EFFECTS OF REPLACING INCANDESCENT BULB WITH COMPACT FLUORESCENT LAMP (CFL) IN ELECTRIC POWER SYSTEM

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ABSTRACT

The clamour to replace the high wattage linear load with energy saving non-linear loads is on the increase. However, side effect of such replacement needs thorough analysis before the full implementation. This study presented the effect of replacing incandescent bulbs with compact fluorescent lamp on harmonic distortion in a model building estimated to require 28 incandescent lamps for lighting. All the incandescent lamps were first switched on and set of readings taken with the waveform. Two of the lamps were replaced with compact fluorescent lamp (CFL) and measurement repeated. The process was repeated until only CFLs were now left to obtain fifteen set of readings. Parameters measured include total harmonic distortion (THD), crest factor, root means square and peak values of both voltage and current. The equipment used was power and harmonic analyzer. The result showed that the THD and CF increased from 1.5% and 1.412 with only linear loads to 100% and 3.045 with only CFL respectively. The waveforms from analyzer's screen show a highly distorted waveform with only CFLs. The various stakeholders in power industries need this information for proper planning and policy to regulate the influx of CFLs and other non-linear devices and to mitigate their impacts in the existing weak electric power system.

Keywords: Lamp, harmonic, distortion, incandescent, fluorescent, loads.

INTRODUCTION

Globally, policy to phase out incandescent light bulb for general lighting in favour of highly efficient CFL is in the increase with Nigeria not an exemption. One of the factors responsible for this is because the world is becoming more concern on preventing global warming and thus many countries are seriously looking into becoming green in their day to day operation, so as to reduce emissions that are poisonous to the environment (Schneider, 2008)

Traditionally, incandescent light bulbs which consist of an air-tight glass enclosure through which an electric current is passed have been commonly used due to certain advantages they possess. For instance, they require no external regulating equipment with low manufacturing costs, and work equally well on either alternating current or direct current. As a result, the incandescent lamp is widely used in household and commercial lighting in Nigeria which is classified among low income earner countries (World Bank, 2015).. However, their disadvantages are outweighing these advantages. The poorly inefficient incandescent bulbs convert less than 10% of the energy they use into visible light with the remaining energy being converted into heat. Also, the luminous efficacy of a typical incandescent bulb is 16 lumens per watt. Incandescent bulbs typically have short lifetimes compared with other types of lighting; around 1,000 hours for home light bulbs.

On the other hands, the Compact Fluorescent Lamps (CFLs), also called compact fluorescent light, energy-saving light, and compact fluorescent tube, is a fluorescent tube which is curved or folded to fit into the space of an incandescent bulb, with compact electronic ballast in the base of the lamp. Compared to general-service incandescent lamps giving the same amount of visible light, CFLs use one-fifth to one-third the electric power, and last eight to fifteen times longer. Though, its wide acceptability in Nigeria is presently being hampered by high initial cost, it is definitely one of the lamps for the future as the overall cost during its life time is far less than the incandescent lamp. Typically, CFL has 10,000 hours life time and 60 lm/W of luminous efficiency.

The growing needs of nonlinear devices therefore necessitate the evaluation of the level of harmonic distortion in a typical distribution feeder (Bogale, 2015). Also, as technology to combat power crisis is increasing, other issues such as grid overloads, power quality problems, technical and non-technical losses may arise with the penetration of distributed generation, electric vehicles and different lighting devices. The power quality disturbance levels created by the equipment require a careful analysis to maintain electromagnetic compatibility (Watson *et al, 2014*). IEEE standard 519-2014 stated that harmonic voltage distortion limits are provided to reduce the potential negative effects on the users and system equipment.

The harmonic interaction between CFLs and the electrical network depends on the quantity of their harmonic current injections, the structure of the electrical network as well as the presence of other loads connected to the system (Wei, 2009). One of the main reasons why much attention has not been paid to non-linear loads is because of their small power rating which is their main advantage. However, their large concentration on any network will become significant. Witherden (2012) estimated that with an average rating of 20W, 30,000 residential customers using a few CFLs per house are able to create a total load of 3MW, which could be sufficient to cause unacceptable VTHD along the feeders. It is estimated that power electronic loads are now responsible for around 30% of the total demand in the Indian residential load sector with expected future rise (Rao et al, n.d). CFLs are generally characterized by their harmonic emission levels, as their current waveform drawn vary greatly with their circuit design. The level of emission from nonlinear devices is also a function so the design by the manufacturers (EPECentre, 2009). A low power factor CFL gives a highly distorted waveform while high power factor gives a low distortion. However, because the former is cheap, it is commonly used in Nigeria. Harmonics are steady state period that produce continuous distortion of voltage and current waveforms (Grady, 2012). For a particular distribution network, the maximum tolerable level of CFLs is dependent on both the topology of the CFL circuit, and system background voltage distortion (partly caused by other non-linear loads connected to the feeders and also the system strength). A study in New Zealand distribution system revealed V_{THD} varied from 0.75% to 3.5% on the LV feeders (Witherden, 2012). However, this work used fixed harmonic current source approach, which is usually not the case when many CFLs are connected to the network and consequently determine the effects of replacing incandescent bulb with compact fluorescent lamp (cfl) in the electric power system.

Theory

Crest factor is the result of interaction between source and loads and it is important to consider it along with THD in harmonically dominated environment due to the presence of many non-linear loads. Like power factor, it is a ratio that relates one quantity to another. They can also be used to relate the general "effectiveness" of a signal. Since it relates the peak value of a signal to its root mean square value, it is a measure of the "purity" of a signal and the capability for a system to output a particular voltage or current.

Electrical quantities such as currents and voltages with rms values are needed in order to characterize energy properties of non-sinusoidal circuits and also to determine the optimum values (Pasko and Maciazek, 2012). Harmonic distortion in the power network is one of the major power quality issues because of the non-linearity of the power electronics devices. Relatedto harmonic distortion is crest factor which is determined by the peak and rms values. In a sinusoidal system, the rms current and voltage are related to the peak current and voltage by the equations 1 and 2 respectively.

$$I_{RMS} = \frac{I_P}{\sqrt{2}} \quad \text{--1}$$

Peak to Peak is 2×Peak value

$$V_{RMS} = \frac{V_P}{\sqrt{2}} \quad \text{--2}$$

The crest factor and the peak currents of a load are important considerations in power source selection.Peak currents are also important in calculating the voltage drop across conductor to minimize voltage drops.

Crest factor is a measure of a wave for, such as alternating current, showing the ratio of peak values to the effective value, that is, the RMS values. Crest factor indicates how extreme the peaks are in a waveform. It describes the ability of an AC power source to generate current or voltage at a particular level.
Crest factor is defined as the ratio of peak value to rms value of a current waveform given by equation 3 as:

$$CF = \frac{Peak\_value}{RMS\_value} \quad \text{-------------------------------3}$$

The crest factor for a sinusoidal current waveform, such as that a resistive load would draw 1.414 since peak of a true sinusoid is 1.414 times the rms value. However, the crest factor for a non-sinusoidal current waveform can differ dramatically for loads that are not power factor corrected, such as a switching power supply or lamp ballast, which give a current waveform that is short in duration but high in amplitude. The crest factor rating is an indication of number of times rated current that the power source can handle for a short period of time.

The presence of harmonics implies that current and voltage are distorted and deviate from sinusoidal waveforms. Through Fourier analysis, any non-sinusoidal periodic waveform can be represented as the sum of a DC component and sine waves of various amplitudes and phase displacement from some relative angle (Tolberth *et al, 1996).*
The Fourier series for a distorted wave is given by equation 4:

$$V_{(t)} = V_o + V_h \sin(hwt + \theta_h) \text{ ----------------4}$$

Where $V_{(t)}$ is the voltage V_0 which is the DC voltage V_h which is the harmonic voltage, w is the frequency and θ_h is the phase angle at the harmonic frequency.

The total harmonic distortion, or THD, of a signal is a measure of the harmonic distortion present and is defined as the ratio of the sum of the powers of all harmonic components to the powers of all harmonic components to the power of the fundamental frequency. THD is used to characterize the power quality of an electric power system. It is an important figure of merit used to quantify the level of harmonics in voltage or current waveforms (Schmilovits, 2005). IEEE 519 harmonic standard limits overall voltage distortion to 5% THD at PCC and maximum single harmonic 3% of fundamental. Generally, for any waveform given by equation 5 expressed by Farooq (2105):

$$(\%)\text{THD} = \frac{\sqrt{\sum_{h=2}^{\infty} M_h^2}}{M_1} \text{ --------------------------------5}$$

Where M_h and M_1 represent harmonic and fundamental quantities respectively.

Most often the percentage symbol (%) are omitted in the equation and only expressed in the unit. Thus for voltage (equation 6), we have:

$$V_{THD} = \frac{1}{V_1}\sqrt{\sum_{h=2}^{\infty} V_h^2} \text{ ------------------------------6}$$

Similar expression for current is given by equation 7

$$I_{THD} = \frac{1}{I_1}\sqrt{\sum_{h=2}^{\infty} I_h^2} \text{ ----------------------------------7}$$

The V_{rms} may also be expressed as equation 8 and 9 (Eduful et al, 2014):

$$V_{rms} = \sqrt{\sum_{h=1}^{\infty} V_{1rms}^2} \text{ ----------------------------------8}$$

$$V_{rms} = V_{1rms}\sqrt{1 + THD_V^2} \text{ -------------------------9}$$

EXPERIMENTAL PROCEDURE

The study was carried out on model five bedroom lightning units with initial incandescent bulbs as lamps and later replaced with CFLs. For the purpose of this study, it is assumed that the CFLs are the only non-linear devices used in this building. Based on the manufacturer's information, the brand of CFL used was Brito bulbs with integrated ballast of 26W rating and consume minimal level of mercury not more than 4mg. They have rated life of 8000hrs, luminous flux of 1300lumens and a lamp efficacy of 50lm/W which indicates the measure of energy efficiency for lamps. The energy consumption of Brito bulbs is 43kWh/yr, it is a spiral bulbs with 80% energy saving. It has high power factor and produces soft light with no flashing. Trend incandescent bulbs were used and have an input power of 60W, and voltage ratings of 240V. Brito CFLs bulbs were manufacture in China while Trend incandescent bulbs were manufacture in United Kingdom.

About 28 fixtures were estimated to supply the required lighting for the building. Based on this, a prototype lighting model was built in the laboratory for experimental purpose as shown in fig 2. At the beginning of the experiment, all the 28 incandescent bulbs were installed without any CFL. Readings were taken and waveform recorded. This first reading is taken as *N=1*. Thereafter, two of the bulbs were removed and replaced by CFLs and readings were also noted as *N=2*. This replacement continued in that sequence until only CFL was left in the circuit with *N=15.* The equipment used was power and harmonic analyzer with the model DW6095. It has capability of measuring up to 24 parameters. The readings obtained were tabulated and plotted on graphs.

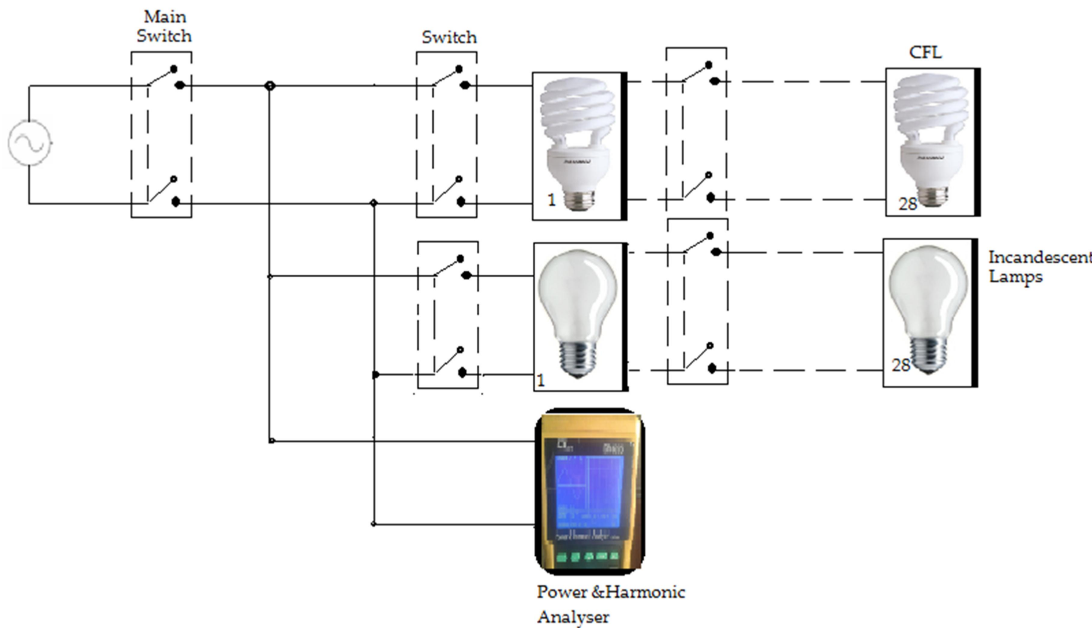


Fig. 1: Model for the experimental set-up

RESULT AND DISCUSSION

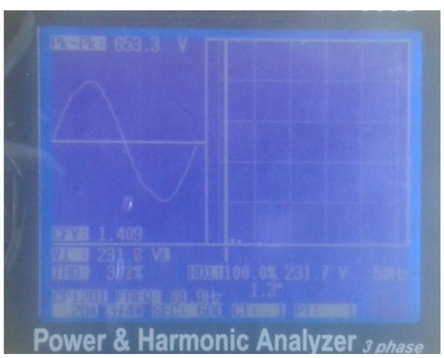
Plates 2-5 show the stages involved with the two lamps

a)  b) 

Plate 2: Experimental set up with 28 incandescent bulbs and CFL without supply

a)  b) 

Plate 3.: Experimental set up with mixture of Incandescent bulb and CFL with supply

a) 

b) 

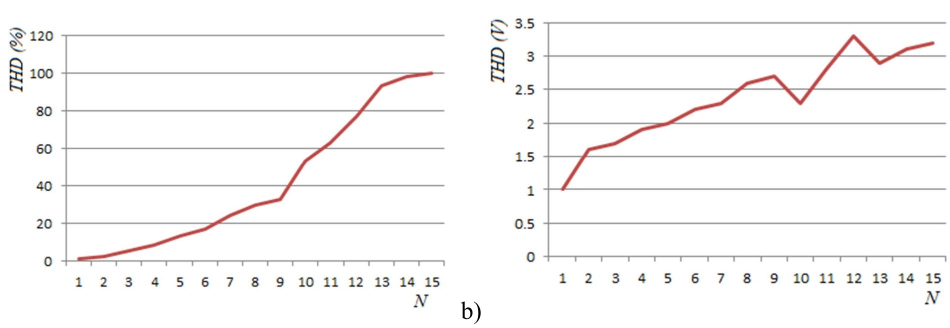
Plate 4: waveform for 28 incandescent bulbs and 28 CFLs and spectrum

Table 1: Current & Power Readings

No. of Readings	No. of Lamps for Inc. Bulb	No. of Lamps for CFL	Ipp (A)	Measured Crest Factor	Measured THD (%)	Measured I (A)	Estimated P(W)	Estimated Irms (A)
1	28	0	21.27	1.410	1.5	7.540	1680	7.304
2	26	2	26.73	1.443	2.6	7.181	1612	7.008
3	24	4	20.65	1.509	5.5	6.842	1544	6.713
4	22	6	20.77	1.649	8.7	6.400	1476	6.417
5	20	8	21.36	1.738	13.1	6.146	1408	6.121
6	18	10	22.06	1.892	17.2	5.829	1340	5.826
7	16	12	23.10	2.167	24.1	5.331	1272	5.530
8	14	14	23.14	2.291	29.5	5.050	1224	5.321
9	12	16	23.76	2.480	32.5	4.281	1136	4.939
10	10	18	23.79	2.621	53.1	4.538	1068	4.643
11	8	20	23.61	2.740	63.09	4.309	1000	4.347
12	6	22	23.53	2.839	76.8	4.144	932	4.052
13	4	24	23.64	2.998	92.9	3.975	864	3.756
14	2	26	24.23	2.998	98.1	4.100	796	3.640
15	0	28	23.72	3.045	100	3.894	728	3.165

Table 2: Voltage Readings

No. of Readings	No. of Lamps for Inc. Bulb	No. of Lamps for CFL	Vpp (V)	CFV (units)	THD (%)	Voltage (V)
1	28	0	632.2	1.407	1.0	224.5
2	26	2	632.2	1.406	1.6	224.6
3	24	4	635.3	1.407	1.7	225.6
4	22	6	636.0	1.410	1.9	225.5
5	20	8	639.7	1.411	2.0	226.7
6	18	10	642.2	1.409	2.2	227.8
7	16	12	642.5	1.410	2.3	227.9
8	14	14	643.2	1.412	2.6	227.6
9	12	16	643.5	1.408	2.7	228.3
10	10	18	645.9	1.411	2.3	228.6
11	8	20	645.7	1.409	2.8	229.0
12	6	22	651.3	1.412	3.3	230.6
13	4	24	653.7	1.412	2.9	231.3
14	2	26	654.5	1.411	3.1	231.8
15	0	28	653.3	1.409	3.2	231.9



a) b)

Fig.5:Measured a) Current THD b) Voltage THD

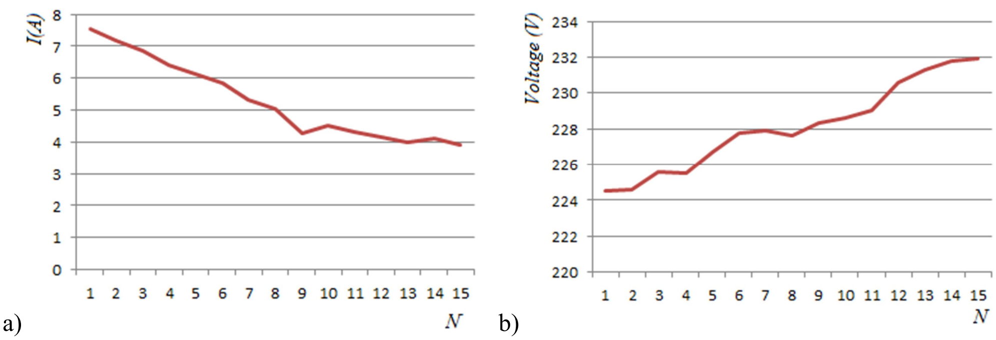


Fig.6:Current Consumption b) Voltage supply

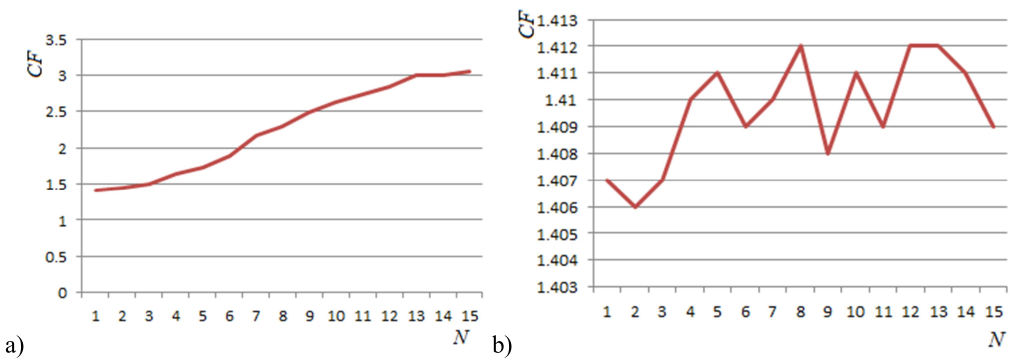


Fig. 7:Crest factora) Current b) Voltage

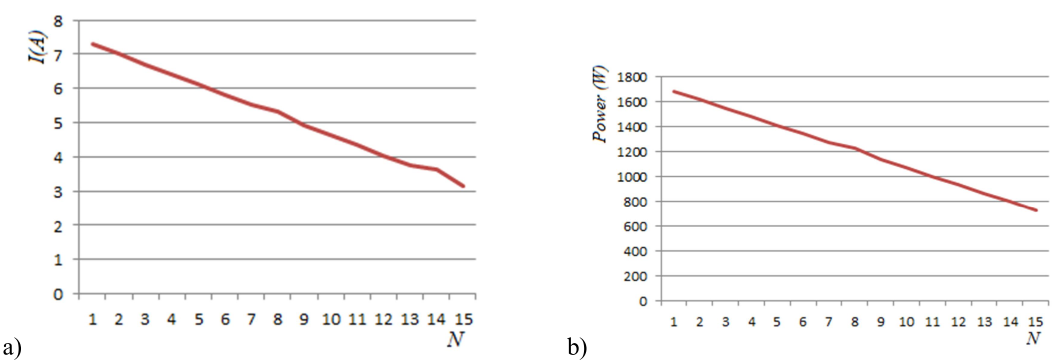


Fig.8: Estimated a) Current consumption and b) Power Consumption Pattern

Discussion

The screen shots (plates 4) show a relatively pure undistorted waveform from the incandescent bulbs and a highly distorted waveform from the CFL respectively with their frequency spectrums.

The graphs show increase in distortion (THD) both for current and voltage at each measuring point as the number of CFLs increased and the consequent reduction in number of incandescent bulbs. Theoretically, the total power reduced from 1680W to 728W (about 60% reductions) and current also reduced from 7.304A to 3.165A as expected. However, the THD measured increased from 1.5% to 100% and crest factor from 1.410 to 3.045 as a result of transition from linear to non-linear loads. The voltage distortion also increased from 1.0% to 3.2 %. The recommended value of 3.0% limit by IEEE 519 2014 on individual loads had been exceeded by replacing all the loads. To remain below the stipulated standard, the loads combination was at 4 numbers of incandescent lamps and 24 CFLs. Load monitoring may be used to know the optimum combination of non-linear loads.

Generally, high linear loads tend to damp distortion effect of non-linear loads in a load mix. Also, there is possibility of harmonic cancellation due to the presence of other non-linear loads in a real building. However, as more non-linear loads are added, the effects of distortion will be more pronounced. It is obvious that current distortion and crest factor for current are more pronounced than voltage distortion due to stiff network.

CONCLUSION

The result revealed that though there were reductions in loads due to the replacement, the distortion effect was higher than the stipulated standard. High harmonic distortion can affect transformer and neutral conductor of three phase network supplying such parts of the network. End users should be properly educated on the usage of non-linear loads while as a matter of urgency there should be policy and regulation in place to mitigate the negative impact of non-linear loads.

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