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Parametric Analysis of the Bidirectional Soft Switching DC/DC Converter for the Proton Exchange Membrane Fuel Cell Hybrid Electric Vehicle

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Abstract

Renewable energy generation is rapidly growing in the automobile sector and power sector industry. This paper gives the insights about fuel cell operation and its classification based on the electrolyte. The fuel cell voltage decreases bit by bit with expansion in current because of losses associated with fuel cell. It is difficult in handling large rated fuel cell based power system without regulating mechanism. In this paper, the challenges to improve the dynamics of controller in fuel cell based applications are mentioned. The issue connected with fuel based structural planning and the arrangements are widely investigated for all sorts of utilization. In order to improve the reliability of fuel cell based automobile system, the integration of energy storage system through soft switching bi-directional dc/dc converter for controlling charging and discharging of the current and advanced research methods are focused in this paper. Analysis modelling and design of soft switching bi-directional dc/dc converter has been carried out through the MATLAB/SIMULINK for the parametric of the filter elements.

Keywords: Accurate Losses Model (ALM), Current Ripple Minimization (CRM), Proton Exchange Membrane fuel cell (PEMFC), Zero current voltage Transition Method (ZCT), Zero Voltage Transition Method (ZVT)

1. Introduction

The fuel cells are exceedingly attractive in the field of the electric vehicle and distribution generation because of their purity, zero pollution more reliability and higher efficiency[1-3].

Besides, the FCs has the following limitations: 1) PEMFCs does not have the storage capability like Li-ion batteries. 2) Slower response compares to the battery however it would be pretty much same response in the steady state. 3) The output voltage is more oscillations with the load because the output portion is specifically associated with the suspension segment of the vehicle. 4) It is having the cold start issue[4]. The FCs are integration with the battery to upgrade the all issues with additional advantages like peak power capacity, improves the dynamic performance and supply power during the cold start of the vehicle[5].

If the battery or ultra capacitor is in parallel particularly with the DC bus, its charge and discharge current can't be controlled[6]. Once the load changes significantly, the surge current would damage the energy storage system. Along these lines, a bi-directional converter should be inserted between the DC bus and the battery or ultra capacitor to deal with the charge and discharge current[7–9].

The FCs hybrid vehicle would control by the controlling the converters which are in unidirectional and in addition bi-directional position with the FC current limit mode, battery current limit mode or battery voltage limit mode[10]. The fuel cell will provide higher peak

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power than each component alone. The system cold start issue was not incorporated in the article and additionally output voltage fluctuation with load also not discussed[11].

It comprises of the following major components such as, a FC, a battery and an ultra-capacitor. The sources are connected to the same DC bus through respective converters[12–14]. The three components need to meet diverse load demand; at that point the entire system includes high peak power limit and excellent dynamic characteristics[15]. The system cold start issue was not said in this article[16].

The PEMFC Hybrid vehicle comprises of the seven major parts such as, PEMFC, a battery, FBTL unidirectional dc/dc converter, Soft switching bi-directional dc/dc converter, an inverter, an induction machine and wheel system[17]. The PEMFC and battery are integrated to the same DC bus through their particular dc/dc converter[18–20]. The proposed novel PEMFC hybrid vehicle has the following a few benefits: 1) it would enhance the power management by the proper optimization. 2) It can enhance the vehicle efficiency. 3) During the beginning of the vehicle, the battery needs to supply the ability to guarantee that the PEMFC cold start easily[21]. 4) When sudden change of load step up or down, as the PEMFC can't respond quick, the battery needs to take think about the unequal power, so the dynamic performance of the hybrid vehicle is enhanced by the integration of the battery[22]. 5) The battery can give peak power, and after that the power rating of the PEMFC system would be diminished, decreasing the cost of the vehicle[23–24].

Mathematical modelling of a PEMFC vehicle has developed over the MATLAB/SIMULINK programming for the dynamic analysis of the whole vehicle performance. The simulation results illustrate that the soft switching bi-directional dc/dc converter under buck mode and boost mode of the converter for the estimation of the filter elements for the continuous operation of the load.

The organization of the article consists of six sections including introductory section. The fuel cell operation and classifications are detailed in section 2. The challenges and future needs are explained in detail in Section 3, whereas the proposed converter structure and its operation are in Section 4. The soft switching bi-directional dc/dc converter under buck and boost mode are explained in detail in the Sections 5 and 6. The simulation results and dicussion are depicted in Section 7. Conclusive remarks are presented in Section 8.

2. An Overview and Types of Fuel Cells

Fuel cells are static devices, which converts chemical energy of Hydrogen and Oxygen directly into electrical energy through an electro-chemical reaction. The fuel cell will generate electrical energy as long as the fuel is supplied to the system. It can produce electricity without recharging unlike battery.

2.1 Fuel Cell Operation

The working principle of the fuel cell is simple but it has complex design. Fuel cell fundamentally comprises of cathodes, electrolyte and fuel. The positive and negative terminals are known as cathode and anode, respectively. These are two terminals are contacted with the electrolyte inside and external electric circuit. The fuel is unceasingly fed to the anode while oxidant supplied to cathode. Usually, the fuel is pure hydrogen or contains some hydrogen gases like methanol, ethanol and natural gases. The oxidants are pure oxygen or contain oxygen gases like air or halogens like chlorine. In most of the cases, the combustion of Hydrogen and oxygen produces the water and it will split into two electrochemical reactions at the electrode independently, which are termed as two cell reaction. The basic reaction taking place in a fuel cell is given in Equation (1)–(3).

At anode,

$$H_2 = 2H^+ + 2e^- \tag{1}$$

At cathode

$$\frac{1}{2}O^2 + 2H^+ + 2e^- = H_2O \tag{2}$$

Overall reaction

$$H_2 + \frac{1}{2}O_2 = H_2O \tag{3}$$

The H^+ moves towards cathode directly and e^- moves to cathode through load. Finally, H^+ and e^- combines with O_2 and produces water (H_2O), which is the added advantage of fuel cell.

2.2 Types of Fuel Cell

Fuel cells are mainly classified based on the type of electrolyte and types of fuel used. The fuel cell block diagram is shown in the Figure 1. The type of fuel cell is based on the electrolyte as follows:

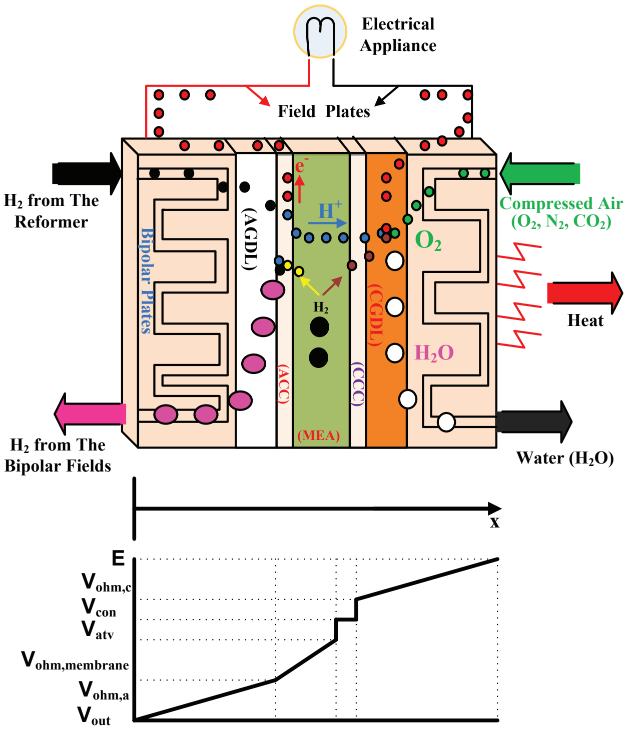

Figure 1. Block diagram of the PEM fuel cell and its characteristics.

2.2.1 Proton Exchange Membrane Fuel Cells (PEMFC)

Acid polymer is used as the electrolyte and pure hydrogen is used as fuel. The operating temperature of the PEMFC is below 100°C. Now days, PEM fuel cell is popular and widely used in vehicle application.

2.2.2 Direct Methanol Fuel Cell (DMFC)

In DMFC, the polymer membrane used as an electrolyte and the fuel used is methanol. The operating temperature of DMFC is below 60°C and it is mainly used for portable power applications below 250 W.

2.2.3 Phosphoric Acid Fuel Cell (PAFC)

In PAFC, The liquid phosphoric acid is used as the electrolyte and pure hydrogen is used as the fuel. The operating temperature is around 180°C. These types of fuel cells are particularly used as stationary power generators and which is not efficient electrically.

2.2.4 Alkaline Fuel Cell (AFC)

Alkaline solutions are used as electrolyte of fuel cell and pure hydrogen as fuel. These types of fuel cells are essentially used in the space applications for the water purpose to astronauts.

2.2.5 Solid Oxide Fuel Cell (SOFC)

This type of fuel cells is widely used as stationary power generator and its operating temperature is around 1000°C. The solid ceramic electrolyte like zirconium oxide and syngas type of fuels are used in this fuel cell.

2.2.6 Molten Carbon Fuel Cell (MCFC)

Molten carbonate salt suspended in a porous ceramic matrix is used as the electrolyte and hydrocarbon is used as fuel. The operating temperature is around 650°C and which is mainly used for high power application.

2.3 V-I Characteristics of the Fuel Cell

The losses of fuel cell technology can be easily understood from the V-I characteristics of the fuel cell. The fuel cell and its characteristics are shown in the Figure 1. The V-I characteristics of a fuel cell can be determined by

$$V_{Out} = E - V_{atv} - V_{ohm} - V_{con} \tag{4}$$

here, V_{Out} is the cell operating voltage, E is the Nernst voltage, V_{atv} is the voltage drop due to activation of the process, V_{con} is the voltage drop resulting from the reduction in concentration of the reactant gases or from the transport of mass of oxygen and hydrogen and V_{ohm} represents the voltage drop due to the resistance offered by the electric circuit. Figure 1 shows the V-I characteristics of a typical fuel cell. From Figure 1, the issues of fuel cell voltage behavior are mentioned as follows,

- The cell voltage is less than the ideal voltage.
- There is a rapid initial fall in voltage.
- The voltage profile is not changing linearly with current.
- After a certain range of current densities, the voltage falls quickly.

3. Challenges and Further Research Needs

Basically, the challenges of fuel cell depend on applications. The fuel cell technologies will take years to overcome the technical hurdles.

The important limitations of the fuel cells are

- The slower dynamics of the fuel cell internal operation.
- Poor voltage profile against current density.
- It should be associated with Energy Storage System (ESS) to provide stable output.
- Higher current ripple.

4. Proposed Converter Structure

A soft-switching topology is proposed for the bi-directional dc/dc converter. The circuit diagram of soft switching bi-directional dc/dc converter has shown in the Figure 2.

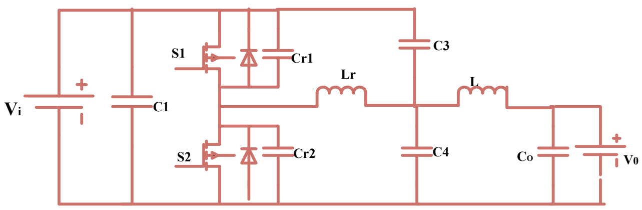

Figure 2. Circuit diagram of soft switching bi-directional dc-dc converter.

In order to achieve soft-switching conditions, the auxiliary circuits including a small inductor and two capacitors are introduced to the bi-directional dc/dc converter. By generating and keeping a recycle current in the auxiliary circuits.

The proposed topology can provide soft-switching conditions for both switches of the bi-directional dc/dc converter in fixed frequency control application. Due to the existence of the auxiliary circuits, the proposed topology can also reduce the current ripple in the main inductor. The entire operation of the proposed dc/dc converter and its modes are shown in the Figure 3.

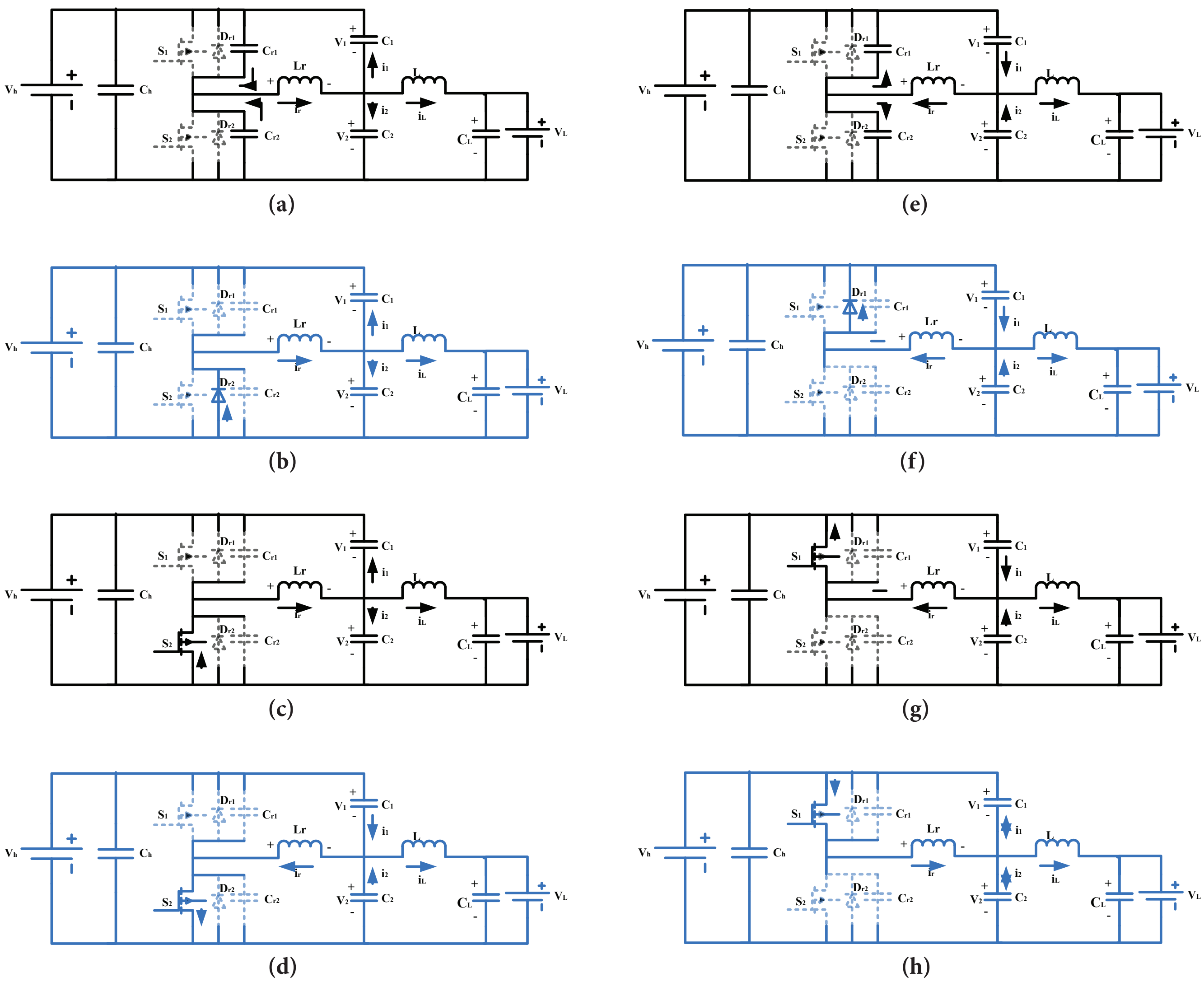

Figure 3. Modes of operation of the soft switching bi-directional dc/dc converter over the entire cycle. **(a)** Mode 1 (t_0-t_1); **(b)** Mode 2 (t_1-t_2); (c) Mode 3 (t_2-t_3); **(d)** Mode 4 (t_3-t_4); **(e)** Mode 5 (t_4-t_5); **(f)** Mode 6 (t_5-t_6); **(g)** Mode 7 (t_6-t_7); **(h)** Mode 8 (t_7-t_8).

5. Buck Mode of Proposed Converter

In this section, mathematical modelling of the proposed converter has been developed for the dynamic analysis of the converter. The simulation model of the soft switching bi-directional dc/dc converter under buck mode has shown in the Figure 4. The soft switching bi-directional dc/dc converter has analysed by two modes of the converter which are buck mode and boost mode. In the buck mode, state space analysis has been carried through the two cases which are shown in the Figure 5 and Figure 7. The design of the filter elements and resonant elements are calculated through the mathematical analysis which is mentioned in the Equation (18, 19). The model waveforms of the voltages across the inductors are shown in the Figure 6 and Figure 8.

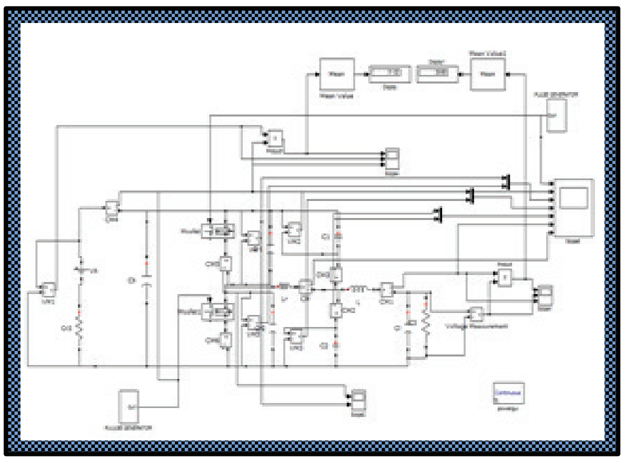

Figure 4. Simulated model of the proposed dc/dc converter in the buck mode of the operation

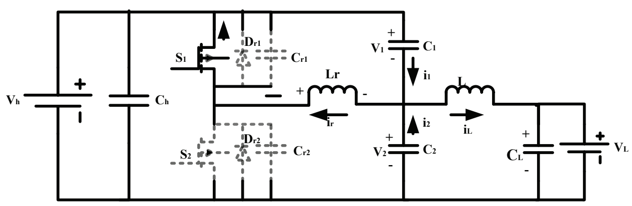

Figure 5. Equivalent model of proposed dc/dc converter under buck mode (S_1-ON and S_2-OFF).

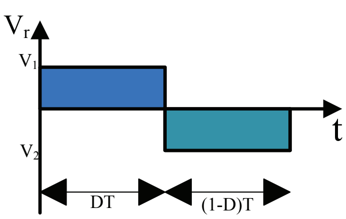

Figure 6. Voltage profile across Lr.

The filter elements are design by the bode plot of the concerned transfer function which is depicted in the Equation (17). The circuit diagram of the soft switching bi-directional dc/dc converter for the calculation of L_r and Cr is shown in Figure 9. The bode plot of the transfer function of the proposed converter has shown in Figure 10 for the find out of the stability of the converter.

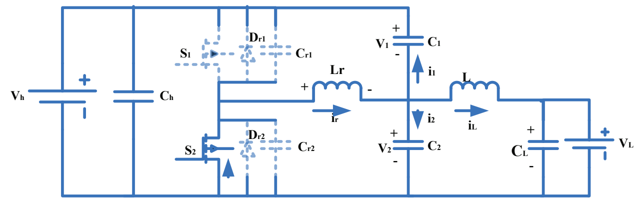

Figure 7. Equivalent model of proposed dc/dc converter under buck mode (S_1-OFF and S_2-ON).

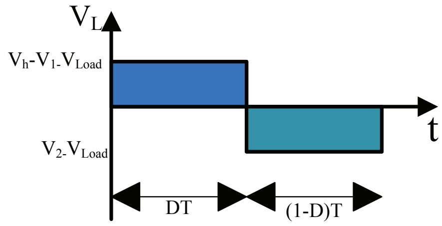

Figure 8. Voltage profile across L.

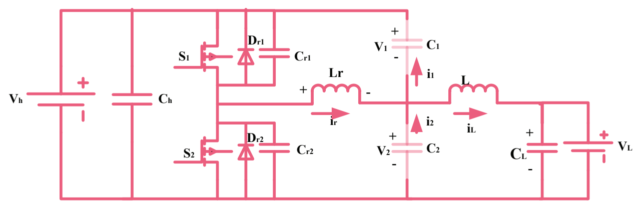

Figure 9. Equivalent model of proposed dc/dc converter for design filter values.

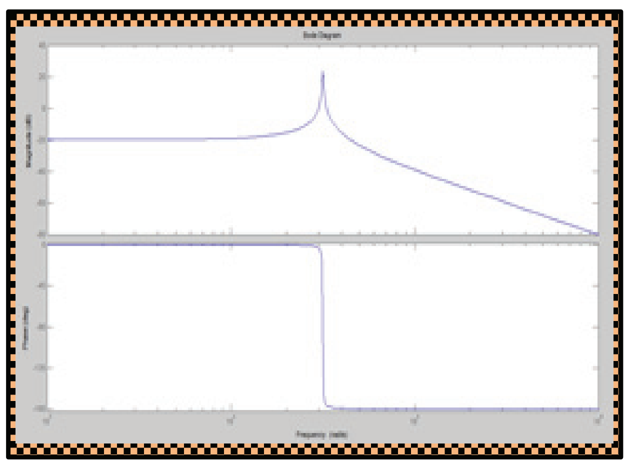

Figure 10. Bode plot of transfer function of the proposed converter.

5.1 Steady State Analysis

$$V_r = V_1 \tag{5}$$

$$V_2 = V_L + V_1 \tag{6}$$

$$V_h = V_1 + V_2 \tag{7}$$

$$I_r + I_L = I_1 + I_2 \tag{8}$$

$$V_1 * DT - V_2 * (1-D)T = 0 \tag{9}$$

$$\frac{V_1}{V_2} = \frac{(1-D)}{D} \tag{10}$$

$$V_r = -V_2 \tag{11}$$

$$V_2 = V_L + V_1 \tag{12}$$

$$V_h = V_1 + V_2 \tag{13}$$

$$I_r = I_1 + I_2 + I_L \tag{14}$$

$$(V_h - V_1 - V_{Load})DT + (V_2 - V_{Load})(1-D)T = 0 \tag{15}$$

$$V_h * D = V_1 \tag{16}$$

5.2 Design L and C

The soft switching bi-directional dc/dc converter has filter circuit for maintain of the constant voltage across the load and continuous power supply to the load. Due to the above reason, filter elements should be design as accurate as possible so that ripple in the output would less. The following are the assumptions to design the transfer function of the converter.

- Assume switch S_1 and S_2 are complementary to each other.
- Assume duty ratio of switch is D.
- Now take current through inductor and voltage across capacitor as a variable parameter.
- After the small signal analysis of proposed dc/dc converter, transfer function of proposed dc/dc converter as follows

$$\frac{V_C}{V_{in}} = \frac{D}{1 + L/R * S + LC * S^2} \tag{17}$$

Based on the bode plot, get the wide scope for the design of the L and C parameters of the filter. Design the filter elements is as large as possible so that does not get instability problem of the converter and achieved better results at L = 85 μH, C = 1020 μF.

5.3 Design Lr and Cr

For ZVS operation, Resonating inductor L_r should have sufficient amount of energy to completely charge and discharge resonating capacitor C_{r1} and C_{r2} for the entire cycle. The mathematical analysis of the filter design is as follows for the continuous mode of operation of the converter.

$$C_r * V_r^2 \le \frac{1}{2} * I_r^2 * L_r \tag{18}$$

Here, V_h = 100, C_{r1} and C_{r2} = 3nF. That's why,

$$30uJ \le \frac{1}{2} * L_r * I_r^2 = \text{Constant} \tag{19}$$

6. Boost Mode of Proposed Converter

The soft switching bi-directional dc/dc converter has been explained in detail under boost mode of operation. The proposed dc/dc converter has shown in the Figure 11 under the boost mode of operation. The soft switching bi-directional dc/dc converter under boost mode has shown in the Figure 12 for the dynamic analysis of the circuit. The average voltage across resonance inductor should be zero over a period of time. Based on the aforementioned concept, have to design the values of the filter elements and resonance elements and model waveforms have shown in the Figure 13 and Figure 15. The steady state analysis of the soft switching dc/dc converter has shown in the Figure 14.

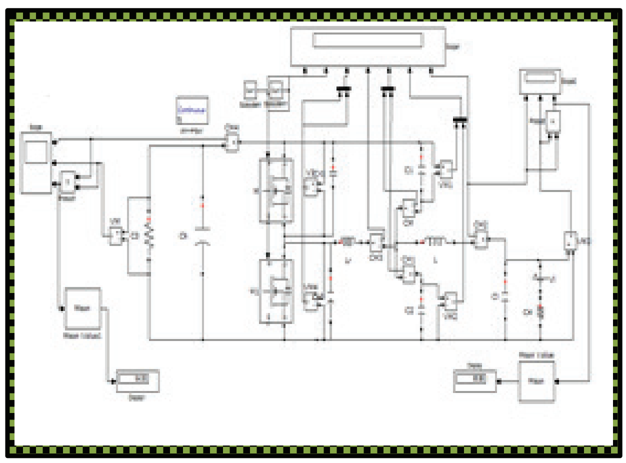

Figure 11. Simulated model of the soft switching bi-directional dc/dc converter under boost mode.

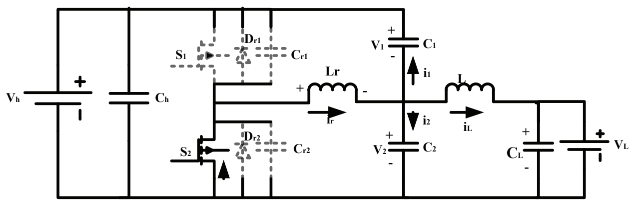

Figure 12. The proposed dc/dc converter under boost of operation for the dynamic analysis.

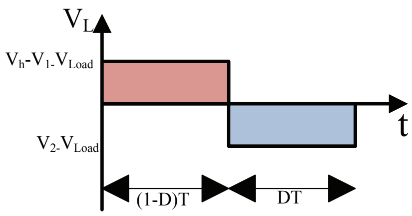

Figure 13. Voltage profile across L.

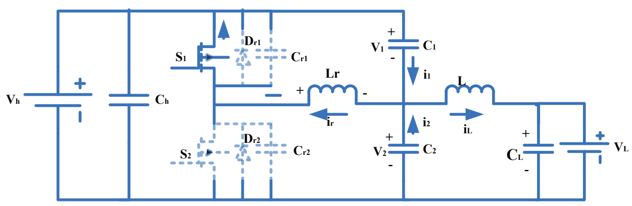

Figure 14. The proposed dc/dc converter under boost mode of operation for calculating steady state mode.

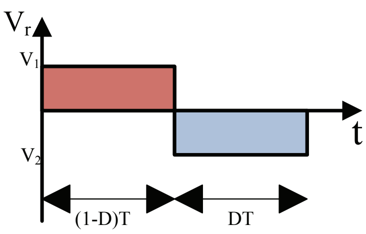

Figure 15. Voltage profile across Lr.

6.1 Steady State Analysis

$$V_r = -V_2 \tag{20}$$

$$V_2 = V_L + V_{a_1} \tag{21}$$

$$V_h = V_1 + V_2 \tag{22}$$

$$I_r + I_2 = I_1 + I_L \tag{23}$$

$$(V_2 - V_L)DT + (V_h - V_1 - V_L)(1-D)T = 0 \tag{24}$$

$$V_r = V_1 \tag{25}$$

$$V_2 = V_L + V_1 \tag{26}$$

$$V_h = V_1 + V_2 \tag{27}$$

$$I_r + I_2 = I_1 + I_L \tag{28}$$

$$V_1(1-D)T + (-V_2)DT = 0 \tag{29}$$

$$\frac{V_1}{V_2} = \frac{D}{(1-D)} \tag{30}$$

$$V_h = \frac{V_1}{(1-D)} \tag{31}$$

7. Simulation Results and Discussion

The simulation results of soft switching bi-directional dc/dc converter have been discussed in this section. The simulation work has been carried through the MATLAB/ SIMULINK. The proposed dc/dc converter has worked on the soft switching operations (ZVT and ZCT). The soft switching has achieved through the different values of the Lr and Cr. In this process, the proposed converter would work properly with good soft switching at 20 micro henry and 2.7 nano Farad. It is clear that ZVS operation is not perform properly with the 30 micro henry (L_r) and 3 nano Farad (C_r). So controller has to tune the valve of L_r for achieving better soft switching and simulated waveforms of the proposed DC/DC converter with (30μh) Lr and (3nF) C_r has shown in Figure 16.

The ZVS of the proposed converter has happened clearly in the Figure 17 but dead time of the transition is very small. Due to the lesser dead time, converter has more probability to the short circuit. The simulated waveforms of the proposed dc/dc converter has shown in the Figure 17 with the (20μh) Lr and (3nF) C_r. The

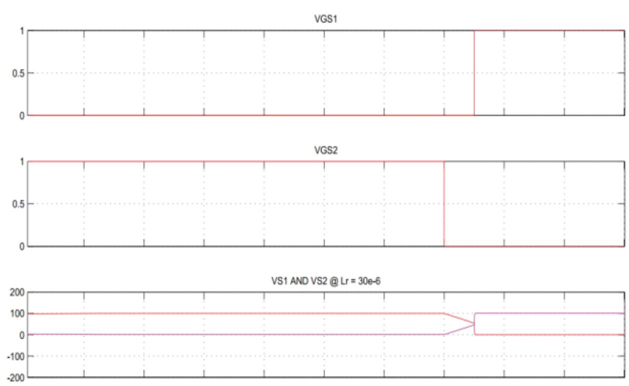

Figure 16. Switching waveforms of buck mode of the proposed dc/dc converter at L_r = 30μh and C_r = 3nF.

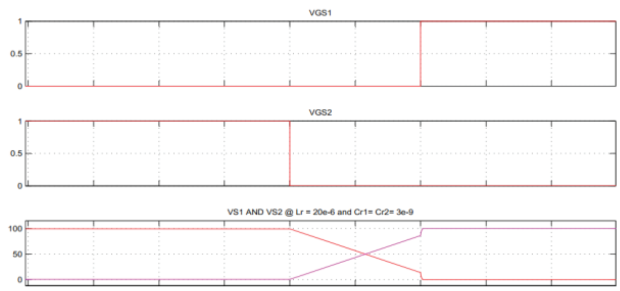

Figure 17. Switching waveforms of buck mode of the proposed dc/dc converter at L_r = 20μh and C_r =3nF.

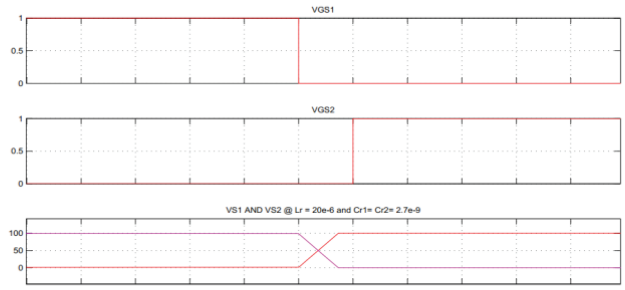

Figure 18. Switching waveforms of buck mode of the proposed dc/dc converter at L_r = 20μh and C_r = 2.7nf.

soft switching of proposed dc/dc converter has achieved clearly with the (20μh) Lr and (2.7nF) C_r through the tuning of the filter elements. The simulated waveforms of the converter with (20μh) Lr and (2.7nF) are shown in the Figure 18 for the closed view of the ZVT operation.

The voltage and current flowing through the switch of the proposed converter is shown in the Figure 19 for the accurate loss model calculation. The dynamic analysis of proposed dc/dc converter has shown in the Figure 20 for the calculation of the filter elements. The input power, voltage and current of the converter have shown in the Figure 21 and the output power, voltage and current of the proposed dc/dc converter shown in the Figure 22. The performance indices of the proposed dc/dc converter are shown in the Table 1.

The proposed dc/dc converter has worked in both bucking and boosting mode depending upon the controller. The proposed converter has placed between the battery and DC bus bar of the fuel cell hybrid electric vehicle. It has to work boost mode when the power flows from the battery to the DC bus bar and buck when energy stores in the battery. The dynamic analysis of the boost mode has shown in the Figure 23 for the tuning of the proper values of the filter elements. The ZVT operation of the proposed converter has shown in the Figure 24 under the boost mode of operation. The simulated waveforms of the proposed converters are shown in the Figure 25 and Figure 26. The parameter analysis of the proposed converter has done on the filter elements. The parametric analysis would helpful for the dc/dc converters for the quick achievement of resonance values of the soft switching network as well as filter elements. This study would helpful for the future work on the dc/dc converters.

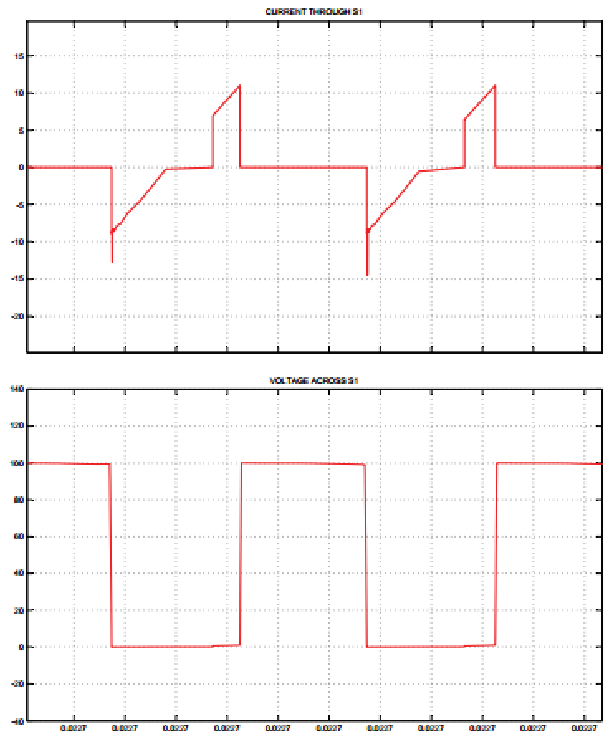

Figure 19. Voltage and current profile across the switch of the bi-directional dc/dc converter.

Table 1. Performance indices of the soft switching bi-directional dc/dc converter

Lr (μH)	Ir max(A)	Energy store in Lr(J)	ZVS PERFORMANCE
12	5	150	better
20	2.6	67.6	More better
30	2.0	60.0	Not better
40	1.6	51.2	worst

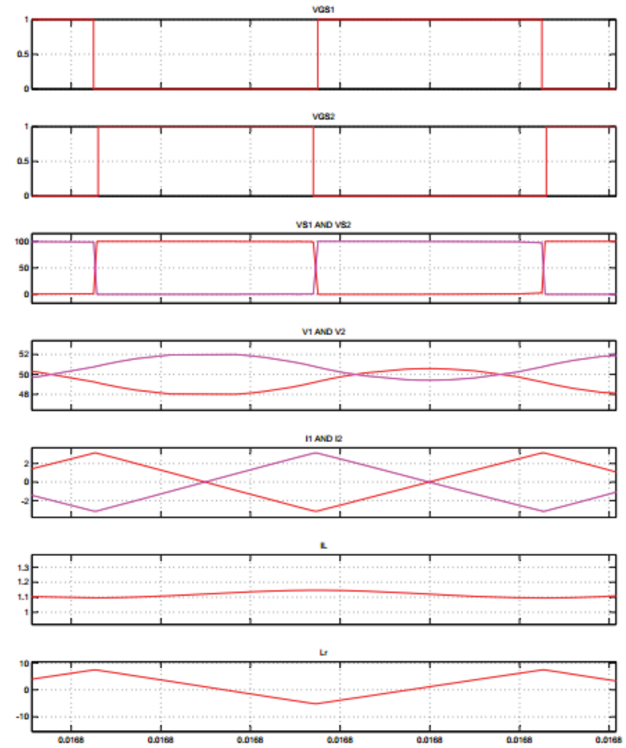

Figure 20. Dynamic analysis of the proposed dc/dc converter under buck mode.

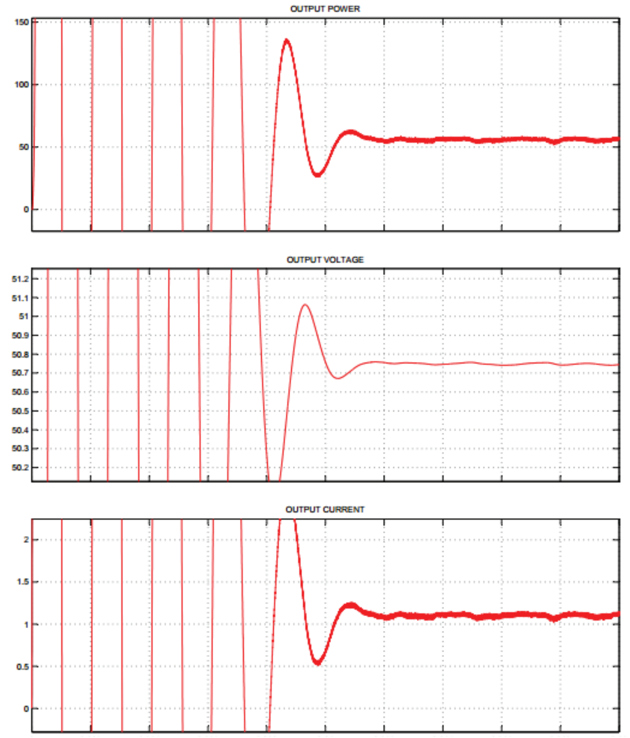

Figure 22. Output power, voltage and current waveforms of the buck mode of the proposed dc/dc converter.

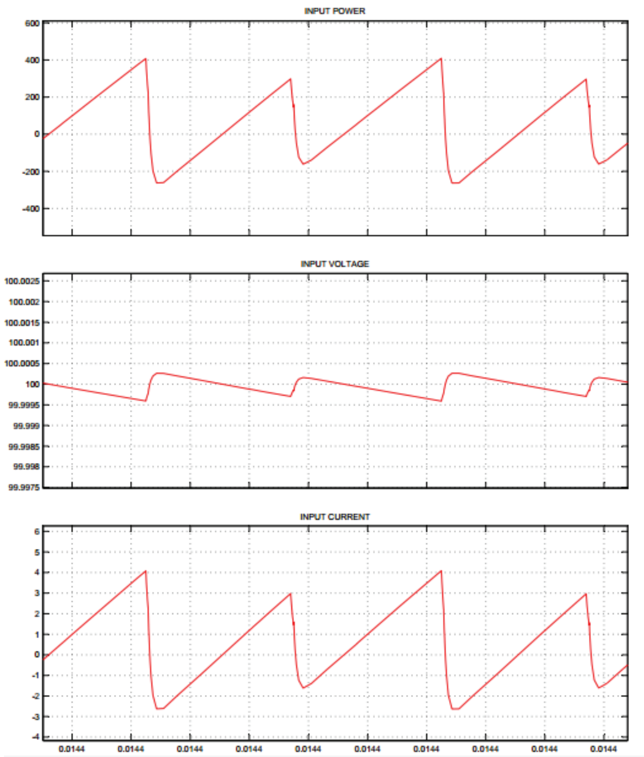

Figure 21. Input power, voltage and current waveforms of the buck mode of the proposed dc/dc converter.

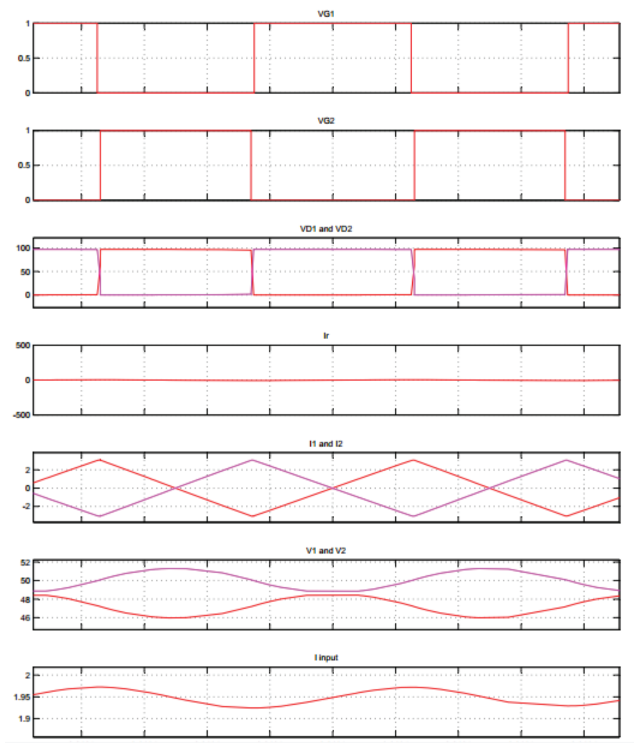

Figure 23. Simulated waveforms of the proposed dc/dc converter under the boost mode of operation at Lr = 20 μH and Cr = 3nF.

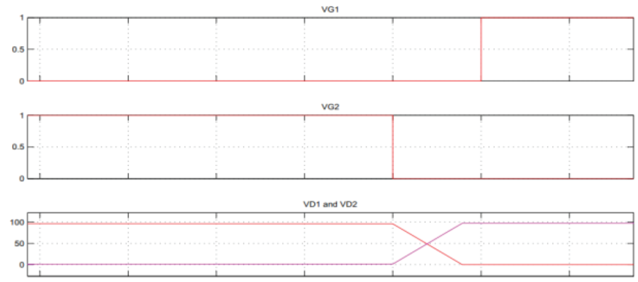

Figure 24. Switching waveform of boost mode of the dc/dc converter for the closed view of ZVS operation at Lr = 20μH and Cr = 3.3nF.

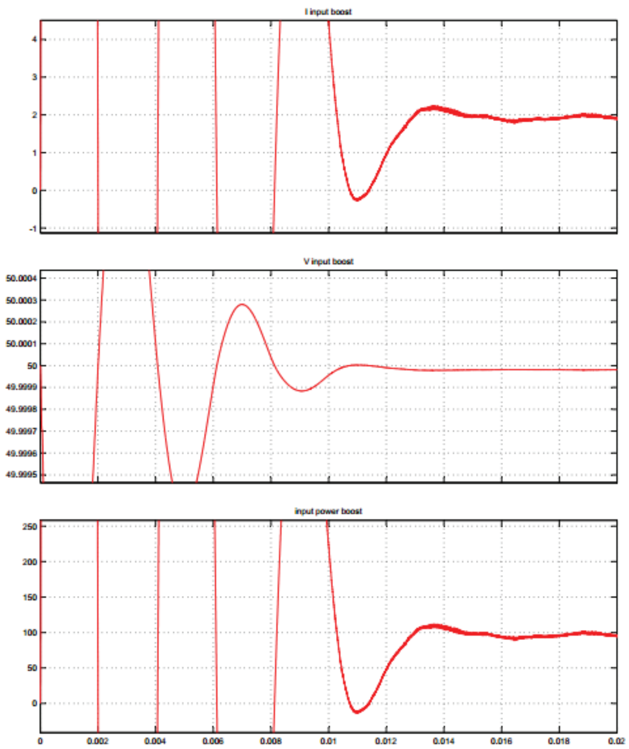

Figure 25. Input current, voltage and power waveform.

8. Conclusions

In this article, discuss about the fuel cell and its applications. But, fuel cell has several disadvantages. To improve demerits of the fuel cell hybrid electric vehicle, uni- and bi-directional dc/dc converters are used as regulating mechanisms. In non-isolated and isolated bidirectional converter, soft switching bidirectional dc-dc converter is most effective and better result among all the topology. The fuel cells are used in many applications which

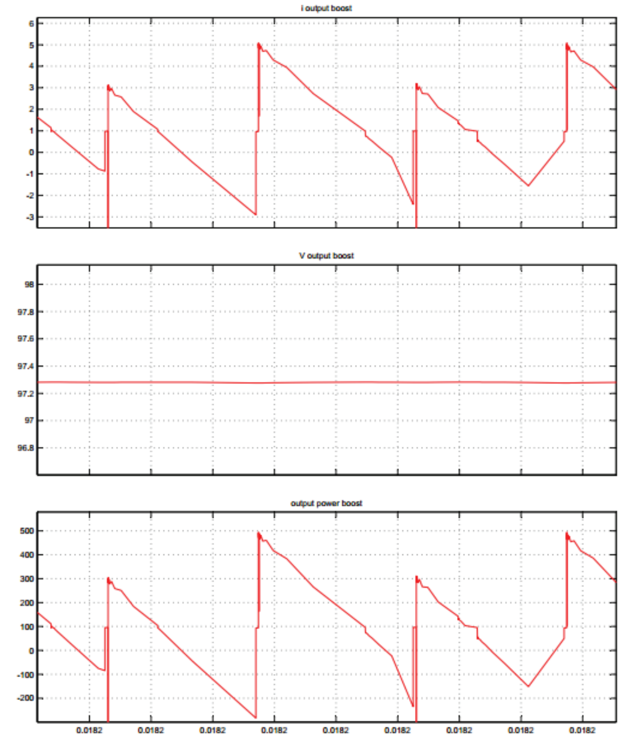

Figure 26. Output current, voltage and power waveform.

includes Electric vehicles, power generation and in space ships etc. The research challenges in this report are better utilization of the fuel cell technology efficiently. Because the low voltage output is the main drawback of fuel cell in electrical application. In order to mitigate this issue, a higher gain and efficient power electronic converters has to be developed. Furthermore, the fuel cell replaces the conventional internal combustion engines in all commercial vehicles.

9. References

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