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Analysis and Design of LLC Resonant Converter for Fuel Cell Used in electrical vehicle

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Abstract— This paper presents design and simulation of full bridge LLC resonant converter suitable for fuel cell used in electrical vehicle. LLC converter has several desired features such as high efficiency, low electromagnetic interference (EMI) and high power density. This paper provides a detailed practical design aspect of full bridge LLC resonant converter. The LLC converter is implemented with a full-bridge on the primary side and a full-bridge rectifier on the secondary side. It includes designing the transformer turns ratio, and selecting the components such as resonant inductor, resonant capacitor and magnetizing inductor. Also performance parameters such as voltage gain and output voltage ripple are calculated. Simulation of LLC resonant converter is carried out using MATLAB / SIMULINK and the results are verified.

***Keywords*— LLC resonant converter, fuel cell, Electrical Vehicle, full-bridge, Planar transformer.**

I. INTRODUCTION

Environmental issues, energy crises, and concerns regarding peaking oil production has spurred research into and development of various types of hybrid electrical vehicles [1]. To satisfy the load demands in vehicular application, we must incorporating fuel cells and energy storage devices, such as ultra-capacitors. Fuel Cells (FCs) produce an electrical energy from an electrochemical reaction between a hydrogen-rich fuel gas and an oxidant (air or oxygen) [1] [2]. The hydrogen fuel cells are fully ecological, taking into account that heat and water are the only by-products, which are excreted into the environment. In order to use the electrical energy which is produced by the fuel cells, characterized by slow dynamic response, low output voltage and large voltage variations, static power converters are researched widely throughout the world [3] [4] [5] [6].

In the dc/dc isolation stage, resonant converters are preferable at high-voltage and high-power. In particular, multi-resonance-based LLC topology has several advantages over other resonant topologies, such as good voltage regulation performance at light load condition, the ability to operate with zero-voltage switching (ZVS) over wide load ranges, no diode reverse recovery losses through soft commutation, low voltage stress on the output diodes, and having only a capacitor as the output filter compared with the conventional LC filters [7] [8] [9] [10] [11].

Basically the resonant technique process power in a sinusoid form and the switching devices are softly commuted. Therefore the switching losses and noise can be theoretically reduced. Hence resonant converters have drawn a lot of attention in various applications. It consists of two inductors ,one capacitor and the converter can regulate the output voltage in contradiction of line and load variation over a wide range [8] [12].

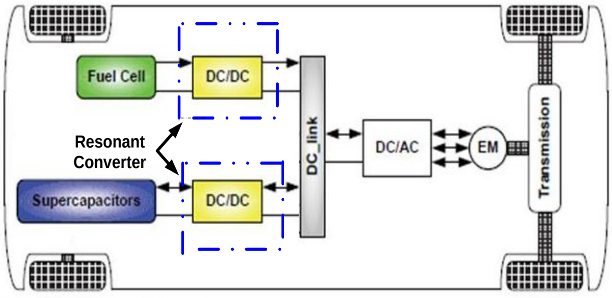

Fig. 1: Electrical vehicle structure

This paper is organized as follows. Section 2: circuit descriptions of the proposed LLC resonant converter are explained in detail, Section 3: presentation of the fuel cell. The analysis of converter for DC characteristics is presented in Section 4. In section 5, design examples of proposed converter are introduced. Then, the simulation results based on LLC resonant converter for high-voltage application are described in section 6. The final part is reserved to conclude the paper.

II. TOPOLOGY OF FUEL CELL LLC RESONANT CONVERTER

Fig. 2 shows a typical topology of a LLC resonant converter. The converter arrangement has three main parts. Such as switching bridge, LLC tank, transformer and rectifier.

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Power switches K1, K4 and K2, K3 which are generally IGBTs to be capable to work at high frequencies in the square wave generator creates a square wave voltage driving with 50% duty cycle for each switch. Usually introduced a small dead time between the consecutive transitions. A half-bridge and full-bridge type can used to make the square wave generator stage. The resonant tank, also called a resonant network, consists of the capacitance (Cr) and two inductances series resonant inductance (Lr) and the transformer's magnetizing inductance (Lm). The higher harmonic current in the resonant tank can be filtered. Basically, in the resonant tank can allow only sinusoidal current to flow through, even though used a square wave voltage. The transformer turns ratio is 'n'. The resonant network circulates the electrical current and as a result, the energy is circulated and delivered to the load through the transformer. The transformer's primary winding accepts a bipolar square wave voltage. This voltage is transmitted to the secondary side, with the transformer given that both electrical isolation and the turn's ratio to distribute the required voltage level to the output. On the converter's secondary side, establishes a full-bridge rectifier to convert AC input to DC output and supply the load R. The output capacitor smooth's the rectified voltage. [13] [14] [15] [16].

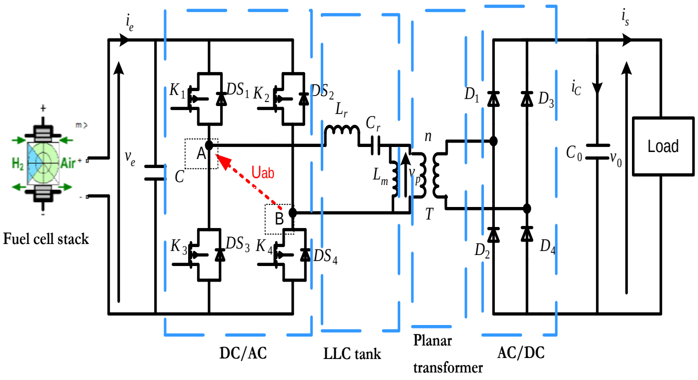

Fig. 2 Schematic diagram of full-bridge LLC resonant circuit

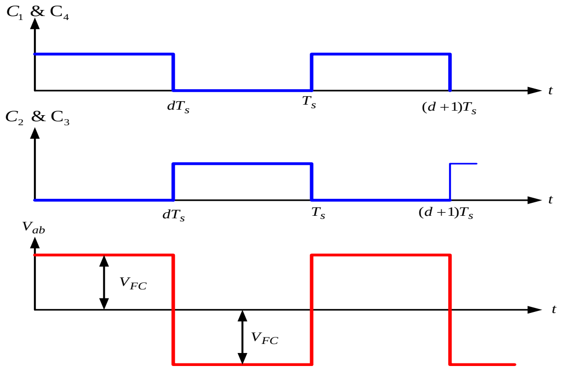

Fig. 3 Control signals

The switching bridge generates a square waveform to excite the LLC resonant thank (composed by two inductors L_r, L_m and capacitor C_r). Fig. 3 shows the operation converter and the input voltage of the resonant tank. C_1, C_2, C3 and C_4 denote, respectively, the control signals of the switches K_1, K_2, K_3 and K_4, where Ts and d denotes respectively the switching period and the controlled duty ratio.

III. DYNAMIC MODELING OF FUEL CELL

A fuel cell is an energy conversion system that converts chemical energy into electrical energy without any thermal or mechanical process. The operating principle of a fuel cell is described by a chemical reaction that reacted hydrogen and oxygen to produce electricity, heat and water, according to the chemical reaction given by equation (1)

$$\begin{cases} 2H_2 \rightarrow 4H^+ + 4e^- \\ O_2 + 4H^+ + e^- \rightarrow 2H_2O \\ 2H_2 + O_2 \rightarrow 2H_2O + electricity + heat \end{cases} \qquad (1)$$

There are many fuel cell models; each model has its own specificities and benefits, according to the phenomena studied. The chosen model should be simple and accurate.

Indeed, this work presents an electrochemical model which can be used to predict the fuel cell behavior in static and dynamic conditions [1] [2] [4].

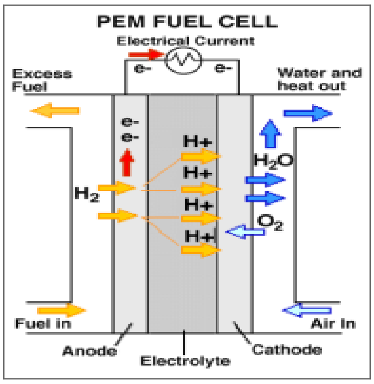

Fig. 4 Illustration of a typical fuel cell structure

The fuel cell voltage depends on the partial pressures of hydrogen and oxygen, the chemical reaction temperature of the membrane hydration and the output current. It is defined by the following equation.

$$V_{FC} = E_{Nernst} - V_{act} - V_{ohm} - V_{con} \qquad (2)$$

Where:

$$E_{Nernst} = 1.229 + \frac{RT}{n_e F} ln\left(\frac{PH_2\sqrt{PO_2}}{PH_2O}\right) \qquad (3)$$

$$\Delta V_{Act} = \frac{RT}{n_e F} ln\left(\frac{i_{FC}}{i_0}\right) \tag{4}$$

$$\Delta V_{Ohm} = R_{FC} i_{FC} \tag{5}$$

$$\Delta V_{Con} = -\frac{RT}{\alpha n_e F} ln\left(1 - \frac{i_{FC}}{i_l}\right) \tag{6}$$

E_{Nernst}: the average thermodynamic potential of each unit cell.

V_{Act}: the activation voltage drop.
V_{Ohm}: the Ohmic voltage drop.
V_{Con}: the concentration voltage drop.

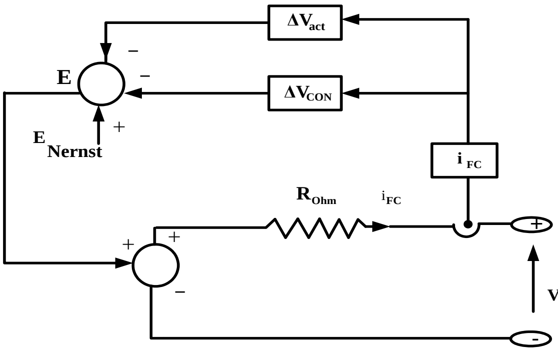

Fig. 5 The electrical model of a fuel cell

The polarization curve of a fuel cell is that which represents the battery voltage as a function of current output. This curve is presented for different temperature values. Fuel cell polarization curves increase with increasing of operating temperature such as shown in Fig. 6.

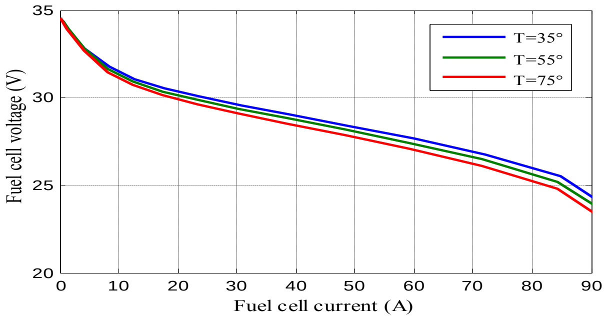

Fig. 6 Polarization curve at different temperatures.

IV. ANALYSIS OF LLC RESONANT CONVERTER

DC characteristics of the LLC resonant converter are discussed in this paper. The equivalent circuit of the LLC topology is derived by applying first harmonic approximation (FHA) acquires an input-output response in the frequency domain. A full-bridge converter as shown in Fig. 2 is to analyze at the LLC resonant circuit. Its equivalent circuit can be represents in fig. 7.

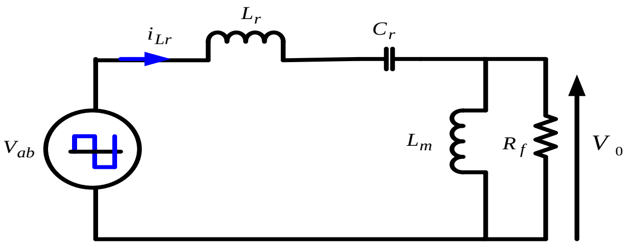

Fig. 7 Equivalent resonant circuit

The resonant tank gain is magnitude of its transfer function is defined as the ratio of output and input voltage.

$$\frac{|V_0(s)|}{|V_{ab}(s)|} = \frac{(m-1)(F_x)^2}{\sqrt{[(m(F_x)^2-1)^2 + (F_x)^2((F_x)^2-1)^2(m-1)^2 Q^2]}} \tag{7}$$

Therefore the standardized transfer function with the following factors is defined.
The resonant frequency:

$$f_r = \frac{1}{2\pi\sqrt{L_r.C_r}} \tag{8}$$

The quality factor can be expressed as following:

$$Q = \frac{\sqrt{L_r / C_r}}{R_f} \tag{9}$$

The reflected load resistance

$$R_f = \frac{8}{\pi^2}.\frac{N_p^2}{N_s^2}.R_0 \tag{10}$$

The normalized switching frequency

$$F_x = \frac{f_s}{f_r} \tag{11}$$

The ratio of total primary inductance to resonant inductance:

$$m = \frac{L_r + L_m}{L_r} \tag{12}$$

One can plot the resonant tank gain K with the normalized switching frequency for different values of Quality factor Q and any single value of m, as shown in Fig. 8. The selection of the m value will be discussed in a later section of this document, but m=5 were used as an example.
It can be seen in Fig. 8 that low Q curves belong to lighter load operation while higher Q curves represent heavier loads. It's also seen that all Q curves (load conditions) cross at the resonant frequency point (at f=1 or fs=fr) and have a unity gain.

Fig. 9 shows that all gain curves has peaks which define the boundary between the inductive and capacitive impedances of the resonant tank, hence we can define the inductive and capacitive operation regions as shaded in the plot, the objective of defining both regions is because it is desired to maintain an inductive operation across the entire input voltage and load current ranges, and never fall into the capacitive region operation. Such requirement is due to that Zero Voltage Switching (ZVS) is only achieved in the inductive region, in addition to that capacitive operation means that current leads the voltage, so the current in the IGBT will reverse direction before the IGBT turns off, then after the IGBT turns off the reverse current will flow in the IGBT's body diode, which will cause a body diode hard commutation once the other IGBT in the bridge turns on, which in turn will cause reverse recovery losses and noise, and might cause high current spikes and device failure.

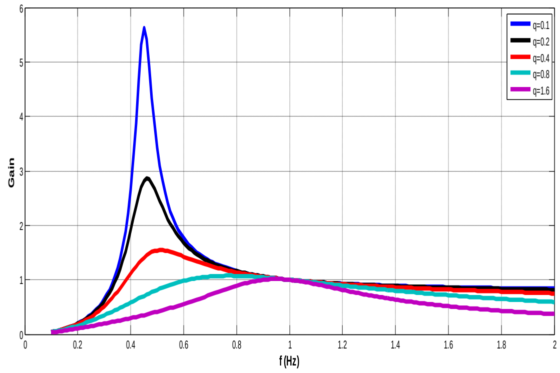

Fig.8 Gain against G with Q as parameter

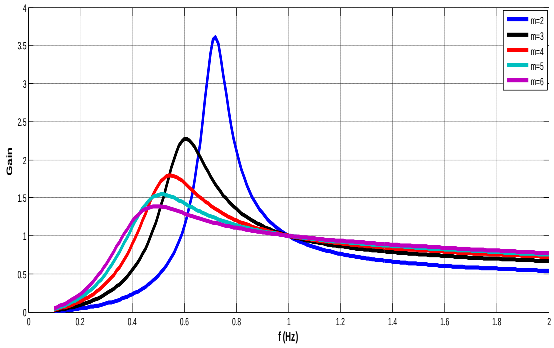

Fig. 9 Gain against G with m as parameter

The bandwidth (distance between peak gain frequency and **f**r) is determined by **m**. For a proper control of the converter the bandwidth should not be too small. At first **m** is chosen according to a proper bandwidth (Fig. 9). Then different **Q** values are plotted (see Fig. 8). Choosing the curve which meets the requested peak gain defines **m** and **Q**.

V. DESIGN OF LLC RESONANT CONVERTER

In this paragraph, a design procedure using the schematic in Fig. 7 as reference. A LLC resonant converter with 180V/300W output has been selected as a design example. The design specifications are listed in the following table.

TABLE I. LLC SPECIFICATIONS

Parameters		Values
Input voltage	V_e	30V
Output voltage	V_0	180V
Output power	**P**	300W
Switching frequency	f_s	20Khz

The proposed design procedure can be outlined in the followings steps:

- Step 1: Determine the transformer turns ratio.

The transformer turns ratio is given as:

$$n = \frac{N_s}{N_p} = \frac{2(V_o + 2V_d)}{M(F_x)V_{FC}} = 7 \qquad (13)$$

- Step 2: Calculate the fictive load resistance

The fictive load resistance is obtained by the equation (10)

$$R_f = 1.78\,\Omega$$

- Step 3: Calculate the components of the resonant thank

If we choice $Q = 0.4$ and m =5, the resonant parameters are obtained as:

$$L_r = (Q.R_f)^2 C_r \qquad (14)$$

$$L_r C_r = \frac{1}{4\pi^2 f^2{}_r} \qquad (15)$$

$$L_m = (m-1)L_r \qquad (16)$$

If we insuring (14) in (15) and (16), the values of the resonant components are:

$$\begin{cases} L_r = 6.3\mu H \\ C_r = 12.4\mu F \\ L_m = 25.1\mu H \end{cases}$$

VI. SIMULATION RESULTS

Simulation studies are carried out using MATLAB/SIMULINK and the simulation circuit of full bridge LLC Resonant DC-DC Converter for an input of 30v is shown in Fig. 2.

The driving pulse of switches K1 and K3 with phase delay of 0° and duty ratio 0.5 is obtained. Driving pulse of switches K1 and K3, current and voltage waveforms are as shown in Fig. 10.

The driving pulse of switches K2 and K4 with phase delay of 180° and duty ratio 0.5 is obtained. Driving pulse of switches K2 and K4, current and voltage waveforms are as shown in Fig. 11.

Output voltage of inverter and current through resonant components is as shown in Fig. 12 and Fig. 13, Fig. 14 shows the simulated voltage waveforms resultant to the primary side and secondary side of the transformer.

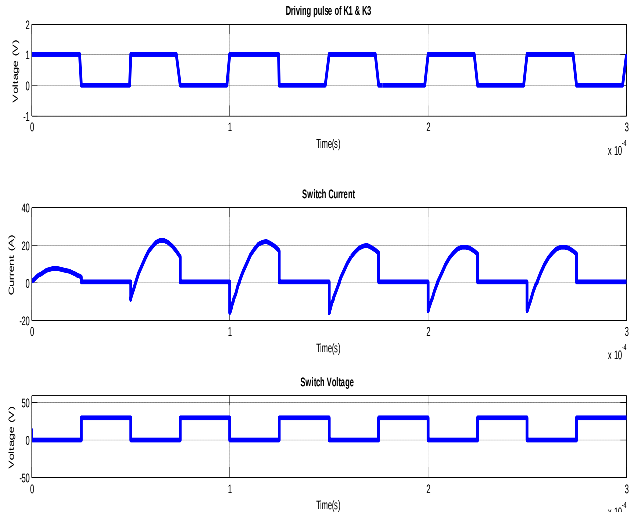

Fig. 10 Driving pulse of switches K1 & K3, current and voltage wavefroms

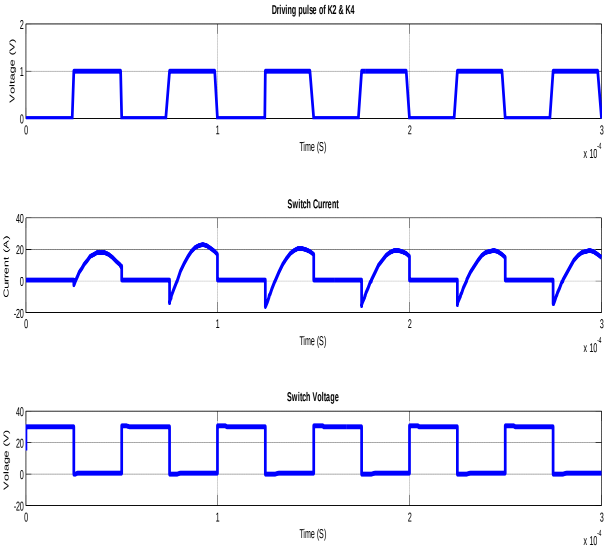

Fig. 11 Driving pulse of Switch K2 & K4, current and voltage wavefroms

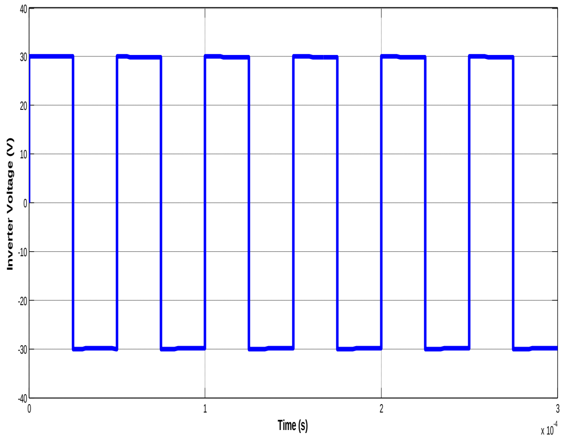

Fig. 12 Output voltage of inverter

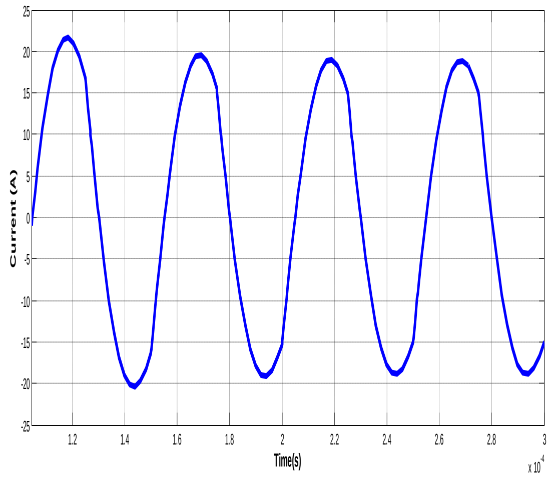

Fig. 13 Current through resonant components

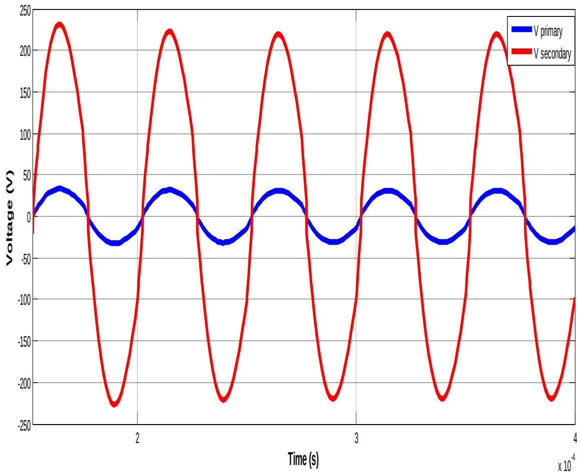

Fig. 14 Primary and secondary voltage of transformer

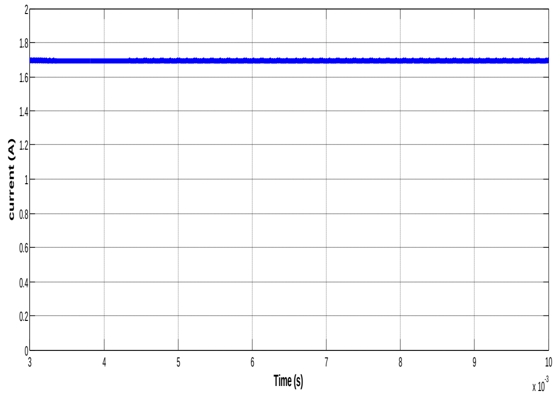

Fig. 15 Output current of LLC resonant converter

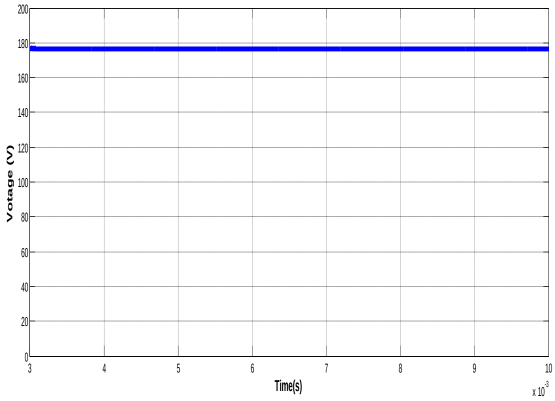

Fig. 16 Output voltage of LLC resonant converter.

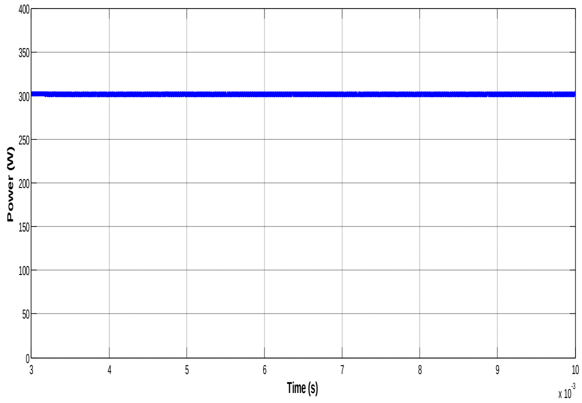

Fig. 17 Output power of LLC resonant converter.

Fig. 15, Fig. 16 and Fig. 17 shows the evolution of output current, output voltage and output power of LLC resonant converter under normal load conditions. It is observed that soft-commutation of both out diodes and IGBT's are achieved. So that simulated output power is near to the estimated value with the input voltage of 30V.

VII. CONCLUSION

The paper presents a design procedure of Full Bridge LLC resonant converter for fuel cell used in electrical vehicle. Theoretical values of resonant component values are calculated using the design equations. Simulation results are provided for LLC resonant converter an input voltage of 30V. The voltage gain and output voltage ripple of LLC resonant converter is calculated which shows that the ripple is less in the proposed converter.

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