International Journal of Power Control and Computation(IJPCSC)
Vol 6. No.2 – Jan-March 2014 Pp. 70-75
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available at : www.ijcns.com
ISSN: 0976-268X

A HIGH EFFICIENCY FUEL CELL REPLACEDBY AN LLC RESONANT DC-DC CONVERTER

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ABSTRACT

In this paper, a high-efficiency fuel cell implemented by an LLC resonant dc–dc converter is proposed to save the cost and energy of fuel cell. The proposed converter has zero-voltage switching (ZVS) operation of the primary switches and zero-current switching (ZCS) operation of the rectifier diodes. By frequency modulation control, the output impedance of an LLC resonant converter can be regulated from zero to infinite without shunt or serial resistors. Proton Exchange Membrane fuel cell (PEMFC) is one of the promising technologies for the distributed power generation. For designing high efficiency fuel cell power systems, a suitable DC-DC converter is required. Among the various topologies, interleavedboost converter (IBC) is considered as a better solution for fuel cell systems, due to improved electrical performance, reduced weight and size.

I. INTRODUCTION

PEMFC is a nonlinear, multiple-input and -output, strongly coupled, and large-delay dynamic system, that converts chemical potential into electric power. In past decades, fuel cells with many reasons such as excellent reliability, high efficiency, high power density, low operating temperature and their low emissions to the environment have been considered by researchers. An electrochemical equivalent model of PEMFC is presented to study the transient and dynamic behavior of PEM fuel cell. A boost converter converts a DC voltage to a higher DC voltage. It can however inject current harmonics into the fuel cell which might otherwise damage the durability of the fuel cell. Among numerous resonant converters, the series resonant converter (SRC) provides satisfied efficiency, but it has the problem of output voltage regulation at light load condition. Although the parallel resonant converter (PRC) has no light load regulation issue, its circulating energy is much higher than SRC and impacts efficiency significantly. The series-parallel resonant converter (SPRC) remains the advantages of SRC and PRC, which are smaller circulating energy and not so sensitive to load change. However, the same as SRC and PRC, SPRC requires operating at very high switching frequency to obtain extremely low output-voltage. Therefore, with low output-voltage operation, all of SRC, PRC, and SPRC possess high circulating energy to lower their efficiencies. This paper proposes to implement a high-efficiency fuel cell by an LLC resonant dc–dc converter. At high input-voltage or low output-voltage operation, the LLC resonant converter has smaller circulating energy than SRC, PRC, and SPRC. Both the active switches of this converter can turn ON with zero-voltage switching (ZVS), and both the output rectifier diodes can turn OFF with zero-current switching (ZCS), which results in higher conversion efficiency. By applying frequency modulation control, the output impedance of an LLC converter can be regulated from zero to infinite without shunt or serial resistors; hence, the efficiency of the proposed fuel cell can be significantly increased. By the way, this converter has a transformer to provide electrical isolation for safety requirements. In this paper, the theoretical equations and operation principles of the LLC resonant converter will be introduced. Circuit parameters are designed based on the practical considerations. Finally, an illustrative example is implemented todemonstrate the feasibility of the proposed high-efficiency fuel cell.

II. BASIC OPERATION OF PEM FUEL CELL

A fuel cell is like a battery in that it generates electricity from an electrochemical reaction. Both batteries and fuel cells convert chemical energy into electrical energy and also, as a

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by-product of this process, into heat. However, a battery holds a closed store of energy within it and once this is depleted the battery must bType equation here.e discarded, or recharged by using an external supply of electricity to drive the electrochemical reaction in the reverse direction.Hydrogen is considered as one of the best alternative fuels for augmenting fossil fuels due to high net energy density1 and its potential for zero local pollution. Proton exchange membrane (PEM), also known as polymer electrolyte membrane fuel cells (FCs) use hydrogen and are considered for vehicular power and portable applications because of high efficiency, low operating temperature, and simplicity in construction.

The PEM fuel cells employ hydrogen and oxygen from the air to produce electricity, water and heat. In PEM FC, hydrogen and air are supplied to the inlet manifolds and flow fields, and then diffuse through porous media to the polymer membrane. The membrane in the middle of the cell contains catalyst layers, one in anode and the other in cathode. The catalyst layer at the anode separates hydrogen molecules into protons and electrons. The membrane permits
transfer of protons, enabling the electrons to flow through an external circuit before recombining with protons and oxygen at the cathode to form water. This migration of electrons produces electricity.

The anode and cathode reactions in PEM fuel cells are shown below

Anode reaction:

$H2^{-} \rightarrow 2H^{+} + 2e^{-}$

Cathode reaction:

$O2 + 2H^{+} + 2e^{-} \rightarrow H2O$

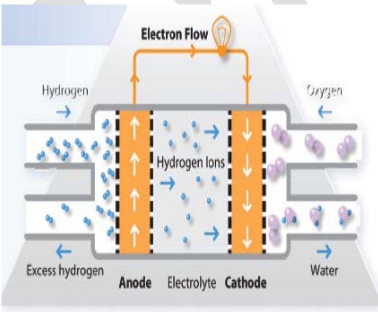

Fig.1 Fuel cell

The electrical characteristics of fuel cells are normally given in the form of a polarization curve which is a relation of cell voltage versus cell current density (current per unit cell active area). The cell voltage varies from the ideal voltage of about 1.2 V to usually below 1 V. Stack temperature and membrane water content affect the fuel cell voltage, as do reactant pressures and flows.

III. ANALYSIS OF THE LLC RESONANT DC–DC CONVERTER

The circuit diagram of an LLC resonant dc–dc converter is shown in Fig. 1, which consists of an LLC resonant inverter, a current-driven transformer with a center-tapped rectifier. The topology of LLC converter is very similar to that of SRC. The main difference is that the magnetizing inductance Lm is only slightly higher than the resonant inductance Lrin the LLC converter. Therefore, at some load conditions, Lm may participatein the resonance with Lrand Cr and change the characteristics of resonant tank.

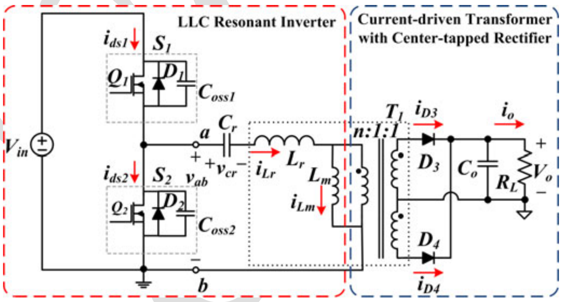

Fig. 2. Circuit diagram of LLC resonant dc/dc converter

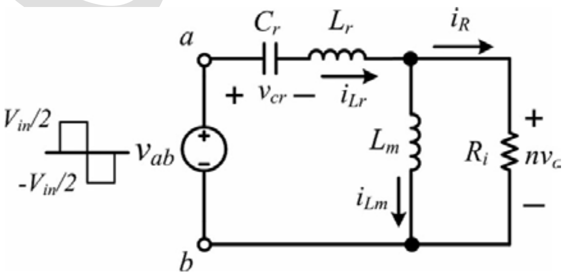

Fig. 3.Equivalent circuit of the LLC resonant converter.

The equivalent circuit of the LLC resonant inverter can be depicted as shown in Fig. 3, in which $R_i$is equivalent load resistance seen in primary side, and can be expressed as R_i=8n2RL /π2 . The input symmetrical squarewaveform $v_{ab}$with the magnitude of Vin /2 can be obtained by alternate conductingof power switches S1 and S2 . The transfer function of output voltage can be determined, where the inductance ratio A, the second resonant frequency ωL, and the load quality factor QL are defined as

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$$A = \frac{L_r}{L_m} \tag{1}$$

$$\omega_L = 2\pi f_L = \frac{1}{\sqrt{(L_r + L_m)\cdot C_r}} \tag{2}$$

$$Q_L = R_i \times \sqrt{\frac{C_r}{L_r + L_m}} = R_i \cdot \omega_L \cdot C_r . \tag{3}$$

the frequency response of output voltage gainof the LLC resonant converter can be illustrated in Fig. 4. It canbe observed that there are two resonant frequencies. The secondresonant frequency ωLhas been defined and the mainresonant frequency ωHcan be determined as follows:

$$\omega_H = 2\pi f_H = \frac{1}{\sqrt{L_r \cdot C_r}} . \tag{4}$$

Fig. 4 can be divided into three operation regions accordingto the resonant frequencies of ωHand ωL. Because theimpedance of resonant tank is capacitive in Region 3, the primaryswitches can operate under ZCS condition. But the currentspike during turn-on transient will result in high-current.

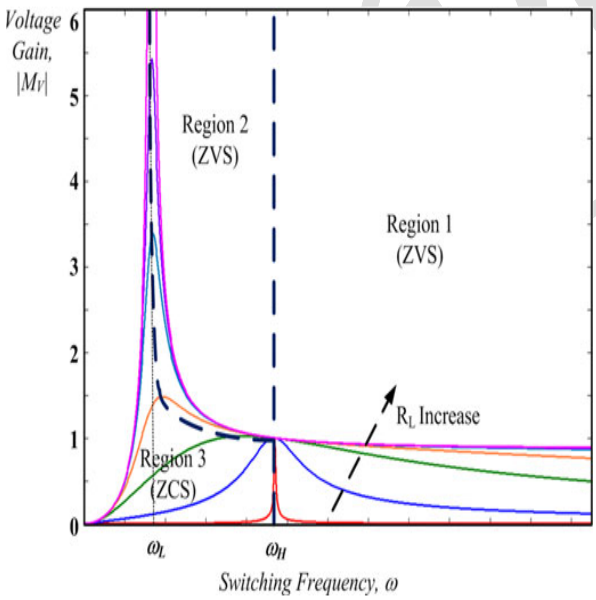

Fig. 4.Frequency response of output voltage gain of the LLC resonant converter.

stress and high-switching loss. The impedance of resonant tank is inductive so that the switches can operate under ZVS condition to reduce switching loss. Since voltage gain is always less than 1, the converter could be regarded as buck type. The operation principlein this region is very similar to SRC; hence, secondary rectifier diodes cannot operate under ZCS. Voltage spike will occur during turn-off transient and results in high switchingloss.

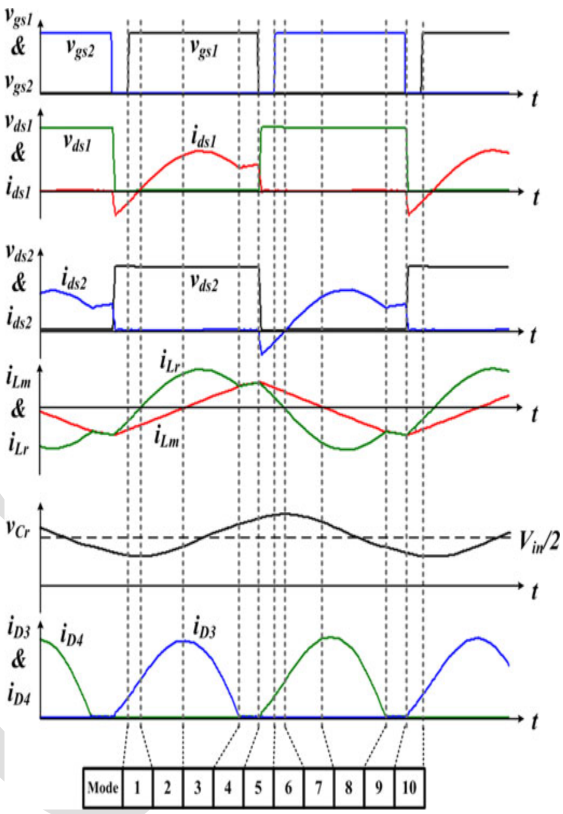

Fig. 4.Main waveforms of the LLC resonant converter operating in region 2.

IV.SIMULATION CIRCUITS FOR LLC RESONANT CONVERTER

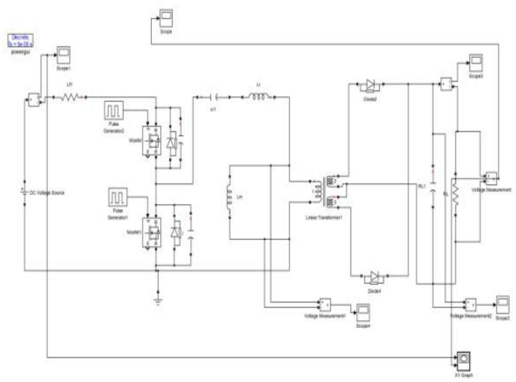

Fig. 5.Simulation circuit for LLC resonsnt DC DC converters.

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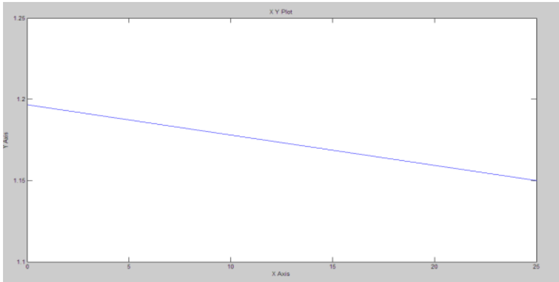

Fig.6. VI characteristics of LLC resonant converters

V.SIMULATION CIRCUIT FOR FUEL CELL

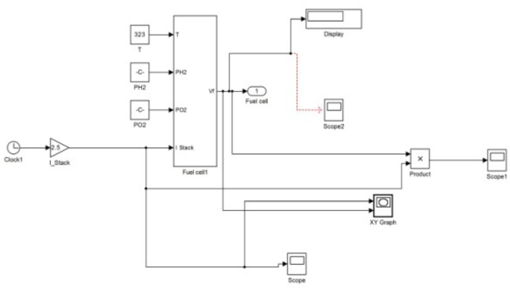

Fig. 7.Simulation circuit for Fuel cell

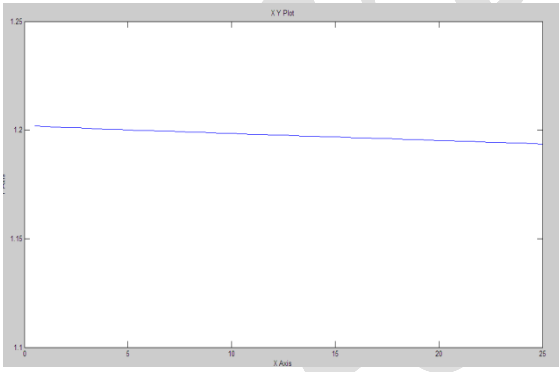

Fig.8. VI characteristics of Fuel cell

The V-I characteristic of the theoretical approach obtained is included. This figure shows that both the electrical circuit and the theoretical model have a good response in static conditions. From the point of view of the dynamic conditions, above figure shows the dynamic behavior of the model during a instantaneous variation of the load.

VI.CONCLUSION

A high-efficiency fuel cell implemented by an *LLC* resonant converter with ZVS feature has been proposed. The detail operation principle, design procedures, and considerations are introduced. An fuel cell is implemented to demonstrate the feasibility and validity of the theoretical discussion. The experimental results show that the fuel cell can provide approximated VI characteristics with high accuracy, and the maximum system efficiency at the range near MPP is up to around 92.5%. Hence, the proposed fuel cell based on an *LLC* resonant converter can significantly save the cost and energy of an fuel cell.

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