Measurement and Simulation of Power Quality Disturbances between 2-150 kHz from Compact Fluorescent Lamps

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Abstract—A set of measurements and simulations describing the relationship between conducted disturbances of a Compact Fluorescent Lamp (CFL) within the range 2-150 kHz, and some variations in its base circuit, are shown and analyzed in this article. Measurements are carried out using some low power CFL devices in single operation. Simulations of a typical CFL circuit without any Power Factor Corrector stage are performed by means of LTSpice® simulator. Measurements show a particular behavior of 2-150 kHz disturbances in current signals in CFL devices, and similarities with some disturbances from LED lamps. Variations at EMI filter, Rectifier, and Smoothing filter stages show strong influence on emissions within this frequency range. Hence, variations in base circuit allow these emissions to change when devices are in single operation. The results from measurements and simulations are a step forward in understanding and modeling emissions in the 2-150 kHz frequency range.

Index Terms—Electromagnetic Compatibility, Power Quality, Distortion, Signal Analysis, Spectral Analysis, Supraharmonics.

I. INTRODUCTION

Switched-mode power supplies (SMPS), electronic inverters and converters, several communication technologies (i.e. Power Line Communication), and Power Electronics systems are in general expected to be part of Smart Grids. Advances in low voltage devices using less energy is one of the main reasons for using power-electronics-based loads. However, quasi-stationary voltage and current emissions within the range between 2-150 kHz (recently called supraharmonics) are nowadays a Power Quality concern[1][2][3][4]. These emissions are attributed to be the main cause of some low voltage devices malfunction, grouped into four categories: devices which are not operating as expected, failed operation or device damage, interference regarding Power Line Communication, and audible noise from a device or installation [1]. Traditional (radial) and future low voltage grids (microgrids, nanogrids, etc.) should be not only designed to well operate under this sort of conducted disturbances, but also to avoid interferences between power electronics and other devices. This in order to integrate renewable energy sources and some communication technologies, among others, with current and future distribution systems. In previous works researchers measured these emissions, named by many of them as supraharmonics [1], in both laboratory and non-controlled environments [2][6].

Nevertheless, emissions measuring and modeling in the 2-150 kHz frequency range are still under development. These emissions are expected to behave different from controlled (laboratory) and non-controlled (distribution grid) environments according to some grid and devices’ circuit features[1][4]. In this way, it is necessary to understand both general features about 2-150kHz conducted disturbances and also how they are related to some components inside the devices. Regardless of their clearly different operation modes, devices such as Compact Fluorescent Lamps (CFL) and LED lamps have shown these sort of disturbances when operate either in single mode or in an electrical installation[5][10]. In addition to measurements from devices in single operation, authors use simulation models in order to understand how variations in a CFL device circuit can modify supraharmonic signals spectrum. Otherwise, circuit modifications would induce authors to directly vary circuit parameters inside the lighting device, which could be not reliable in terms of measurements repeatability and accuracy.

This article shows measurements and simulations of supraharmonic emissions (2-150 kHz disturbances) from some CFL devices. Devices under measurement are described in SectionII-AMeasurements from some Compact Fluorescent Lampssubsection.2.1. Section II-BCompact Fluorescent Lamp (CFL) simulation modelsubsection.2.2 shows the simulation setup and the set of variations carried out inside the simulated CFL circuit. Finally, Section Results summarizes how 2-150 kHz disturbances show off in current signal spectrograms from measurements in CFL single operation, and from some variations in the EMI filter, Rectifier and Smoothing Filter stages.
II. COMPACT FLUORESCENT LAMPS IN THE 2-150 KHZ FREQUENCY RANGE

Compact Fluorescent Lamps (CFL) are known to have power quality disturbances in the range between 2 kHz and 150 kHz, operating either in single mode or connected to the grid[1][2]. Indeed, previous works have shown some LED lamps have a similar set of emissions within this range compared to some CFL devices, even though their different operation principles (inverters for CFL, DC/DC converters for LED lamps). Since other devices present these emissions regardless their operation principle, it is relevant to study how supraharmonic emissions behave under both device’s normal operation and some variations in its circuit parameters. A typical set of stages in modern domestic appliances are the AC Main Voltage supply, EMI filter, Rectifier and the Smoothing filter stages shown in Figure 1Typical circuit stages in CFL devices.figure.caption.1. Other stages as Inverter, Resonant tank and Lamp bulb stages depicted in Figure 1Typical circuit stages in CFL devices.figure.caption.1 vary according to the device.

Because of the lack of standards in the supraharmonic frequency range, domestic appliances are normally designed to comply only with harmonic emissions typically below 9 kHz[11]. However, many of the commonly used domestic low-power lighting devices available in the Colombian market present high distortion levels and low power factor, among other power quality issues.

A. Measurements from some Compact Fluorescent Lamps

CFL measurement setup is shown and described in Reference [6], Table ICompact Fluorescent Lamps under measurement.table.caption.2 show the set of CFL devices under measurement. Additionally, a set of LED lamps were measured too so as to find some of the specific similarities between CFL devices and LED lamps in the 2-150 kHz frequency range.

Analysis techniques used to process data from measurements can be classified into three categories:

- Time domain: Digital realization of Equation 1Measurements from some Compact Fluorescent Lamps equation.2.1 were developed to obtain average active power of measured devices. This was achieved by means of Newton-Cotes formulae.

\[
P_{avg} = \frac{1}{nT} \int_0^{nT} v(t) i(t) dt
\]

- Frequency domain: RMS and Total Harmonic Distortion values were computed with equations 2Measurements from some Compact Fluorescent Lamps equation.2.2 and 3Measurements from some Compact Fluorescent Lamps equation.2.3 respectively. These expressions were developed for single-sided signals spectrum.

\[
a_{rms}^2 = \sum_{h=0}^{H} |C_h|^2
\]

\[
THD a^2 = \sum_{h=2}^{H} \left( \frac{C_h}{C_1} \right)^2
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\]

\[
THD a^2 = \sum_{h=2}^{H} \left( \frac{C_h}{C_1} \right)^2
\]
\[ S = V_{RMS} \times I_{RMS} \]

\[ S = (I_1 \sqrt{THD_i^2 + 1}) (V_1 \sqrt{THD_v^2 + 1}) \]  
\[ (4) \]

\[ PF_{tot} = \frac{P_{avg}}{I_1 V_1} \left( \frac{1}{\sqrt{(THD_i^2 + 1)}} \right) \left( \frac{1}{\sqrt{(THD_v^2 + 1)}} \right) \]

\[ PF_{tot} = \left( PF_\alpha \right) \left( PF_\beta \right) \]  
\[ (5) \]

- **i vs. v curves**: Other non-linear behavior can be analyzed by means of the current vs. voltage relationship, where other aspects about current and voltage signals can be perceived at device terminals.

**B. Compact Fluorescent Lamp (CFL) simulation model**

In order to simulate supraharmonics emission, authors simulated a low power CFL circuit without any Power Factor Corrector stage. In the Colombian market, lighting devices not complying neither with harmonics emission regulations are commonly used, among others, because of their reduced costs and size. The simulated CFL Ballast circuit it is summarized in Figure 1Typical circuit stages in CFL devices.figure.caption.1. Inverter stage in Figure 1Typical circuit stages in CFL devices.figure.caption.1 is simulated as a BJT Half Bridge Resonant Inverter Self-Oscillating ballast, and it is described in Reference [9]. Details about circuit simulation are shown and explained in Reference [9].

**TABLE II: EMI Filter Model [9]**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>C_{EMI}</td>
<td>1 μF</td>
<td></td>
</tr>
<tr>
<td>L_{EMI}</td>
<td>5 mH</td>
<td></td>
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</table>

**TABLE III: Variations in CFL Circuit Parameters**

<table>
<thead>
<tr>
<th>CASE</th>
<th>Rectifier</th>
<th>Smoothing Filter</th>
<th>EMI Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>II</td>
<td>✓</td>
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<td></td>
</tr>
<tr>
<td>III</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>VI</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>VII</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>VIII</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Some CFL devices were physically examined in order to obtain several values of their circuit components. After this, authors could determine some lighting devices seemed to have half-wave rectifiers, small values of Smoothing filters, and sometimes devices which did not have any EMI filter. In Table IIIVariations in CFL Circuit Parameterstable.caption.4 is summarized the set of variations at Rectifier, EMI filter and Smoothing filter simulated stages. These variations were performed through simulations in order to evaluate how 2-150 kHz disturbances behave when CFL circuit parameters are modified. Current and voltage measurement from simulations are taken at Common Connection Point, Figure 1Typical circuit stages in CFL devices.figure.caption.1. This represents the connection between a CFL device and the AC main supply (120 Vrms, 60 Hz in Colombia).

**III. RESULTS**

**A. Measurements**

Table IVCompact Fluorescent Lamps results from measurement.table.caption.5 summarizes main electrical features of CFL devices under measurement.

Disturbances within the 2-150 kHz frequency range are strongly related to the switching frequency of the inverter/converter under operation. Nevertheless, these emissions can even affect the entire signal distortion perceived from current and voltage signals, among others, by means of harmonics of these emissions ("harmonic supraharmonics").

![Fig. 2: Current vs. Voltage curves in some CFL devices.](image)

A set of current vs. voltage curves from some low power CFL devices and low power LED lamps are shown in Figures 2Current vs. Voltage curves in some CFL devices.figure.caption.6 and 5Current vs. Voltage curve in some LED lamps.figure.caption.9. Figure 3CFL current signal spectrum between 2kHz and 200 kHz.[6]figure.caption.7 and 6LED current signal spectrum between 2kHz and 200 kHz.figure.caption.10 show emissions from low power CFL devices and LED lamps in the supraharmonic range [6]. Figure 411W CFL current spectrogram up to 200 kHz.figure.caption.8 shows the spectrogram of a 11 W CFL device up to 200 kHz, 50ms.
### TABLE IV: Compact Fluorescent Lamps results from measurement.

<table>
<thead>
<tr>
<th>Rated Power [W]</th>
<th>Irms [mA]</th>
<th>$I_{rms60}$ [mA]</th>
<th>THDi [%]</th>
<th>Vrms [V]</th>
<th>$V_{rms60}$ [V]</th>
<th>THDv [%]</th>
<th>$P_{avg}$ [W]</th>
<th>$PF_{\alpha}$</th>
<th>$PF_{\beta}$</th>
<th>$PF_{tot}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>141.6</td>
<td>95.8</td>
<td>108.9</td>
<td>122.5</td>
<td>122.4</td>
<td>2.9</td>
<td>10.9</td>
<td>0.93</td>
<td>0.68</td>
<td>0.63</td>
</tr>
<tr>
<td>15</td>
<td>167.2</td>
<td>118.8</td>
<td>99.2</td>
<td>122.2</td>
<td>122.1</td>
<td>2.6</td>
<td>13.3</td>
<td>0.92</td>
<td>0.71</td>
<td>0.65</td>
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<tr>
<td>7</td>
<td>87.2</td>
<td>60.1</td>
<td>104.0</td>
<td>121.8</td>
<td>121.7</td>
<td>2.7</td>
<td>6.9</td>
<td>0.94</td>
<td>0.69</td>
<td>0.65</td>
</tr>
<tr>
<td>7</td>
<td>86.8</td>
<td>60.2</td>
<td>105.1</td>
<td>121.8</td>
<td>121.8</td>
<td>2.8</td>
<td>6.8</td>
<td>0.93</td>
<td>0.69</td>
<td>0.64</td>
</tr>
<tr>
<td>20</td>
<td>283.2</td>
<td>193.7</td>
<td>106.4</td>
<td>121.9</td>
<td>121.8</td>
<td>2.6</td>
<td>19.9</td>
<td>0.84</td>
<td>0.68</td>
<td>0.58</td>
</tr>
<tr>
<td>5</td>
<td>67.1</td>
<td>45.9</td>
<td>105.5</td>
<td>122.2</td>
<td>122.1</td>
<td>2.7</td>
<td>5.4</td>
<td>0.97</td>
<td>0.69</td>
<td>0.67</td>
</tr>
<tr>
<td>11</td>
<td>105.2</td>
<td>72.3</td>
<td>107.9</td>
<td>122.2</td>
<td>122.2</td>
<td>2.5</td>
<td>8.0</td>
<td>0.91</td>
<td>0.68</td>
<td>0.62</td>
</tr>
</tbody>
</table>

### TABLE V: Compact Fluorescent Lamps results from simulation.

<table>
<thead>
<tr>
<th>CASE</th>
<th>Irms [mA]</th>
<th>$I_{rms60}$ [mA]</th>
<th>THDi [%]</th>
<th>Vrms [V]</th>
<th>$V_{rms60}$ [V]</th>
<th>THDv [%]</th>
<th>$P_{avg}$ [W]</th>
<th>$PF_{\alpha}$</th>
<th>$PF_{\beta}$</th>
<th>$PF_{tot}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>646.06</td>
<td>353.12</td>
<td>153.17</td>
<td>127.17</td>
<td>127.17</td>
<td>0.16</td>
<td>39.22</td>
<td>0.87</td>
<td>0.55</td>
<td>0.48</td>
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<tr>
<td>II</td>
<td>190.01</td>
<td>189.22</td>
<td>7.65</td>
<td>127.21</td>
<td>127.21</td>
<td>0.27</td>
<td>24.11</td>
<td>0.99</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>III</td>
<td>492.27</td>
<td>340.23</td>
<td>104.66</td>
<td>127.18</td>
<td>127.18</td>
<td>0.34</td>
<td>38.06</td>
<td>0.88</td>
<td>0.69</td>
<td>0.61</td>
</tr>
<tr>
<td>IV</td>
<td>441.32</td>
<td>216.54</td>
<td>177.58</td>
<td>129.85</td>
<td>127.23</td>
<td>0.41</td>
<td>27.46</td>
<td>0.99</td>
<td>0.48</td>
<td>0.48</td>
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<tr>
<td>V</td>
<td>594.76</td>
<td>277.71</td>
<td>174.57</td>
<td>127.21</td>
<td>127.20</td>
<td>0.14</td>
<td>28.71</td>
<td>0.81</td>
<td>0.49</td>
<td>0.38</td>
</tr>
<tr>
<td>VI</td>
<td>134.34</td>
<td>94.23</td>
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<td>127.25</td>
<td>127.25</td>
<td>0.19</td>
<td>11.98</td>
<td>0.99</td>
<td>0.89</td>
<td>0.70</td>
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<tr>
<td>VII</td>
<td>481.31</td>
<td>263.34</td>
<td>133.79</td>
<td>127.94</td>
<td>127.22</td>
<td>10.67</td>
<td>25.73</td>
<td>0.77</td>
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<tr>
<td>VIII</td>
<td>270.69</td>
<td>107.02</td>
<td>214.02</td>
<td>127.67</td>
<td>127.23</td>
<td>8.29</td>
<td>13.62</td>
<td>0.99</td>
<td>0.42</td>
<td>0.39</td>
</tr>
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**Fig. 3:** CFL current signal spectrum between 2kHz and 200 kHz.[6]

**Fig. 4:** 11W CFL current spectrogram up to 200 kHz.

### IV. DISCUSSION

#### A. Measurements

Current signals from CFL devices seem to have a similar behavior: according to Figure 2Current vs. Voltage curves in some CFL devices.figure.caption.6, CFL current signal is only different from zero close to voltage’s peak magnitude. This pulsate behavior seems to be a typical behavior of Self-Oscillating inverters. Indeed, according to Table IVCompact Fluorescent Lamps results from measurement.table.caption.5, the part of the total power factor $PF_{\alpha}$ related to current and voltage displacement is near 0.99 in all cases. However, the part of the total power factor related to distortion $PF_{\beta}$ is lower and therefore dominant. In addition, some LED lamps seem to have the same behavior of current and voltage signals in
Fig. 5: Current vs. Voltage curve in some LED lamps.

Fig. 6: LED current signal spectrum between 2kHz and 200 kHz.

CFL devices. Because of this similitude, some LED lamps and Compact Fluorescent lamps could be analyzed in the same way.

B. Simulations

In Table VCompact Fluorescent Lamps results from simulation.table.caption.11 can be seen variations in EMI filter and Smoothing filter affect directly the amount of current the device requires for operation. However, the higher or lower value of THDi does not match with the higher or lower value of RMS Current.

It can be seen from cases II to IV Table IIIVariations in CFL Circuit Parameters. More information can be obtained from simulation.results.figure.caption.12. Harmonic supraharmonic emissions appear in these cases too. However, case I (base case) shows switching frequency is not well determined by spectrum, since EMI filter and Smoothing filter modify supraharmonic current and set a supraharmonic disturbance at a higher frequency, 93 kHz. When half wave rectifier is used and EMI filter is avoided, simulation shows higher supraharmonic emissions near to 2kHz. Smoothing filter seems to decrease supraharmonic magnitude when included in CFL circuit.

<table>
<thead>
<tr>
<th>CASE</th>
<th>2-150 kHz Disturbances</th>
<th>Lower Frequency [kHz]</th>
<th>Higher Amplitude [mA]</th>
<th>Supraharmonic Harmonics [kHz] n=1,2,3...</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE</td>
<td>93</td>
<td>0.128</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>66</td>
<td>9.13</td>
<td>66n</td>
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<td>III</td>
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<td>VIII</td>
<td>66</td>
<td>95.24</td>
<td>66n</td>
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</table>

V. CONCLUSIONS

Although CFL devices and low power LED lamps operate under different operation principles, some current signals from LED device are close to CFL current signals under single operation. Therefore, some low power LED lamps could be analyzed in Time Domain in a similar way that some CFL devices.

The Rectifier stage, EMI filter and Smoothing filter show strong impact on simulated current supraharmonic emissions in a CFL circuit simulation. It can be seen from simulation.results.figure.caption.12. Harmonic supraharmonic emissions are originated by the simulated switching frequency when a full wave rectifier is used. However, EMI filter shifts emissions related to switching frequency to higher frequency values. Due to the fact that switching frequency is not constant within a supply voltage cycle, supraharmonic emissions are likely to appear as frequency bands. From these results, current emissions in supraharmonic range can be classified using frequency bands in order to understand
and classify these emissions in real distribution grids.

REFERENCES


