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Harmonic Analysis of Federal University of Petroleum Resources, Effurun (FUPRE) Distribution Network

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ABSTRACT
The goal of several electrical power industries is to provide higher-quality power. Electrical power network harmonics are one of the most fundamental causes of poor power quality. This has become a significant issue in terms of power quality issues. As a result, harmonic analysis became necessary to investigate when modeling the distribution network in order to reduce or eliminate harmonic current or voltage. Federal University of Petroleum Resources, Effurun, (FUPRE) Delta State Distribution Network harmonic analysis, has been implemented in this work using Electrical Transient Analyzer Program (ETAP) software with the support of accelerated Newton Raphson method. To detect the existing harmonic distortion, a harmonic load flow analysis was performed. Harmonic frequency scan analysis, which calculates plots of impedance angle and impedance magnitude, was also used to investigate system resonance problems. According to IEEE 519, the standard limit for voltage total harmonic distortion (VTHD) is 5%, but the VTHD obtained from the FUPRE Network was 26.54 – 29.94%. The IEEE 519 Standard states that voltage individual harmonic distortion (VIHD) should not exceed 3%; however, 3.02 – 18.83% was obtained in the FUPRE Network. To eliminate the prevailing harmonic distortion, capacitors of 0.4MVar, 15Mvar, 0.7Mvar, and 0.1MVar were used, and the VTHD obtained was between 1.26 – 2.59 percent, with VIHD eliminated. This significantly improved the FUPRE Distribution Network's performance.

KEYWORDS: ETAP, Harmonic load flow analysis, Harmonic frequency scan, Individual harmonic distortion, Total harmonic distortion.

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1. INTRODUCTION

In the domain of electrical power generation, a foremost point of reflection has always been to accomplish satisfactory execution regarding the issues of power quality. In this unique circumstance, a significant feature is the generation, organization and decrease/compensation of longitudinal and time harmonics in the entire power distribution network (Viveksheel *et al.*, 2019). From the main advancements in the mid-1800s of electrical power generation, transmission and distribution systems, harmonic content development and reduction has developed from a localized generator structure issues to a universally controlled supply representative that must be deliberated at all points of the power distribution network (Mahendar *et al.*, 2018; Tasneem and Varsha, 2018). This view is strengthened by the reports of Mjzhar *et al.* (2003) and Osamah (2018) that harmonic analysis of the power system is to explain the effect of producing harmonic loads on the power distribution network. Harmonic research has been used extensively for system planning, troubleshooting, process improvement, equipment design, and ensuring standard compliance and more. Over the past two decades, major efforts and development have been made in the area of harmonic analysis of the power system (Ganyu & Adedapo, 2015). Well-accepted element models, simulation methods and analysis procedures for showing harmonic studies have been time-honored (Viveksheel *et al.*, 2019). Harmonic studies are becoming a significant constituent of power system analysis and design. According to Viveksheel *et al.* (2019) harmonic occurrence in the power network may cause a variety of problems including overheating of the equipment, reduced power features,

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deterioration of electrical equipment, improper operation of protective relays, communication equipment interference, in the same case circuit resonance causes dielectric failure of the electrical component and other types of high voltage mutilation. Worse, harmonic currents created in one area can enter the power grid and transmit to other areas, leading to voltage and current distortion throughout the network (Daniel, 2002; Nurul, 2011; Anne *et al*., 2011).

By means of electrical transient analyzer program (ETAP), the singularity of power distribution network harmonic can be analyzed and modeled. It provides the most appropriate tool to correctly model numerous power distribution network devices and component to include their non-linearity, frequency dependency and other features under the occurrences of harmonic sources.

Non-linear loads are those load whose impedance deviates when the voltage is applied. The variation in impedance means that the current drawn by the non-linear load will be non-sinusoidal even when it is connected to a sinusoidal voltage. The non-sinusoidal current holds harmonic structures that leads to the voltage distortion in the power network equipment (Alberto & Leva 2012; Jaisiva *et al.*, 2016). Haroon *et al.* (2011) and Srijan *et al.* (2014) suggest that harmonics are normally referred to as the periodic steady state spontaneous frequency which apply to the fundamental frequency. The harmonics are formed by the domestic appliances which show nonlinear connection between voltage and current waveform. These harmonics in the supply system in Federal University of Petroleum Resources Effurun, has severe influences on fluorescent light compact type, personal computer, printers, uninterrupted power supply (UPS), mobile battery charger, heating of appliances, and telephonic lines. The analysis of harmonics in domestic sector is somewhat crucial as it leads to increase in competitive economy, efficiency and suitable utilization of appliances (Bagheri *et al.*, 2016).

The usage of power electronic device in the industrial sector are increasing every day as technology increases, industrial loads in FUPRE contains harmonic thereby making the voltage of current waveform non - sinusoidal, resulting to harmonic distortion and such devices include rotary converters, saturation of transformer, electric welding machines and electronic furnaces (Bhagyashri *et al.*, 2016). The distribution transformer supplies non-linear load, since they suffer from heating in metallic parts, overheating of windings insulation and oil, bushing and cable end connection. The aim of this paper is to determine the impact of harmonic source on the FUPRE distribution network including: identifying the potential risk due to particular harmonic voltage or current, verifying weather harmonic distortion level comply with IEEE 519 – 2014 standard and identifying resonance frequencies and location of dangerous resonance parts.

2. MATERIALS AND METHODS

2.1. Materials

The materials used in this work are the historical data of the six (6) distribution injection substations within the Federal University of Petroleum Resources Effurun network under review and was obtained from the works department of the institution.

2.2. Network Description

The network under review is the 2.5 MVA, 33 / 11 kV situated at Federal University of Petroleum Resources Effurun. The institution is situated Warri, Delta State, Nigeria. It gets its power supply from the Effurun Transmission Substation 33 kV feeder. The feeder coming from Effurun transmission substation through Ugbumoro goes into the 2.5 MVA transformer situated in the university premises. Plate 1 shows the 2.5 MVA substation and its accessories. The 2.5 MVA transformer feeds six (6) substations within the university premises. They are one (1) MVA transformer situated behind the administration block, five (5) 500 kVA, 11 / 0.415 kV transformers situated at the hostel, health center,

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college of science, college of Engineering buildings and Tetfund Classroom Building. Plate 2 shows a 500 kVA, 11/0.415 kV substation situated at the college of technology. Figure 1 presents the single line diagram of the entire FUPRE network in Electrical Transient Analyzer Programme (ETAP).

Plate 1: 2.5 MVA transformer and its accessories

Plate 2: 500 kVA, 11/415 V transformer situated at college of technology

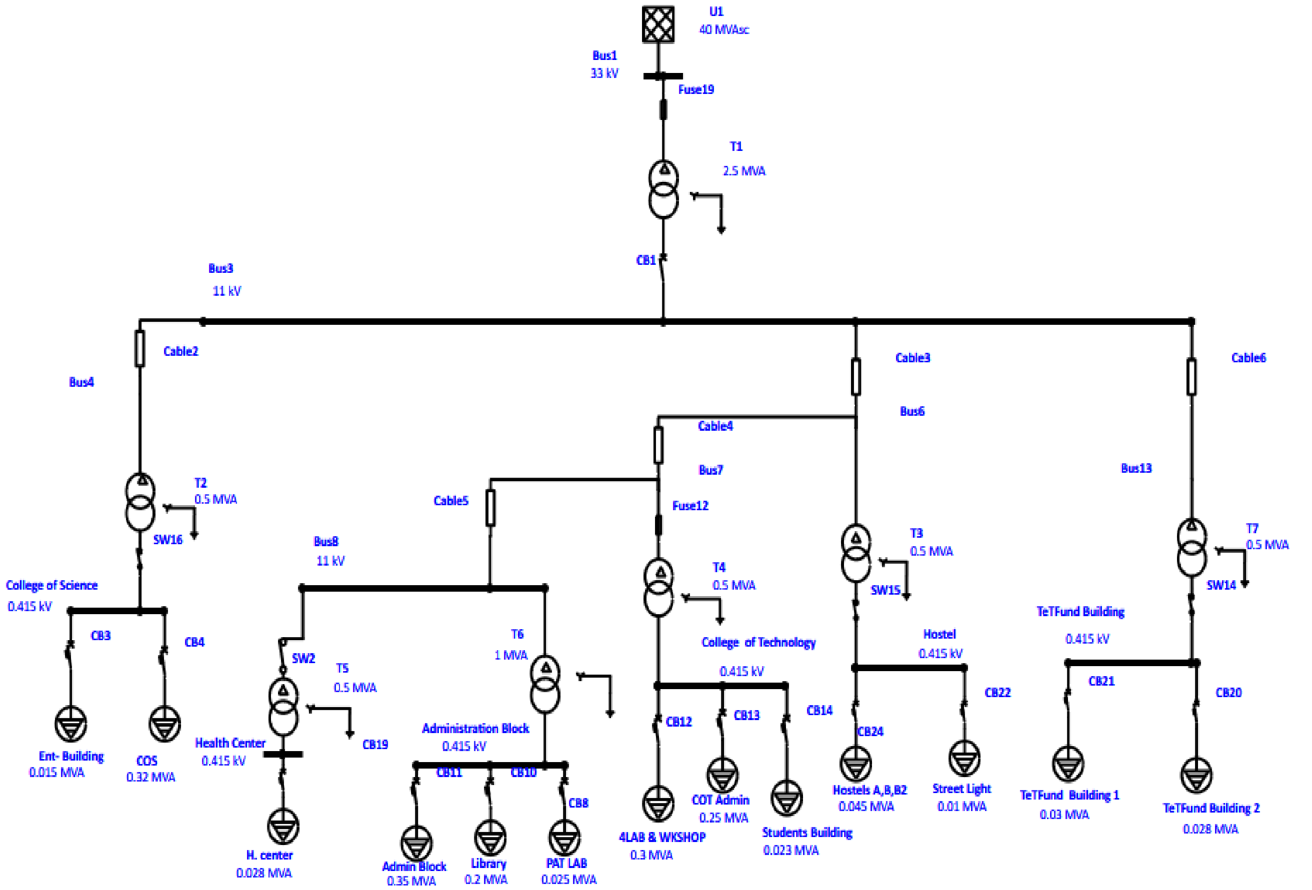

Figure 1: FUPRE network in ETAP programme

2.3. Methods

The ETAP harmonic analysis module provides the best tool to model different power networks components and devices to include their frequency dependence, nonlinearity, and other faces under the existence of harmonic sources. This module applies two analytical methods: harmonic load flow and harmonic frequency scan. Both methods are the most widely used and effective approaches to power system harmonic analysis. In combination of these methods, different harmonic indices were worked out and compared with the industrial standard boundaries. Load flow calculations was based on the Newton - Raphson method (Abeer et al., 2019).

2.4. Harmonic Indices

The effect of harmonic is usually measured in terms of several indices that are defined below. Note that the definition is applied to both voltage and current.

2.4.1 Total harmonic distortion (THD)

Total harmonic distortion is the most popular index to measure the level of harmonic distortion to current and voltage. It is a measure that displays the ratio of the root mean square of all harmonic to the fundamental component.

This index is used to measure the deviation of the waveform of the period containing harmonics on the fundamental sinusoidal wave. For one wave of fundamental current, THD is zero (Sambasivaiah & Naran, 2016). THD was determined using Equations (1) to (3).

$$THD = \frac{\sqrt{\sum_{h-2}^{\infty} F_i^2}}{F_1} \times 100\% \qquad (1)$$

Where:
THD = Total harmonic distortion (%)
Fi = RMS value of current or voltage harmonics to the i^{th}
F1 = the RMS value of current or voltage at the fundamental frequency (fundamental)

$$THDv = \frac{\sqrt{\sum_{i-2}^{\infty} V_i^2}}{V_1} \times 100\% \qquad (2)$$

Where:
THDv = Total harmonic voltage distortion (%)
Vi = RMS value of voltage harmonics to the i^{th}
V1 = the RMS value of voltage at the fundamental frequency (fundamental)

$$THDi = \frac{\sqrt{\sum_{i-2}^{\infty} I_i^2}}{I_1} \times 100\% \qquad (3)$$

Where:
THDi = Total harmonic voltage distortion (%)
Ii = RMS value of current harmonics to the i^{th}
I_1 = the RMS value of current at the fundamental frequency (fundamental)

2.4.2. Individual harmonic distortion (IHD)

Individual harmonic distortion (IHD) simply calculates the ratio of a given harmonic component to the fundamental component. This value is sometimes used to track the effect of each individual harmonic and examine its magnitude. IHD was determine using Equation (4 & 5).

$$IHDv = \frac{Vi}{V_1} \; X \; 100\% \qquad (4)$$

$$IHDi = \frac{Ii}{I_1} \; X \; 100\% \qquad (5)$$

Where Vi and Ii is the RMS value of voltage and current harmonic of the i^{th} and V_1 and Ii is the RMS value of voltage current at the fundamental component.

2.4.3. Root mean square (RMS)

The THD factor pertaining to the RMS value of the current waveform is given by Equation (6).

$$RMS = \sqrt{\sum_{i-2}^{\infty} I_i^2} = I_1 \sqrt{I + THD_1^2} \qquad (6)$$

Where I_1 is the RMS value of current at the fundamental component and THD is the THD factor pertaining to the RMS value of the current waveform.

3. RESULTS AND DISCUSSION

3.1. Harmonic Load Flow Analysis and Results

The harmonic load flow in ETAP software is presented in Figure 2. On running the harmonic load flow study, it can be seen that there was some harmonic frequency with greater magnitude exceeding the THD and IHD limit. From Figure 2, Table 1 and Table 2, it can be seen that the 5^{th}, 7^{th}, 11^{th}, 13^{th}, and 17^{th} order harmonic were donating to all the buses. The harmonic orders given in Tables 1 and 2 exceed the previously stated threshold for THD and IHD as in IEEE Standard 519 - 2014, IEEE recommended practice and the need for harmonic control in power systems (ETAP. 19.0)

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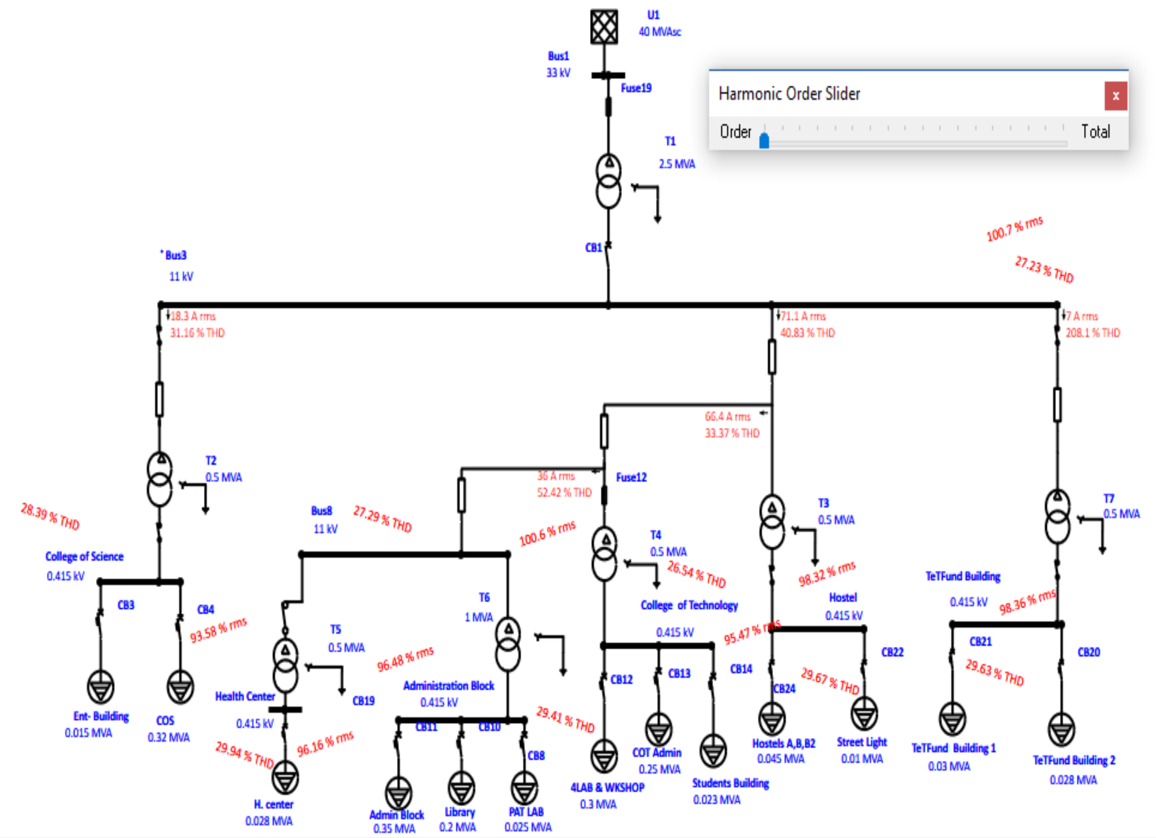

Figure 2: Harmonic load flow result

Table 1: Voltage total harmonic distortion (VTHD) level at the university network buses

Bus ID	Nominal voltage	Fund % voltage profile	VTHD	IEEE 519, THD standard
Admin block	0.415	92.56	29.41	5
College of science	0.415	90.02	28.39	5
College of technology	0.415	92.28	26.54	5
Health centre	0.415	92.12	29.94	5
Hostel	0.415	94.26	29.67	5
TeTFund building	0.415	94.31	29.85	5

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Table 2: Voltage individual harmonic distortion (VIHD) level at the university network buses

Bus ID	FUND %	IEEE 519, IHD Standard	VIHD %				
			5 order	7 order	11 order	13 order	17 order
Admin block	94.54	3	11.81	10.67	18.60	13.89	5.20
College of science	94.27	3	11.09	10.46	17.97	13.53	4.92
College of technology	92.25	3	11.00	10.19	16.76	12.34	4.32
Health centre	96.67	3	11.27	10.73	18.83	14.38	5.42
Hostel	96.49	3	11.16	10.64	18.69	14.27	5.34
Tetfund building	96.49	3	11.14	10.62	18.67	14.28	3.02

After running the harmonic load flow analysis, voltage waveform of six bus bars (0.415 kV) were all distorted because of the harmonic source that are connected with these bus bars. All harmonic distortions for various segments in FUPRE are presented in Figures 3 and 4 which describe the voltage waveform and voltage spectrum at Admin block, College of Science, College of Technology, Health center, Hostels and Tetfund building region after stepping down with transformer 11/0.415 kV. The voltage harmonic waveform and spectrum in Figure 5 shows harmonics distortion which affect the entire distribution all the way down to the loads. In this case increased eddy current and hysterics current losses in transformers resulting to over-heating, over-loading the neutral conductor, nuisance tripping of circuit breakers (Xu, 2001).

On running frequency scan study, impedance angle(radii) and impedance magnitude (ohms) can be seen on the single line diagram of the distribution network. This was displayed in the plotted curves using ETAP software as seen in Figure 5 and the graphs as a result of harmonic frequency scan presented in Figure 6 (impedance angle vs frequency level for all buses) and Figure 7 (impedance magnitude vs frequency level for all buses). Also, the frequency scan alarm view (Table 3) shows that there is harmonic source exceeding the limit in 83th order. So, parallel resonance will create problem for this power network because source of harmonics is present at that frequency where the impedances match each other and it shows harmonic resonance that generate highly rated circulating currents and voltages at the resonant frequency and causes power quality problems (Nurul, 2011). The frequency chosen for this distribution network.

3.3. Elimination of Harmonic using Capacitor Banks

To eliminate harmonics distortion from the FUPRE distribution network, 0.4 Mvar, 15Mvar, 0.7Mvar, and 0.1 Mvar capacitor banks were used with the College of Science, Administration Block, Hostels and Tetfund Classroom Blocks bus bars respectively. These Mvar values were chosen by the IEEE standard 519, 2014 on capacitor load ratio to provide necessary reactive power to control the voltage and bring it up to above 99% of the nominal voltage of the bus. Figure 8 presents the ETAP software with capacitor placement on FUPRE network. On running the harmonic load flow analysis, after connecting the capacitor banks, the results can be seen in Table 4 and Figure 8. The waveform or voltage spectrum in Figures 9 and 10 shows that the THD distortion reduced greatly and all the buses were within harmonic limits. IHD value is sometimes used to track the effect of each individual harmonic and examine its magnitude, after using the capacitor

IHD has been eliminated that is there is no effect of individual harmonic.

Figure 3: Voltage harmonic distortion waveform level for all buses

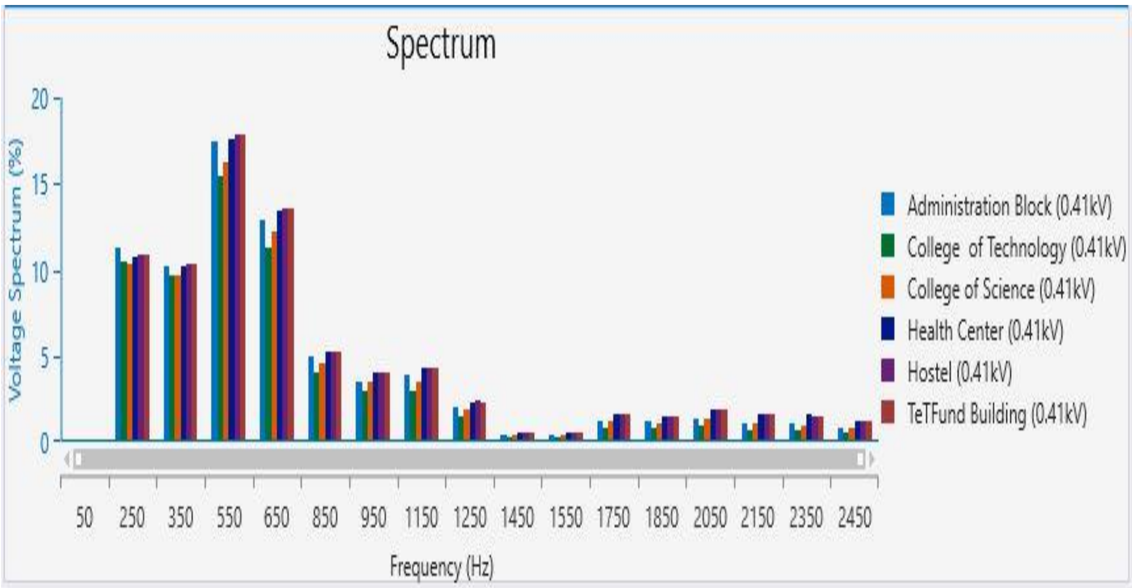

Figure 4: Voltage spectrum vs frequency level for all buses

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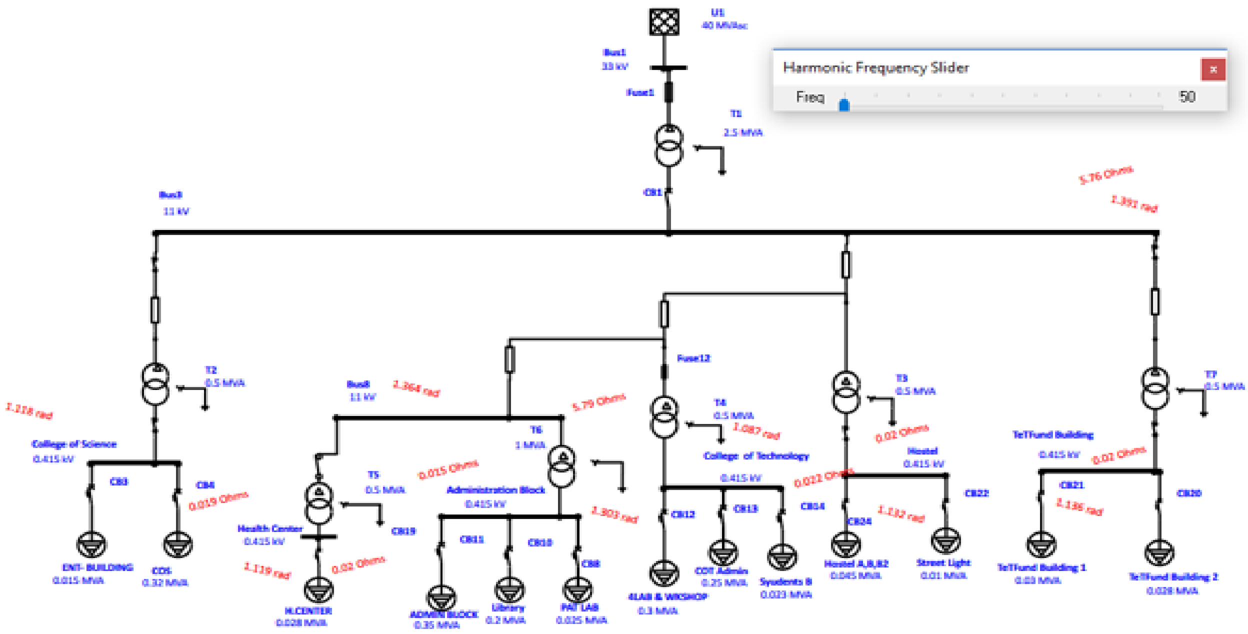

Figure 5: Harmonic Frequency Scan Result

Table 3: Harmonic frequency scan alarm report

Bus ID	Zmag (ohm)	Harmonic (%)	Frequency (Hz)
Admin block	0.25	83.00	4150

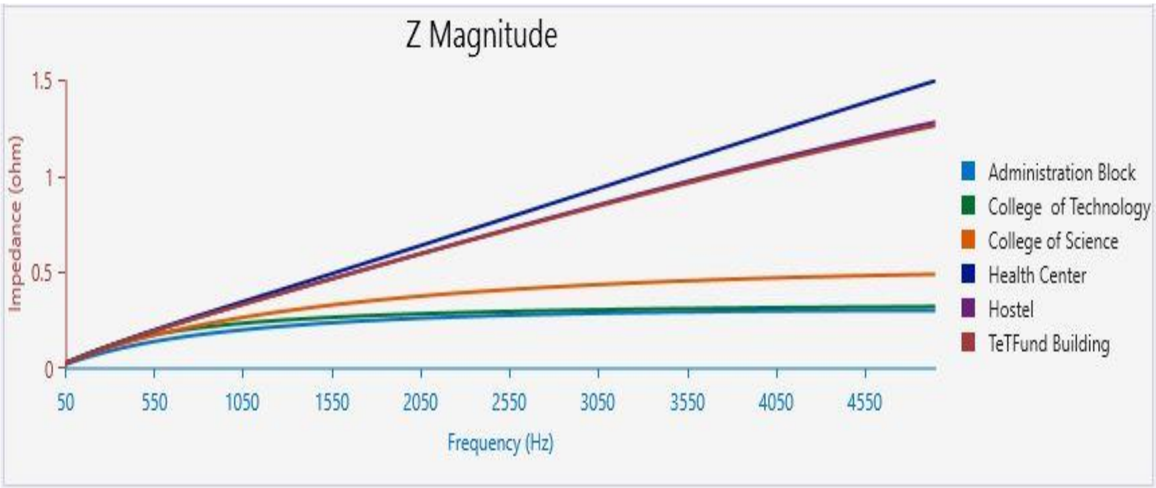

Figure 7: Impedance magnitude vs frequency level for all buses

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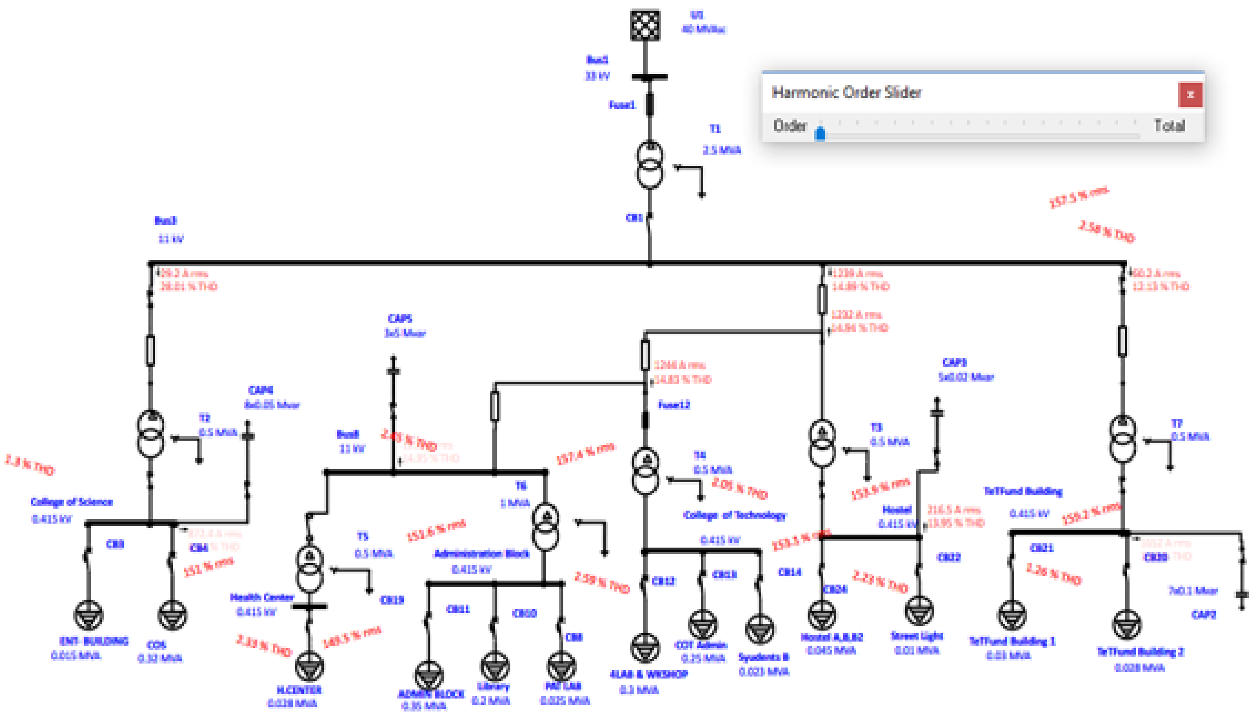

Figure 8: Harmonic load flow analysis (with connection of capacitor bank)

Table 4: Voltage total harmonic distortion (VTHD) level at the university network (with connection of capacitor bank)

Bus ID	Nominal voltage (kV)	RMS (%)	THD (%)	THD (IEEE 519 Standard) %
Admin block	0.415	151.54	2.59	5
COS	0.415	151.00	1.30	5
COT	0.415	153.10	2.05	5
Health Center	0.415	149.50	2.33	5
Hostels	0.415	153.90	2.23	5
TeTFund building	0.415	159.20	1.26	5

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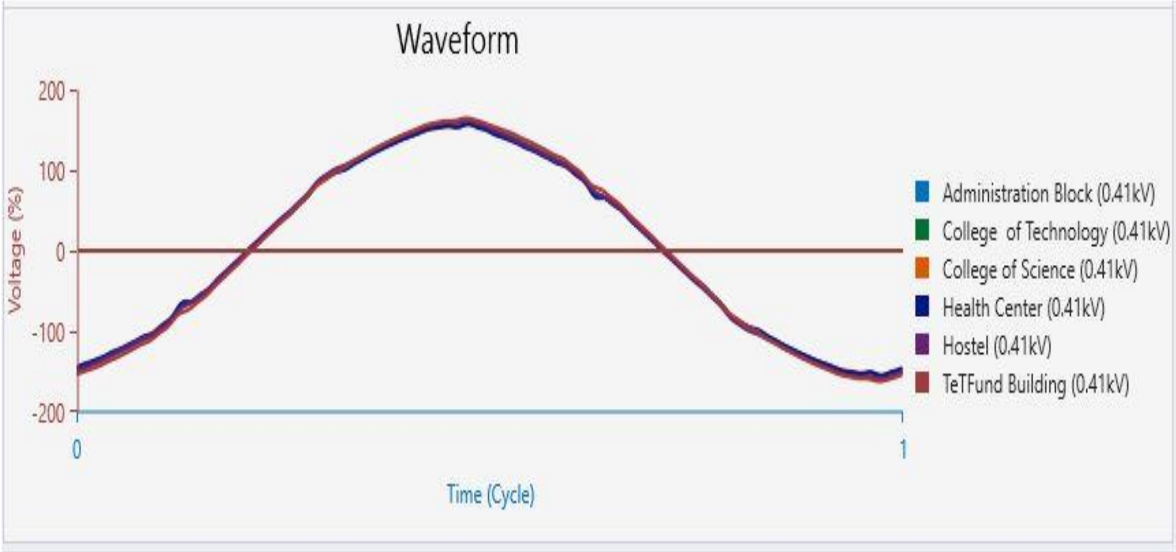

Figure 9: Voltage harmonic distortion waveform level for all buses (with link of capacity)

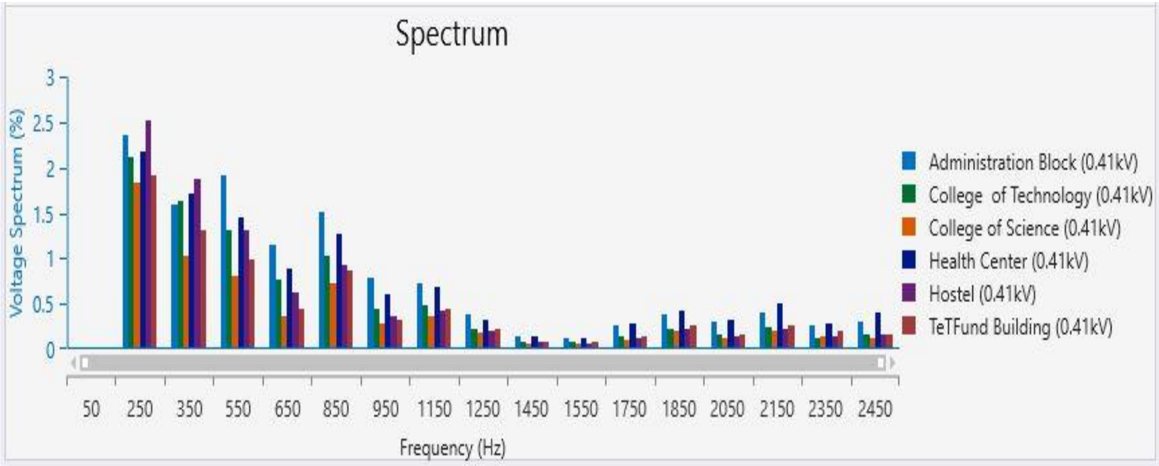

Figure 10: Voltage spectrum vs frequency level for all buses (with the link of capacity)

After running harmonic frequency scan study, parallel resonance point can be identified. The result of this harmonic resonance that generate highly rated alternating currents and voltages at the resonance is equal or close to a natural frequency of the system on which it acts. The parallel resonance frequency will create problem only if a source of harmonics is present at that frequency where the impedances match each other. From the frequency scan alert view Table 5 and figure 11, it can be seen that, parallel resonance occurred at 1^{th} and 4^{th} harmonic order at frequency of 50 Hz and 200 Hz, this shows that there is no harmonic source exceeding the limit in 1^{th} and 4^{th} order. So, this parallel resonance will create no problem for this power network (Nurul, 2011). The impedance magnitude and impedance angle curves after harmonic frequency scan are given in figure 13 and 13.

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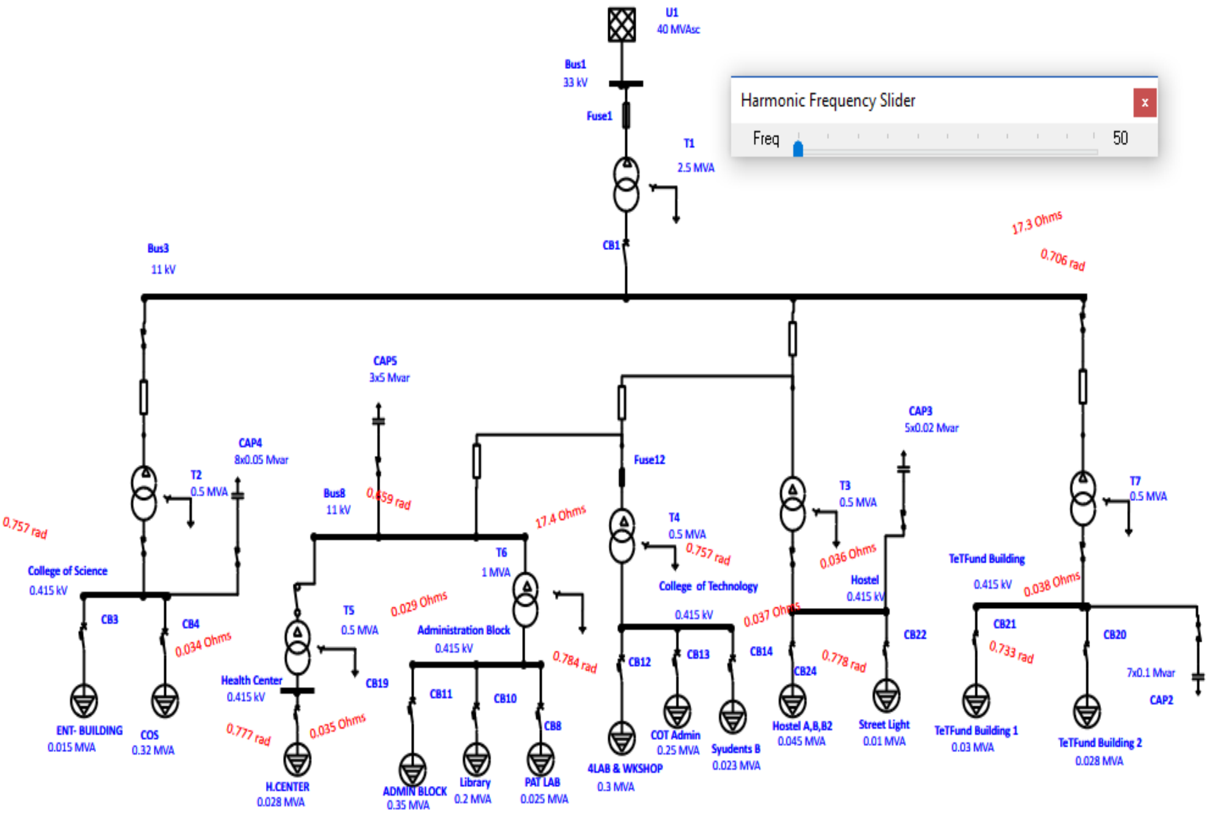

Figure 11: Harmonic frequency scan result

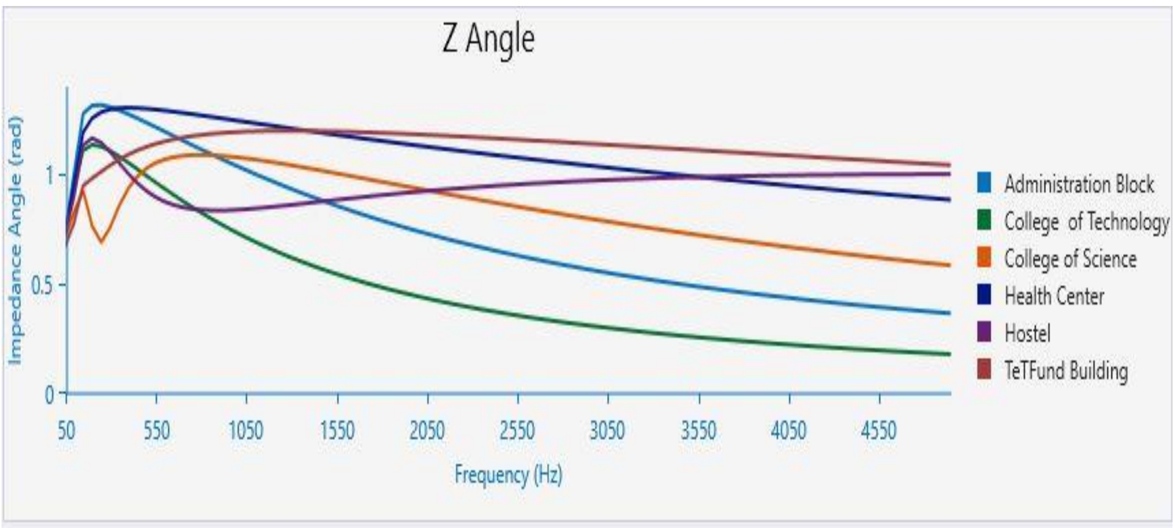

Figure 12: Impedance angle vs frequency level for all buses (with capacitor)

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Vol 3, Issue 4, December 2021
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Table 5: Harmonic frequency scan alert view report

Bus ID	Zmag (Ohms)	Z-Angle(rad)	Harmonic (%)	Frequency (Hz)
Admin block	0.029	0.784	1.00	50
College of Science	0.034	0.757	1.00	50
College of Technology	0.037	0.757	1.00	50
Health Center	0.025	0.777	1.00	50
Hostels	0.036	0.778	1.00	50
TeTfund Building	0.038	0.733	1.00	50
TeTfund Building	0.030	0.633	3.00	150
College of Science	0.04	0.664	4.00	200

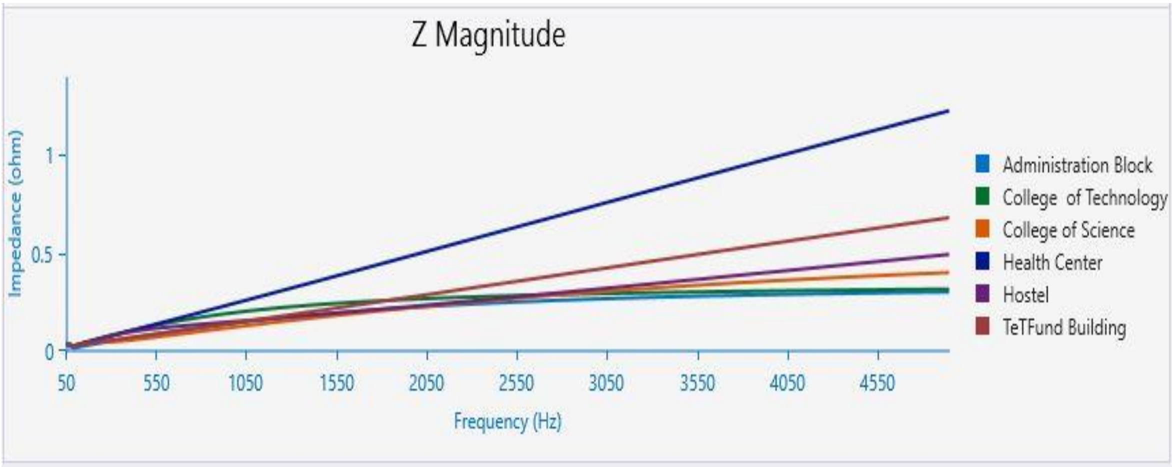

Figure 13: Impedance magnitude Vs frequency level for all buses (with capacitor)

3.4. Summary of Results

A study of harmonic analysis module in ETAP was performed in other to identify the existing harmonic distortion, and to eliminate the harmonic distortion in order to meet the electrical industrial requirement point of view. In this harmonic study a regorous THD and IHD analysis were underlined. Furthermore VTHD initualy was measured 29.41% for Admin block, 28.39% for College of science, 26.54% for College of technology, 29.94% for health center, 29.67% for hostels and 29.85% for TeTFund building,and also IHD at the highest 0.415kV bus was 18.71%. A capacitor was proposed to improved harmonic distortion caused by the FUPRE network component such as transformer etc. The results shows is interesting, performance of the distribution network with capacitor operation, the VTHD reduce to 1.26% which is below the IEEE 519 standard of 5% total harmonic distortion while VIHD was eliminated totally from the network.

4. CONCLUSION

Harmonic distortion is a huge problem in maintaining power quality. The results show that using capacitor banks reduces harmonics to above-minimum levels. Harmonics have an impact not just on the power quality but also on the useful life of the power apparatus. It is linked to the major power system elements, such as transformers, synchronous motors, protective relays, power converters, and electrical furnaces. Because these elements are constantly powered up system, harmonics are a constant concern in the fundamental signal. As a result, it is absolutely essential to reduce or eliminate this distortion. Harmonics analysis is also essential for studying all of the effects that we must bear. As a result, ETAP (Electrical Transient and Analysis Program) is an important simulation software to test the system effects before installing capacitors. We conclude that we use ETAP to perform Harmonics Analysis and that capacitor banks can be used to remove harmonics.

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