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Research article

Conducted electromagnetic emissions of compact fluorescent lamps and electronic ballast modeling

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Abstract: The higher frequency electromagnetic (EM) emission in low voltage power systems is rising continuously due to the increasing use of modern electronic devices. The electronic ballast of a compact fluorescent lamp (CFL) is one of the sources of conducted EM emission in the power system. Conducted EM emission measurements are performed on compact fluorescent lamps (CFL) in the range of 2–150 kHz and compared with simulation results. The LTSpice simulation of typical 11W compact fluorescent lamps is used to analyze the measured values. Comparisons are made in both the time and frequency domains. The EMI filter in the ballast circuit can reduce the level of high-frequency EM emission. However, in order to get a more accurate result, it is necessary to find out the main cause of conducted EM emission in the ballast circuit, as the HF distortion spreads through the LV network in current signal between electronic devices.

Keywords: supraharmonics frequency; resonant inverters; self-oscillating ballasts; conducted EM emissions; power quality

1. Introduction

The use of non-linear electronics devices with high switching frequencies above 2 kHz is becoming increasingly common in power distribution systems, such as switched-mode power supplies (SMPS), energy-saving lighting equipment, photovoltaic (PV) and electric vehicle (EV) converters, and so on, while also increasing electromagnetic interference (EMI) and causing power quality issues such as equipment malfunctions, falsification of energy/smart meters, and overvoltage [1,2].

Nowadays, the rise in conducted EM emission from lighting equipment due to the shift from old incandescent lamps to more efficient and low-cost lamps like CFL and LED lamps brings a new set of challenges to the low voltage (LV) grid and interferences to consumer electronic equipment. However, the real impact on the grid due to conducted EM emission in the supraharmonic frequency range needs to be studied in more detail [3–5].

The main difference between magnetic and electronic ballast circuits is the operating frequency at which they drive the ballast circuit. The electronic ballast uses a switching frequency of 30–50 kHz, but the magnetic ballast uses the line frequency of 50 Hz [6]. Electronic ballast is often based on a switch mode power supply (SMPS) topology, such as a push-pull inverter, half-bridge inverter, or full-bridge inverter [5].

The high-frequency operation of the half-bridge inverter of the electronic ballast causes conducted EM emission on the distribution system and results in a significant decline in power quality because of CLF non-linear load characteristics [5]. It is obvious that interference is generated by the internal circuit of the lamp, but the conducted EM emission indirectly depends on the external/mains power supply.

As stated in [4], the source equivalent impedance (Zs) contributes to the EM emission, but the switching frequency of the resonant inverter determines the primary cause of the EM emission magnitude at the point of common coupling (PCC). An EMI filter is the best choice to prevent any kind of electromagnetic disturbance in the power system. Most of the CFL lamps have EMI filters to meet the limits for conducted EM emission set by the CISPR 15 for lighting equipment.

For this work, laboratory measurements have been conducted on CFL lamps to characterize current distortion within the frequency range of 2 kHz and 150 kHz operating from the main power supply. Thus, the LTSpice simulation model for electronic ballast is used to investigate the HF distortion spectrum of compact fluorescent lamps (CFL). The aims are to model the CFL circuit and analyze the main cause of the conducted EM emission of the CFL. Then the model is used to determine the characterization level of the conducted EM emission from the electronic ballast. The simulation results for the lamps with and without the EMI filter are presented. The result of the measurement is presented in both the time and frequency domains.

This article, organized as in Section II, includes the processing of measurement setups in the frequency range of 2 to 150 kHz. The operation of the CFL lamp model and the function of the main parts of the electronic ballast circuit are described in Section III. The simplified model of a CFL lamp is presented in Section IV. The measurement and simulation results in the time and frequency domain for CFL lamps are provided in Section V, and finally, Section VI gives the conclusion of the proposed CFL model circuit.

2. Measurement setup

There is standard to measure conducted EI emission, the connection set up of the instrument must be according to the standard. In this paper the measurement was made according to CISPR-15 standard on typical low cost 11 W CFL lamp with electronic self-ballast. The emission measurements are taken with the line impedance stabilization network (LISN) that is defined in CISPR 16-2-1 for a frequency range from 9 kHz to 30 MHz. LISN must use to filter out the dominant lower order harmonics below 9 kHz.

Before doing any conducted EM emission measurement, the connection set up of the instrument must be according to the standard. A line impedance stabilization network (LISN) must be used to filter out the dominant lower order harmonics. As prescribed in [7], the spectrum of the voltage has been measured by applying a discrete Fourier transform (DFT) to the 200-ms window (5-Hz).

The resulting spectrum components of the signals with 5-Hz resolution $(Y_{C,f})$ is merged into harmonic band of 200 Hz $(Y_{B,b})$ according (1).

$$Y_{B,b} = \sqrt{\sum_{f=b-95Hz}^{b+100Hz} Y_{Cf}^{2}} \tag{1}$$

where $Y_{B,b}$ the r.m.s. output value of each band, b the centre frequency.

3. Operation of CFL lamp model

A. *Self-Oscillating electronic ballast*

A typical single-stage electronic ballast circuit of a CFL lamp consists of six main sections: the ac voltage source, an EMI filter, a diode rectifier, a smoothing filter, a resonant inverter, and the lamp bulb. The AC mains voltage is connected to a bridge rectifier, which then charges a capacitor to produce a smooth DC voltage. The DC bus voltage is then converted into a high frequency (typically more than 40 kHz) square wave voltage using a half-bridge inverter circuit. The gate-drive methods for the switches of the inverter in the electronic ballast are self-exciting controlled types. The high-frequency AC square-wave voltage then drives the resonant tank circuit and becomes filtered to produce a sinusoidal current and voltage at the lamp. As shown in Figure 1, a half-bridge self-oscillating resonant inverter is regarded as one of the most common and cheapest circuit topologies for a CFL lamp.

The single operation of the electronic ballast without a power factor correction (PFC) circuit (power of 25 W) is used since most manufacturers don’t consider PFC due to cost, complex schemes, and implementation of the control algorithms needed.

Active PFC is used in power electronics devices to reduce the low-order harmonic distortion in the current signal much better than passive PFC circuits, but it generates HF harmonics because of switching elements [8].

The ballast serves to supply a suitable high voltage required for igniting the lamp while controlling the amount of current flowing through the lamp to avoid damaging the tube in both types of ballast, the conventional electromagnetic ballast and the high frequency electronic ballast [5,9,10].

The basic parts of the half-bridge inverter are the BJT switches (Q1 and Q2) that conduct alternately, producing a square wave at their junction, and anti-parallel diodes (D5 and D6) on both switches used to protect the overvoltage at the emitter collector (EC) junction and used to avoid the reverse-recovery problem; a path for over-damped or under-damped current; and two transition capacitors used to minimize the turn-off loss of BJT transistors [5].

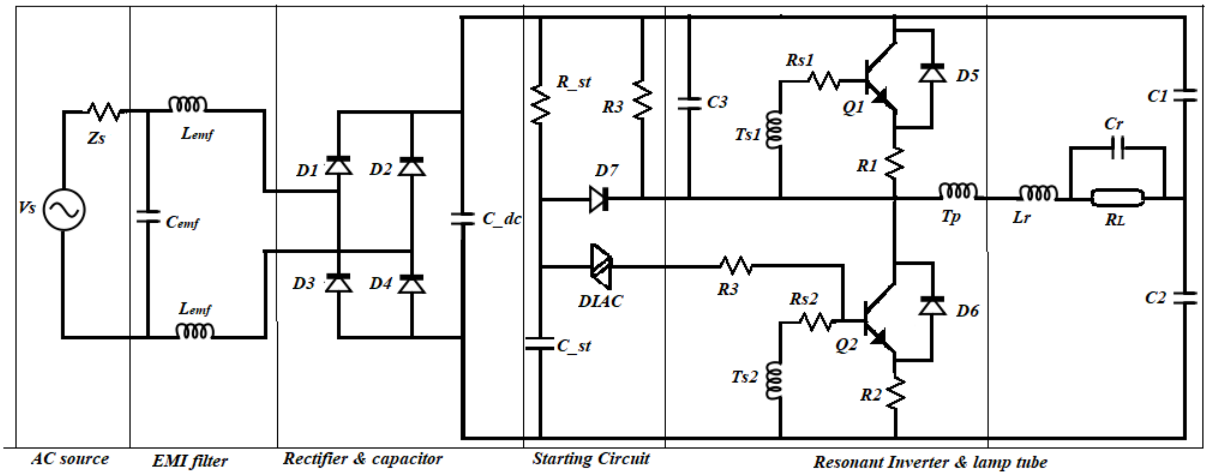

Figure 1. Schematic model of self-oscillating electronic ballast lamp.

Before the half bridge inverter, the starting circuit must activate switch Q2 after charging C_{st} through the high DC voltage V_{dc}, via the resistor R_{st}. And then the DIAC voltage reached a triggering point [5] that is the voltage across Cst reaches 32V, DIAC will breakdown and switched on Q_2. Trigger Circuit has a higher time constant than oscillation frequency in order to guarantee C2 will always discharge through D_7 before it reaches DIAC trigger voltage again [9].

After Q2 is activated, collector-emitter resistance of Q2 becomes a short path for current to start flow through C1-R_L-Q2 and the primary winding of transformer Tp, this induces voltage alternatively into the base of both switches Q1 and Q2 using coupled secondary winding of transformer Ts1 and Ts2. When high frequency voltage crosses zero, the process is reversed and now Q1 is activated, changing the current flow through the fluorescent bulb. Self-oscillation process will be derived by saturable transform Tp, resonate tank inductor Lr and capacitor Cr [5]. That is ON and OFF the switch is controlled by the transformer and resonant inductor and capacitor.

B. *Electrical model for the CFL lamp*

The model is based on 11W CFL lamp operating at a 40 kHz switching frequency. At start-up condition the lamp is open circuit but at high frequency and steady state operation the lamp considers as an equivalent resistance under resonant conditions, that is during the dimming operation, the lamp consider as a variable resistance [10].

The various papers proposed a different mathematical model for the lamp operating at HF. The paper [10,11] use more complex polynomial equation to model the equivalent resistance of the lamp. But articles like [12,13] use linear equation by ignoring filament preheating, temperature, starting behavior and the aging effect of lamps from the model. The electrical model for the lamp equivalent resistance is necessary in order to recognize the HF harmonic distortion.

A CFL lamp with a rated current of 96mA and for a line voltage of 230 V and the line frequency of 50 Hz. At steady state internal circuit of the CFL lamp is modeled by an equivalent resistance [12,13]. The equivalent resistance for 11 W CFL lamp is calculated as given in (2)

$$R_L = \frac{P_L}{I_{L,rms}^2} \tag{2}$$

C. *Smoothing capacitor filter*

The LF harmonics emitted from the rectifier circuit are low-order harmonic emission magnitudes determined by the rectifier and smoothing capacitor. Usually, a single relatively high capacitance is used after the full wave rectification. The filter capacitor is used to limit the ripple in the DC voltage.

In practice, most CFL lamps use an additional inductor element in series with the DC-link capacitor because it provides high impedance at HF to attenuate the harmonic EM emission. The lifetime of a capacitor is affected dramatically by thermal stress or a rise in temperature due to the effects of HF voltage components [15].

D. EMI filter

There are different types of EMI filters for reducing interference from such electrical appliances. The EMI filter is modeled as a low-pass passive filter with a series inductor L (high impedance) and a parallel capacitor C (low impedance). In order to reduce the conducted EM emission levels from the CFL lamp model at PCC, a suitable EMI filter was designed to reduce conducted interference (CM or DM noise) from the electronic ballast [17]. Figure 2 presents the simplified CFL model connected to the grid.

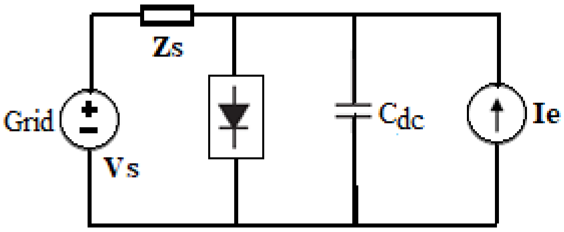

Figure 2. Simplified CFL model connected to the grid.

Assuming the maximum line impedance is 50 ohms for switching frequency of 40 kHz, then the capacitor value is calculated in Equation (3)

$$C_{EMI} = \frac{1}{2\pi f Z_C} \tag{3}$$

To reduce the noise levels in approximately 20 dB/decade at 40 kHz, then inductor is calculated using (4) and (5)

$$A = \frac{Z_s}{Z_s + Z_L} \tag{4}$$

$$Ts = \frac{Z_L}{2\pi f} \tag{5}$$

where, A is linear attenuation; Z_C is capacitive impedance; Z_L is inductor impedance.

E. Series parallel load-resonant model

The main function of the LC resonant network is to provide a steady state high frequency sinusoidal wave to the lamp load, which filters out the higher harmonic components in the square wave signal of the inverter [14].

Parallel loaded resonant inverter is used for this electronic ballast, because high gains voltage and allows zero-voltage switching (ZVS) [14].

The resonant inductor (Lr) and parallel capacitor (Cr) are calculated form the corner/resonant frequency (f_r) and is given in (6) and (7) respectively

$$L_r = \frac{Q * R_L}{\omega_r} \tag{6}$$

$$C_r = \frac{1}{L_r * (\omega_r)^2} \tag{7}$$

Selecting high-enough Quality (Q)-factor value in the resonant circuit, close-to sinusoidal waveforms are achieved at the output

The characteristics impedance (Zo) of the resonant circuit is also defined in (8), as in to relate the quality factor and lamp resistance.

$$Z_0 = \sqrt{\frac{L_r}{C_{bulb}}} = QR_{Lamp} \tag{8}$$

To ensure zero voltage switching (ZVS) always, the switching frequency must be greater than the larger of the resonant frequency [10,14]

At the startup moment, the lamp is regarded as open circuitry, the lamp resistance is infinite, the current in ignition parallel capacitor rises C_{rp} but at the steady state, the current through the ignition capacitor reduces [9,10,14]

4. Simplified model of CFL lamp

For this paper, a simplified model has been developed to represent the simplified model of the CFL lamp. The electronic ballast (EB) is basically a source of high frequency emission [16] and can be represented by a current source as shown in Figure 2.

The simplified configuration of a CFL lamp with a smoothing capacitor, used as a link between the AC grid and the current source, has low impedance for the high frequency current flowing through the capacitor. In the steady state condition, the switching frequency of the half bridge inverter is constant; that is, it draws a steady lamp current because of the self-oscillating resonant circuit and can be modeled as a current source, injecting EM emission into the grid.

The switching inverter is considered the major source of EMI interference in electronic devices since the fast switching action of the inverter generates a square waveform with harmonics noise up to several kilohertz. Table 1 presents the electronic ballast circuit parameters.

Table 1. Electronic ballast circuit parameters.

Parameter	Value/ Rating	Parameter	Value/ Rating	Parameter	Value/ Rating
R_L	1.2 kΩ	2 X BJT switch	13002 HJ	C_2, C_3	47 µF
C_1	2.2nF	C_{dc}	2,2 µF	T_P	200 µH
R_{st1}, R_{st2}	560 kΩ	C_{EMI}	0.08 µF	T_{S1}, T_{S2}	20 µH
R_1, R_2	2,2 Ω	L_{EMI}	1,8mH	R_{S1}, R_{S2}	10 Ω
Cst	22 nF	Lr	4,5mH		
5 X Diodes	1N4007	Cr	2,7 nF		

5. Results and discussion

A. *Time domain result*

The results are presented in both the time domain and the frequency domain. The measured voltage and current waveform are presented in Figure 3; the input current has high frequency noise in addition to LF harmonic distortion.

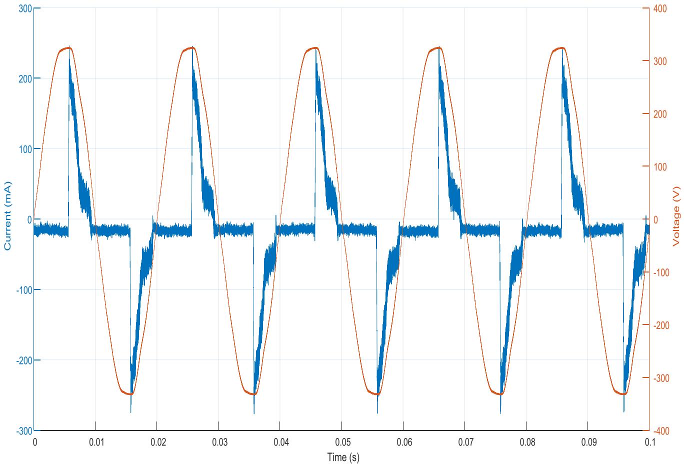

Figure 3. Measured input voltage and current.

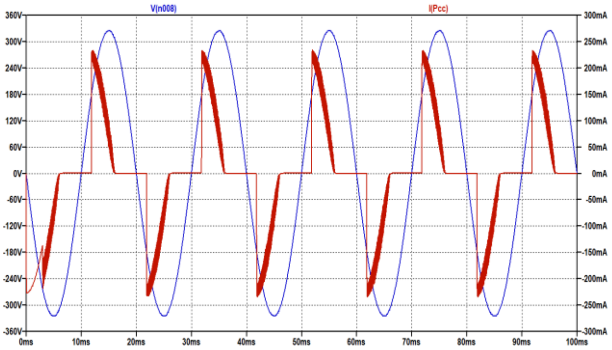

Figure 4. AC input voltage and current on simulation.

The voltage supply from the main network is measured using a digital oscilloscope, but that brings an additional HF component from the grid into the current flowing through the lamp.

Figure 4 shows the simulated voltage and current signal at the point of common connection (PCC). The simulated current signal is heavily distorted, with both low- and high-frequency HF components.The CFL lamp models are based on the typical values of lamp components as presented in Table 1.

The simulated result and the measured current waveform are analogous, even if there is a slight difference due to the distortion of the supply voltage, background noise in the system from other devices; parasitic parameters aren't included in the simulation, etc. The HF noise measurement is influenced by a variety of factors.

B. *Frequency domain result*

The measured result of the conducted EM emission spectrum of the input current is presented in Figure 5. There are some dominant broadband spectrum components around 40 kHz and 80 kHz and a third component around 120 kHz in the CFL lamps, which is associated with the ballast oscillation frequency. The conducted EM emission spectrum of the CFL lamp is characterized by the highest magnitude at switching frequency and decreasing as the frequency increases.

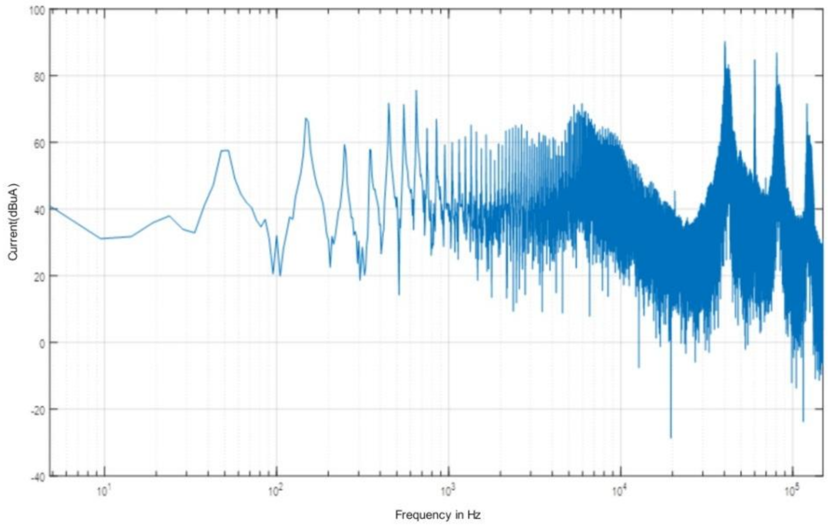

Figure 5. EM Emission spectrum of the input current of a single of CFL lamp.

The conducted EMI is due to high frequency switching operations in the electronic ballast. The main cause is related to the switching action of the MOSFET/BJT (active component).

When the EMI filter is not included in the actual CFL lamp, the FFT of the input current is represented in dB μA as shown in Figure 6, and the highest magnitude occurs at the fundamental switching frequency (40 kHz), with decreasing amplitudes at its harmonics order.

The oscillation frequency for this CFL lamp is around 40 kHz, which is a multiple of the switching frequency (40 kHz) that exists in the system.

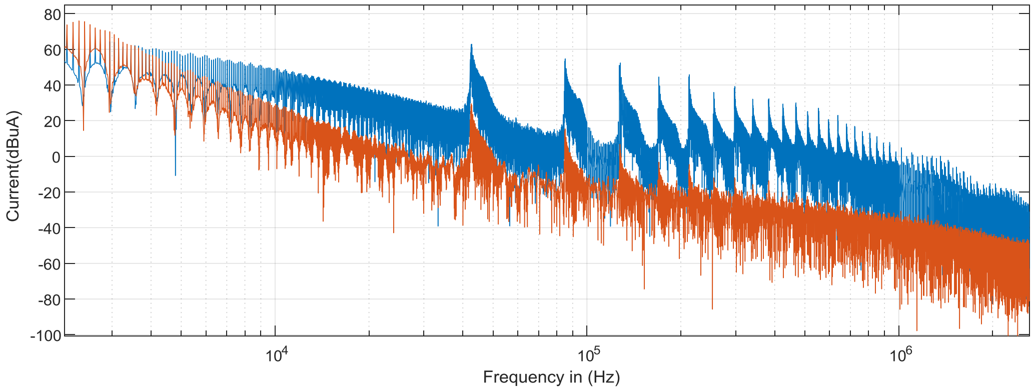

Figure 6. FFT for input current without EMI filter.

Comparative simulation results of the CFL lamp without and with the filter are shown in Table 2.

The EMI filter has reduced harmonic noise up to 20 dBuA for the frequency range above 40 kHz. The comparison of the simulation results with and without the EMI filter is presented in Table 2. The influence of the filter on the signal distortion is examined using the Total Harmonic Distortion for both currents (THDI).

Table 2. Current level distortion.

Simulated Circuit	I_{rms} (mA)	THD_i (0-150 kHz) (%)	THD_i (<2 kHz) (%)	THD_i (2 kHz-150 kHz) (%)
With EMI filter	95,54 mA	97,78%	97,77%	1.4%
Without EMI filter	81,27 mA	91.07%	90,23%	12.34%

The current THD increases when an EMI filter is included in the simulation model, but it reduces the high frequency distortion in the supraharmonic range because the EMI filter acts as a low-pass filter and removes conducted EM emission. The result is that the observed demand for adequate filtering components to be incorporated into the electronic ballast circuitry.

6. Conclusions

The aim of this paper is to model the CFL ballast circuit and show the level of the conducted EM emissions generated by the electronic ballast. It also presents a comparison of harmonic distortion from the electronic ballast with and without an EMI filter. The self-oscillating electronic ballast was an approximate model that allowed obtaining simulation results in steady state conditions close to experimental results. However, an EMI filter in the ballast circuit can reduce the level of high-frequency emission. However, in order to get a more accurate result, it is necessary to find out the main cause of conducted EM emission in the ballast circuit since the HF distortion spreads through the LV network in the current signal between electronic devices. In the future scope of this work, the proposed analysis can be performed with light emitting diode (LED) lamps as LEDs are future of the lighting system.

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Conflict of interest

There is no conflict of interest of any authors in any form.

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