

Harmonics of CFL and LED lamps – Maximum Penetration Perspective on Power Quality in Distribution Systems

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Abstract— Global energy saving efforts have led to replacement of incandescent lamps with energy-efficient ones like light-emitting diode (LED) and compact fluorescent lamps (CFLs). These lamps, being non-linear loads, have the potential of injecting harmonics into distribution networks. In this paper, harmonics injection of common CFL and LED lamps at a facility point of common coupling is investigated. To gain insight into large scale penetration effects on power quality, field measurement results of popular lamps used in Ghana were replicated in MATLAB/Simulink through simulation. The field results showed that LED lamps exhibit more harmonics compared to CFL lamps. Maximum possible loading on a 100-kVA, 11kV/0.433kV distribution transformer was found to be 24.02% for CFL, 27.14% for LED, and 40.91% for a mixture of the two lamps, respectively, in order not to violate IEEE 519-2014 standard. The influence of other common loads such as ceiling fans on the lamps' harmonics were assessed in the field measurement. The use of ceiling fans with the lamps in the facility reduced the harmonics and improved the power factor of the facility. Since the lamps exist in residential and commercial facilities with other loads, more penetration of energy-saving lamps in the distribution system will have little influence on power quality.

Keywords: Compact fluorescent lamps, light emitting diodes, maximum power loading, total harmonic distortion, point of common coupling

1. Introduction

With an increased awareness of energy conservation, incandescent lamps (ILs) were identified to be wasteful in energy consumption. This led to worldwide governmental policy on prohibition of ILs, giving way to the use of compact fluorescent lamps (CFLs) and light emitting diode (LED) lamps [1]. CFL and LED lamps are noted to be energy-saving, efficient and last longer than ILs. However, the evolution of energy-efficient lamps, particularly, CFL and LED lamps were met with an open rejection on the grounds that their integration into power systems would lead to increase in total harmonic distortion (THD) [2]. These lamps are made from non-linear solid-state devices such as diode rectifiers and are operated on switching techniques [3, 4]. These devices and the switching techniques upon which they are operated are potential sources of harmonics in the power distribution system [5].

Technically, effects of harmonics in power system come through line current and voltage

distortions [6]. Power system harmonic effects include frequent tripping of protective devices, high neutral-to-earth voltages, reading error in energy meters and overheating of transformers, among others [7-9]. In 2017, harmonic currents contributed to over 100% increase in technical losses of distribution transformers in the Electricity Company of Ghana's (ECG's) distribution zones [7]. The system losses resulting from the harmonics threaten the financial sustainability and operational efficiency of utility companies. In ECG operation zone, the cost of energy resulting from the harmonic losses is found to be US\$ 555,098.78 per year [7].

On the harmonics of the lamps, most of the studies reported in the literature investigated the harmonics of the lamps either by taking measurements of their harmonic characteristics in laboratory installation or through experimental setups. The lamps' harmonics were measured at the terminals of the lamps to determine their harmonic injections into the power distribution system. In

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some studies, mathematical models were used to determine the harmonic injections and their effects on power system distribution network [10, 11]. Since the ban of ILs in Ghana, there has been an influx of imported energy-saving lamps into the country with few manufactured locally. There appears to be no details on the power quality of the lamps and no clear control of their power quality [12].

Ghana's power distribution system has been undergoing constant improvements; where long radial 11kV lines routed from district substations are intercepted with 100 – 200kVA transformers to improve the voltage level for consumers to meet the ever-increasing loads [13]. Research results on the harmonics of energy-efficient lamps have shown that the harmonic levels increase with increase in the supply voltage [14, 15]. This, in addition to the evidence of increase in harmonic currents in the Ghana power distribution system [7], calls for an investigation of CFL and LED lamps' harmonics impact on the Ghana power distribution system.

The authors in [16] researched and analyzed harmonic distortion of IL and CFL lamps on residential consumers and reported that there was substantial increase of current harmonic injection into the supply. Matvoz, et.al [17] by simulation developed a model of electricity network and investigated the effect of LED and CFL lamps in connection with other loads. The simulation results revealed that there is a considerable harmonic voltage distortion in the system. Jabbar et al [1] in an experimental investigation found out most CFLs produced about 120% of current harmonic distortion which could significantly affect supply power quality. McLorn et al. [14] studied the non-linear characteristics of CFL and LED lamps notably on how their behavior varies with supply voltage level. Experimental measurement was undertaken in the laboratory. The obtained data from the measurement was used to formulate polynomial load model in a ZIP format which featured active power, reactive power and harmonic current flow behaviors. From the results and discussion, the paper concluded that these CFL and LED lamps have poor harmonic performance and that their proliferation would bring about high technical losses on low voltage networks and high operational cost to utilities.

As stated, most works on the lamps' harmonics investigation were based on taking their harmonics measurement in laboratory installation and others through experimental set-ups by taking the

harmonics measurement at the input terminals of the lamps. To the best of our knowledge, no work has been done to assess the impact of CFL and LED lamps at a facility point of common coupling (PCC). The harmonics of these energy-saving lamps just as any other non-linear loads are recommended to be measured at a supply PCC for the mutual benefit of the user and utility provider. In commercial and residential installations, the lamps are distributed in the facility. It is believed that the lamps' individual harmonics influence could effectually converge at a common point – the PCC.

A measurement at a facility level PCC could possibly reflect the actual influence of the lamps' harmonics into the distribution system than the practice of individual lamp harmonic measurement at the input terminals. Therefore, there is a merit to investigate the harmonic distortion at the PCC since it is associated with the interaction between the utility supply system and the customer facility. This is justified by IEEE 519-2014 standard on Recommended Practices and Requirements for Harmonic Control in Electric Power Systems [18] as well as other standards [19, 20].

The approach by taking measurements at the PCC provides a comprehensive analysis of the distributed nature of the observed disturbance rather than the individual measurements of their harmonics as observed in the literature. Hence, this study proposes to contribute to existing knowledge on harmonics injection of energy-saving lamps by taking field harmonic measurements of the lamps at a facility PCC; use the obtained data to determine by simulation the maximum possible loading of each lamp with reference to IEEE std. 519-2014 voltage total harmonic distortion (THD_v) limit of 8% on Ghana's power distribution system. Assessment by [2, 20] concluded that it is not clear what the growing use of energy efficient lamps has on power quality, and no power quality problems are expected for low penetration level. Therefore, the quest for the determination of maximum possible penetration level could provide perspectives into large scale influence of the lamps' harmonics on power quality of distribution systems.

The rest of the paper is organized as follows. Section 2 presents the methodology for the field measurements of CFL and LED lamps' harmonics in an installation. Simulations to match field measured values and predict maximum possible penetration that will not violate the THD_v limit of

8% is given in section 3. Results and discussions are presented in section 4. Conclusions are given in section 5.

2. Methods used

The IEEE 519-2014 standard recommends measurement of harmonic distortion at the PCC. The PCC is considered as a point in the power system closest to the customer where the utility power provider may tap the supply lines to provide power to another user. In low voltage distribution systems, the PCC is at the low voltage side of the service transformer. Typically, on pole mounted distribution systems for commercial and domestic facilities, the PCC could be the point at which the supply is connected to the customer's facility. An extension of the PCC in this case could be taken at the supply authority energy meter input terminal but not to be considered at the input terminal of an appliance within the building [19]. The essence of these designated points for the PCC, is for either the customer or the utility provider to assess the level of harmonic distortion so as to put in corrective measures in order that high levels of distortion does not affect the power quality of the neighbors on the same line.

In this work, harmonics of CFL and LED lamps were investigated at a facility PCC with HT 9022 power quality (PQ) analyzer. The PQ analyzer was placed at the input area of the energy meter at the facility. Figure 1 shows a picture of actual measurement of the lamps' harmonics. Forty-three CFL and LED lamps each from different manufacturers with power rating between 15W to 26W were acquired from the Ghanaian market. Among the 43 CFL and 43 LED lamps investigated, Focus CFL and Ant Electrical LED lamps were the common ones on the Ghanaian market. A sample of nine Focus CFL lamps were investigated. The following steps were taken:

- 1) after connecting the PQ analyzer at the facility PCC, all other appliances in the installation were switched off
- 2) the nine CFL lamps were connected one after the other progressively into lamp

holders in the facility and their harmonic measurements taken and sent via Bluetooth to a laptop computer

- 3) afterwards, five 80W ceiling fans in the facility were switched on and the harmonic measurement taken and transferred to the laptop computer
- 4) the captured data is then plotted as shown in Fig. 2 for the case of one CFL (A1), nine CFLs (A9) and nine CFLs plus five fans (A9+5Fans) in circuit, respectively.

Similarly, a sample of eight Ant Electrical LED lamps were used to study the harmonic effects of LED lamps at the facility PCC. The following steps were taken:

- 1) after connecting the PQ analyzer at the facility PCC, all other appliances in the facility were switched off
- 2) the eight LED lamps were connected sequentially from one lamp to eight lamps in lamp holders in the facility and their harmonic measurements taken and sent via Bluetooth to a laptop computer
- 3) afterwards, five 80W ceiling fans in the facility were switched on and their harmonic measurement taken and sent via Bluetooth to the laptop computer
- 4) the data is then plotted as shown in Fig. 3 for the case of one LED lamp (M1), eight LED lamps (M8) and eight LED lamps plus five ceiling fans (M8+5Fans) in circuit, respectively.

A similar process was repeated for a combination of CFL and LED lamps. In this case, CFL and LED lamps were loaded in pairs of one up to five in the facility and the measurements taken. Figure 4 shows the current distortion and the supply voltage waveforms of one pair (MA₁) as well as five pairs of lamps (MA₅). The harmonic spectrum of the combined lamps is positioned to the right side of their respective waveforms.



Fig. 1 Field measurement at facility PCC: A – power quality analyzer HT 9022 captures data and sends by Bluetooth to laptop, B– 23W Focus CFL lamps in installation, C – 20W Ant Electrical LED lamps in installation

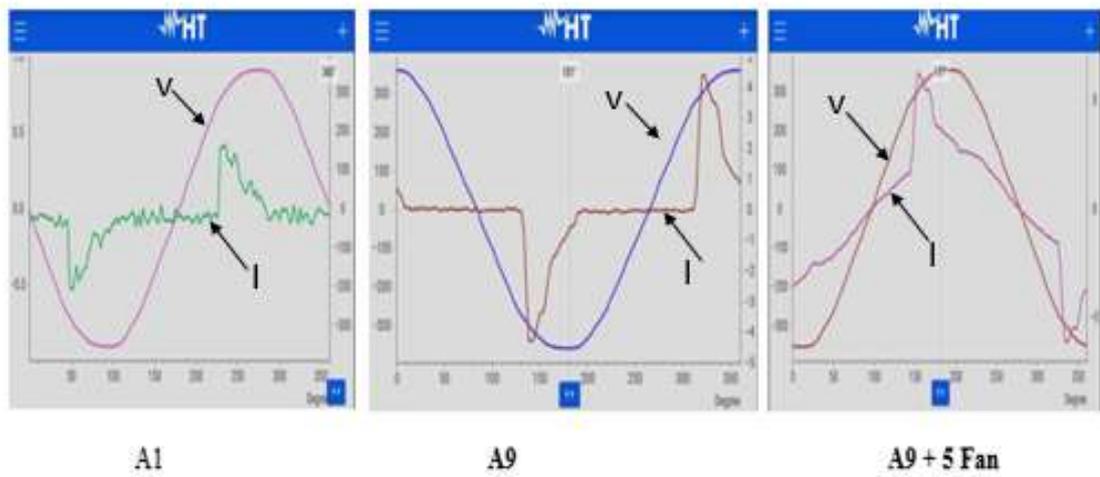


Fig. 2 Voltage and current distortion at facility PCC due to presence of CFL lamps and ceiling fans in circuit

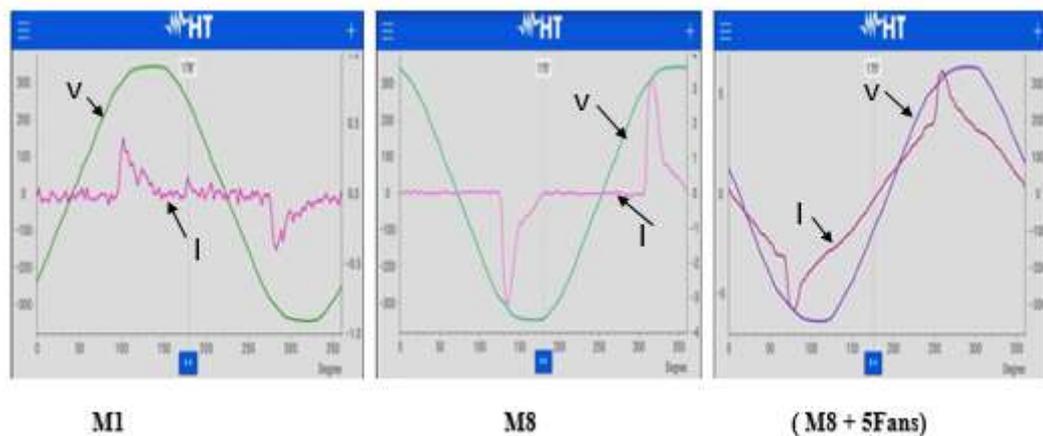


Fig. 3 Voltage and current distortion at facility PCC due to presence of LED lamps and ceiling fans in circuit

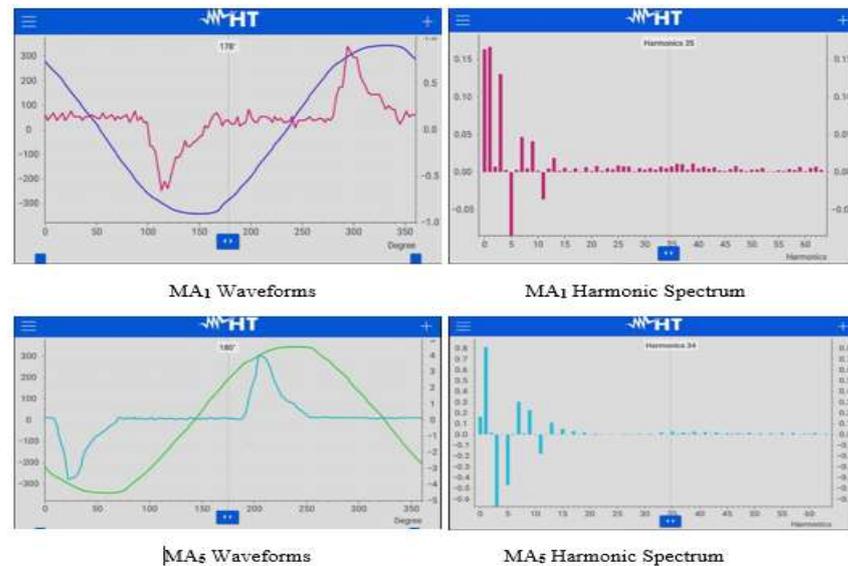


Fig. 4 Harmonic waveforms and spectrum of the mixed lamps (MA₁ – MA₅)

3. Simulations to predict maximum penetration limits

In order to predict the maximum possible penetration of the CFL and LED lamps on a local distribution transformer that will not violate the 8% THD_V limit, simulations were carried out in MATLAB/Simulink. The area power network structure consisted of a 2km, 11kV overhead lines from a nearby district power sub-station. The overhead lines are horizontally laid and equally spaced at 90 cm apart. The overhead line feeds the area 100-kVA pole-mounted transformer (11kV/0.433kV delta/star) which provides the area with 3-phase, 4-wire distribution lines. The 3-phase, 4-wire lines are vertically mounted on pin insulators and spaced equally from each other at a distance of 30cm. The distance between adjacent poles is about 45m. The 433V lines are composed of 120mm² All Aluminum Conductors (AAC).

The selected facility for the field harmonic measurement of the lamps is supplied with a single-phase line, connected from the 3-phase, 4-wire radial lines. The single-phase line is a 6m by 25mm² PVC insulated AAC. The total length of cable supplying power from the transformer output to the energy meter input point of the building is about 30m. Figure 5 shows a simple diagram of the area network structure to the building. Possible points of

common coupling are indicated as PCC1, PCC2 and PCC3. PCC2 is at the pole where the building supply was connected. Since PCC3 is the closest point to the consumer the field harmonic measurement of the lamps was taken at that point [18].

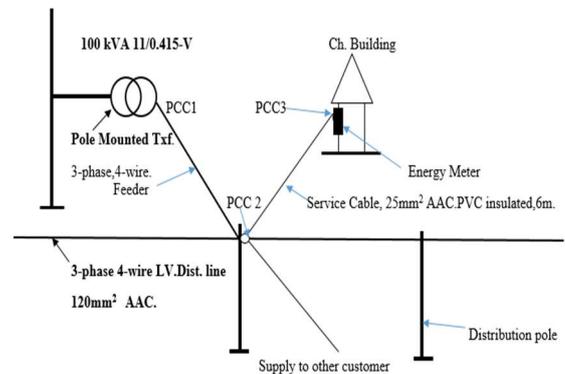


Fig. 5 Area network structure of the selected facility

The components of the network structure are represented by the single line diagram shown in Fig. 6.

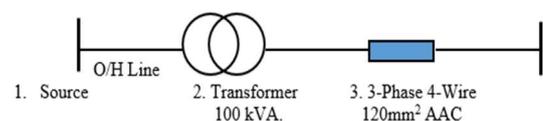


Fig. 6 Network single line diagram

The utility company provided the upstream short circuit current (I_{SC}) as 3263 A at a distance of 2km from their nearby sub-station to the local area network transformer. The power source component parameters were determined using (1) and (2) where V_L represents the primary line voltage [19, 20].

$$\text{Fault VA} = \sqrt{3} \times V_L \times I_{SC} \quad (1)$$

$$Z_s = \frac{CV_0^2}{\text{Fault VA}} \quad (2)$$

In (2), Z_s represents the source impedance in ohms, V_0 is the nominal line-to-line source voltage, and C is the voltage factor. For a 230/415V system C equals 1, for a system with 1kV to 250kV, C equals 1.1, and C equals 1.05 for other low voltages.

The primary and secondary windings parameters of the service transformer were determined with the length of the 2-km overhead transmission lines from the substation to the input of the transformer. The obtained primary windings values were referred to secondary side to obtain secondary winding parameters. The overhead distribution line (19 strands, 120mm² AAC) with resistance of 0.2459-Ω/km and a geometric mean radius (GmR) of 5.06mm were obtained from manufacturer's data sheet. The spacing of the overhead conductor is 90cm. The geometric mean diameter is calculated using (3), where D_{RY} , D_{YB} and D_{BR} represent the distances between the red and yellow, yellow and blue, and blue and red phases, respectively. The inductance of the overhead line L_1 was obtained using (4).

$$GmD = \sqrt[3]{(D_{RY} \times D_{YB} \times D_{BR})} \quad (3)$$

$$L_1 = 10^{-7} \left(0.5 + 2 \ln \left[\frac{GmD}{GmR} \right] \right) H/m \quad (4)$$

The distribution line was modeled using the π -equivalent circuit. The line resistance and inductance values were determined from manufacturers data sheet whilst the capacitance value was determined using (5).

$$C = \frac{2\pi\epsilon_0}{\ln\left(\frac{GmD}{r}\right)}, r = 7.0 \times 10^{-3}m \quad (5)$$

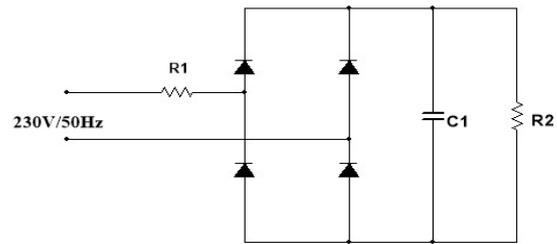


Fig. 7 Model for CFL and LED lamps

The model for simulating both the CFL and LED lamps' harmonics is shown in Fig. 7. The model parameters were determined using the procedure given in [21, 22]. According to [21 - 23], the value of $R1$ could be estimated using (6).

$$R1 = 0.2868 \times 0.6852 P_{CFL_LED} \quad (6)$$

The DC capacitor $C1$ and resistor $R2$ values, according to [21] could also be estimated by (7) and (8), respectively.

$$C1 = 0.24 \times 10^{-6} P_{CFL_LED} \quad (7)$$

$$R2 = \frac{3.924V}{I} \quad (8)$$

In (6), (7) and (8), V , I and P_{CFL_LED} refer to the rated voltage or operating voltage, measured fundamental current, and rated power of the CFL and LED lamps, respectively. In the absence of the measured fundamental current I , the value could be estimated using the rated current of the lamp as:

$$I = 0.85 \times I_R \quad (9)$$

where I_R is the rated current of the lamp.

Table I Parameters for CFL and LED lamps

Lamps	Parameter Values		
	$R1$ - (Ω)	$C1$ - (μF)	$R2$ - (Ω)
1. Focus 23W CFL	23.4	5.6	3460
2. Ant Electrical 20W LED	16.57	5.14	5341

On the basis of (6) to (9), the model parameters of the Focus 23W CFL lamp were determined using its field measured power of 30W instead of 23W on its label. For the Ant Electrical 20W LED, its field

measured value was found to be 20W so this value was used in the calculations. Table I shows the model parameters for the two chosen energy-saving lamps. Each of the models' three parameters were tuned in the simulation until the lamps' field measured values matched the simulated values.

Total harmonic distortion (THD) is the amount of harmonic distortion in a signal. This is quantified as the ratio of the sum of powers of all harmonic components to the power of the fundamental frequency. THD is the commonly used index to quantify current and voltage distortion in power systems. Current total harmonic distortion (THD_I) and voltage total harmonic distortion (THD_V) values show the level of distortion in the current and voltage waveforms with respect to pure sine waves. The implication on levels of each quantity of distortion has been given by [21]. The recommended power factor requirement for lamps' power rating is also given in IEC 62612-2013 [24]. A low power factor of a lamp implies more current is drawn than needed by the lamp. This leads to higher electricity bills. The level of current and voltage harmonic distortions present in a power system are given by (10) and (11), respectively.

$$THD_I (\%) = \frac{\sqrt{\sum_{h=2}^n I_h^2}}{I_1} \times 100 \quad (10)$$

$$THD_V (\%) = \frac{\sqrt{\sum_{h=2}^n V_h^2}}{V_1} \times 100 \quad (11)$$

In (10), I_1 is the fundamental rms value of the current waveform, I_h refers to the rms value of the current harmonic of order 'h', while 'n' is the highest harmonic order present in the current waveform. Similarly, V_1 refers to the fundamental rms value of the voltage waveform, V_h denotes the rms value of voltage harmonic with harmonic order 'h'. With the presence of harmonics in power systems, power factor (pf) is defined as the product of displacement factor (dpf) and distortion factor (ϕ), with these indices defined as:

$$\phi = \frac{I_1}{I_{RMS}} = \frac{1}{\sqrt{1+THD_I^2}} \quad (12)$$

$$pf = \frac{\cos \theta}{\sqrt{1+THD_I^2}} = \phi \times dpf \quad (13)$$

In (12), I_{RMS} refers to the total rms value of the current waveform. The angle θ is the phase difference between the fundamental components of

the current and voltage waveforms. With all the network parameters represented and power quality (PQ) model obtained in MATLAB/Simulink, the lamp model was tuned to obtain values close to the field measured ones. The tuning process is as shown in the flow chart of Fig. 8. In the chart, a single-phase voltage (1ph volt.) was obtained from a 3-phase supply, for the lamp model. As the model went through simulation, field measured (Fm) values such as power, displacement factor, power factor, THD_V and THD_I were compared with the simulation generated values until the simulation and field measured results were similar. From here, the simulation was advanced to where the modeled lamps were connected progressively onto the formulated network. The lamp model as shown in Fig.7 cannot be used for successive loading of the lamps from one to higher values on the modeled grid. Masking in MATLAB/Simulink allows the lamp model to be compressed to a small size. With the compressed lamp model, the lamps were loaded equally across each phase in ones, tens, hundreds, etc. and simulated. The rms values were recorded and the THD_V values evaluated. The CFL and LED lamps and the combination of the two were simulated in turns to the maximum limit of 8% THD_V .

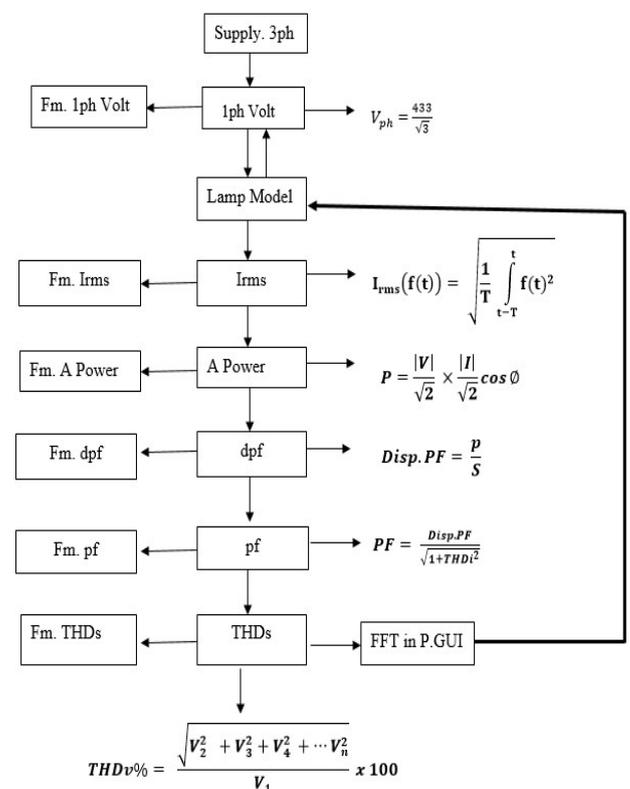


Fig. 8 Lamp model parameter tuning

4. Results and discussion

In this section, the simulated results for the Focus CFL lamps, Ant Electrical LED lamps and mixture of the two are presented. There were nine Focus CFL lamps, eight Ant Electrical LED lamps and five pairs of the combined lamps. As described in section 2, the lamps were loaded onto the modeled supply network one after the other. Thus, when one lamp is connected in circuit, the simulation was carried out and the values recorded, then the next lamp was added to the first in the circuit and the simulation ran again. The process was repeated until the last lamp.

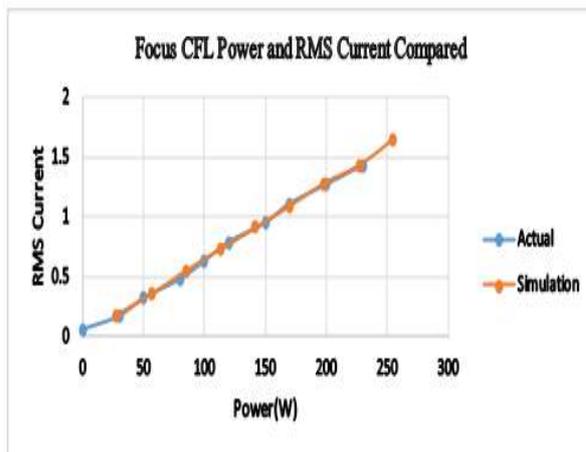


Fig. 9 Comparison of simulated results with field measured results for Focus 23W CFL lamps

Figure 9 presents a graphical comparison of the simulated and field measured results for the Focus 23W CFL lamps, in terms of rms currents and power. It is clear the two graphs match closely. A similar graph for the 20W Ant Electrical LED lamps is shown in Fig. 10 where the correlation of the two graphs is very clear.

In the simulation to determine the maximum possible loading limit, the same procedure was adopted but the lamps were loaded in ones, tens, hundred, etc. until the 8% THD_v was attained.

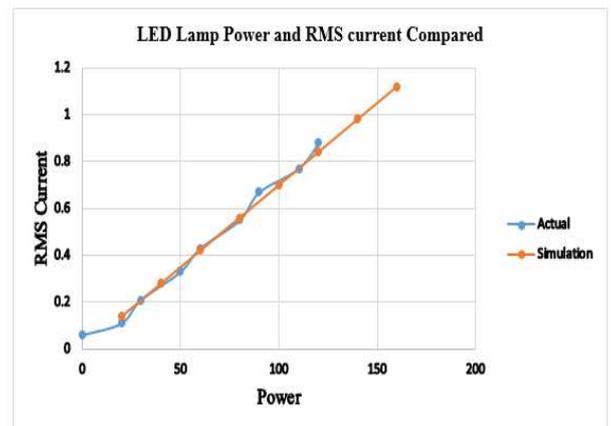


Fig. 10 Comparison of simulated results with field measured results for Ant Electrical 23W LED lamps



Fig. 11 Maximum possible loading limit of CFL lamps

From Fig. 11, the 8% THD_v limit was attained with 724 of the Focus 23W CFL lamps. The maximum power at the limit was 24.02 kW. It is evident from this graph that as more CFL lamps are added to the circuit, the THD_v values remain relatively low, around 1.0 – 1.5% when the number of lamps is less than 100. However, as hundreds of lamps are added, the rise in THD_v values become more pronounced reaching the 8% limit in no time. There is also a close correlation between the power drawn by the lamps and the THD_v injected into the network. The variation of the THD_i, however, remains within a tight window of 104 – 108% as more lamps were added and the power consumption increased.

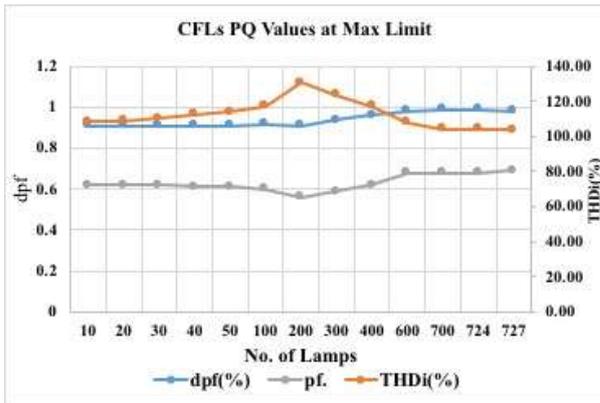


Fig. 12 Power quality values of CFLs at maximum loading limit

Figure 12 presents the power quality in terms of displacement power factor (dpf), power factor (pf) and THD_i of the CFL lamps in relation to more lamps' penetration in the network. As can be clearly seen from the graph, with the lamps' load increased from 10, the THD_i increased steadily up to 200 lamps and begun to decrease. The dpf also increased and remained steady from 0.91 to unity. The pf in this regard declines somehow and rises as the lamp load increases and THD_i decreases. The dpf and pf values are better from 600 lamps penetration. THD_i declines with increasing loads.

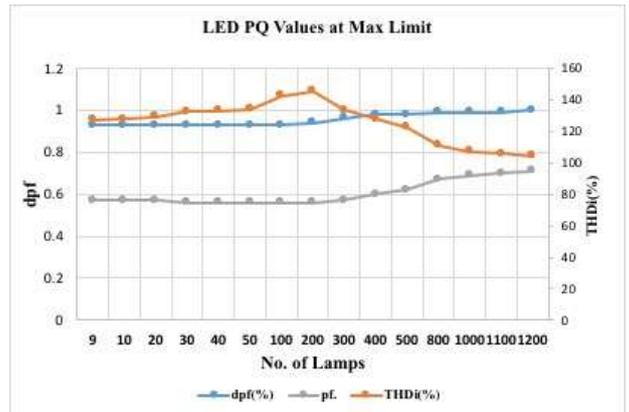


Fig. 14 Power quality values of CFLs at maximum loading limit

Figure 14 presents the power quality in terms of dpf, pf, and THD_i of the LED lamps in relation to number of lamps. As the number of lamps increased from ten, the THD_i increased steadily and started declining when the number exceeded 200. The dpf remained steady in the region of 0.93 and increased gradually close to unity as was the case for the CFL lamps. The pf in this regard increased as the THD_i decreased from 300 lamps penetration. The dpf and pf values are better from 400 lamps upwards as the THD_i declines.



Fig. 13 Maximum possible power loading limit of LED lamps

Similarly, the LED lamps were loaded equally to the phases of the network in tens, hundreds, etc. and simulated increasingly until the recommended THD_v of 8% limit was attained at 7.97%. From Fig. 13, the THD_v of 7.97% which is close to the recommended 8% limit was attained with a total of 1200 LED lamps. The maximum power at this value was 27.14kW.

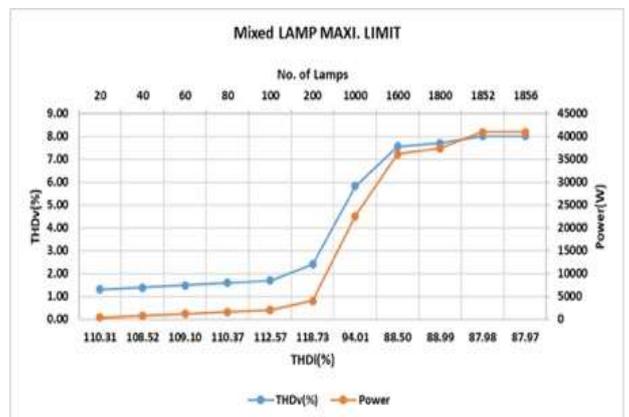


Fig. 15 Maximum possible power loading of the mixed lamps

The maximum power loading limit for the mixture of CFL and LED lamps was determined by loading equally across the phases from 10 pairs of lamps and simulated increasingly until the recommended THD_v limit of 8% was attained at 8.01%. The number of mixed lamps in circuit was 1852 (926 pairs). This corresponds to a total lamp power of 40.91kW. This is shown in the graph of Fig. 15.

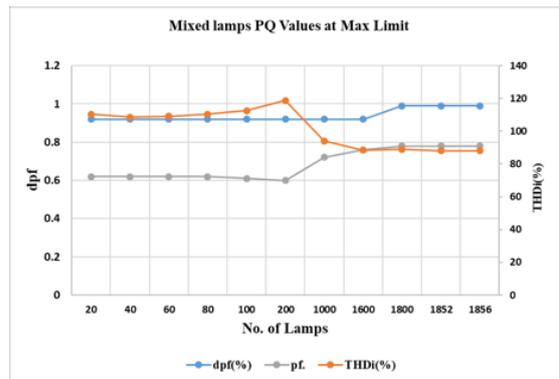


Fig. 16 Power quality values of the mixed lamps at maximum loading limit

As more lamp load penetrate, the power quality values of the mixture of CFL and LED lamps show improvement in both dpf and pf. THD_v values also drop with increasing lamp load. In Fig. 16, this is shown conspicuously as more lamps are loaded. From 200 lamps and above, the pf improved from 0.6 to 0.78. Similarly, the dpf improved from 0.92 to 0.99.

5. Conclusion

Harmonics of energy-saving lamps have been studied by many researchers through either laboratory installations or experimental set ups. Measurement of the lamps' harmonics are usually taken at the supply input of the lamps' terminals. This paper investigated the harmonics of CFL and LED lamps through field measurement at a facility point of common coupling as recommended by IEEE 519-2014 standard. A local network of 100kVA, 11kV/0.433kV capacity was formulated in MATLAB/Simulink. The obtained field measurement of popular lamps used in Ghana such as Focus CFL and Ant Electrical LED lamps were replicated through simulation in MATLAB/Simulink.

Also, the influence of other loads such as ceiling fans on the lamps' harmonics were assessed. The maximum possible power loading limit with reference to the recommended 8% THD_v limit were obtained for each lamp through simulations. A maximum power of 24kW was obtained for 724, 23W Focus CFL lamps while 1200, 20W Ant Electrical LED lamps attained the maximum power limit at 27kW. Field harmonic assessment of the two lamp groups indicated that LED lamps are of lower power factor and exhibit more harmonics than CFL lamps. This is found to be in line with

other research findings. However, more penetration of the lamps into the power distribution system shows an improved power quality. This was revealed by the simulation results. Since the lamps exist in residential and commercial facilities with other loads, more penetration of energy-saving lamps in distribution systems will have little influence on power quality.

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