Class-E^2 Capacitive Wireless Power Transfer DC-DC Converter for LED Lighting Applications

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***Abstract*—In this paper, a Capacitive Wireless Power Transfer (CWPT) Class-E2 DC-DC converter for LED lighting application is presented. The design procedure to operate under Zero Voltage Switching (ZVS) conditions is proposed. The design procedure of the rectifier and the impedance matching with the CWPT is analyzed. The achievement of ZVS condition and the desired output power under the nominal operating condition are evaluated with several simulation results.**

***Index Terms*-- LED Lightning, Class-E inverter, DC-DC Power Converter.**

I. Introduction

LEDs (Light Emitting Diodes) offer several advantages over traditional lighting sources. Firstly, this technology can produce the same amount of light as traditional lighting sources while using significantly less power [1]. In addition, LEDs have a much longer lifespan than traditional lighting sources leading to significant cost savings over time [2]. Finally, they are environmentally friendly and are characterized by higher resistance to shock and vibration, making them ideal for use in harsh environments and increasing durability [3].

LED lighting requires a constant and stable power source to operate efficiently and effectively. DC-DC power converters can provide this by converting the voltage of the power source to a level that is suitable for LED lights [4]. This ensures that the LEDs receive the right amount of power they need while minimizing energy waste and increasing lifespan [5]. Additionally, a DC-DC power converter allows LED lights to be used with a wider range of power sources, including batteries and solar panels [6]. This is important for applications with limited or unavailable access to an AC power source [7].

One of the primary characteristics required of a LED driver is its conversion efficiency [8]-[9]. If the driver converter is not well designed, a large amount of power will be dissipated, which may overheat the LED lamp, reducing its lifespan [10]. Another important aspect is related to Electromagnetic Interference (EMI) [11]. In fact, LED drivers can generate electrical noise that can interfere with other electronic devices or cause flickering in the LED lighting [12].

These two main problems could be solved using resonant converters. Soft switching techniques minimize switching losses by ensuring that the voltage or current waveforms transition smoothly between their high and low states, reducing the amount of energy lost as heat during each switching cycle [13]. This is typically achieved by carefully tuning the resonant circuit, allowing for a smooth and efficient transfer of energy between the input and output of the converter [14]-[15]. This allows for operating at a higher switching frequency, leading to the miniaturization process of the LED driver, which usually cannot be excessively bulky.

Since the overall dimensions must be minimized, choosing the topology is a key aspect. The Class-E resonant converter is an excellent compromise between conversion efficiency and overall dimensions. In fact, this converter is characterized by a single power switch. Still, thanks to the ability to work in Zero Voltage Switching (ZVS) conditions, it can manage power ratings compatible with LED lighting applications using a minimum number of components. Additionally, if properly sized, this topology can achieve Zero Derivative Switching (ZDS), minimizing EMI issues [16]-[18].

This topology has already been widely used for LED lighting applications [19]-[25].

In this paper, a Class-E converter is used to supply a LED lamp exploiting Capacitive Wireless Power Transfer (CWPT). Differently from Inductive Wireless Power Transfer (IWPT), this technology uses electric fields to transmit electrical power wirelessly between a transmitter and a receiver. Usually, the transmitter and the receiver consist of aluminum plates separated by a small distance. The transmitter generates a high-frequency AC voltage that is applied across the transmitting electrodes, creating an electric field that extends into the space between the electrodes [26]. When the receiver is placed within this electric field, an electrical current is induced in the receiving electrodes.

The paper is organized as follows. In Section II, the simplified model of the CWPT system is presented. In Section III, the equivalent electrical model of LED lighting is explored. In Section IV, the design procedures of the Class-E inverter and Class-E rectifier are presented. The

circuit is simulated in PLECS, and the results are shown in Section V. Finally, in Section VI, the obtained results are discussed.

II. Capacitive Wireless Power Transfer Modeling

II. In Fig. 1, the capacitive four plates systems are shown. The plates P_1 and P_2 are located on the primary side, while plates P_3 and P_4 are on the secondary side. The capacitances C_{ij} model the electric coupling between the plate P_i and P_j.

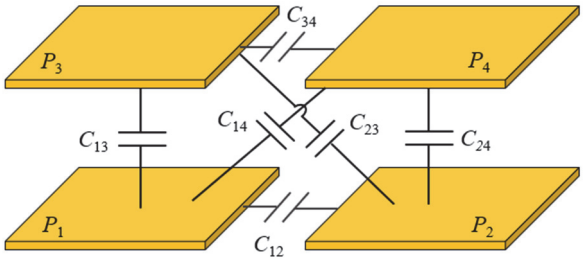

Fig. 1. Four plates capacitive system and related capacitances.

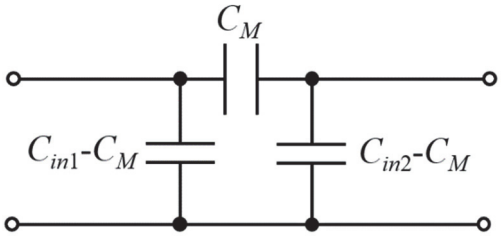

Fig. 2. Equivalent electrical model of CWPT system.

Several equivalent electric circuits have been proposed in the literature. In this paper, the π-equivalent model, proposed in [27], is adopted. The four plates can be equivalently represented by three capacitors, as shown in Fig. 2. The values of each capacitance can be calculated as

$$C_M = \frac{C_{24}C_{13} - C_{14}C_{23}}{C_{13} + C_{14} + C_{23} + C_{24}} \quad (1)$$

$$C_{in1} = C_{12} + \frac{(C_{13} + C_{14})(C_{23} + C_{24})}{C_{13} + C_{14} + C_{23} + C_{24}} \quad (2)$$

$$C_{in2} = C_{34} + \frac{(C_{13} + C_{23})(C_{14} + C_{24})}{C_{13} + C_{14} + C_{23} + C_{24}} \quad (3)$$

It is assumed that the distance between P_1-P_3 and P_2-P_4 is large enough to neglect the cross-couplings C_{12}, C_{14}, C_{23}, and C_{34}. In addition, it is assumed that the plates have the same dimension. Under these assumptions, the capacitive coupling can be simply modelled with a capacitance C_M=C/2.

The capacitance between two square plates must also consider the fringing field effects, which are more significant when the distance between P_1-P_3 and P_2-P_4 is comparable with the plate dimension. Several studies have been performed to estimate the coupling between square metal plates [28]-[29]. In [29], the coupling between two square plates with side l separated by an airgap d is

$$C = \varepsilon_0 \varepsilon_r \left[1 + 2.34 \left(\frac{d}{w} \right)^{0.891} \right] \left(\frac{l^2}{d} \right) \quad (4)$$

Where w is the width of the plates and $\varepsilon = \varepsilon_0 \varepsilon_r = 8.875 \cdot 10^{-12}$ F/m is the dielectric constant of air.

Assuming the use plates with l = 50 mm, w = 2 mm, and operating with an air gap d =10 mm, a capacitance C_M=2.31 nF is obtained. Thus, neglecting the cross-coupling capacitances, the electrical coupling between the four plates can be modeled by an equivalent capacitance $C = C_M / 2$ = 1.16 nF.

III. LED Lightning Modeling

The electrical equivalent model of a light-emitting diode (LED) is typically represented using a combination of a diode and a current source. The diode represents the non-linear current-voltage (I-V) characteristics of the LED, while the current source represents the light emission of the LED, which is proportional to the current flowing through it.

The I-V characteristics of an LED are non-linear and can be described using an exponential function. The forward voltage drops across the LED, which is typically around 2 to 3 volts, depending on the LED material and colour and on the current through the LED. At low voltages, the LED has a high resistance and a low current flow. Once the forward voltage reaches the threshold value, the LED turns on, and the current through the LED increases rapidly with a small increase in voltage as follows:

$$i = I_S \left(e^{\frac{qv}{NkT_m}} - 1 \right) \quad (5)$$

where q is the elementary charge on an electron, k is the Boltzmann constant, N is the emission coefficient, I_S is the saturation current, and T_m is the temperature at which the diode parameters are specified.

In Table I, the characteristics of the LED used in this paper are summarized.

TABLE I. LED Characteristics

Parameter	Description	Value
q	Elementary Charge on an Electron	$1.602176 \cdot 10^{-19}$ C
k	Boltzmann Constant	$1.3806503 \cdot 10^{-23}$ J/K
N	Emission Coefficient	10
I_s	Saturation Current	$5 \cdot 10^{-7}$ A
T_m	Measurement Temperature	25°C

In the electrical equivalent model, the diode is typically represented using a current-controlled current source, where the current source produces a current that is proportional to the exponential function of the diode voltage.

IV. Class-E DC-DC Converter Design

Once the capacitive coupling C_M has been estimated and the LED load modeled, the design of the Class-E inverter

and rectifier that allows to delivery of the desired output power operating in ZVS condition is presented.
The electrical constraints of the proposed circuits are summarized in Table II.

TABLE II. LED CHARACTERISTICS

Parameter	Description	Value
f_s	Operating Frequency	2 MHz
R_L	Load Resistance	10 Ω
I_o	Output Current	2.2 A

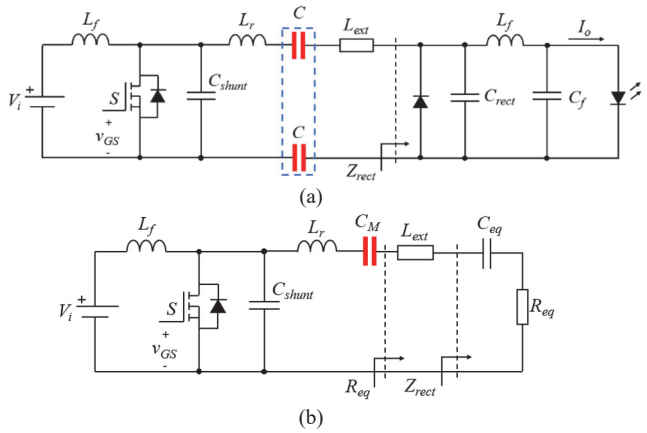

Fig. 3. Class-E2 resonant converter. (a) Electrical circuit. (b) Circuit with the equivalent model of the rectifier.

where ω is the angular frequency, and R_{eq} is the equivalent resistance seen by the inverter, as shown in Fig. 3(a). Since the impedance of the rectifier Z_{rect} has a real and imaginary part, an external inductance is added, such as X_{ext}=-X_{rect}. In this way, the impedance R_{eq} seen by the inverter is purely resistive, and ZVS can be reached.

A. Class-E Low dv/dt Rectifier with Parallel Capacitor

A Class E low dv/dt rectifier with a parallel capacitor is shown in Fig. 3(a). The rectifier consists of a diode, a shunt capacitor C, and a second-order low-pass output filter L_f - C_f. As shown in [30], the equivalent resistance can be calculated by the following equations:

$$\tan(\varphi)=\frac{1-\cos(2\pi D)}{2\pi(1-D)+\sin(2\pi D)} \tag{6}$$

$$\frac{R_{eq}}{R_L}=2\sin^2(\varphi) \tag{7}$$

$$\omega C_{rect}R_{eq}=\omega C_{rect}R_L\frac{R_{eq}}{R_L}=\frac{\sin^2\varphi}{\pi}\left[1-2\pi^2(1-D)^2-\cos(2\pi D)+\frac{2\pi(1-D)+\sin(2\pi D)}{\tan\varphi}\right] \tag{8}$$

B. Class-E DC-AC Inverter

The topology of the Class-E inverter is shown in Fig. 3(b). In this paper, the design procedure presented in [30] has been used to design the components. Assuming to operate at a constant duty cycle D, the components can be designed using the equations:

$$\frac{C_{eq}}{C}=\pi\left[\pi(1-D)+\sin(2\pi D)-\frac{1}{4}\cos(2\varphi)\sin(4\pi D)-\frac{1}{2}\sin(2\varphi)\sin^2(2\pi D)-2\pi(1-D)\sin\varphi\sin(2\pi D-\varphi)\right]^{-1} \tag{9}$$

Assuming to operate at fixed duty cycle D=0.5, the previous equations can be simplified to C_{rect}=1/($\pi\omega R_L$), R_{eq}=0.5768·R_L and C_{eq}=4.726·C_{rect}. The transformer turn ratio n is assumed to be n=1. Using the previous equations and assuming to operate at a constant frequency f_s=2MHz and duty cycle D=0.5, the components' values are summarized in Table III.
A load resistor R_L=10 Ω was selected to obtain an output voltage and current compatible with this application.

TABLE III. LED CHARACTERISTICS

Parameter	Description	Value
R_L	Load Resistance	10 Ω
C_f	Filter Capacitance	10 µF
L_f	Filter Inductance	100 µH
C_{eq}	Equivalent Capacitance	12 nF
L_{ext}	External Inductance	0.52 µH
V_F	Diode Forward Voltage	0.3 V
r_F	Diode Conduction Resistance	0.1 Ω

$$V_i=\sqrt{\frac{\pi^2+4}{8}P_oR_{eq}} \tag{10}$$

$$C_{shunt}=\frac{8}{\pi(\pi^2+4)}\frac{1}{\omega C_1 R_{eq}} \tag{11}$$

$$L_r=\frac{Q_L R_{eq}}{\omega} \tag{12}$$

$$C_r=\frac{1}{\omega R_{eq}\left(Q_L-\frac{\pi(\pi^2-4)}{16}\right)} \tag{13}$$

$$L_f=\frac{14\pi R_{eq}}{\omega} \tag{14}$$

Where Q_L is the quality factor and R_{eq} is the equivalent resistance of the rectifier. Using the values shown in Table II, the values of the components using (6)-(10) are summarized in Table IV.

V. SIMULATION RESULTS

A Plecs simulation has been performed, as shown in Fig.4

TABLE IV. LED CHARACTERISTICS

Parameter	Description	Value
L_f / r_{Lf}	Choke Inductor / Parasitic Resistance	200 µH / 50 mΩ
C_{shunt} / r_{Cshunt}	Shunt Capacitor / Parasitic Ressitance	1.9 nF/ 50 mΩ
V_i	Input DC Voltage	25.8 V
L_r / r_{Lr}	Resonant Inductor / Parasitic Resistance	6.1 µH/ 50 mΩ

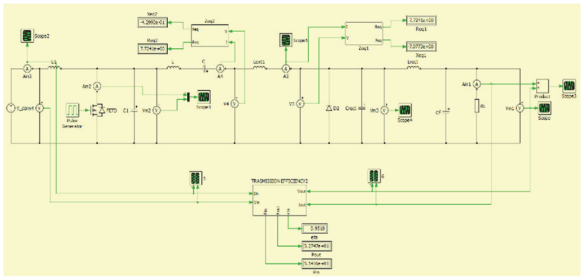

Fig. 4. Plecs simulation schematic of the electrical circuit.

In Fig. 5, the drain-to-source voltage and current waveforms on the MOSFET are shown. As it can be seen the ZVS condition is reached, leading to low switching losses.

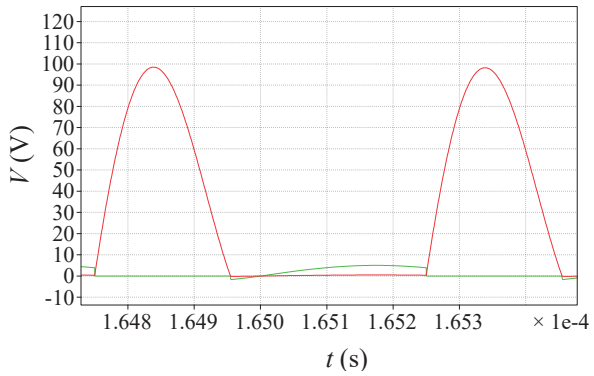

Fig. 5. Power MOSFET drain-to-source voltage (red trace) and drain-to-source current (green trace).

In Fig. 6 the current on the resonant tank is shown. As expected, since the converter operates in resonance, the current is approximately sinusoidal.

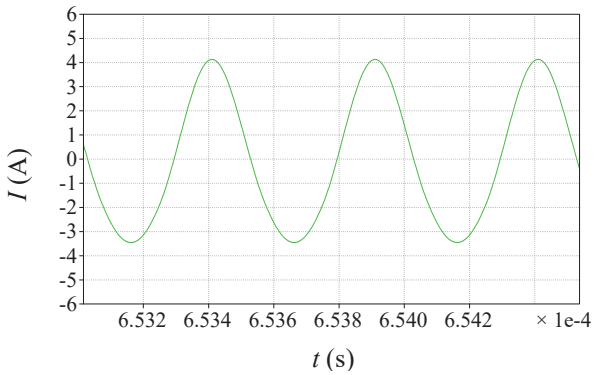

Fig. 6. Primary resonant current.

In Fig. 7, the voltage and the current on the rectifier diode is shown. As it can be seen, also here the ZVS consition is reached, leading to low power losses.

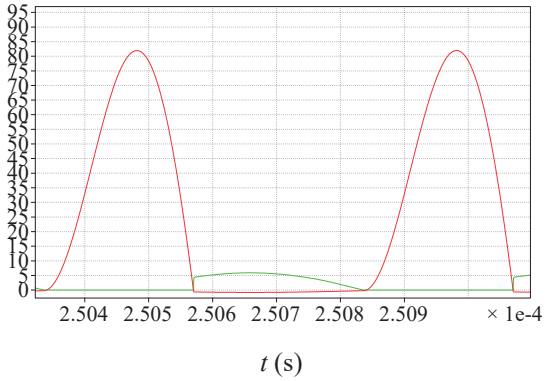

Fig. 7. Voltage across the rectifier diode (red trace) and current (green trace).

Finally, in Fig. 8, the transient of the output power is shown. As it can be seen, the desired value of output power is reached, allowing to light the LEDs.

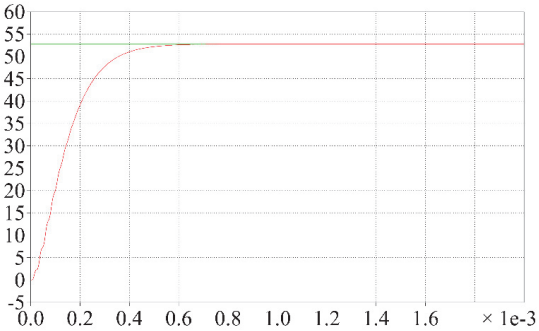

Fig. 8. Transient of the output voltage vo (red trace) and target value (green trace).

The DC-DC conversion efficiency measured by simulation is $\eta_{DC\text{-}DC} = 0.96$.

VI. CONCLUSIONS

In this paper a Class-E^2 CWPT DC-DC converter for lighting applications is presented. The model of the electric coupling between capacitive plates is presented. Starting from the model of the LEDs load, the design procedure of the Class-E rectifier is proposed. The impedance matching required to obtain operate the Class-E inverter at ZVS is presented. The performance of the CWPT system is evaluated through several PLECS simulation.

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