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Experimental Determination and Analysis of Harmonic Characteristics of Domestics Electric Lamps

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ABSTRACT
The aim of this study is to represent coexistence of harmonics in the power system through an extensive comparison among the different electric bulbs. The Harmonics in the electrical distribution system are the by-products of modern electronics. They are especially prevalent where there are large numbers of nonlinear loads such as compact fluorescent lamp, light emitting diode lamp, personal computers, printers, copiers, hospital equipment, fluorescent lighting and adjustable speed drives. Harmonics do no useful contributions; they degrade the power quality and efficiency in a commercial building or industrial facility. Most people do not comprehend those harmonics have been around for more than 100 years ago. The harmonics at that time were inconsequential and had no detrimental effects. Very often, the operation of electrical equipment may seem normal, but under a certain combination of conditions, the impact of harmonics is enhanced, with damaging results. In this study, we have observed the effects of harmonics and performed a comparison among the four types of electric bulbs which are Light Emitting Diode (LED), Compact Fluorescent Lamp (CFL), Fluorescent Lamp (FL) and Filament Lamp or incandescent lamp. Here, we have evaluated the performance and characteristics of these electric bulbs through experimental set up using Power Logger to evaluate the power quality of the electric bulbs which are common use in the low voltage distribution networks. The results obtained during the experimental analysis exhibit the high number of harmonics produced by LED and CFL bulbs which affirms their contributions to degradation of power distribution networks.

Keywords:lamps, harmonics, power quality, total harmonic distortion.

1. INTRODUCTION

Harmonics are electric voltages and currents that appear on the electric power system because of certain kinds of electric loads. These are the distortion of the utility supplied waveform and are caused by “nonlinear” (distorting) loads, which include motor controls, computers, office equipment, CFLs, light dimmers, televisions and in general, most electronic loads. High harmonics increase lines losses and decrease equipment lifetime. Past to Present, power systems are designed to operate at frequencies of 50 or 60Hz depending on the operating frequency of each country. However, certain types of loads produce currents and voltages with frequencies that are integer multiples of the 50 or 60 Hz fundamental frequency. These higher frequencies are a form of electrical pollution known as power system harmonics[1].

The proliferation of non-linear loads such as Personal Computers, Fluorescent Lamps, Compact Fluorescent Lamps, etc. in commercial buildings has adverse effects on the power quality and the overall performance of distribution networks as these loads inject harmonics into the networks[2]. These adverse effects have been known since the 1980s but the increased concern about in this period is due to the infiltration and popularity of non-linear loads. There is a need to assess the harmonic behaviour of non-linear loads individually and collectively to determine how this behaviour ties with the power quality of commercial buildings. The increased scrutiny around power quality requirements is due to the sensitivity of equipment of commercial customers as reported by[3] and [4].

Harmonics generated by non-linear loads often cause power quality disturbances such as voltage sags, voltage swells, switching transients, impulses, flickers, notches, etc. [5]. This may cause various technical problems to the devices of customers such as increased heating, maloperation, early aging of devices etc. Poor power quality often results in financial loss to affected customers especially in the industrial and commercial sectors [6].

In this study, our undivided focus is to analyse the characteristics of different harmonic components injected by different electric bulbs to the power system networks. We want to evaluate that which kind of bulb produce huge amount of different harmonic components in the power system and affect the electrical devices of our home appliances.

2. THEORETICAL AND MATHEMATICAL ANALYSIS

The differentiator between linear and non-linear loads is the way the applied voltage relates with the current drawn by the load. The voltage and current of linear loads are sinusoidal and proportional to one another while for non-linear loads either the current, voltage or both are non-sinusoidal and have a non-linear relationship. The non-linear relationship is referred to by [7],[8] and,[9]as harmonic distortion. This linear and non-linear relationship between voltage and current are illustrated by Figure 1a and Figure 1b respectively.

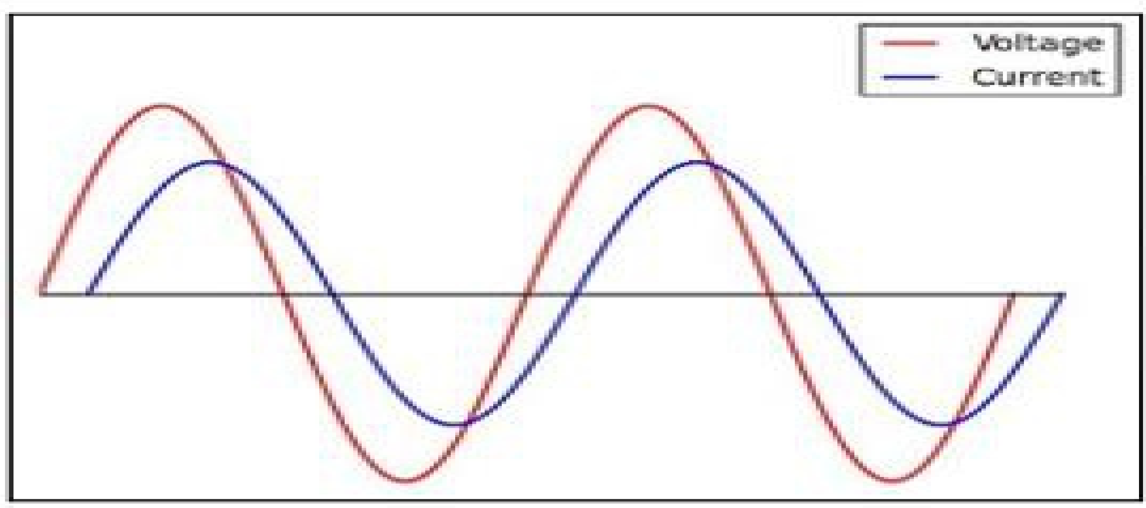

Figure 1 (a): Linear relationship between voltage and current (9).

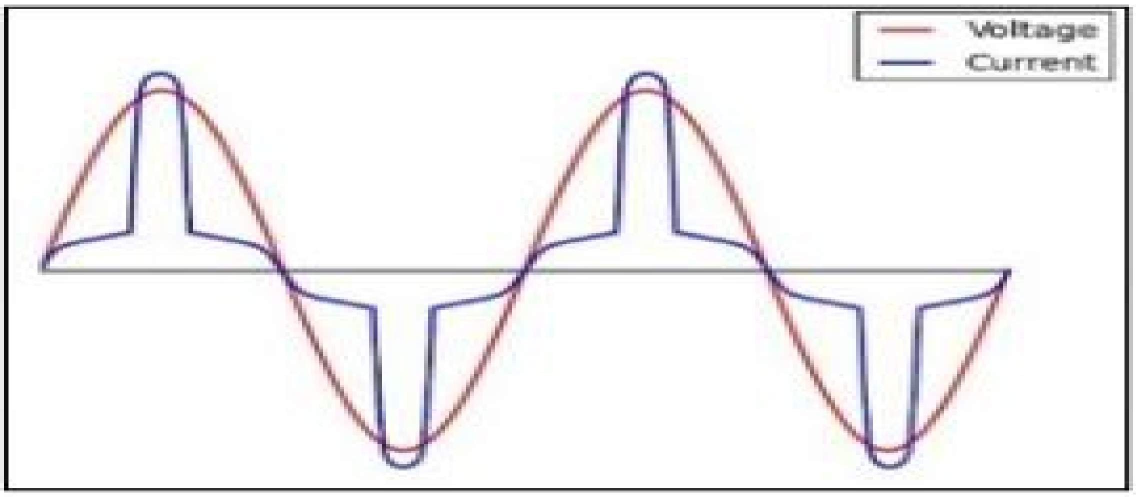

Figure 1 (b): Non-linear relationship between voltage and current (9)

2.1 Harmonic distortion

Harmonics are integer multiples of the fundamental frequency. In Nigeria, the fundamental frequency is 50 Hz, making the 2nd harmonic 100 Hz, the 3rd harmonic 150 Hz, and so on. A distorted waveform results when the waveforms with higher order frequencies are superimposed on the fundamental waveform resulting in a waveform that is no longer sinusoidal.

Even harmonics

Usually, even harmonics exist in small quantities in the power system and are not a great threat under normal operations as they tend to cancel each other out. However, in conditions where equipment malfunctions, large quantities of even harmonics can be generated. This could be exacerbated by harmonic filters in the power system that may excite the resonance of even harmonics. It is shown in[10] that large 4^{th} harmonic currents, generated by rectifiers, flowed in the system that was being analysed as a result of serious resonance and amplification. The 8^{th} and 12^{th} harmonic currents however were minimal and could be attributed to the inductance of the transformer blocking higher order harmonics according to[11] .

Odd harmonics

Odd harmonics, especially triplen harmonics which are odd multiples of the 3rd harmonic (also known as zero-sequence harmonics), are of the greatest concern when analysing the effects of harmonics. It is common for transformers connecting the medium voltage and low voltage to have a Dyn connection. Overheating of transformers due to harmonic currents is a common issue. Contrast to fundamental currents which cancel out in the neutral wire, triplen harmonics add up constructively in the neutral wire. This causes the triplen harmonic current that is in the neutral wire to be three times when compared to the triplen current in each phase which results in overheating of the wire, potential burn off of the wire, and damage to transformers. On the delta side of transformers, triplen currents circulate in the delta connection resulting in overheating of the transformer and additional eddy current losses.

2.2 Harmonic Analysis Methods

The waveforms of both voltage and current associated with nonlinear loads can be obtained at the PCC using appropriate meter such as power quality analyser, spectrum analyser etc.[7]. In the year 1822, Jean Baptiste Fourier[1] postulated that any continuous function with a repetitive pattern can be represented by the sum of the fundamental sinusoidal component, DC component and the higher order sinusoidal components at the multiples of the fundamental frequencies. Harmonic analysis involves the act of calculating the magnitudes and phases of the fundamental and higher order harmonics of period waveforms while the resulting series are known as Fourier series which established the time domain and frequency domain functions.

Fourier Analysis

The common techniques used for Fourier analysis considering the waveform identity, either continuous or discrete signals, are Fourier series, Discrete Fourier Transform and Fast Fourier Transform, these techniques are based on the signals or waveform decomposition or transformation. Any periodic waveform can be decomposed into a Fourier series of DC, fundamental frequency and harmonic terms which contains a sum of simple oscillating functions, namely cosines, sine or complex exponentials.
Considering line current of a waveform represented by a f(t), the decomposition can be done as shown in equation (1).

$$\mathbf{f(t) = \frac{A_0}{2} + \sum_{n=1}^{\infty}[(A_n \cos(n\omega t)) + B_n \sin(n\omega t)]} \quad (1)$$

Where n = 1, 2, 3, 4, 5, 6, 7……………………

A_0 = the average value of the function f (t), A_n and B_n = the coefficients of the series at nth harmonic. Likewise,

$$\mathbf{A_0 = \frac{1}{T}\int_0^T f(t)dt} \quad (2)$$

$$\mathbf{A_n = \frac{2}{T}\int_0^T f(t)\cos(n\omega t)\, dt} \quad (3)$$

$$\mathbf{B_n = \frac{2}{T}\int_0^T f(t)\sin(n\omega t)\, dt} \quad (4)$$

The sine and cosine terms in equation (1) can be converted into polar form to determine the angle using trigonometry function as follows:

$$A_n\cos(n\omega t) + B_n\sin(n\omega t) = \sqrt{A_n^2 + B_n^2} * \frac{(A_n\cos(n\omega t)) + B_n\sin(n\omega t)}{\sqrt{A_n^2 + B_n^2}}$$

$$= \sqrt{A_n^2 + B_n^2} * \left[\frac{A_n}{\sqrt{A_n^2 + B_n^2}}\cos(n\omega t) + \frac{B_n}{\sqrt{A_n^2 + B_n^2}}\sin(n\omega t)\right] ,$$

$$= \sqrt{A_n^2 + B_n^2} * [\sin(\theta_n)\cos(n\omega t) + \cos(\theta_n)\sin(n\omega t)] \quad (5)$$

From which trigonometric identity can be applied as follows:

$$\sin(X + Y) = \sin X\cos Y + \cos X\sin Y \quad (6)$$

The resulted polar form is as shown in equation (7),

$$\sqrt{A_n^2 + B_n^2} * \sin(nwt + \theta_n) \quad (7)$$

This implies,

$$\tan(\theta_n) = \frac{\sin(\theta_n)}{\cos(\theta_n)} = \frac{A_n}{B_n} \quad (8)$$

2.3 Harmonic Parameters Formulation in Power System

The most commonly used measure for harmonic analysis is the total harmonic distortion which also determines the distortion factor in the system. If voltage or current signals contains harmonics, the individual harmonic distortion for the signal at any frequency is given as:

$$V_n(\%) = \frac{V_n}{V_1} * 100 \quad (9)$$

$$I_n(\%) = \frac{I_n}{I_1} * 100 \quad (10)$$

Where V_n and I_n represents the voltage and current harmonic of or n respectively while V_1 and I_1 is the voltage and current at the fundamental frequency respectively.
The total harmonic distortion of both voltage and current signals are

$$THD_V = \frac{\sqrt{\sum_{n=1}^{\infty} V_n^2}}{V_1} \quad (11)$$

$$THD_I = \frac{\sqrt{\sum_{n=1}^{\infty} I_n^2}}{I_1} \quad (12)$$

The RMS values of voltage and current can be determine by equations (13) & (14)

$$V_{rms} = \sqrt{V_1^2 * (1 + THD_V^2)} \quad (13)$$

$$I_{rms} = \sqrt{I_1^2 * (1 + THD_I^2)} \quad (14)$$

The apparent power can be resolved using the separation of the RMS current and voltage in fundamental and harmonic terms as shown below[12]

$$S^2 = (V_1^2 + V_h^2) * (I_1^2 + I_h^2) = (S_1^2 + S_N^2)$$

Therefore,

$$S_N = \sqrt{(S^2 - S_1^2)} \quad (15)$$

Where S_N is the apparent power due to harmonics which can also be broken into currents.

2.4 Harmonics Classification

Harmonics are classified according to their frequencies which also determines the sequence and effects of each in a three-phase power system. The classification based on sequence is given in table 1[13]

Table 1: Classification of Harmonics

Harmonics Order	Frequency [Hz)	Sequence	Direction of Rotation	Effects
1, 4, 7, 10, 13, 16, 19..	50,200,350,500...	Positive	Forward	Heating and loss in motors
2, 5, 8, 11, 14, 17, 20..	100,250,400,550…	Negative	Backward	Heating and breaking torque in motors
3,9,12,15,18,21…	150,300,450,600…	Zero	Insignificant	Overloading and Heating of neutral conductor

2.5 Harmonics Distortion Limits

IEEE Standard 519-1992 gives the guidelines for acceptable levels of both voltage and current distortions in power systems network. The acceptable total voltage distortion for voltage level up to 16kV is limited to below 5% while the individual harmonic should not be more than 3%. Other voltage levels and the harmonic limits are shown in table 2 while the current harmonic limits are as shown in table 3.

Table 3: Harmonic Voltage Limits, IEEE Standard 519-1992

Voltage level	Maximum Individual harmonic component (%)	Maximum THD (%)
<69kV	3.0	5.0
69kV<Vn≤161kV	1.5	2.5
>161kV	1	1.5

Table 3: Harmonic Current Limits, IEEE Standard 519-1992

Maximum Harmonic Current Distortion, % of I_L						
Vn≤69kV						
I_{sc}/I_L	h <11	11<h<17	17<h<23	23<h<35	35<h	TDD
<20	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
69kV<Vn≤161						
<20	2.0	1.0	0.75	0.3	0.15	2.5
20<50	3.5	1.75	1.25	0.5	0.25	4.0
50<100	5.0	2.25	2.0	0.75	0.35	6.0

100<1000	6.0	2.75	2.5	1.0	0.5	7.5
>1000	7.5	3.5	3.0	1.25	0.7	10.0
Vn >161kV						
<50	2.0	1.0	0.75	0.30	0.15	2.5
≥ 50	3.0	1.5	1.15	0.45	0.22	3.75
**All power generation equipment is limited to these values of current distortion regardless of actual I_{SC}/I_L						

3. EXPERIMENTAL SET-UP AND MEASUREMENT (METHODOLOGY)

This section presents the methodology used for the power quality measurement of some commonly used electric lamps for residential and commercial buildings as applicable low voltage distribution networks in Nigeria. In this study Light Emitting Diode, Compact Fluorescent, Choke/ballast Fluorescent and Filament bulbs are considered while voltage, current, Active Power waveforms, Total Harmonic Distortions (THDs), and the power factor of each bulb are the parameters considered. All the measurements were carried out in the Power System Laboratory at Department of Electrical and Electronic Engineering of the Federal Polytechnic, Ado- Ekiti using DENT Power Logger with high resolution for effective power quality measurement. Figure 2 and Figure 3 show the schematic diagram and experimental setup of the methodology used.

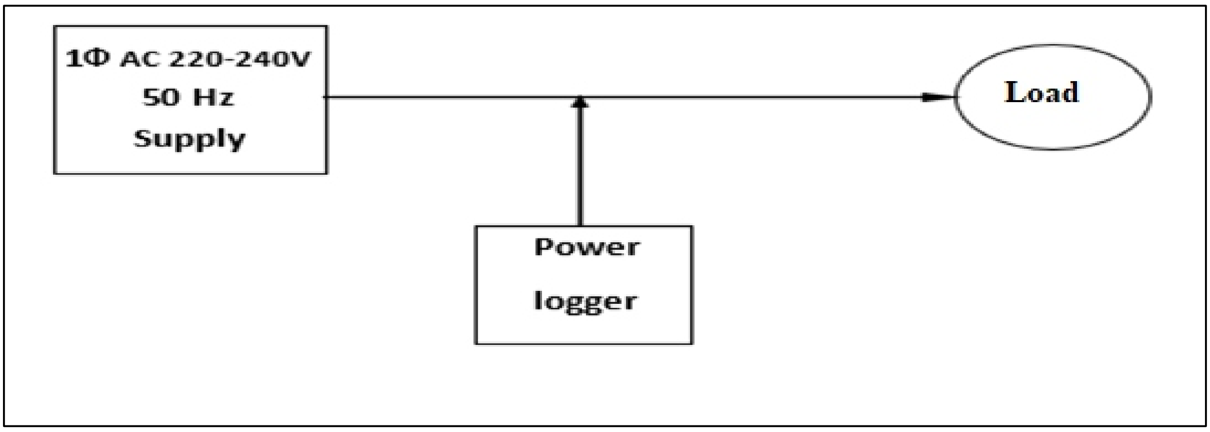

Figure 2: Schematic Diagram for the Experimental Setup

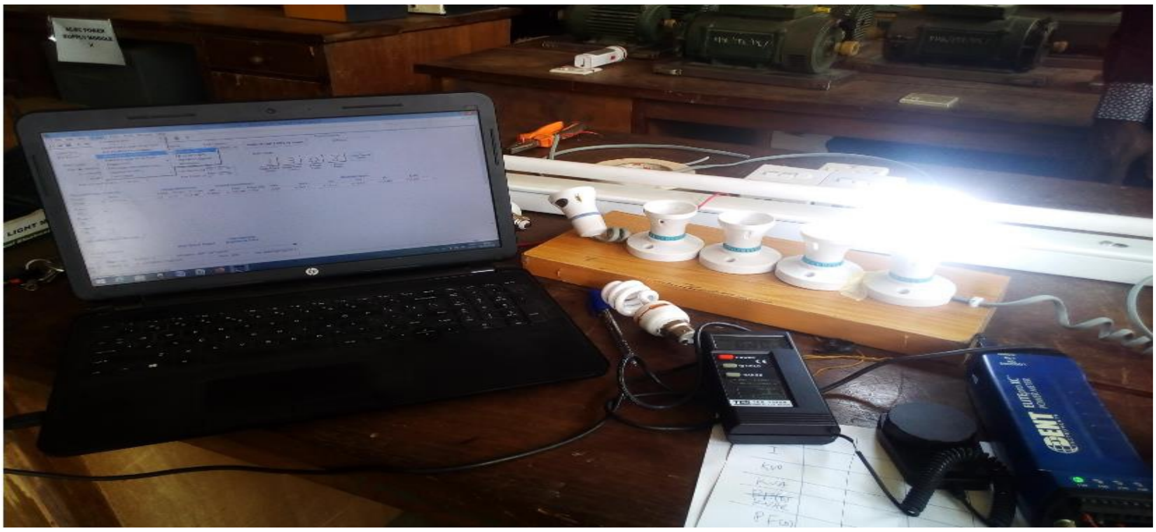

Figure : Experimental setup for power quality measurement with DENT Power logger

4. RESULTS AND DISCUSSION

Following theoretical analysis in Section II, experimental analysis of power quality parameters such as voltage, current, power waveforms, individual harmonics, THDs and power factor of the bulbs are done in this section to validate the pollution of distribution networks through the use of energy saving bulbs if not well monitored and controlled.

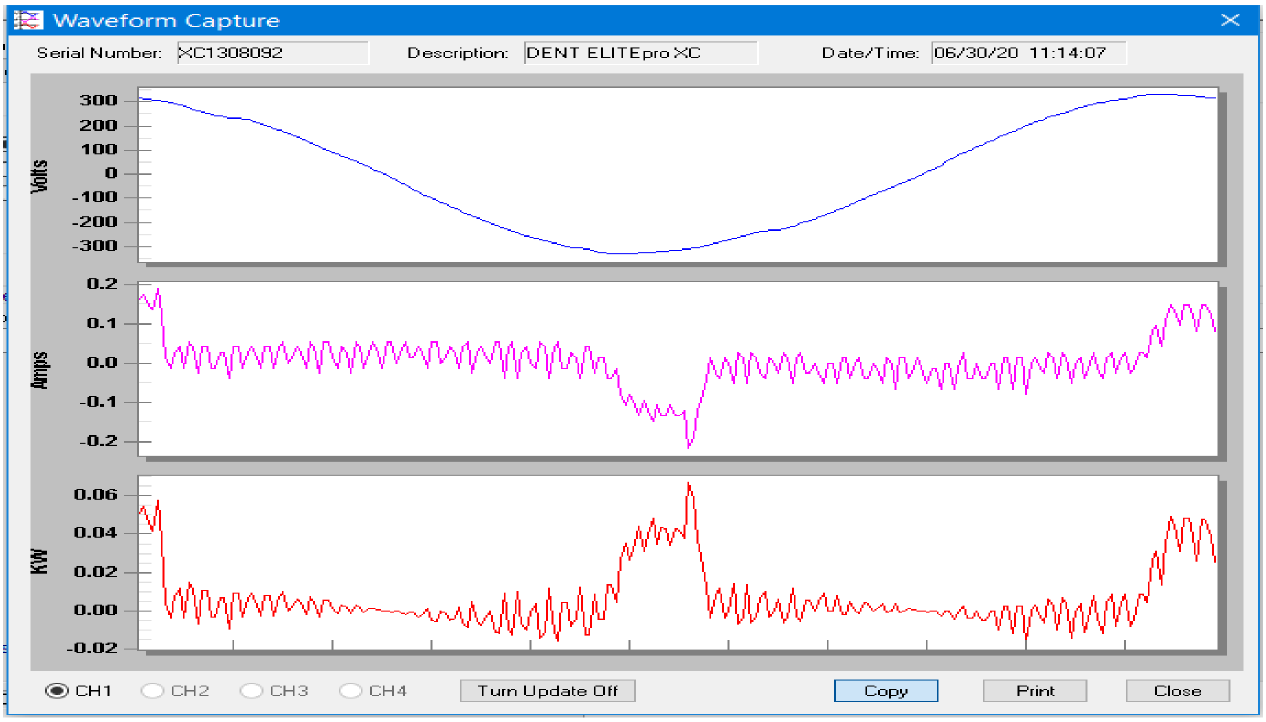

Figure 4: Voltage, Current and Active Power Waveforms of 8W_ LED

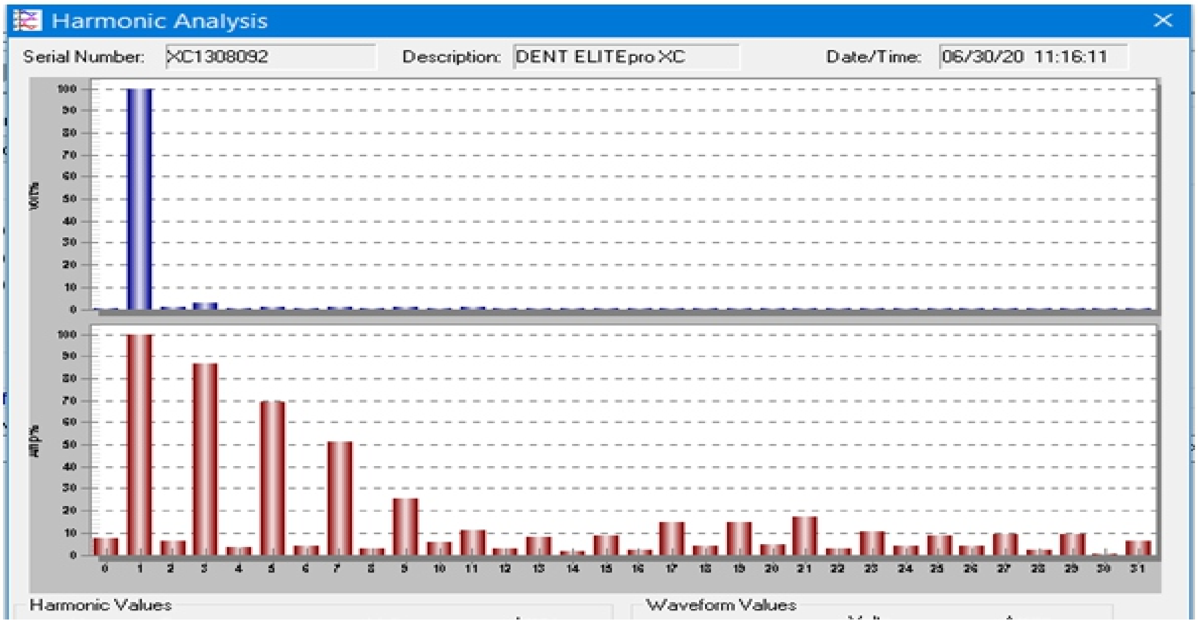

Figure 5: Voltage and Current Harmonics Spectrum of 8W_LED

Light Emitting Diode Lamp: In figures 4 and 5 above, the current and voltage waveforms of LED bulb show the presence of harmonic distortion with decrease in the individual harmonic distortion from 3rd order to 9th order while there is an increase 15th up to 21st harmonics.

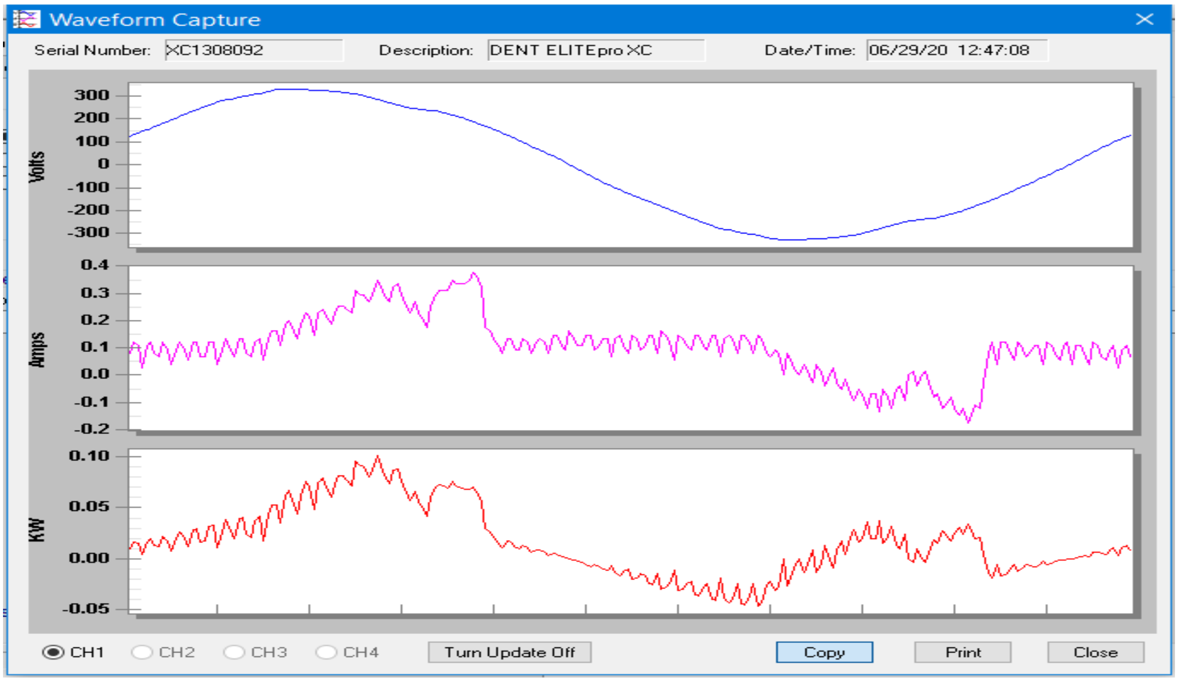

Figure 6: Voltage, Current and Active Power Waveforms of 40W_CFL

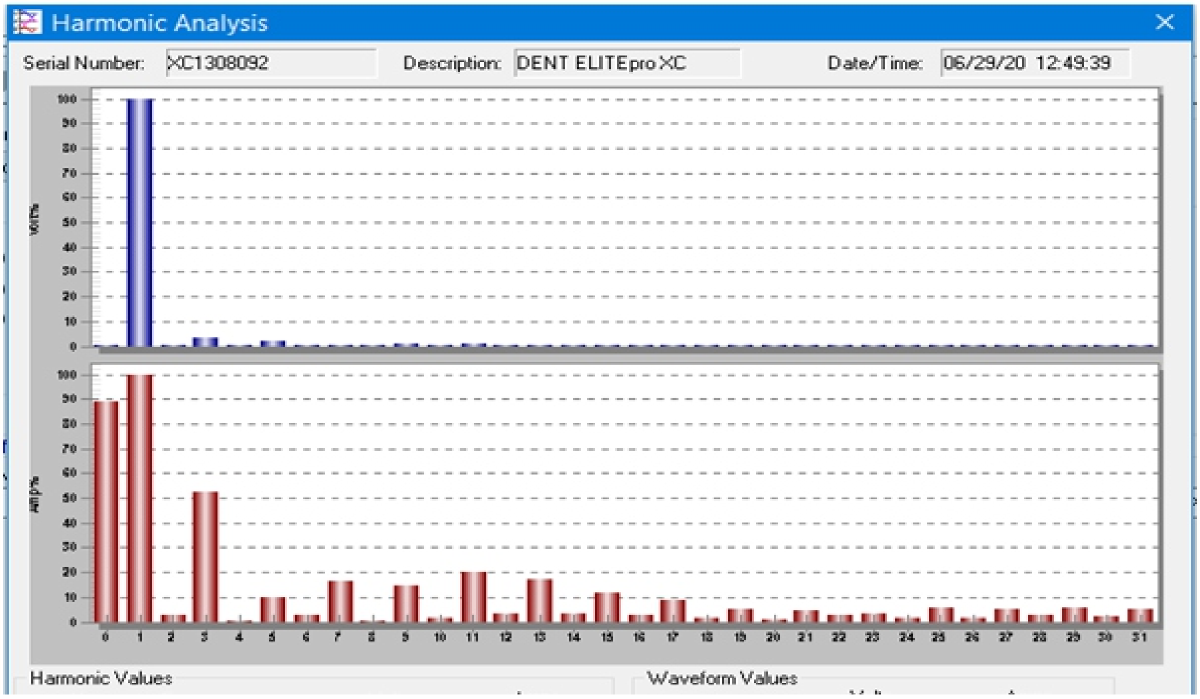

Figure 7: Voltage and Current Harmonics Spectrum of 40W_CFL

Compact Fluorescent Lamp: In figure 6 above, the level of distortion in CFL is on the high due to switch mode power supply embedded in the design which depicts high level of harmonic distortion. There is also a d.c component in the harmonic spectrum shown in figure 7. It is shown further, the presence of odd harmonics from 3rd harmonic order which can lead to pollution of the distribution networks if the usage is not monitored of controlled.

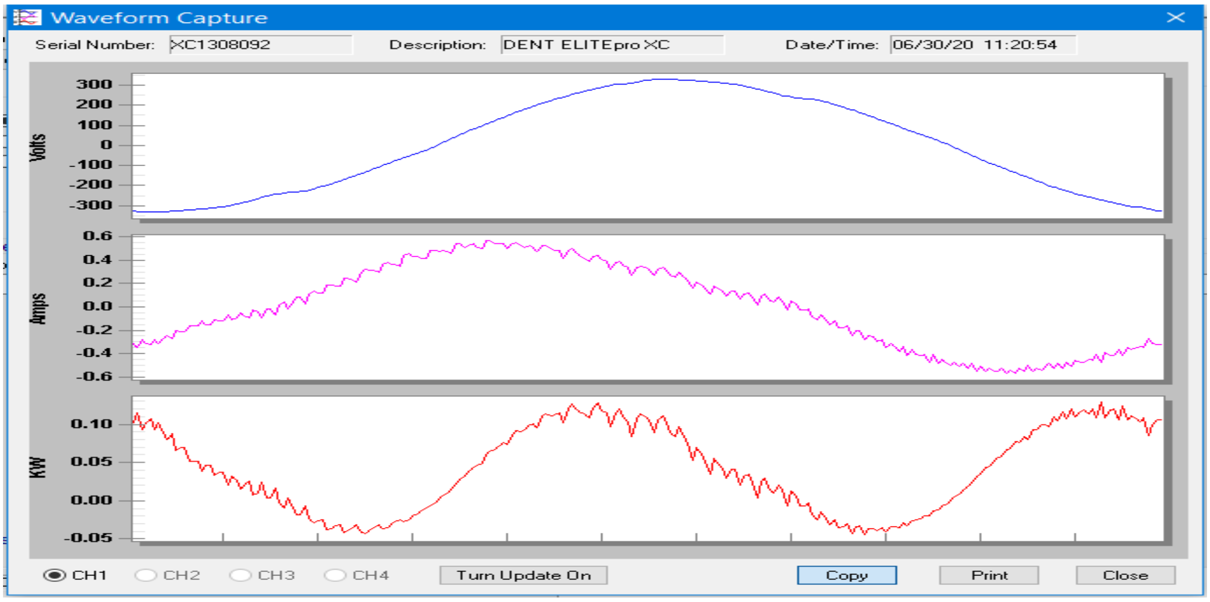

Figure 8: Voltage, Current and Active Power Waveforms of 36W_FL

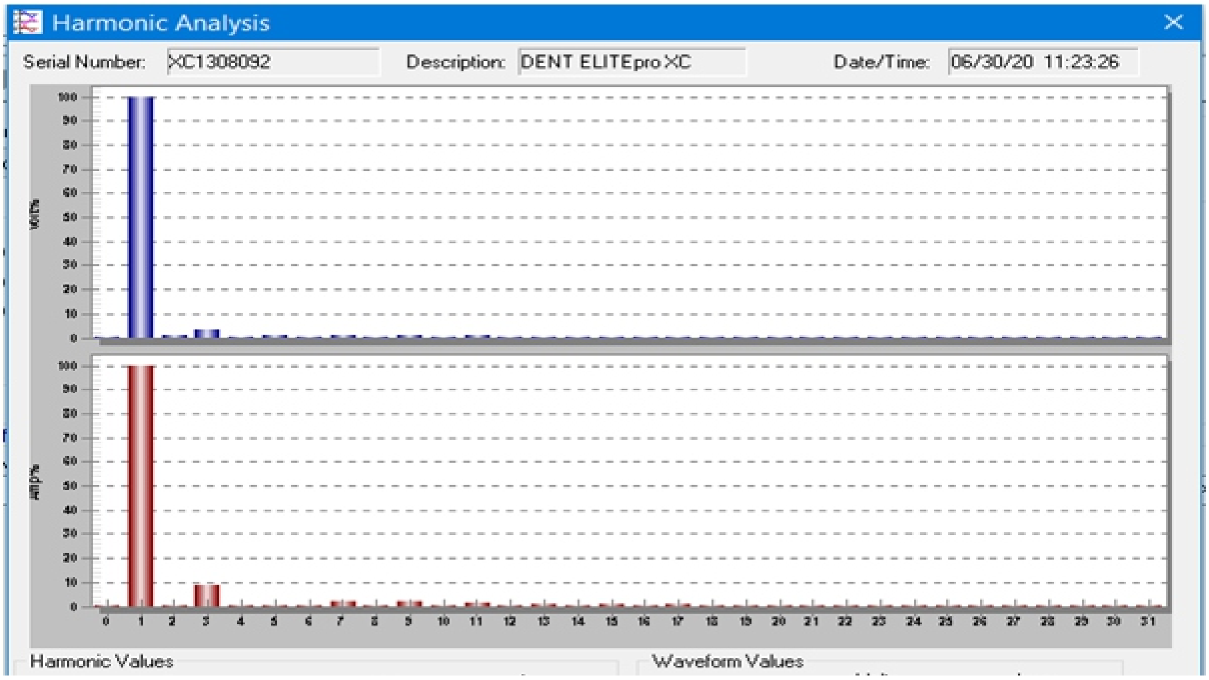

Figure 9: Voltage and Current Harmonics Spectrum of 36W_FL

Fluorescent Lamp: The voltage and current waveforms of a choked fluorescent lamp are shown in figure 8, the current waveform is almost in phase with the voltage waveform which depicts the linearity of the current as compared to LED and CFL bulbs. In figure 9, the harmonic spectrum shows a very small distortion as displayed by less than 10% 3rd harmonics.

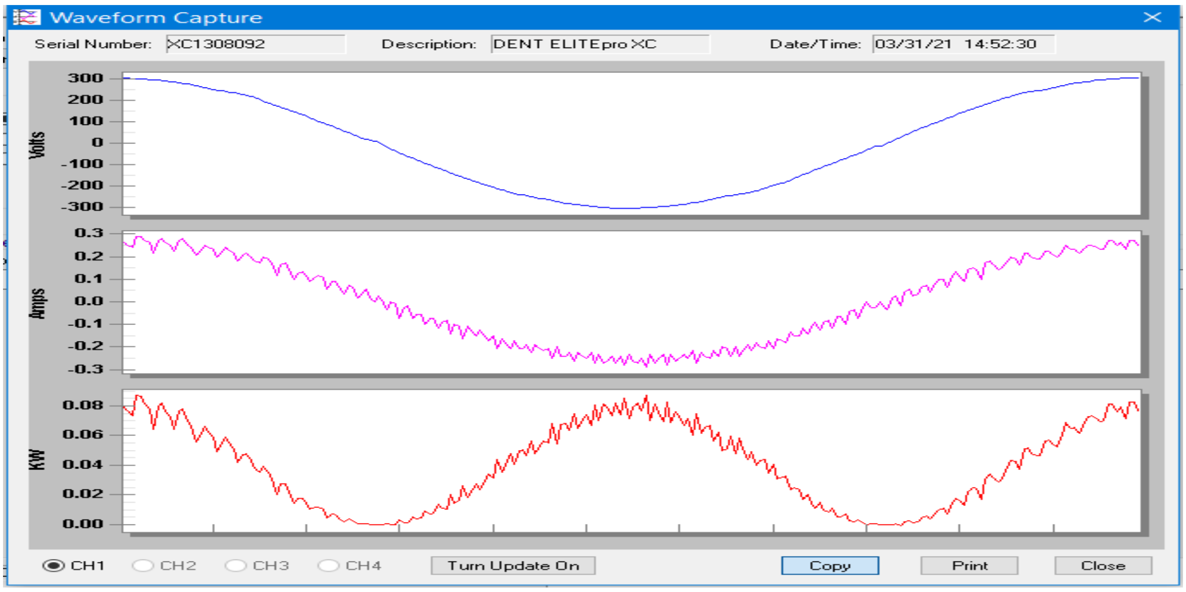

Figure 10: Voltage, Current and Active Power Waveforms of 36W_FL

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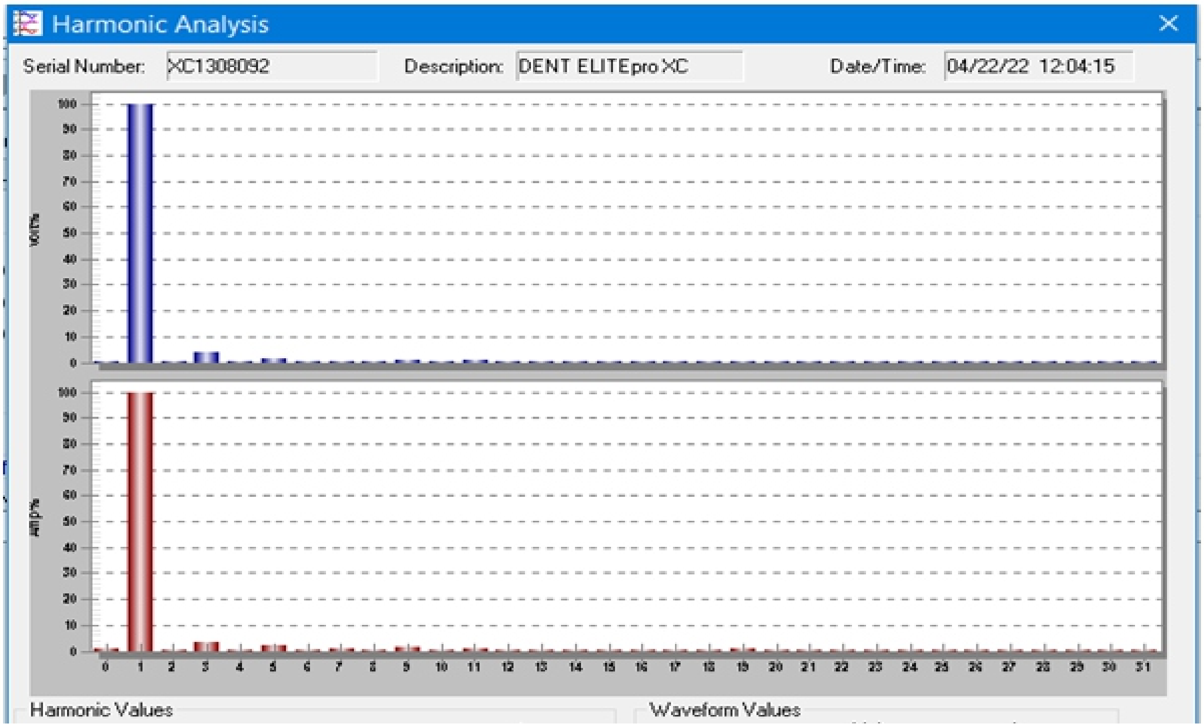

Figure 11: Voltage and Current Harmonics Spectrum of 60W_Filament Lamp

Filament Bulb: As in this bulb, because of its pure resistive in nature, harmonics in this type of bulb is minimum which is close to zero. The unity power factor of these lamps also indicates its zero harmonics. The waveform in figure 10 also depicts that only system frequency is present.

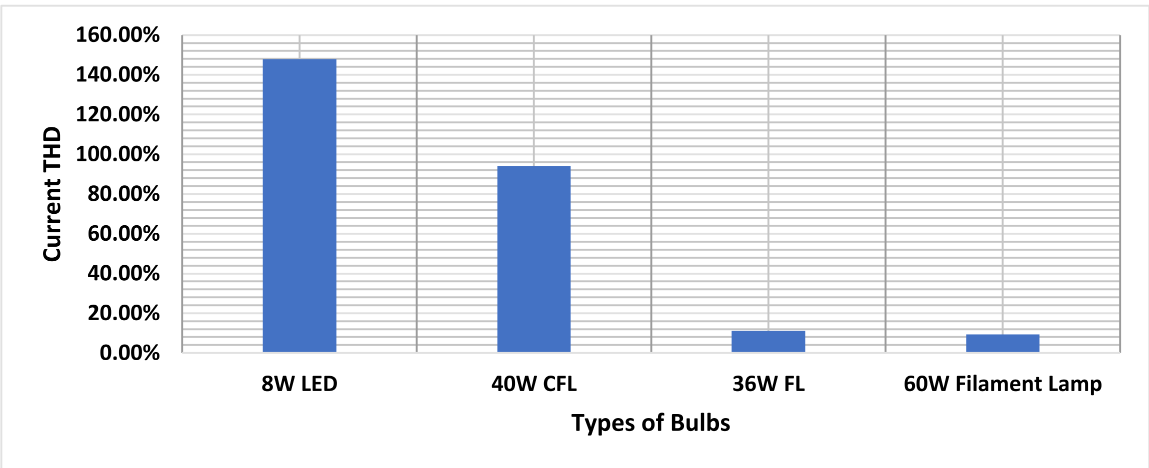

Figure 12: THDs of the Electric Bulbs

THDs: Figure 12 shows the Current THD of LED, CFL, FL and Filament bulb in which LED and CFL have high harmonic distortions of 145% and 92% respectively as shown in figures 4-7. While fluorescent and filament bulbs have little or no distortion which have no dangerous effect on the distribution networks.

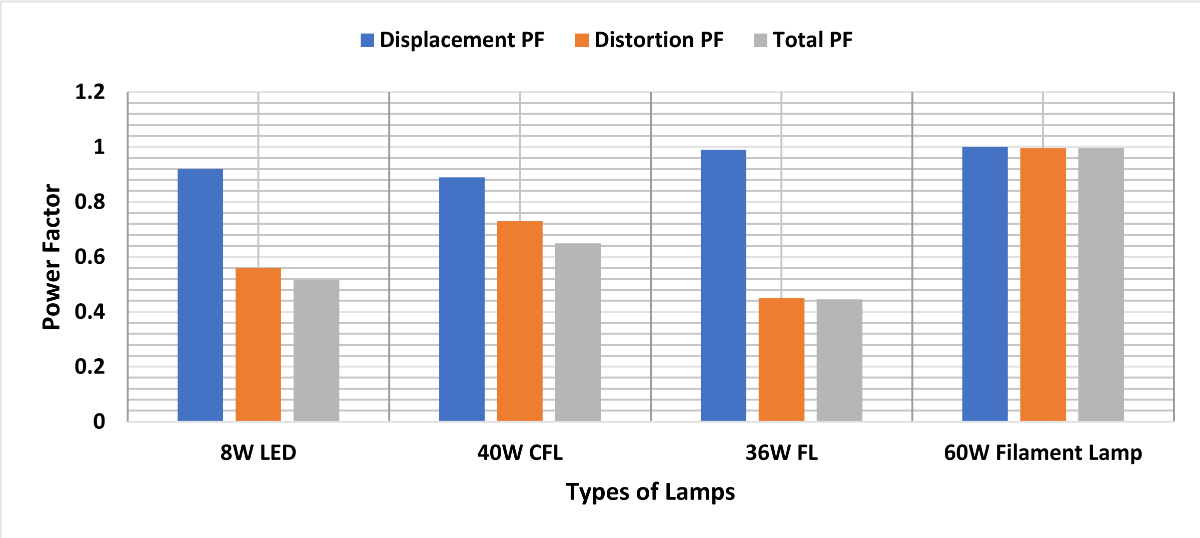

Figure : Power Factor of the bulbs

Power Factor: Figure 13 shows the relationship between the displacement power factor, distortion power factor and the true power factor. In power system analysis, the displacement power factor is the same with true power factor under pure sinusoidal waveforms of voltage and current. As shown in the figure 13, filament lamp maintained that principle but differs in other three bulbs due to harmonic distortions.

5. CONCLUSION

Based on the literature reviewed and experimental measurements of some electric bulbs, commonly used in residential and commercial electrical installation, and the results obtained using a Power logger, it has been shown that energy saving bulbs such as LED and CFL are harmonics injecting loads which affects the overall power quality of the system. These loads are mostly used in the distribution networks feeding residential and commercial sectors as applicable in most of the distribution companies in Nigeria. Hence, there is a need for the distribution companies to monitor and assess the recent power quality issues due to the proliferation of nonlinear loads resulted from energy efficiency measures. In other to improve the power quality and reduce losses in our distribution networks, it therefore recommended that Distribution Companies should ensure adequate and regular power quality assessment of their networks through collaboration with Academic Institutions and there should be proper awareness on power quality issues affecting the distribution networks with proper assessment to be done on electrical installations before adding more energy efficient loads to avoid dangerous pollution of the entire network.

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