HARMONIC ANALYSIS OF A SUB-DISTRIBUTION NETWORK: THE CASE OF A NIGERIAN FEDERAL UNIVERSITY

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Abstract: This paper investigates the harmonic distortion level in sub-distribution networks in a university community. Quantitative analysis of load data was used to model the distribution network using occupancy harmonic source modeling. Phone (GSM charging), Compact Florescent Lamp (CFL), Laptop (LAP), Personal Computer (PC), and Television (TV) were discovered to be the highest contributors of harmonics with 16%, 14%, 12%,11%, and 11% respectively. The results showed that four (4) units of the 19 PCCs contributed about 56 % of the total harmonic distortion level. This research underscores the importance of addressing harmonic distortion in academic institutions, contributing to better operational performance.

Keywords: harmonic distortion, harmonic ranking, non-linear loads, harmonic analysis

1. INTRODUCTION

Harmonic Analysis of distribution network is becoming a matter of concern not only due to the nature of connected loads but also to the effect of harmonic current on the loads and the distribution network infrastructure [1]. The power quality performance of the distribution network in terms of harmonic level distortion requires adequate evaluation for both the planning and operation of the distribution network [2]. The distribution network operation is yet to put harmonic performance into perspective due to infrastructural requirements for wide monitoring of harmonic levels.

Higher education institutions are among the largest electricity consumers in the electrical power system user group. Power systems provided by electricity supply companies to consumers usually involve long cables. This results in a low power factor and a high percentage of voltage drop [3]. At the same time, it increases the susceptibility to harmonic problems due to the high usage of non-linear and sensitive loads, such as computers, variable speed drives, electronic ballasts, etc. Another factor is that educational institutions today are more concerned about the power quality and efficiency of the electric power system [4].

This is because the energy and maintenance cost are retrieved from an internal allocation fund, affecting the institution's operating cost. These conditions concern the effect and consequences of harmonics in the power system and ways to mitigate it in the sense of better understanding and selecting mitigation techniques that can be applied. An evaluation of harmonic Analysis in the existing electrical power system can be used as a benchmark

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for further mitigation methods. This valuable information can be gathered and published for educational purposes [5].

Identifying harmonic sources and the harmonic distortion level for PCCs in the distribution network is paramount. Several commonly used loads have been investigated for harmonic injection into the distribution network in several studies. The cumulative effects of these combined loads have also been shown to produce significant harmonic distortion levels in the distribution network [6].

These issues have become more common in residential and commercial power apparatuses, especially in three phases, four-wire reticulation feeding retrofitting lighting fixtures and information and communication technology (ICT) equipment at research institutes and universities. [7-9] Globally, residential non-linear loads account for 38 – 42 % of utility loads, and lighting loads are 40 – 70 % of total connected loads [10].

High harmonic distortion levels can result in various consequences, including but not limited to elevated temperatures of transformers, capacitors, motors, or generators; erroneous functioning of electronic devices that depend on voltage zero-crossing detection or wave shape sensitivity; inaccurate meter readings; false protective relay operation; interference with telephone circuits, and so forth. Any equipment with non-linear properties will create harmonic distortion, as it is caused by non-linear elements linked to the power supply.

Common sources of power system harmonics include transformer saturation and inrush, transformer neutral connections, Magnetomotive Force (MMF) distribution in AC rotating machines, electric arc furnaces, fluorescent lighting, switch mode power supplies, battery chargers, imperfect AC sources, variable frequency motor drives (VFD), inverters, and television power supplies. [11].

Several techniques have been proposed for harmonic Analysis in the distribution network. Harmonic state estimation (HSE) has been used to guess the probable location of harmonic sources and for the estimation of harmonic level in transmission systems [12], whereas HSE is still being developed for the distribution network [2].

The widely used technique for harmonic Analysis in the distribution network is the harmonic penetration analysis in which non-linear loads are modeled as constant current sources using the harmonic spectrum of the non-linear load [7]. This simulation modelling technique assumes the non-linear load as a fixed harmonic current injector with fixed magnitude and phase angles in the simulation studies [13].

Power quality standards such as the [14] and [15] specifies recommended limits for harmonic distortion levels at the point of common coupling (PCC) in electricity networks. This was based on the limit of distortion that a load and the effect of the harmonics on other devices of the same supply source can tolerate. These standard limits are used as a guideline for manufacturers to produce a product with minimal harmonic emission [16].

The manufacturers of the load and source may also define a special threshold limit to accommodate the device used. This will allow a defined compatibility between the product and the source. This method has become quite effective in today's use, although ensuring the standards are met is rather costly. [17].

The voltage total harmonic distortion limits THDv and current total harmonic distortion limits are the indices used to quantify harmonic distortion levels in the power system. A THDv of 8 percent is specified for voltage level ($V \leq 1.0$ kV) and 5 percent for voltage level (1 kV $< V \leq$ 69 kV) [14, 15].

This paper aims to conduct a harmonic analysis of sub-distribution networks in a university community's primary distribution network. The PCCs' harmonic contributions are then used to determine the overall harmonic distortion level in the primary distribution network. The harmonic simulation modeling technique determines the node contribution to harmonic distortion in the primary distribution network.

2. METHODOLOGY

2.1. Description of the distribution network

The distribution network consists of 1 unit of 33/11 kV 7.5 MVA power transformer, 3 Feeders, and 20 units of 11/0.415 kV distribution transformer. The 3 feeders are Feeder A, Feeder B, and Feeder C. The secondary side of these distribution transformers is herein considered as Point of Common Coupling (PCC). **Feeder A** has Ten (10) transformers, **Feeder B** consists of six (6) transformers, and **Feeder C** consists of four (4) transformers. The single-line diagram of the Distribution Network is shown in Figure 1.

The low voltage overhead distribution network is connected to the respective load busbar chamber, with underground cable connections to load consumers within the university community.

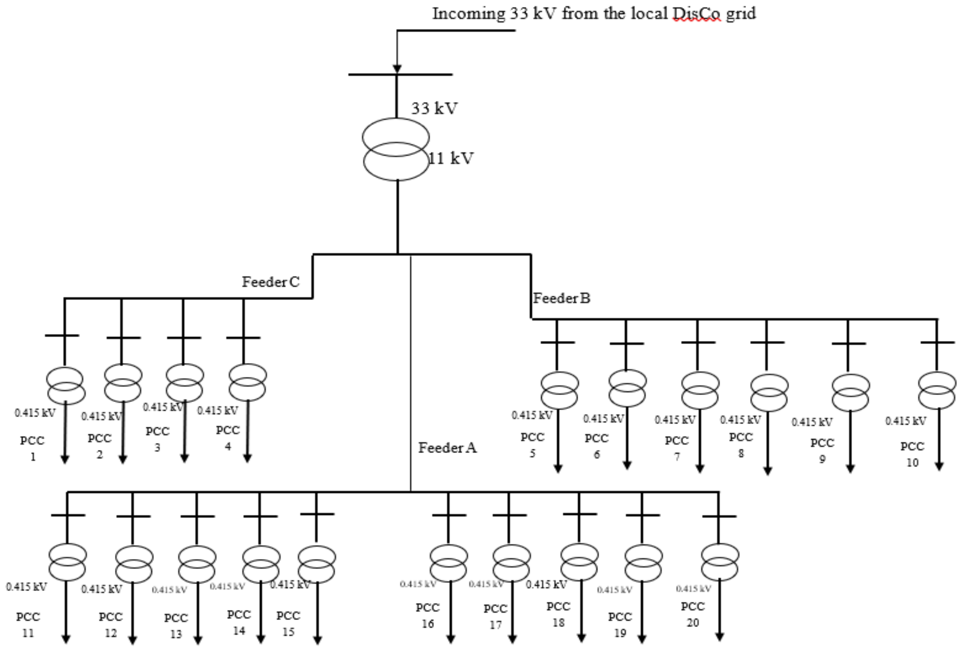

Fig. 1. Single-line diagram of the distribution network.

The connected loads are classified as linear and non-linear loads for power flow analysis [18]. The network data was obtained from the university's department of work. The load data was obtained through a questionnaire approach by the authors.

The load data obtained was used to aggregate the linear and non-linear loads connected to the PCC of the sub-distribution network. The non-linear loads considered in this study are typical residential and commercial loads based on the increasing trend of common non-linear loads penetrating the distribution network in Nigeria such as Television (TV), Compact Fluorescent Lamp (CFL), Fluorescent (FL), Refrigerator (FR), Microwave (MW), air-conditioner (AC), Iron (IR), Laptop (LAP), Phones (GSM), Uninterrupted Power Supply (UPS), Washing Machine (WSM), Hot Plate (HP), Fan (FN), Electric Cooker/Kettle/Oven (EC), Printer (PR), and Photocopier (PH).

The non-linear loads were modelled into the distribution network using a bottom approach for harmonic injection modelling for harmonic flow analysis [19].

The sub-distribution networks were modelled and simulated separately to determine the harmonic injection from each sub-distribution network. The harmonic analysis module of NEPLAN software was used to simulate the modelled networks.

The harmonic distortion level at the PCC of the sub-distribution networks was compared with the recommended level in IEEE Standard 519. The single-line diagram of the distribution network was modelled using NEPLAN software. NEPLAN model is shown in Figure 2.

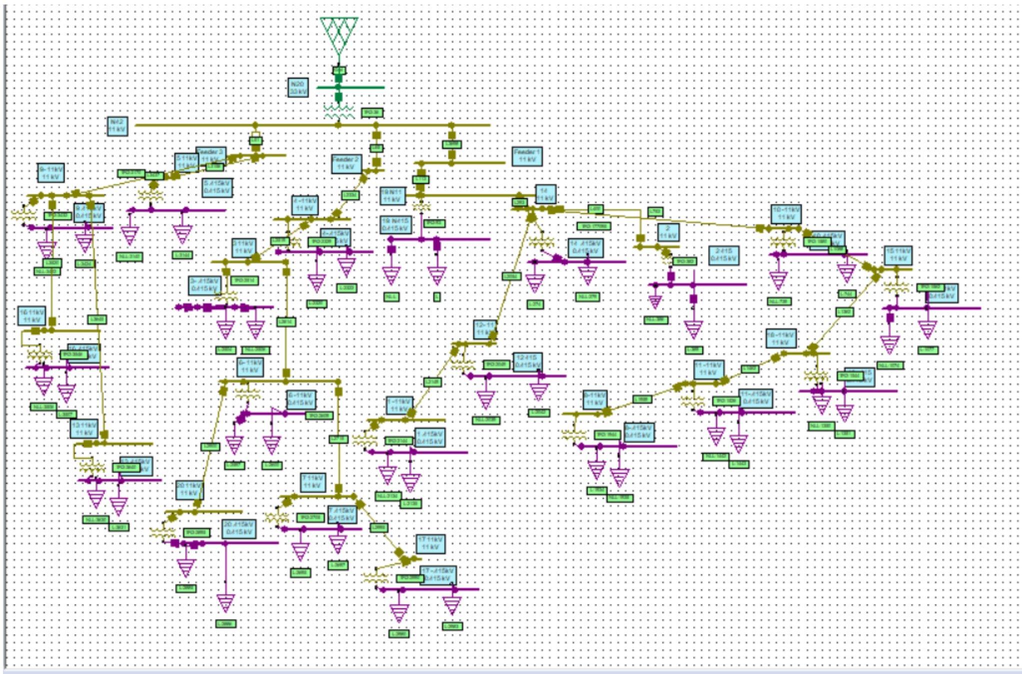

Fig. 2. NEPLAN Model of the distribution network.

2.2. Harmonic analysis formulation for the distribution network

Fourier series was used to determine the spectral components of each non-linear load to obtain the harmonic signal as presented in equations (1) to (5)

.

$$f(t) = \frac{a_o}{2} + \sum_{h=1}^{\infty}(a_h \cos(hw_o t) + b_h \sin(hw_o t)) \quad (1)$$

where w is $\frac{2\pi}{T}$.

Equation (1) can be further simplified into equation (2).

$$f(t) = C_o + \sum_{h=1}^{\infty}(C_h \sin(hw_o t) \quad (2)$$

$$C_h = \frac{a_o}{2} \quad (3)$$

$$C_h = \sqrt{a_h{}^2 + b_h{}^2} \quad (4)$$

$$\emptyset_h = \tan^{-1}\left(\frac{a_h}{b_h}\right) \quad (5)$$

where (hw_o) are the h^{th} order harmonic of the periodic function, C_o is the magnitude of the DC component, C_h is the magnitude of the h^{th} harmonic component, and $\emptyset_h$ is the phase angle of the h^{th} harmonic component.

2.2.1. Evaluation of total harmonic distortion indices on the distribution network

2.2.1.1. Total harmonic distortion

The major type of analysis performed during harmonic analysis is the current and voltage distortion analysis. Total harmonic distortion considers the contribution of every individual harmonic component to the signal. THD is defined for voltage and current signals as shown in equations (6) and (7).

$$THD_V = \frac{\sqrt{\sum_{h=2}^{\infty} V_h{}^2}}{V_1} \quad (6)$$

where V_h are the voltage at h harmonic, and V_1 is the voltage of fundamental harmonic.

$$THD_I = \frac{\sqrt{\sum_{h=2}^{\infty} I^2}}{I_1} \tag{7}$$

where I_h are the current at h harmonic, and I_1 is the current of the fundamental harmonic.

2.2.2. Percentage contribution of individual non-linear load on distribution network

For i[th] Non-linear Load, the percentage contribution to the distribution network was evaluated using equation (8).

$$\%THD_i = \frac{THD_i}{\sum_i^{kD} THD_i} 100 \tag{8}$$

2.3. Harmonic contribution ranking of PCCs in the distribution network

The PCCs distortion level was ranked based on the index given in equation (9). This index is introduced to determine the impact of each PCC harmonic level on the total harmonic distortion level. This index is similar to the new index used for non-linear load ranking described in [6], which was used to classify the loads based on their harmonic effect on the feeder THD in the presence of other loads. This new index is introduced because the harmonic current is known to flow from the load to the PCCs, where other electricity consumers are affected by the harmonic distortions.

$$THD_{FC} = \frac{THD_k \times I_{rms_k}}{\sum_1^K I_{rms_k} \times THD_k} \tag{9}$$

where THD_{NC} are the contribution of each PCC to the total THD of all sub-distribution networks, THD_k is the total harmonic distortion of the PCC $_k$, and $Irms_k$ is its current rms value.

3. RESULTS AND DISCUSSION

3.1. Evaluation of total harmonic distortion indices on the distribution network

3.1.1. Current total harmonic distortion (THD_i)

Figure 3 shows the current total harmonic distortion (THDi) of each of the non-linear loads considered across the PCCs in the distribution network. Phone Charging (GSM), CFL, Laptops, and Personal Computers showed relatively high THD_i across all PCCs.

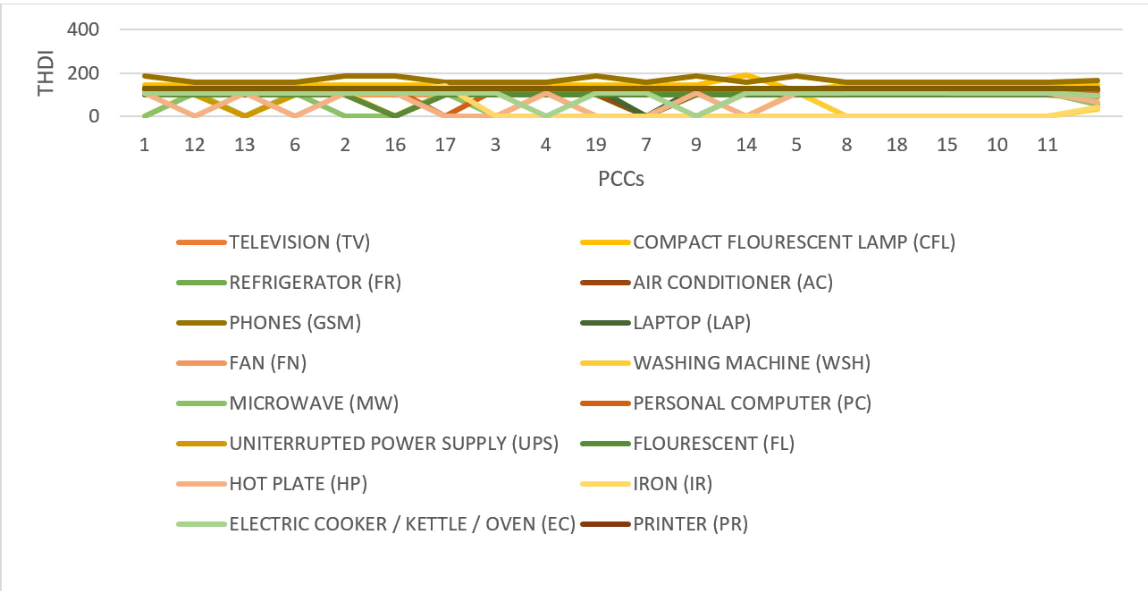

Fig. 3. THD_i of non-linear loads on each PCCs of the distribution network.

3.1.2. Voltage total harmonic distortion (THD_v)

The THD_v at the PCCs of the sub-distribution network is shown in Figure 4 and 5. The voltage total harmonic distortion (THDv) on the 11 kV side of the PCC was observed to be lower than the 5 % recommended limit.

Therefore, the 5 % recommended THDv limit is not violated on the 11 kV sides. However, the recommended 8 % THD_V limit on the 0.415 kV side was violated in nine (9) of the PCCs. This means that 45 % of the PCCs have harmonic distortion problems.

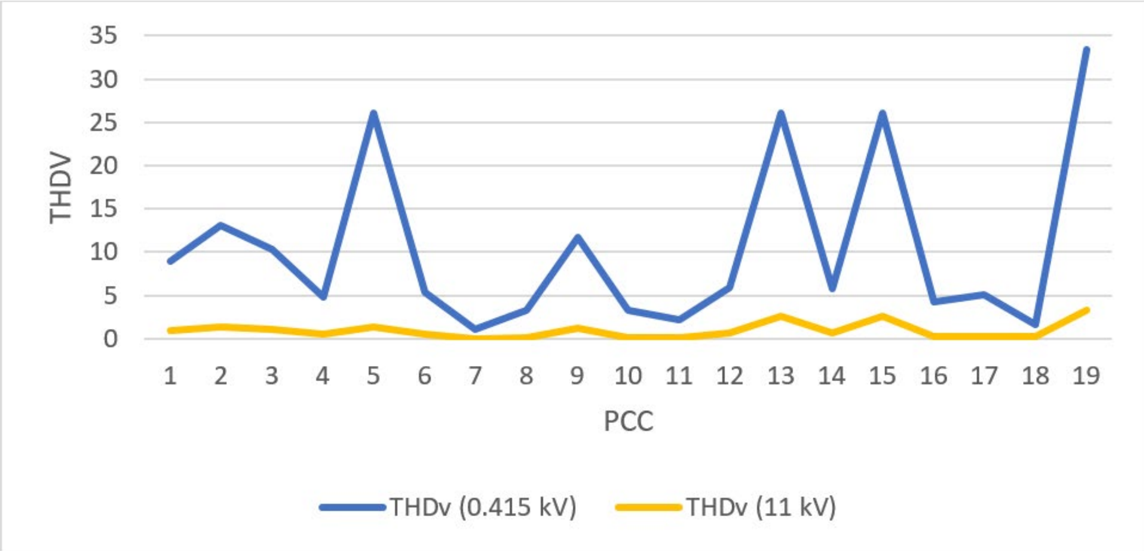

Fig. 4. Voltage total harmonic distortion level on the sub-distribution networks.

The sub-distribution networks with harmonic limit violations are shown in Figure 5.

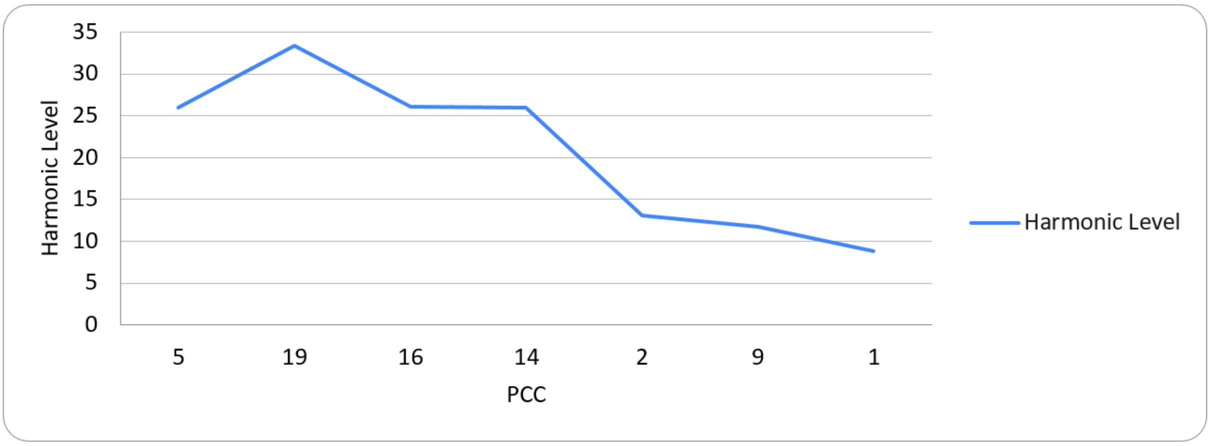

Fig. 5. PCCs with THDv violations.

3.2. Percentage contribution of individual non-linear load on distribution network

The quantitative analysis of the collected data depicting the percentage contribution of individual non-linear load (NLL) to the distribution network is shown in Figure 5.

Figure 6 shows that phones (GSM charging), compact florescent lamp (CFL), laptops (LAP), personal computers (PC), and televisions (TV) are the highest contributors of harmonics sources on the sub-distribution networks with 16%, 14%, 12%,11%, and 11% respectively.

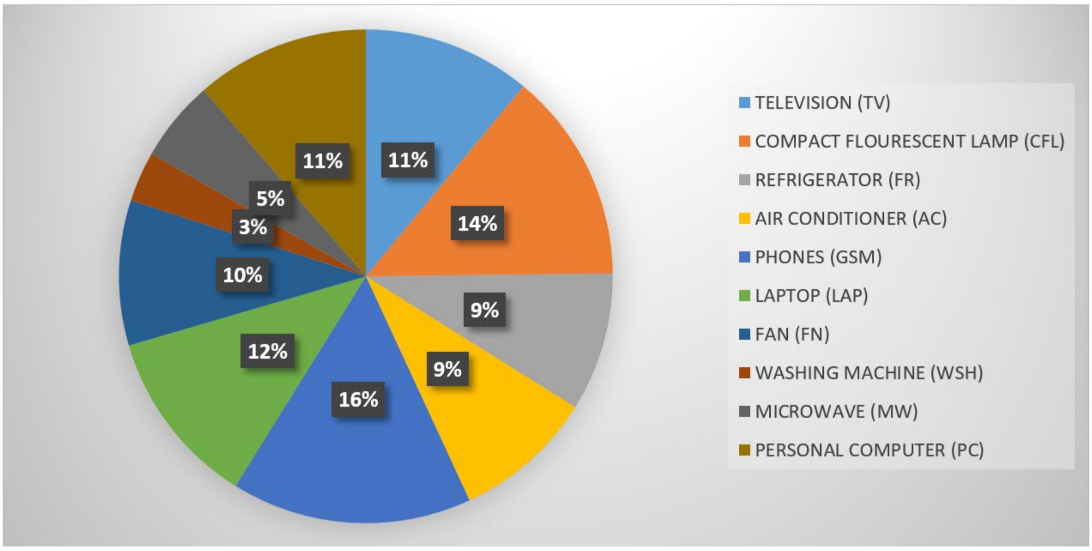

Fig. 6. Percentage contribution of individual NLL on sub-distribution network.

3.2.1. Relationship between the THD_i, Irms of the transformers and the THD_v of the PCCs connected to each transformer

Figure 7 shows the relationship between the THD_i of the transformers, the THD_v of the PCCs connected to each transformer and the I_{rms} of the transformers. It can be observed from Figure 4 that the THD_i of the transformers, the THD_v of the PCCs connected to each transformer and the I_{rms} of the transformers are directly proportional to each other.

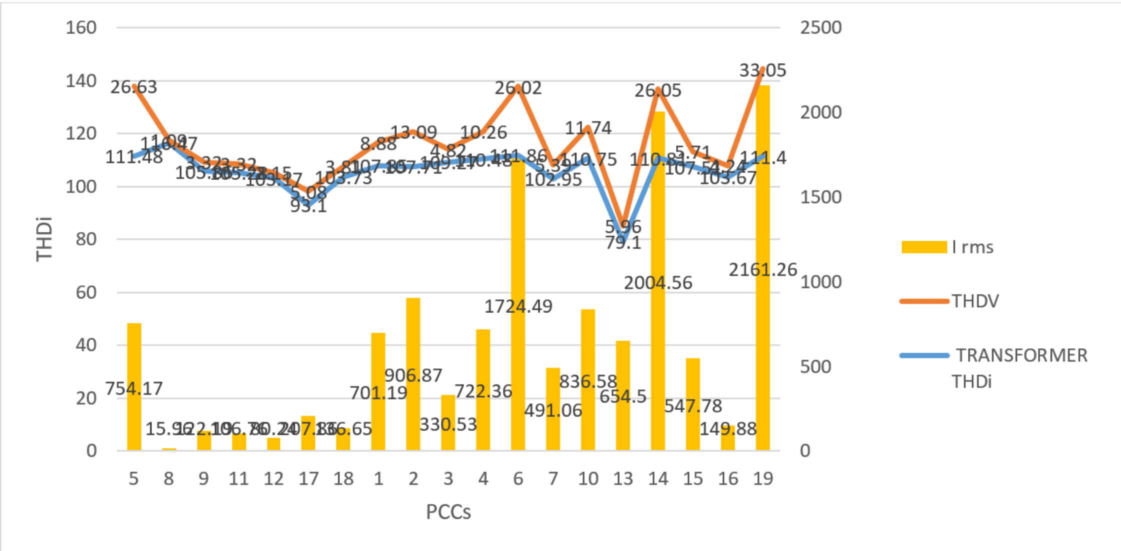

Fig. 7. Relationship between the THD_i , I_{rms} of the transformers, and THD_v of the PCCs connected to each transformer.

3.3. Harmonic contribution ranking of PCCs in the distribution network

The results obtained for ranking the sub-distribution network based on the total harmonic current distortion contribution of the individual PCCs in the primary distribution network are shown in Figure 8. The chart shows the sub-distribution networks ranked from the highest to the lowest based on their harmonic contribution.

The harmonic ranking of the sub-distribution network shown in Figure 8 showed that Cerad, Eng. 2500, New Undergraduates, and Senate contributed significantly to the total harmonic distortion in the distribution network under study.

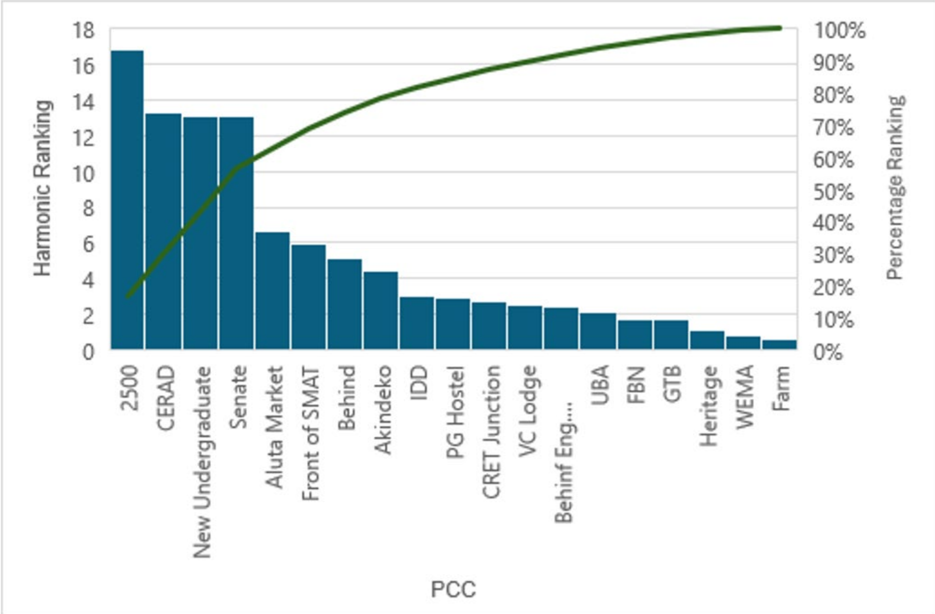

Fig. 8. Harmonic contribution ranking of the PCCs.

The ranking is brought into a better perspective by computing the cumulative contribution of some combined PCCs. The computation results are shown in Table 1.

Table 1. Percentage cumulative contribution of harmonic distortion.

PCCs	Cumulative contribution of harmonic distortion (%)
PCC 19 + PCC 5 + PCC 13 + PCC 15	56
PCC 2 + PCC 9 + PCC 3 + PCC 1	22

Table 1 shows that four (4) PCCs contributed about 56 % of the total harmonic distortion in the distribution network. The combination of four (4) other PCCs contributed about 22% of the total harmonic distortion in the distribution network. Therefore, 78 % of the harmonic distortion in the distribution network was produced from eight (8) PCCs. It can be further deduced that the remaining eleven (11) PCCs contributed 22 % of the total harmonic distortion in the distribution network under study.

4. CONCLUSIONS

This study conducted a comprehensive harmonic analysis to determine the harmonic distortion levels in a university sub-distribution network. The common non-linear loads in the networks were analyzed quantitatively, and a simulation modelling technique was used to determine the impacts of the non-linear loads on the primary distribution network using NEPLAN. The indices used for the evaluation were THD_i, THD_v, and THD_{NC}.

The results obtained for the THD_V showed that harmonic problems exist in nine (9) of the nineteen (19) PCCS in the primary distribution network considered in this study. Phone (GSM charging), Compact Florescent Lamp (CFL), Laptop (LAP), Personal Computer (PC), and Television (TV) were also discovered to be the highest contributors of harmonics sources on the Sub-Distribution Networks with 16%, 14%, 12%,11%, and 11% respectively.In addition, the THD_i of the transformers, the THD_v of the PCCs connected to each transformer and the I_{rms} of the transformers are directly proportional to each other.

The results showed that four (4) units of the 19 PCCs contributed about 56 % of the total harmonic distortion level. In comparison, eight (8) units of the 19 units of sub-distribution networks contributed 78% of the total harmonic distortion level.

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