3) single tuned harmonic filters were coupled to bus 2 to eliminate 5^{th}, 7^{th}, and 11^{th} order harmonics present in the voltage signal so as to have a smooth sinusoidal waveform. The single tuned filter parameters used in this study are stated below:

Rated kV = 33kV
Max.kV = 1.05*33kV=34.65kV
Qfactor = 30
Harmonic Order = 5, 7, and 11 for each of the filters
Existing P.F =85%
Desired P.F = 95%
Load MVA = 119.27MVA
Capacitor bank = 27783.2kVar per phase
Capacitive reactance (X_C) = 81.21μF per phase
Inductive reactance (X_L) = 1.5679H
Resistance = 2Ω

The harmonic load flow simulation with the single tuned filters coupled is shown in figure 6.

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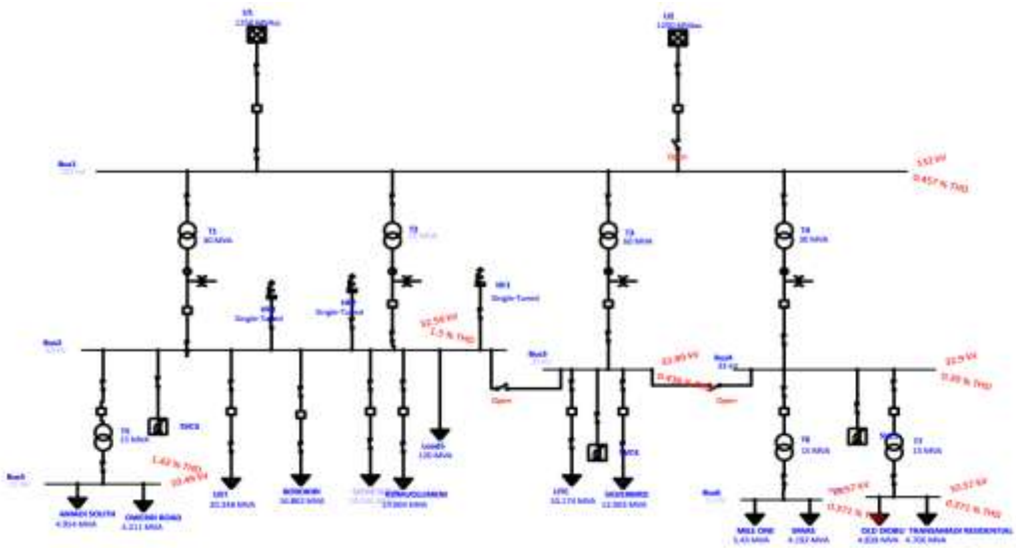

Fig. 6: Harmonic load flow with three (3) single tuned filter

The filter in this paper was properly sized to give the power network enough reactive power and reduce losses at the fundamental frequencies.Table 5 summarizes the results of the impact of the three (3) single tuned filter connected to the network at the point of common coupling, on the power quality.

Table 5: harmonic voltages and total harmonic distortion with filter

	With Harmonic Filter			
Bus Number	**Fundamental harmonic voltage (kV)**	**5th order harmonic voltage (kV)**	**7th order harmnic voltage (kV)**	**Total Harmonic Distortion (THD) %**
Bus 1	132	0.544	0.261	0.457
Bus 2	32.59	0.439	0.215	1.5
Bus 3	32.89	0.13	0.061	0.436
Bus 4	32.9	0.117	0.052	0.39
Bus 5	10.49	0.136	0.064	1.43
Bus 7	10.57	0.036	0.015	0.371

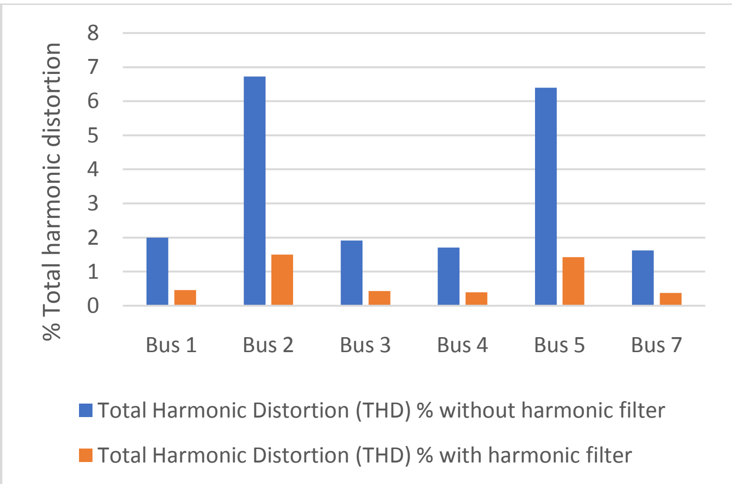

Fig. 7: Total harmonic distortion with and without harmonic filter

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Fig. 7 shows a chart comparing total harmonic distortion (THD) of the voltage signal with and without harmonic filter. The chart gives a display of the impact of harmonic filter in eliminating 5th, 7th, and 11th order harmonics in the voltage signal thus giving a smooth sinusoidal waveform shown in fig. 8 below.

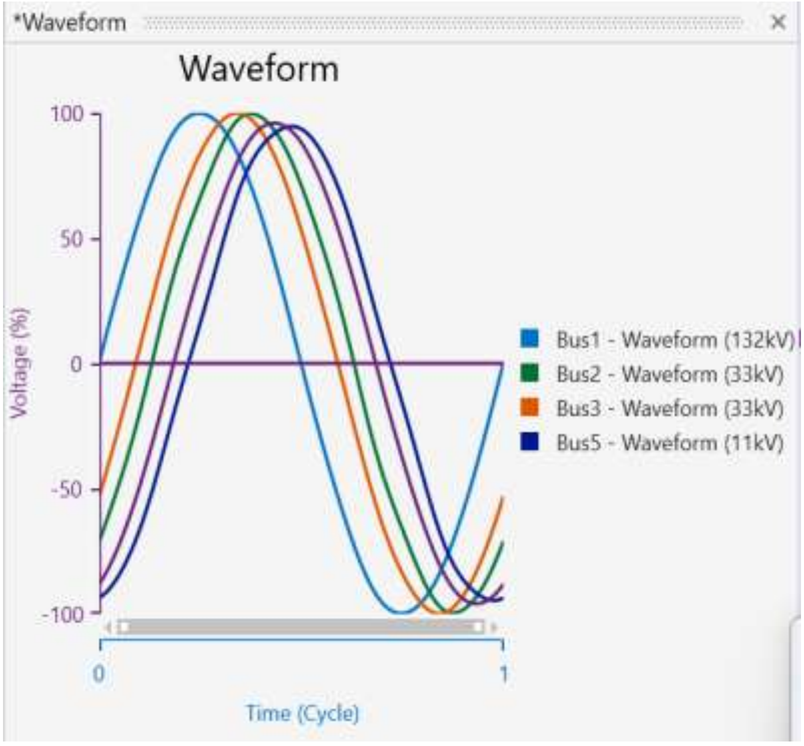

Fig. 8: Waveforms of buses 1, 2, 3, and 5 with harmonic filter

V. CONCLUSION

ETAP 19.0 software was used to conduct a harmonic analysis of the Port Harcourt 132/33 kV distribution network. Bus 2 was used as the point of common coupling for a harmonic source of 120 MVA rating, and harmonic analysis load flow was carried out. Due to its greater distance from the harmonic source than the other buses, bus 1 has the least distorted waveform, according to the simulation results. Due to its proximity to the harmonic source, bus 2 exhibits the most harmonically deformed waveform, followed by bus 5.The flow of harmonic voltage was impacted by the open switches that connected buses 2 and 3, as well as 3 and 4. Installation of three (3) single tuned harmonic filters whose frequencies were set to eliminate 5th, 7th, and 11th order harmonics has proven to be effective in eliminating the harmonics and thus producing a smooth sinusoidal voltage waveform shown in fig. 8.From the study, power electronic devicesconnected to the study case power distribution network can cause harmonic voltage distortion limits to be exceeded. This study will be of great significance to the Port Harcourt distribution network operators. It will help to keep an eye on customers' usage of power electronics devices that can cause this level of harmonic distortion and take the necessary precautions such as installing single tuned harmonic filters as shown in the study to lessen its effect on the power quality.

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