# HARMONIC EFFECTS AND MITIGATION IN ELECTRICAL POWER DISTRIBUTION SYSTEM

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**ABSTRACT:** All nonlinear loads cause some levels of harmonic distortions in electric power system and thus becoming power quality problems. While harmonics have other origins such as arc devices, the non-linear source is becoming more prominent due to the proliferation of electronics devices. This paper examines the harmonic at the distribution end of the power network with the aim of proffering a solution. It is to design and simulate a passive harmonic filter to mitigate the effect of the harmonics. The simulated model is to be validated with experimental field measurement of harmonics. The study was carried out at the Information and Communication Centre (ICT) section of the Federal Polytechnic Ilaro using Harmonic Estimator and Power and Harmonics Analyser for simulation and field measurement respectively. It was established that the THD for current from both simulation (23.2%) and measurement (23.86%) are above the international standards and the limit has been violated. The measured and simulated values of the THD shows a high correlation. However, with the introduction of a passive filter, the distortion was reduced to 3.93% using simulation. The need to introduce a passive filter in any location with a high density of nonlinear loads such as ICT of tertiary Institutions for mitigating harmonic distortion becomes imperative.

**KEYWORDS**: Nonlinear loads, Harmonics distortion, Passive filter.

## INTRODUCTION

This work is to design and simulate a passive harmonic filter to mitigate the effect of the harmonics in a distribution network feeding nonlinear loads. Harmonics problems is one of the power quality issues caused by the presence of nonlinear loads and sometimes resonance in the system. Popular nonlinear loads known for producing total harmonic distortion (THD) include a switched-mode power supply (SMPS), personal computer (PC) and variable frequency drive (VFD) (Khan and Ahmed, 2008). The distribution transformers used in four-wire (i.e. three-phase and neutral) distribution systems have typically a delta-wye configuration that allows triplen harmonics to propagate (Grady, 2012; Bhujbal, Joshi and Chate, 2015). Harmonic distortion also has significant effects on distribution equipment and can lead to increased costs due to increased maintenance, component failures or devices de-rating. It causes heating in transformers, cables, problems in switching circuitry and malfunctions in control systems; there could be false tripping, interference in ripple control and unstable, unpredictable operation in other systems. Among other symptoms of harmonics include nuisance tripping and malfunctioning of equipment, premature failure of equipment, losses in machines, equipment, neutral burnouts, excess energy consumption etc. One of the effects of harmonic distortion is that it reduces the service life of the equipment (Schneider, 2010).

Passive filter application is one of the mitigation measures to limit harmonic pollution include (Olatoke, 2011). Though it is well known that the presence of harmonics will result in negative effects on the system, yet the actual harmonic distortion levels at points of common coupling (PCC) needs to be accurately modelled (Rao *et al*, 2011; Papic *et al*, 2019; Amoo *et al*, 2018).

Passive series filters work by providing a high-impedance path for the harmonics and thereby blocking those while allowing the fundamental to pass through the filter unhindered. They are used primarily for current harmonics mitigation since their main component is the inductor which resists fast changes in a current filter. Figure 1 shows typical series and shunt filters topologies.

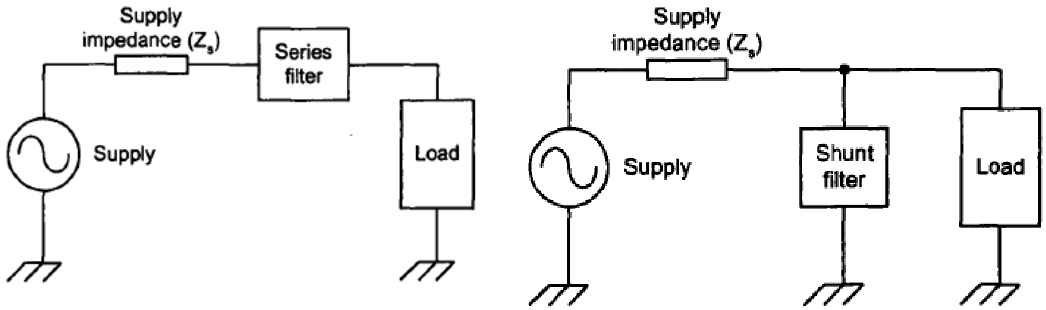



Figure 1: Harmonic filter topologies a) Series b) Shunt filters (Palethorpe, 2002)

Basically, a filter is an electrical network designed to modify or reject unwanted frequencies of a signal to eliminate or reduce harmonics in voltage and current, improve PF, reduce harmonic power losses or combination of the above (Adejumobi *et al*, 2017; Bhuiyan, 2011). The IEEE Standard 519-2014 provides recommendations to satisfy harmonic distortion limits with IEEE 519. For designing the single tuned filter, it is essential to select the appropriate capacitor value that enables a good power factor at system frequency. To design a filter according to IEEE 1531 procedures; first, the harmonic filter bank kVAR is determined.

In Nigeria, most mitigating equipment includes a voltage stabilizer and an uninterrupted power supply (UPS). Their performance evaluations have been reported (Ogunyemi and Adejumobi, 2013). Passive filters are used primarily for current harmonics mitigation since their main component is the inductor which resists fast changes in the current filter. Ivry *et al*, (2017) presented a method of predicting current harmonics at PCC of an EPS in the presence of uncertainties in filter parameter and operating power of multiple variable source converters (VSCs). Various measures are been used to solve PQ problems depending on the applications, cost, and technology. PQ improvement at a specific site using various techniques such as harmonic filter in places like the textile industry, metro highway and single substation site has been reported (Pradhan *et al*, 2008; Monem and Mahfouz, 2010; PQ View, 1995; Bhuiyan, 2011; Memon *et al*, 2012). Though the use of Y-zig-zag method among other mitigation methods can reduce the neutral current up to 90% (Omar *et al*, 2010), yet the most commonly used passive filter is the single-tuned filter because of its simplicity and cost-effectiveness.

## EXPERIMENTAL PROCEDURE

To realise the objective of this work, the following steps were adopted:

i) Design analysis to determine the components.
ii) Simulation model
iii) Experimental verification using analysing equipment for validation.
iv) Comparison with the standard.

### Design Analysis

Figure 2 shows a model for passive filter feeding a polluting non-linear load. For designing the single tuned filter, it is essential to select the component value that enables a good power factor at system frequency.

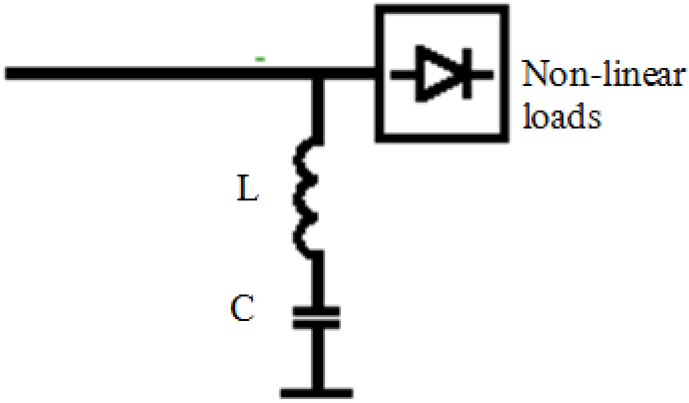



Figure 2: Passive filter's model with nonlinear polluting loads

Using an IEEE 1531 procedures, the harmonic filter bank kVAR size is first determined.
The reactive power of the filter is obtained from the expressions:

kVAR= kVAR1-kVAR2 ------------------------------------------------------------ 1

$kVAR_1$= kVA Sin ($Cos^{-1}pf_1$) ------------------------------------------------------------ 2

$kVAR_2$= kVA Sin ($Cos^{-1}pf_2$) ------------------------------------------------------------ 3

where:

Where kVA is the apparent power, kVAR is load reactive power.

$pf_1$= power factor of load without filter placement.

$pf_2$= desired power factor.

The values chosen for $pf_1$ and $pf_2$ based on common values of power factor are 0.75 and 0.98 respectively.

The apparent power (kVA) in the area of study is estimated to be 450kVA for the entire ICT section.

From equations 1-3 above, the kVAR is calculated as:

$kVAR_1$= kVA Sin ($Cos^{-1}pf_1$)

$kVAR_1$= 450xSin (41.41) = 450x0.6613 = 297.6

$kVAR_2$= kVA Sin ($Cos^{-1}pf_2$)

$kVAR_2$= 450xSin (11.48) = 450x0.199 = 89.6.

Therefore, kVAR = 297.6-89.6 = 208

Selecting the initial harmonic filter tuning: the expression for filter reactance $X_{filter}$ is given by equation 4:

$$X_{filter} = \frac{kV^2 * 1000}{kVAR} \quad \text{------------------------------------------------------------ 4}$$

Where kVAR is load reactive power and kV is load voltage.

With V= 400V or 0.4kV

Hence,

$X_{filter}$ = 0.769Ω.

The capacitance reactance $X_{cap}$ is obtained from equation 5

$$X_{cap} = \frac{X_{filter} * h^2}{h^2 - 1} \quad \text{------------------------------------------------------------ 5}$$

Where h is the order of harmonics.

With h= 11, then

$X_{cap}$ = 0.776Ω

Filter capacitance is given as:

$X_{cap}$ = 1/2πfC ------------------------------------------------------------ 6

C = 1/2πfx $X_{cap}$

C = 0.00410F or 4100µF.

Similarly, the Inductive reactance $X_{Lh}$ is:

$$X_{Lh} = \frac{X_{cap}}{h^2} \quad \text{------------------------------------------------------------ 7}$$

Substituting the values for $X_{cap}$ and h

$X_{Lh}$ = 0.00641ohms

Filter inductance $L_h$ is therefore given as:

$$X_{Lh} = 2\pi f L_h \quad \text{------------------------------------------------------------ 8}$$

$L_h = X_{Lh}/2\pi f = 20.4 \times 10^{-6}$ H

To calculate the quality factor Q, using equation 9:

$$Q = 2\pi f L_h / R \quad \text{------------------------------------------------------------ 9}$$

With Q taken as 50;

$R = 2\pi f L_h / Q = 128 \times 10^{-6}\ \Omega$

**Simulation**

The approach here is to use the estimator to determine the harmonic content using software developed by Rockwell Automation purposefully dedicated for this purpose. The circuit model adapted is as shown in figure 3. It consists of the main utility transformer at Gbokoto staff quarters of the Federal Polytechnic Ilaro and the ICT transformer with about a 2km distance of separation. The substation supplying the ICT equipment is used to replace with adjustable speed drive features. However, it was adapted by feeding only relevant data.

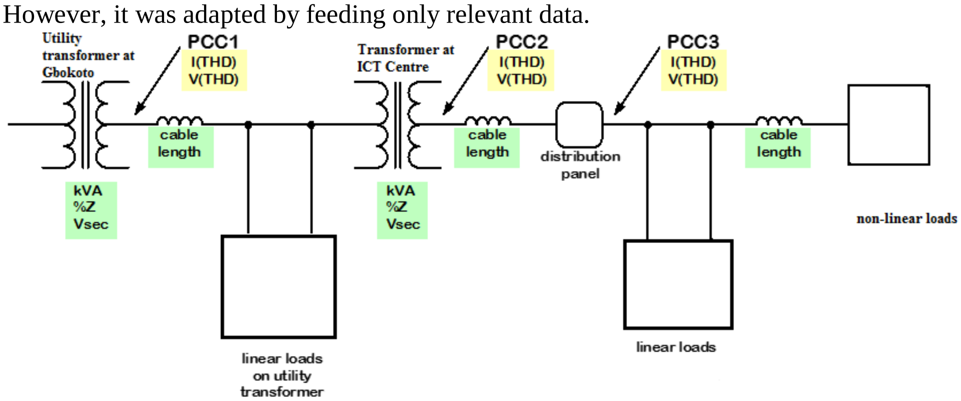



Figure 3: Harmonic Estimator model adapted from Rockwell Automation

The distance between the user transformer and distribution panel is the approximate length of cable connecting the distribution panel to the user transformer. If the drive is powered directly by a generator, the kW rating of the generator, its pf, impedance and its output voltage are then used to fill in the required information. The parameters used for inputs are as shown in table 1

Table 1: Input parameters for the harmonic estimator Sources

| Sources | Power (kVA) | Voltage (kV) | | Frequency (Hz) | Impedance (%Z) |
|---|---|---|---|---|---|
| | | Primary | Secondary | | |
| Utility transformer | 5000 | 33 | 11 | 50 | 8.0 |
| User transformer | 500 | 11 | 0.4 | 50 | 5.75 |
| Distance between utility transformer and user transformer (m) | | | | | 2000 |
| Distance between user transformer and distribution panel (m) | | | | | 15.2 |
| Distance between distribution panel and non-linear loads (m) | | | | | 3 |

**Field Measurement**

To validate the simulation models, field measurement survey was carried out in area of the distribution network under study.

a) 

b) 

Plate 1: Measurement set up with a) the Power & Harmonic Analyser and b) connection of the three clamp meters during the measurement.

The equipment used for the study is a power and harmonic analyser (PHA) with the model DW 6095 and set up for the measurements is as shown in Plates 1a and b.

**RESULTS AND DISCUSSION**

Table 2 shows the results of simulation with Harmonic Estimator without a filter at different PCCs for voltage and current. The THD for current at PCC3 is 23.2% and that of voltage is 3.7%. At PCC1 and PCC2, the THD values for voltage are 0% and 3.26% respectively. Figures 4 and 5show the waveform spectrum for harmonic current and voltage respectively at PCC3. For lack of space, that of PCC1 and PCC2 are omitted with their values stated above. The simulation results when passive filter was employed show that the THD for PCC3 to be 3.26% and 1.93% for current and voltage respectively. Table 3 shows the IEEE & IEC Compliances Tests carried out with the simulator indicating the degree of compliance for special, general and dedicated services.

Figures 6 and 7 show the plot of measured total harmonic distortion at the ICT center of Federal Polytechnic Ilaro for two days. The harmonics measurement at the ICT centre shows a distorted current of 23.86% on the average. Table 4 shows the statistical analysis for THD at the ICT centre. Figure 8 shows the comparison between the system without and with filter installation.

There is no significant difference between the simulated (23.2%) and measured (23.86%) results showing the correctness of the model used. Both the simulator and actual measurement results show that the distortion (>23%)

above the stipulated limit of 5% specified by the standard. Table 3 shows the value failed the compliance tests for the three areas. However, with the filter installed, it shows a reduction from 23.2% to 3.93% which is within the standard. The comparison of the ICT centre's THD (3 phase) with the simulation result of 23.20% shows that there was no significantly difference between the simulation result and the field measurement's result.

Table 2: Total harmonic distortion at PCCs

| Harmonic Number | Frequency, Hz | % Irms at PCC1 | % Vrms at PCC1 | % Irms at PCC2 | % Vrms at PCC2 | % Irms at PCC3 | % Vrms at PCC3 |
|---|---|---|---|---|---|---|---|
| 1 | 50 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 | 100.000 |
| 2 | 100 | 0.154 | 0.000 | 0.154 | 0.007 | 0.154 | 0.008 |
| 3 | 150 | 0.657 | 0.000 | 0.657 | 0.043 | 0.657 | 0.048 |
| 4 | 200 | 0.107 | 0.000 | 0.107 | 0.009 | 0.107 | 0.010 |
| 5 | 250 | 18.593 | 0.003 | 18.593 | 2.013 | 18.593 | 2.284 |
| 6 | 300 | 0.054 | 0.000 | 0.054 | 0.007 | 0.054 | 0.008 |
| 7 | 350 | 12.860 | 0.003 | 12.860 | 1.949 | 12.860 | 2.211 |
| 8 | 400 | 0.048 | 0.000 | 0.048 | 0.008 | 0.048 | 0.009 |
| 9 | 450 | 0.146 | 0.000 | 0.146 | 0.028 | 0.146 | 0.032 |
| 10 | 500 | 0.011 | 0.000 | 0.011 | 0.002 | 0.011 | 0.003 |
| 11 | 550 | 3.925 | 0.001 | 3.925 | 0.935 | 3.925 | 1.061 |
| 12 | 600 | 0.010 | 0.000 | 0.010 | 0.003 | 0.010 | 0.003 |
| 13 | 650 | 2.230 | 0.001 | 2.230 | 0.628 | 2.230 | 0.712 |
| 14 | 700 | 0.027 | 0.000 | 0.027 | 0.008 | 0.027 | 0.009 |
| 15 | 750 | 0.097 | 0.000 | 0.097 | 0.031 | 0.097 | 0.036 |
| 16 | 800 | 0.010 | 0.000 | 0.010 | 0.003 | 0.010 | 0.004 |
| 17 | 850 | 1.691 | 0.001 | 1.691 | 0.622 | 1.691 | 0.706 |
| 18 | 900 | 0.006 | 0.000 | 0.006 | 0.002 | 0.006 | 0.003 |
| 19 | 950 | 1.252 | 0.001 | 1.252 | 0.515 | 1.252 | 0.585 |
| 20 | 1000 | 0.015 | 0.000 | 0.015 | 0.007 | 0.015 | 0.007 |
| 21 | 1050 | 0.061 | 0.000 | 0.061 | 0.028 | 0.061 | 0.031 |
| 22 | 1100 | 0.014 | 0.000 | 0.014 | 0.007 | 0.014 | 0.008 |
| 23 | 1150 | 0.820 | 0.001 | 0.820 | 0.408 | 0.820 | 0.463 |
| 24 | 1200 | 0.014 | 0.000 | 0.014 | 0.007 | 0.014 | 0.008 |
| 25 | 1250 | 0.687 | 0.001 | 0.687 | 0.372 | 0.687 | 0.422 |
| 26 | 1300 | 0.009 | 0.000 | 0.009 | 0.005 | 0.009 | 0.006 |
| 27 | 1350 | 0.049 | 0.000 | 0.049 | 0.028 | 0.049 | 0.032 |
| 28 | 1400 | 0.010 | 0.000 | 0.010 | 0.006 | 0.010 | 0.007 |
| 29 | 1450 | 0.551 | 0.000 | 0.551 | 0.346 | 0.551 | 0.392 |
| 30 | 1500 | 0.005 | 0.000 | 0.005 | 0.004 | 0.005 | 0.004 |
| 31 | 1550 | 0.397 | 0.000 | 0.397 | 0.267 | 0.397 | 0.302 |
| 32 | 1600 | 0.011 | 0.000 | 0.011 | 0.008 | 0.011 | 0.009 |
| 33 | 1650 | 0.045 | 0.000 | 0.045 | 0.032 | 0.045 | 0.036 |
| 34 | 1700 | 0.007 | 0.000 | 0.007 | 0.005 | 0.007 | 0.006 |
| 35 | 1750 | 0.409 | 0.000 | 0.409 | 0.310 | 0.409 | 0.352 |
| 36 | 1800 | 0.008 | 0.000 | 0.008 | 0.007 | 0.008 | 0.007 |
| 37 | 1850 | 0.318 | 0.000 | 0.318 | 0.255 | 0.318 | 0.289 |
| 38 | 1900 | 0.009 | 0.000 | 0.009 | 0.008 | 0.009 | 0.009 |
| 39 | 1950 | 0.030 | 0.000 | 0.030 | 0.025 | 0.030 | 0.028 |
| 40 | 2000 | 0.010 | 0.000 | 0.010 | 0.009 | 0.010 | 0.010 |
| 41 | 2050 | 0.270 | 0.000 | 0.270 | 0.240 | 0.270 | 0.272 |
| 42 | 2100 | 0.004 | 0.000 | 0.004 | 0.003 | 0.004 | 0.004 |
| 43 | 2150 | 0.242 | 0.000 | 0.242 | 0.225 | 0.242 | 0.255 |
| 44 | 2200 | 0.007 | 0.000 | 0.007 | 0.007 | 0.007 | 0.007 |
| 45 | 2250 | 0.022 | 0.000 | 0.022 | 0.022 | 0.022 | 0.025 |
| 46 | 2300 | 0.010 | 0.000 | 0.010 | 0.010 | 0.010 | 0.011 |
| 47 | 2350 | 0.193 | 0.000 | 0.193 | 0.196 | 0.193 | 0.223 |
| 48 | 2400 | 0.005 | 0.000 | 0.005 | 0.005 | 0.005 | 0.006 |
| 49 | 2450 | 0.162 | 0.000 | 0.162 | 0.172 | 0.162 | 0.195 |
| 50 | 2500 | 0.007 | 0.000 | 0.007 | 0.008 | 0.007 | 0.009 |
| % THD | | 23.20 | 0.00 | 23.20 | 3.26 | 23.20 | 3.70 |

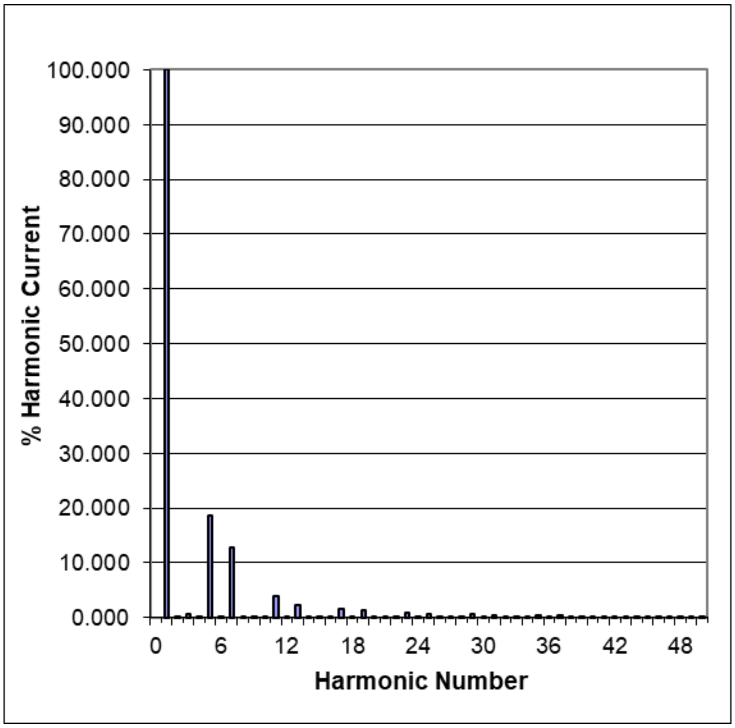



Figure 4: Harmonic current spectrum

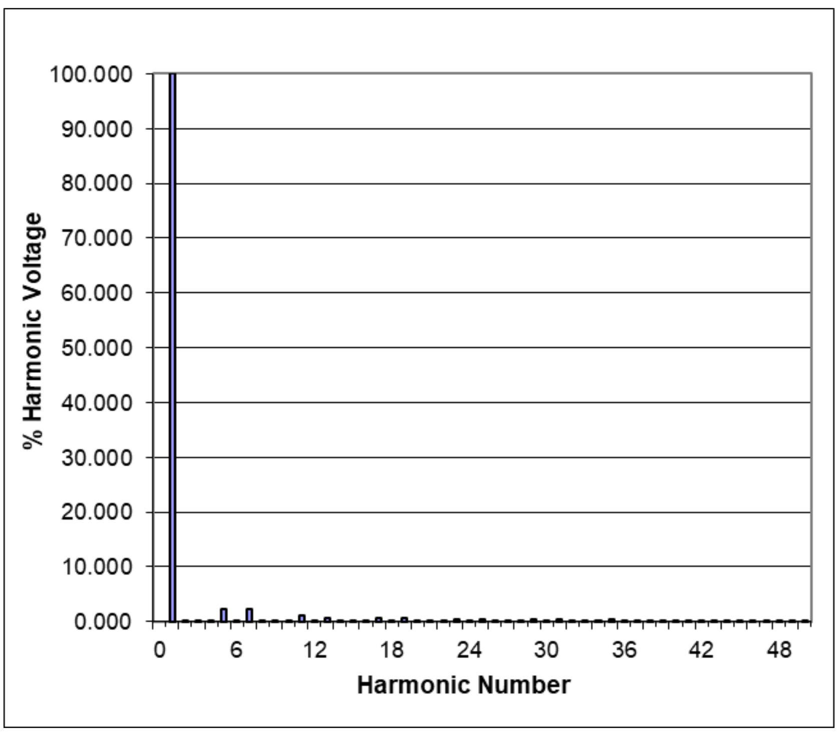
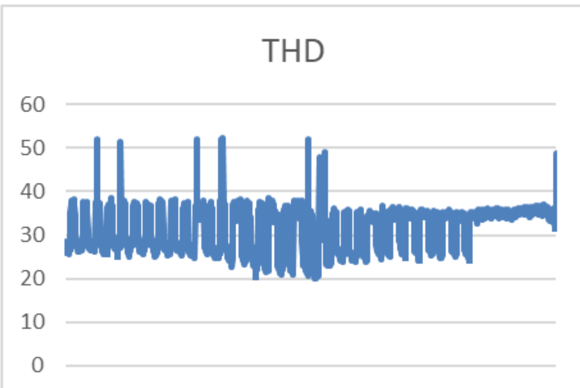



Figure 5: Harmonic voltage spectrum at PCC3

Table 3 IEEE & IEC Compliances Test

| IEEE Compliance | | | IEC Compliance |
|---|---|---|---|
| Special | General | Dedicated | |
| No | No | No | Yes |
| No | No | No | No |
| No | No | No | No |

a) 

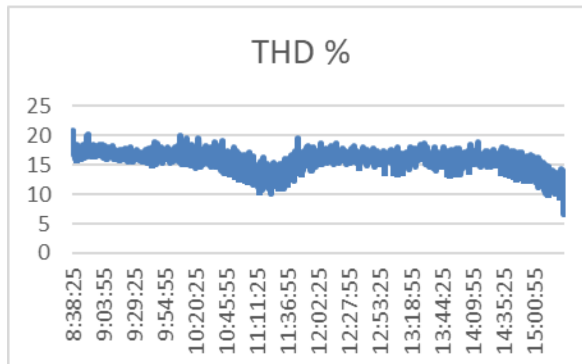

b) 


Figure 6: THD for day one at ICT centre. Figure 7: THD for day two at ICT centre.

Table 4: THD for ICT

| | Mean | S. D. | Std. Error Mean |
|---|---|---|---|
| THD | 23.73 | 9.895 | .143 |

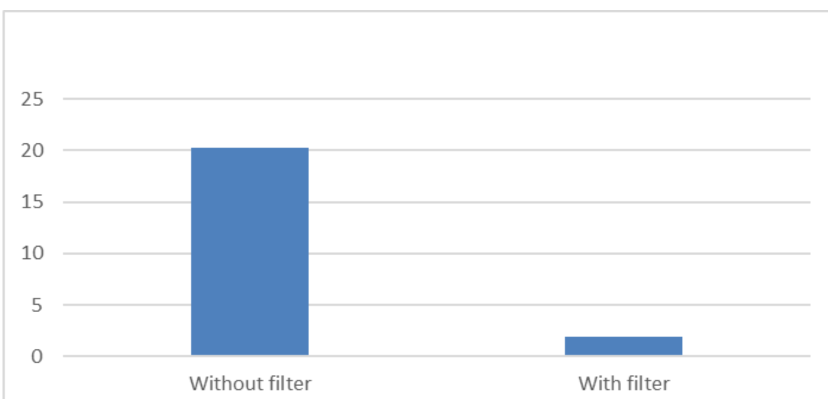



Figure 8: THD without filter and with filter

**CONCLUSION AND RECOMMENDATIONS**

Harmonic simulation result for the ICT centre shows that the current total harmonic distortion (THD) was 23.2% and this agrees with the measured value of 23.86%. Comparison of the results using statistical tools shows a significant deviation of the harmonics from the international standard limit of 5%. Introducing the passive harmonic filter shows a significant reduction from 23.2% to 3.93% which is within the standard limit. Therefore, it can be concluded that the obtained high distortions are due to the presence of large numbers of nonlinear loads at the study areas and mitigation using a passive filter is desired for all the ICT centres, not only in Ilaro but other organizations or Institutions in Nigeria to minimise the impact of nonlinear loads on the power distribution network.

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