Experimental Measurements and Computer Simulations of FL and CFL Lamps for Harmonic Studies

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Abstract—Due to poor efficiencies of Incandescent Lamps (ILs), Fluorescent Lamps (FLs) and Compact Fluorescent Lamps (CFLs) are increasingly used in residential and commercial applications. This proliferation of FLs and CFLs increases the harmonics level in distribution systems that could affect power systems and end users. In order to quantify the harmonics produced by FLs and CFLs precisely, accurate modelling of these loads is required. Matlab Simulink is used to model and simulate the full models of FLs and CFLs to give close results to the experimental measurements. Moreover, a Constant Load Power (CLP) model is also modelled and its results are compared with those of the full model. This CLP model is much faster to simulate and easier to model than the full model. Such models help engineers and researchers to evaluate the harmonics exist within households and commercial buildings.

Keywords—Fluorescent Lamp; Compact Fluorescent Lamp; harmonics; distortion; PFC; THD

I. INTRODUCTION

The rapidly increasing use of Fluorescent Lamps (FLs) and Compact Fluorescent Lamps (CFLs) nowadays increase concerns regarding the harmonics and their impacts on the quality of supply. In general, nonlinear loads such as FLs and CFLs can cause severe problems to power systems and end users such as voltage distortion, conductors and transformers overloading, increased system losses, interference with communications networks, impact on energy metering, improper operations of electronic devices, thermal effects on rotating machines, incorrect tripping of circuit breakers, a decrease in the overall system efficiency and reduced system reliability [1-6].

Lighting is considered one of the most important loads in power systems. It has been estimated by [7] that lighting consumes about 25%-35% of the global generated power. Due to the advancement in power electronics technology nowadays, FLs and CFLs are becoming increasingly more attractive for many reasons. First, the efficiency of CFLs is three to four times the efficiency of Incandescent Lamps (ILs). Second, lifetime of a typical CFL is thousands times that of an IL. Third, due to the high switching frequencies used in FLs and CFLs (>25 kHz), they are less in weight and size compare to ILs [2, 8].

To establish a high initial voltage across the lamp tube, FLs require electronic ballasts. Ballasts are also important for proper lamp ignition and to limit the lamp current once the arc is established [2, 3, 8]. These electronic ballasts use Switch Mode Power Supplies (SMPSs); therefore, their current distortion could be low or as high as 100% depending on whether a Power Factor Correction (PFC) circuit is used [9-12].

The proposed Constant Load Power (CLP) model is introduced in [13, 14] and has been proved to give very close results to the PC full model and experimental results. In order to validate that the CLP model can also be used to model FL and CFL, its results are compared with those of full FL and CFL models as well as with experimental measurements.

To prevent any variation within the systems to affect the harmonics generated by the FL and CFL, these two loads were supplied using a programmable AC source Chroma™ 61511 [15] that helps in isolating the test rig and filtering out harmonics and fluctuations from the main power supply. The conditions of the system under which the experiments conducted were 240V, 50Hz and 0.25Ω. The input voltage and current of the FLs and CFLs were monitored using a KinetiQ PPA1530 Power Analyzer [16].

In this paper, Voltage and Current Total Harmonic Distortion indices (THD, and THD) as well as Individual Current Harmonic Distortion (IHD) up to the 11th order harmonic are considered. The Root-Mean-Square (RMS) values of the input voltage and current, Power Factor (PF), active (P), nonactive (N) and apparent power (S) are also taking into account. These quantities are calculated according to the IEEE Std 1459 [17].

The paper is organized as follows: section II presents the models used to simulate the FL and CFL. Section III discusses the harmonics quantification indices. Then, experimental and simulation results are introduced in section IV. Finally, Section V presents the summary and conclusions.
II. FL AND CFL MODELLING

Fig. 1 shows a schematic diagram of a fluorescent lamp with PFC circuit [7-9, 18-20]. According to [2], because of the rapid changes of $d/dt$ and $dv/dt$ at high switching frequency, Electromagnetic Interference (EMI) filters are employed to attenuate high switching noise currents generated. However, PFC circuit is used to improve the Power Factor (PF) by monitoring the output voltage of the PFC stage and forcing the input current to be sinusoidal and in phase with the input voltage. This also significantly helps in reducing current distortion. The function of the resonant inverter is to convert the dc voltage to ac voltage at a very high switching frequency suitable to drive the fluorescent lamp.

![Figure 1. A schematic diagram of a fluorescent lamp with PFC Circuit.](image)

A. Full Model

A half-bridge series-resonant inverter based electronic ballast configuration is shown in Fig. 2. A step-up dc –dc converter is used to improve the fluorescent lamp power factor. The capacitor $C_{bulk}$ is used to minimize the ripple content of the inverter dc input voltage. $S_1$ and $S_2$ are turned on and off symmetrically and alternatively at a high switching frequency $F_s$ to convert the dc voltage into ac.

The series resonant circuit $L_r$ and $C_r$ is used to bypass the switching frequency component only. $C_p$ is also important to block the dc component. The capacitor $C_p$ helps in maintaining a sufficiently high voltage across the lamp during starting for proper ignition. Furthermore, it limits the lamp current at steady state. $C_p$ is also used to reduce the harmonic contents of the lamp current which consequently improve the crest factor of the lamp current [7-12, 21].

It is widely accepted that when a fluorescent lamp is operated at a high frequency, it can be modelled as a pure resistance ($R_{lamp}$) with four series resistances ($r_f/2$), where $r_f$ is the filament resistance [8, 18, 19].

B. CLP Model

The CLP model is simulated using a Voltage-Controlled Current Source (VCCS) as shown in Fig. 3. This comprises a rectifier circuit and a constant power load.

![Figure 3. CLP Model.](image)

A typical EMI filter configuration and design procedure are used with the assumption that an attenuation of 24dB/decade is required at the switching frequency [7, 22-25].
III. HARMONIC INDICES CALCULATIONS

The presence of harmonics makes waveforms to be nonsinusoidal. The most commonly used indices to quantify voltage and current distortions are Voltage and Current Total Harmonic Distortion that can be calculated as follows.

\[
THD_v = \frac{V_h}{V_1} = \left( \frac{V}{V_1} \right)^2 - 1 \tag{3}
\]

\[
THD_i = \frac{I_h}{I_1} = \left( \frac{I}{I_1} \right)^2 - 1 \tag{4}
\]

where:

\( V, V_1 \) and \( V_h \) represent the total, fundamental and harmonic voltages.

\( I, I_1 \) and \( I_h \) denote the total, fundamental and harmonic currents.

IV. MEASUREMENTS AND SIMULATIONS RESULT

A. Fluorescent Lamp

A 58 W FL was monitored and the harmonics and power quantities, spectrum and typical waveform can be shown in Figs. 4 and 5 and Table I. The FL was simulated using the full and CLP models.

![Figure 4. Current spectrum of a FL](image)

![Figure 5. FL current waveforms](image)

It can be seen from the results that the full and CLP models give close result to measurements. Results also show how PFC circuit play an important role not only in improving the PF to be about 0.98 but also in reducing the harmonics injected to the grid and lowering the THDi value to be 5.25%.

### TABLE I. FL HARMONICS AND POWER QUANTITIES

<table>
<thead>
<tr>
<th>Index</th>
<th>Simulation Results</th>
<th>Experimental Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Full Model</td>
<td>CLP</td>
</tr>
<tr>
<td>%THD_v</td>
<td>0.010</td>
<td>0.004</td>
</tr>
<tr>
<td>%THD_i</td>
<td>5.27</td>
<td>5.23</td>
</tr>
<tr>
<td>1st, mA (%)</td>
<td>239.98 (100)</td>
<td>240.10 (100)</td>
</tr>
<tr>
<td>3rd, mA (%)</td>
<td>8.82 (3.67)</td>
<td>8.88 (3.70)</td>
</tr>
<tr>
<td>5th, mA (%)</td>
<td>3.28 (1.37)</td>
<td>3.25 (1.35)</td>
</tr>
<tr>
<td>7th, mA (%)</td>
<td>2.10 (0.88)</td>
<td>1.8812 (0.78)</td>
</tr>
<tr>
<td>9th, mA (%)</td>
<td>2.62 (1.09)</td>
<td>3.18 (1.32)</td>
</tr>
<tr>
<td>11th, mA (%)</td>
<td>3.6906 (1.54)</td>
<td>3.6582 (1.52)</td>
</tr>
<tr>
<td>V, V rms</td>
<td>239.95</td>
<td>239.94</td>
</tr>
<tr>
<td>I, I rms</td>
<td>0.24</td>
<td>0.24</td>
</tr>
<tr>
<td>P, W</td>
<td>56.60</td>
<td>56.56</td>
</tr>
<tr>
<td>N, Var</td>
<td>11.02</td>
<td>11.37</td>
</tr>
<tr>
<td>S, VA</td>
<td>57.66</td>
<td>57.69</td>
</tr>
<tr>
<td>P.F.</td>
<td>0.98</td>
<td>0.98</td>
</tr>
</tbody>
</table>
B. Compact Fluorescent Lamp

An 11 W CFL was monitored and the harmonics and power quantities, spectrum and typical waveform can be shown in Figs. 6 and 7 and Table II. Full and CLP models are used to simulate the CFL but with no PFC circuit and with different harmonic filter design.

![Figure 6. Current spectrum of a CFL](image)

![Figure 7. CFL current waveforms](image)

Due to the fact that a PFC circuit is not used in the CFL, its harmonics, especially the 3rd and 5th, and THD, are too high. Again, the full and CLP models give close results to measurements.

<table>
<thead>
<tr>
<th><strong>Index</strong></th>
<th><strong>Simulation Results</strong></th>
<th><strong>Experimental Measurement</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>%THD&lt;sub&gt;r&lt;/sub&gt;</td>
<td>0.014</td>
<td>0.014</td>
</tr>
<tr>
<td>%THD&lt;sub&gt;i&lt;/sub&gt;</td>
<td>106.97</td>
<td>106.50</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt;, mA (%</td>
<td>57.50 (100)</td>
<td>57.51 (100)</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt;, mA (%</td>
<td>45.80 (79.6466)</td>
<td>45.48 (79.0749)</td>
</tr>
<tr>
<td>5&lt;sup&gt;th&lt;/sup&gt;, mA (%</td>
<td>27.22 (47.33)</td>
<td>26.11 (45.40)</td>
</tr>
<tr>
<td>7&lt;sup&gt;th&lt;/sup&gt;, mA (%</td>
<td>16.98 (29.53)</td>
<td>17.53 (30.48)</td>
</tr>
<tr>
<td>9&lt;sup&gt;th&lt;/sup&gt;, mA (%</td>
<td>11.09 (19.28)</td>
<td>11.59 (20.16)</td>
</tr>
<tr>
<td>11&lt;sup&gt;th&lt;/sup&gt;, mA (%</td>
<td>11.41 (19.84)</td>
<td>11.33 (19.70)</td>
</tr>
<tr>
<td>V&lt;sub&gt;rms&lt;/sub&gt;</td>
<td>239.99</td>
<td>239.99</td>
</tr>
<tr>
<td>I&lt;sub&gt;rms&lt;/sub&gt;</td>
<td>84.20</td>
<td>84.00</td>
</tr>
<tr>
<td>P, W</td>
<td>12.19</td>
<td>12.07</td>
</tr>
<tr>
<td>N, Var</td>
<td>16.12</td>
<td>16.15</td>
</tr>
<tr>
<td>S, VA</td>
<td>20.21</td>
<td>20.16</td>
</tr>
<tr>
<td>P.F.</td>
<td>0.60</td>
<td>0.60</td>
</tr>
</tbody>
</table>

It should be noted that the harmonics filter was used to shape the current waveforms of the FL and CFL to be close to measurements. However, current waveforms can be different for different FLs and CFLs. Hence, this paper suggests that waveforms of this kind of loads are measured first. Then, the CLP can be used with the help of the harmonic filters to simulate the behaviors of these loads precisely. This allows engineers and researchers to estimate the harmonics produced by these loads and assess their simultaneous effects on power systems accurately.
V. CONCLUSION

The proliferation of FLs and CFLs increases the harmonics level in power systems. For precise quantification of harmonics caused by these power electronics based loads, accurate modelling of these loads are required as they can affect the quality of the systems. The FL and CFL are simulated using the full and CLP models and their results are compared with experimental measurements.

The harmonics generated by both models give very close results to measurements; hence, for easy modelling and faster simulation, CLP model can be used to simulate FLs and CFLs loads taking into account that the FL considered in this research uses a PFC circuit while the CFL does not. Although the rating power of the FL and CFL are low; however, lightning consumes about large portion of the total generated power. Also, residential houses and commercial buildings use lots of FLs and CFLs. Hence, the aggregated generated power. Also, residential houses and commercial buildings use lots of FLs and CFLs loads taking into account that the FL considered in this research uses a PFC circuit while the CFL does not. Although the rating power of the FL and CFL are low; however, lightning consumes about large portion of the total generated power. Also, residential houses and commercial buildings use lots of FLs and CFLs. Hence, the aggregated sum of the injected harmonics by FLs and CFLs also contributes to the increased current distortion within distribution systems.

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REFERENCES