



## Modeling and Simulation of Compact Fluorescent and Light Emitting Diode Lamps for Harmonics Analysis

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### ABSTRACT

*This work presents the modelling and simulation of compact fluorescent lamp and Light emitting diodes fittings for the analysis of harmonics introduced into power distribution network. The THD was determined using a simplified Fast Fourier transform (FFT) harmonics analysis algorithm in the simulation package. A laboratory test was conducted to validate the simulation results of the CFL and LED fittings using Linear Technology spice (LTspice) software package. For the waveforms acquired with the Fluke 435, the CFL was observed to have Total Harmonic Distortion (THD) in current waveform up to 90.4% in comparison to LED of 21%. In the LT spice, the results showed that 130.2% and 32.2% were obtained for CFL THD in the current and voltage waveforms respectively. The laboratory test results thus validated the accuracy of simulation to about 56%. It also revealed that the CFL produced more distortion than LED. However, the voltage THD lies within the IEEE 519-2014 recommendation of 8% for the both devices in the actual lighting devices. Nonetheless, suitable methods of harmonic mitigating might be continued as improved production processes to prevent the excessive harmonic injection into the distribution network.*

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### INTRODUCTION

The nonlinearity exhibited by many industrial and commercial loads has considerably increased due to the application of emerging power electronic devices in electrical power distribution network. There are power converters driven large wind or PV plants [1], the Compact fluorescent lamps providing significant energy savings [2, 3], the microcontrollers based real time pricing [4] and the effective light dimmer designs and applications [5, 6] which have been introduced as new trends in the grid structure for smarter power systems. From the viewpoint of the electric utility industry, it is important to understand the impacts of such devices on distribution network.

In this paper, CFLs and other associated discharged lighting loads are singled out for a critical assessment. This is because CFLs create harmonics including supraharmonics [7] and the magnitudes of harmonics generated vary significantly between manufacturers and control systems adopted in the design of plasma current that kindles the light [3]. Consequently the replacement of incandescent lamps with fluorescent or LED lamps in its entirety needs a proper assessment for the integrity of power systems at the utilization side.

Power system harmonic is defined as a sinusoidal component of a periodic wave having a frequency that is an integral multiple of the power

system fundamental frequency[8]. Harmonic currents create voltage distortion as they pass through the impedance of a power system. A high impedance system can create very high voltage distortion. The basic challenge rising in the mass usage of switching electronic devices is the problem with the network voltage distortion which must be kept 8% for voltage level up to 10 kV [9].

Lighting loads account for roughly 20% of the electricity consumption all over the world [10, 11]. Compact fluorescent lamps (CFLs) provide significant energy saving over incandescent lighting (IL). To promote energy saving, many utilities in the world are promoting the use of CFLs as part of their energy conservation programme. More importantly, many governments in the world have introduced laws to ban these energy inefficient Incandescent Light (IL) bulbs in distribution networks [12]. Thus, CFLs are increasingly being used for residential and commercial applications as well as the retrofit of a large number of IL and other lighting devices.

On personal investigation during a research work, it was observed that many power consumers in the urban areas in Nigeria have replaced the IL with either the CFLs or associated electronic lighting loads. Unfortunately, power quality issues associated with CFLs cannot be ignored as the number of these lamps on the system has increased and the according to [10]

there is a great diversity with penetration level. The situation is unlikely to change in the near future as large numbers of CFLs penetrate the market place and as a result harmonic emissions may have to be restricted [13, 14]. On the technical aspect, this would require implementation of harmonic mitigation techniques of different forms such as passive and active filters for the circuitry of these energy savers. It has been established that one of major disadvantages of CFL is that it will increase the level of disturbances that might invariably affect consumers as well as utility equipment on the distribution system [15]. It emits and injects harmonics into the power distribution network. On the economic aspect, there is need to guarantee consumers' trust on emerging lighting loads on one hand, as there could be direct relationship between consumers' perception and manufacturers' assurance of subverted, fake or counterfeit products. Accordingly, it might become imperative to invigorate techno-economic assessment of different types of CFLs or LEDs available in the market as in [16-21] to enhance secure and clear assurance of consumers.

Compact fluorescent lights, like all discharge lights, create harmonics on the supply system because of the control systems limiting the plasma (an electric arc) current, which produce light. These harmonic currents are then injected into the distribution system. Because most electrical systems are designed for linear voltage and current waveforms (i.e. nearly sinusoidal), excessive nonlinear loads can cause serious problems such as mal-operation of important control and protective equipment, overheating of conductors and transformers, capacitor failures, and overloading of other power apparatus, as well as mal-function of sensitive electronic equipment used in hospitals. However, it could be established that the magnitudes of harmonics generated by the CFLs vary between manufacturers and between ranges of lamps from the suppliers. Consequently, the purpose of this paper is the modeling and simulation of compact fluorescent and LED lamps for harmonics analysis in power distribution network.

## METHODOLOGY

### Theoretical Background

Although, harmonic study was conducted in this paper and achieved using the LT Spice simulation package and a 3 phase power quality analyzer (Fluke 435), the theoretical basis of CFL and LEDs as well as analyses are necessary. It will provide a review of circuit conditions that contributed to the harmonics generation in the lamps.

Consider a voltage source half bridge resonant inverter shown in Figure 1(a) comprises of two power switches (static type), a resonant tank which may be series loaded resonant (SLR), a parallel loaded resonant (PLR) or a hybrid series-parallel loaded resonant (SPLR) and resistivity load having a negative temperature coefficient (NTC). Depending on the inverter topology (half-wave, push-pull, Class E LCC or current source), control strategy adopted and the resonant circuit selected, the CFL can be developed to have distinctive merits for improved lamp size or robust efficiency. The waveform of voltage and current are provided in Figure 1(b) which relies on zero voltage switching (ZVS) for a typical power switch,  $S_2$  changing from OFF to ON as depicted.

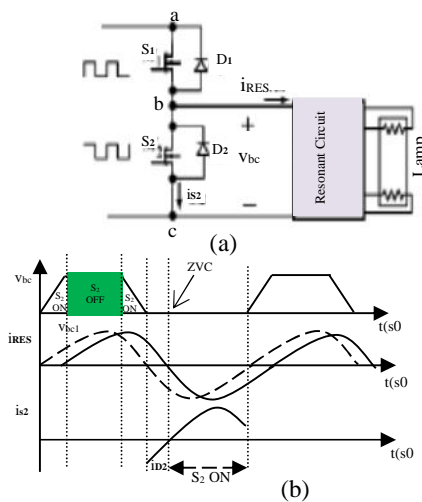


Figure 1: Schematic Diagram and Waveforms of a CFL

The resonant conditions are set using Eqns. (1) and (2) for series and parallel circuit quality factors respectively.

$$Q_s = \frac{2ff_0L_r}{R_{lamp}} \quad (1)$$

$$Q_p = \frac{R_{lamp}}{2ff_0L_r} \quad (2)$$

Where:  $L_r$  is inductor in Henry,  $R_{lamp}$  is the lamp resistance in ohms and  $f$  in Hertz is the resonant frequency given by Eqn. (3).

$$f_0 = \frac{1}{2f\sqrt{L_rC_r}} \quad (3)$$

### LT Spice Design of CFL

The circuit diagram of real CFL 15W half spiral, white in color, screw type CFL based on the research in the Ref.[22] has been implemented in LT Spice. The LT Spice schematic is shown in Figure 2.

A Cursory look in the circuit diagram will

reveal that the values of each of the elements/components of the CFL were indicated in Figure 2. The required input voltage of the circuit was injected into the circuit model and then the subsequent simulations of the circuit replicated on LT Spice. With the help of virtual probe, current and voltage waveforms were obtained with the probe placed at points A1, A2, A3 and A4 (as indicated with arrows) on the designed CFL circuit. The Simulation time was 25 ms at simulation speed between 22 and 37  $\mu\text{s/s}$ .

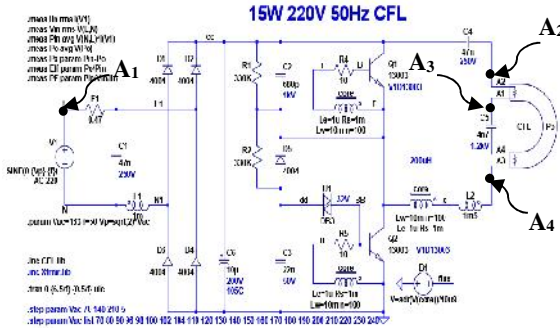


Figure 2: CFL Circuit diagram in LT Spice

### LT Spice Design of LED Lamp

The LEDs designed in the simulation platform is shown in Figure 3 as a series parallel network of diodes. The LEDs are arranged in series to improve the circuit voltage level and the parallel connection will boost the current capability.

The results of the circuit simulations are presented in the subsequent subsections while the experimental rig is shown in Plate 1. Plate 1 comprises of Fluke 435 and CFLs and LEDs lighting lamps as labeled.

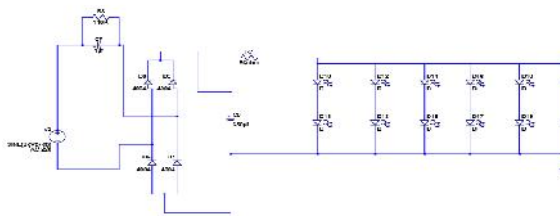


Figure 3: LED Lamp Circuit Diagram

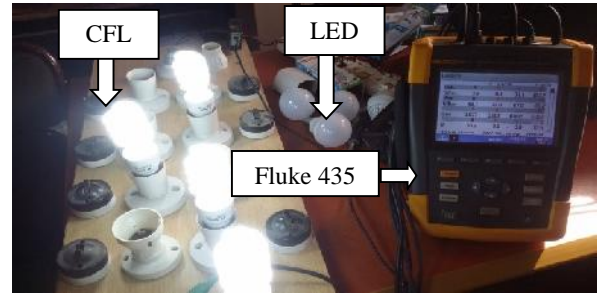


Plate I: Experimental setup

The specifications of the lamps are tabulated in Table 1.

Table 1. Specifications of the Lamps

Trade mark	Type of Lamp	Nominal Power (W)	Life Span (hours)
FD Royal	CFL	20	8000
Rosy Light	LED	5	4380

## RESULTS AND DISCUSSION

### CFL Waveforms in LT Spice

The output voltage waveform at point A1 on Figure 2, selected for presentation out of the other three points, gives distorted waveform at the mains with the period of 20 ms. The waveforms of CFL in the LT Spice based on the circuit designs shown in Figure 2 are therefore shown in Figures 4, 6 and 8. Figure 4 represents the mains voltage and as expected the distortion level is low. The waveform is nearly sinusoidal but the FFT plot shown in Figure 5 indicated that at higher frequencies from 400 Hz to 700Hz, power spectrum changes very rapidly from 0.01 W and 0.0001 W and phase angle drift to positive. Figure 6 gives high distortion current waveform appearing as spike which is evidently portrayed in FFT having significant voltage magnitude of a least 0.05 V at 100 Hz, 180 Hz and 250 Hz (Figure 7). Figure 8 superimposes voltage with current waveforms.

The waveform was later fitted into the Fourier series modeling framework. This framework is given in Equations (4) to (8).

$$v(t) = \frac{1}{2} a_0 + \sum_{n=1}^{\infty} (a_n \cos(n\omega_0 t) + b_n \sin(n\omega_0 t)) \quad (4)$$

$$v(t) = c_0 + \sum_{n=1}^{\infty} c_n \sin(n\omega_0 t + \phi_n) \quad (5)$$

Where:  $c_0$  is the dc value of the function,  $c_n$  is the peak value of  $n^{\text{th}}$  harmonic component which are expressed by the Eqns.

$$c_0 = \frac{a_0}{2} \quad (6)$$

$$c_n = \sqrt{(a_n^2 + b_n^2)} \quad (7)$$

$$W_h = \tan^{-1}\left(\frac{a_n}{b_n}\right) \quad (8)$$

The plot of  $f(t)$  yields the original distorted waveform which is the basic concerns of the harmonics analysis and bedrock of power quality engineering. Other derivative transforms such as Fast Fourier Transform (FFT), Wavelength Transform (WT), etc are more easily adapted for computer methods.

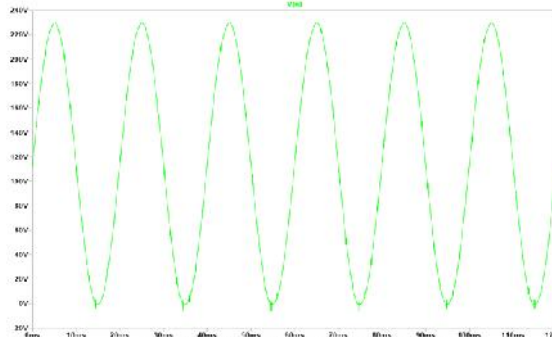


Figure 4: CFL Voltage Waveform (LTSpice)

The waveform of Figure 4 was analyzed to be a cosine function without dc offset and the Equation (4) reduces to Equation (9).

$$v(t) = \sum_{n=1}^{\infty} (v_n \cos(n\omega_0 t)) \quad (9)$$

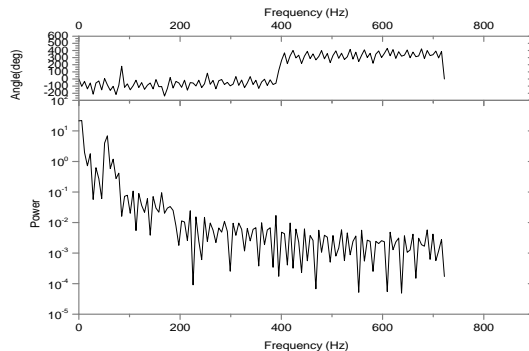


Figure 5. Power Spectrum/Phase Frequency Plot

As shown in the Figure 8, the current waveform is a highly distorted waveform. Unlike the voltage waveform, the current waveform contains DC component. Presence of harmonic is clear on the waveform due to its non-smoothness.

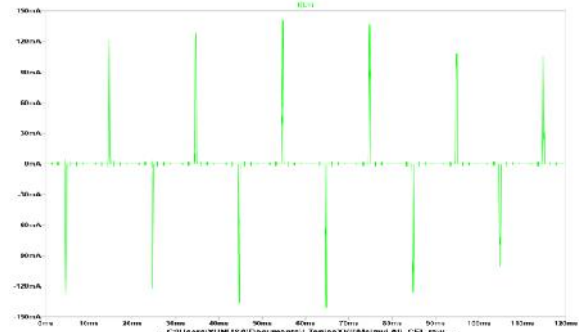


Figure 6: CFL Current Waveform (LTSpice)

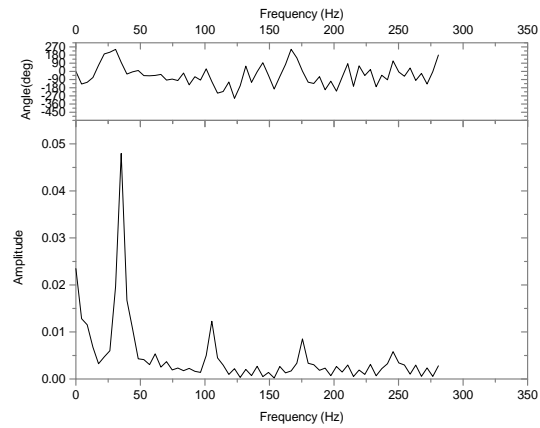


Figure 7: Current Magnitude/phase vs frequency plot

The mathematical functions of the current signal of the waveform, Figure 6, are correlated to Equations (10) and (11).

$$i(t) = i_0 + \sum_{n=1}^{\infty} i_n \sin(n\omega_0 t + \omega_n) \quad (10)$$

$$i(t) = \begin{cases} -6150t + 84.865 & 1.38 \leq t \leq 1.388ms \\ 0 & 1.388 \leq t \leq 1.396ms \\ 1700t + 238.39 & 1.396 \leq t \leq 1.388ms \end{cases} \quad (11)$$



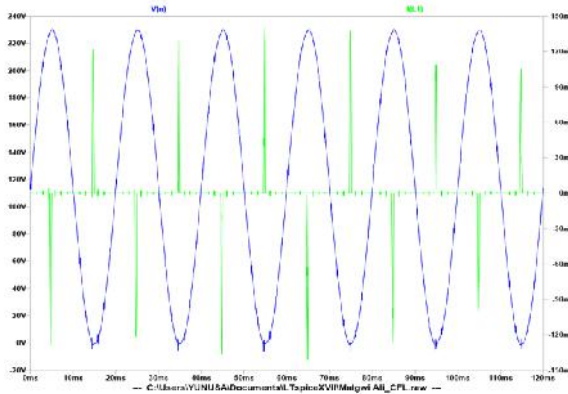


Figure 8: CFL voltage and current waveforms in LTSpice

#### LED Lamps Waveforms in LT Spice

The simulation procedure was repeated for LED lamps and the waveforms are presented in Figures 9 and 10. A cursory examination on the waveforms revealed the superiority of LEDs to CFLs in terms of harmonic distortion. Unlike the CFL current waveform which produces dc offset and spike of current magnitude, the LEDs current waveform is nearly a sinusoidal waveform.

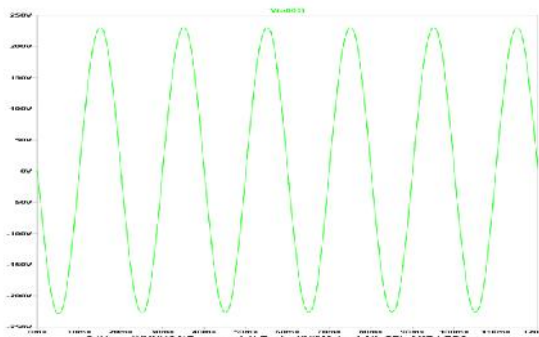


Figure 9: LED Voltage Waveform (LTSpice)

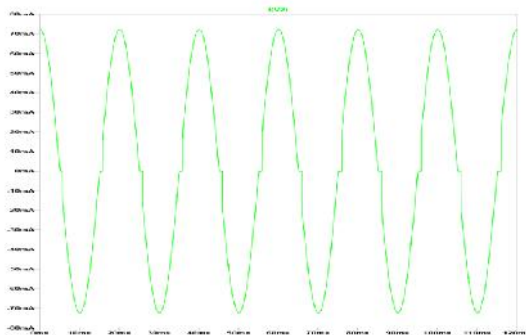


Figure 10: LED Current Waveform (LTSpice)

#### Experimental Waveforms

The distortion level from the LED and CFL are validated with experimental responses as

shown in Figures 11 and 12 respectively.

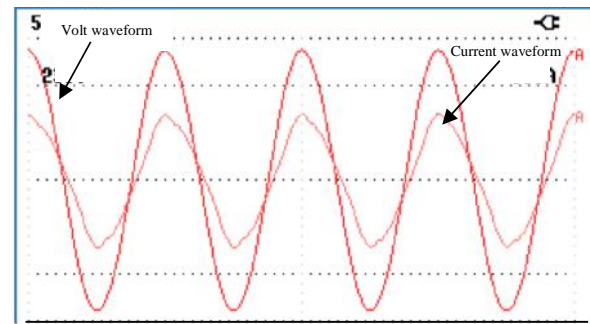


Figure 11: LED Current Waveform (Experimental)

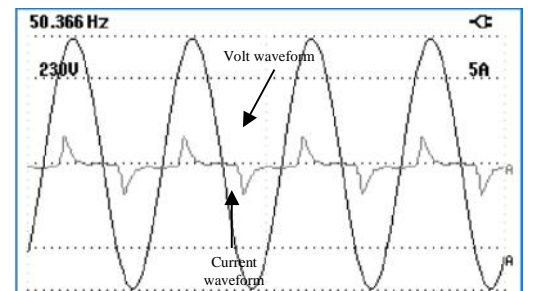


Figure 12: CFL Current and Volt Waveform (Experimental)

The voltage and current THD in the experimental rigs were 0.80% and 87.91% respectively for CFL and the corresponding values of 0.72% and 22.76% for LED which underpins that these values exceed the IEEE 519-2014 maximum current THD limits of 20% but were below the maximum voltage THD limits of 8%.

For the CFL, it was observed that the simulated waveforms of the voltage and current are in  $180^\circ$  phase difference (see Figure 8); depicting a leading capacitive loading which conforms with the open literature [23] while for the experimental waveforms of current and voltage are nearly in-phase.

Similarly, it was apparent that LED current waveform, Figure 10 is not a perfect sinusoid on the simulation pane; there exist some waveform notch and distortion at the zero crossing; a similar phenomenon as reported in Ref. [24]. On the contrary, this was a slight different between the simulated and experimental waveforms of current (Figures 10 and 11). Figure 11 does not portray such zero crossing notch factor even though it has noticeable distortion signature. This anomaly could be attributed to the imperfection in power switching commutation. Again, there is another difference between the simulation and experimental results in term of

phases of the two waveforms (Figures 10 and 11). The simulated current waveform is observed to be nearly 90° phase difference of the simulated voltage waveform. However, in the experimental rig the current and voltage waveforms are in-phase (Figure 11). This could be due to imperfect switching commutation and stray capacitances of the power transistor switches in the virtual environment which may tend to delay or advance the waveform outputs.

## CONCLUSION

From the results obtained it can be concluded that the CFLs and LED lamps connected to a distribution network cause distortion to the supply voltage and increase current distortion level. As lighting accounts to roughly 20% of the electricity consumption all over the world and the need for energy savings on the network, there continues to be significant increase in the level of voltage distortion, which causes disturbances and invariably affects customers as well as utility equipment on the distribution system. Therefore, there is a need to mandate Standard Organization of Nigeria (SON) to certify the integrity of energy saving lamps such as LEDs and CFLs and impound any of such lighting apparatus while encouraging manufacturers to incorporate quality filtering devices to mitigate the harmonics.

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