Control of Energy Sharing Between Fuel Cell and Battery

Amit Kumar, Ashwani Arora, Anoop Tiwari

Abstract— Renewable energy sources like wind, sun, hydro and fuel cell are seen as a reliable alternative to the traditional energy sources. Some of them are also being identified for Distributed Generation purposes. As a consequence, the control of distributed generation systems should be improved to meet the requirements for grid interconnection without compromising on power quality. This paper proposes a control scheme for energy sharing between fuel cell and battery. The system consists of a Fuel Cell, a Battery, a Unidirectional DC-DC converter (UDC), a Bidirectional DC-DC converter (BDC) and a DC load bus. Fuel Cell is the main source of energy and battery is used as an energy storage element. Battery also helps in improving the dynamic response of the system, to reduce the voltage fluctuations and improves system efficiency. The goal is to design a control circuit to operate BDC in Buck, Boost or Shut down mode. The mode of operation depends upon cold start of the system, charging and discharging of the battery, step up or step down of load.

Index Terms— Battery, BDC, Control Circuit, Energy Sharing, Fuel Cell, PID,PWM Generation.

1. Introduction

FUEL cell is developing and attractive power supply source for future distributed generation because of its cleanness, high Efficiency and high reliability. But there are some disadvantages of using fuel cell which can't be ignored [1-2]:
1) It cannot store energy;
2) The response is slow;
3) Its output voltage varies with the load;
4) It is difficult to cold start;
5) It has limited ripple current capacity.
So an energy storage unit such as ultra capacitor or battery is used with fuel cell system to improve the dynamic characteristic, improve the peak power capacity and power the load during cold start. Battery is connected through Bidirectional DC-DC converter to control charging and discharging current. It also prevents battery from getting damage by inrush current. A unidirectional interleaved boost converter is used with to fuel cell to maintain dc bus voltage.

The major challenge of designing a unidirectional DC-DC converter (boost converter) for high power application is how to handle the high current at the input and high voltage at output so that both remain constant as load changes or when any variation in fuel cell voltage occurs [3].

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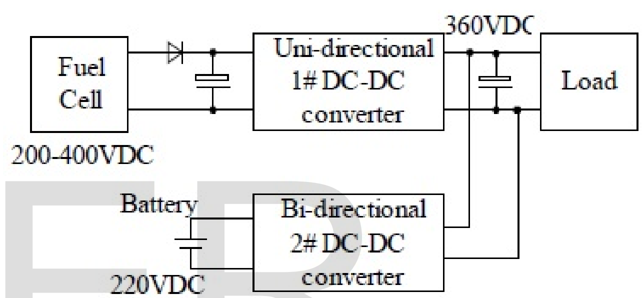

Fig. 1. Hybrid fuel cell power system

There are two power sources in this system: FC is the major source, and battery is the secondary source. Hence power flow of the system should be managed to ensure that entire system operates with high efficiency and high consistency. This paper suggests energy sharing control scheme for hybrid fuel cell system.[1] The FC/battery hybrid system has following advantages-
1) Under cold start condition battery will power the load, making the fuel cell easier to start cold.
2) When the load steps up or down battery will supply or absorb the unbalanced energy due to slow response of FC, therefore dynamic characteristics of overall system can be improved.
3) Battery can provide maximum power so the power rating of fuel cell can be decreased which leads to reduce cost.
4) Overall energy management is optimizing and system efficiency is improving.[5]

2. System Power Flow

BDC can operate in three different modes: Buck, Boost and Shut down mode. Its operation is decided by the DC bus voltage and battery state of charge. The BDC should control

	$V_{bus} < V_{min}$	$V_{min} \le V_{bus} \le V_{max}$	$V_{bus} > V_{max}$
$V_{bat} < V_{bat-min}$	SD	Buck	Buck
$V_{bat-min} \le V_{bat} \le V_{bat-max}$	Boost	Buck	Buck
$V_{bat} > V_{bat-max}$	Boost	SD	SD

Table1 Bi-Directional converter mode of operation

in suitable mode so that system cooperates with high reliability. The current state of charge of battery is predicted by the battery terminal voltage V_{bat}. Battery overcharged and undercharge stage will be at maximum voltage $V_{bat-max}$ and minimum voltage $V_{bat-min}$. If $V_{bat} < V_{bat-min}$ then battery is undercharged and it needs to get charged. If $V_{bat} > V_{bat-max}$ then battery needs to be discharged. Battery is said to be operating in normal condition if $V_{bat-min} \le V_{bat} \le V_{bat-max}$ means it can receive or deliver power to bus. [1]

Similarly operating condition of fuel cell can be predicted by DC bus voltage V_{bus}. Upper and lower limits for bus voltage are V_{min} and V_{max} respectively. If $V_{bus} < V_{min}$ then fuel cell is unable to supply power to load. When $V_{bus} > V_{max}$ it means load feedbacks energy so surplus power must be transferred to battery. If $V_{min} \le V_{bus} \le V_{max}$, it shows that FC is in good condition and is capable of providing enough power to the load.

Based on above analysis operation can be divided into nine regions. Each region depict special mode of BDC as shown in table1.

3. Unidirectional converter Design

Since the voltage rating of fuel cells are usually low whereas the DC load bus are driven at higher voltages, hence a high power, high voltage DC-DC boost converter is required for providing the interface between fuel cell energy and high voltage dc link. Boost converter regulates the output voltage at a level greater than the input voltage. [3]

3.1 Conventional DC-DC boost converter

Boost converter is referred as step up converter. The DC input voltage in series with inductor acts as a current source. A switch in parallel with this source and output is turned off periodically, providing energy from the inductor and the source to increase the output voltage.

The circuit diagram for conventional boost converter is shown in figure 2.At steady state the DC voltage in inductor V_L can be expressed as follows and is equal to zero.

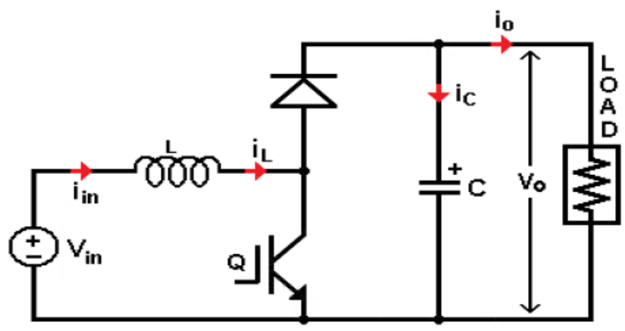

Fig. 2. Conventional DC-DC boost converter

$$V_L = D\,(V_{in}) - (1-D)\,(V_{in} - V_o) = 0 \qquad (1)$$

At steady state the ratio between output voltage and input voltage becomes-

$$\frac{V_o}{V_{in}} = \frac{1}{1-D} \qquad (2)$$

The inductor current can be obtained by equating input and output power:

$$V_{in}.I_L = V_o.I_o$$

$$I_L = \frac{V_o}{V_{in}}.I_o \qquad (3)$$

The boost converter inductor current will increase with the increase of the ratio of output and input voltage. This resulted in high inductor currents of boost converter at high power applications. To reduce that current we need a control circuit to control the output current and voltage of the boost converter. [1]

3.2 Control circuit loop

DC-DC converter consists of power semiconductor devices which are operated as electronic switches. Operation of the switching devices causes the inherently nonlinear characteristic of the DC-DC converters including one known as the Boost converter. Consequently, this converter requires a controller with a high degree of dynamic response. Proportional-Integral- Differential (PID) controllers have been usually applied to the converters because of their simplicity. However, the main drawback of PID controller is unable to adapt and approach the best performance when applied to nonlinear system so a saturation block is needed to saturate the output [6].

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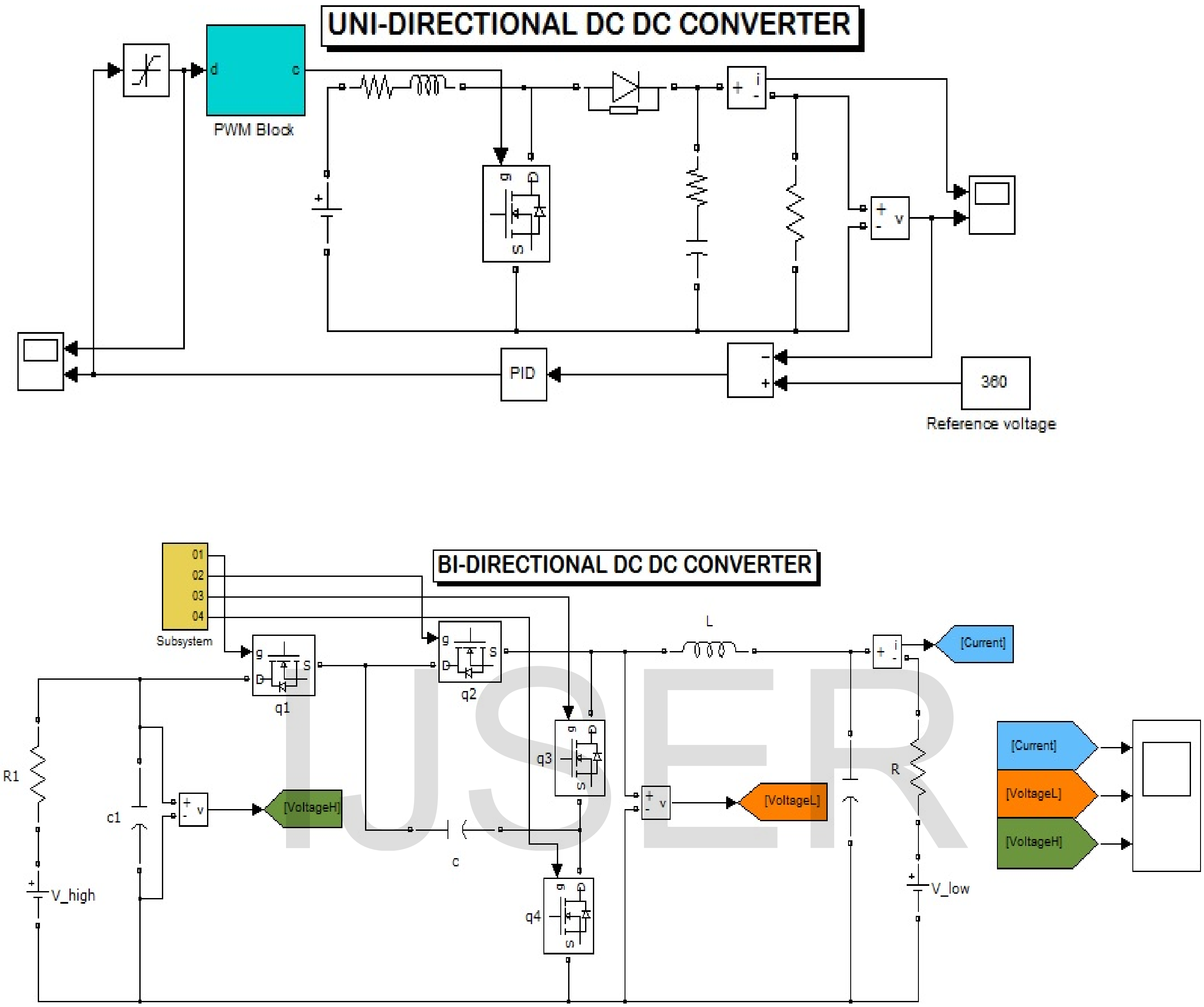

Fig. 3. UDC and BDC circuit in MATLAB

4. Bidirectional converter Design

In FC hybrid system BDC need to transfer energy in both direction from bus to battery and battery to bus. There are two types of BDC: isolated and non isolated. Assuming small difference between dc bus and battery voltage, non -isolated BDC can be employed. Figure 4 shows the circuit used for 3L BDC. It works in buck mode when power transfer from high voltage side V_H to low voltage side V_L and operate in boost mode when power transfer from low to high voltage side[5].

The advantages of using 3L bidirectional converter is that stress on switches is only half of the input voltage so it is suitable for high voltage application. Also its inductance value can be reduced significantly leading to fast dynamic response. The objective of this paper is to introduce the 3L concept to the BDC and employ this unique advantage to obtain a fast system dynamic characteristic for the FC/battery hybrid power system.

Figure 4 shows the 3L BDC, where V_H and V_L are high and low voltage sides respectively, C_H and C_L are the filtering capacitor of each side, L is the inductor and C_{fly} is the flying capacitor. Q_1 to Q_4 are main power switches. Q_1, Q_4 and Q_2, Q_3 are controlled in complementary operation.

In buck mode Q_1 and Q_2 are controlled to regulate the output, they act as active switches. Similarly in boost mode Q_3 and Q_4 act as active switch. It is assumed that all switches are ideal and flying capacitor C_{fly} is high enough to treat as voltage source with voltage as $V_H/2$. For bock mode duty ratio D is less than 0.5 and for boost D is greater than 0.5.

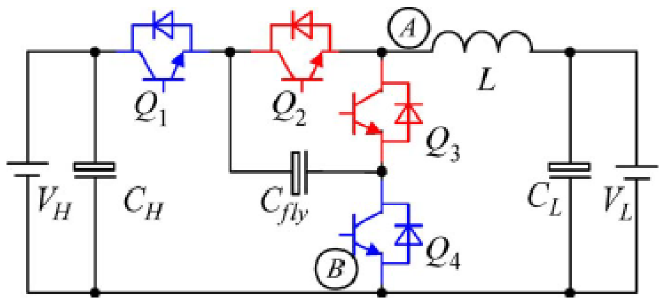

Fig. 4. Bidirectional DC-DC converter

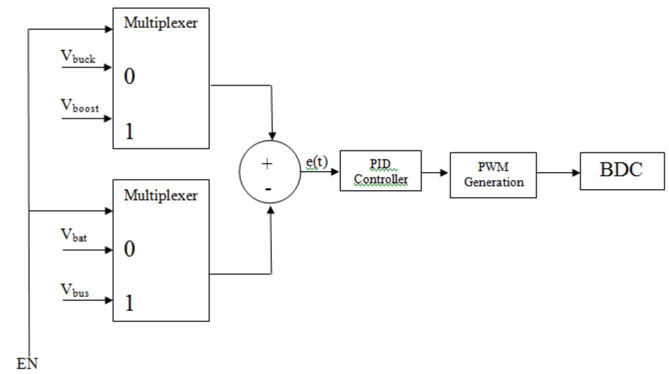

Fig. 6. BDC Control Circuit

5. DESGIN OF A CONTROL CIRCUIT

5.1 Unidirectional Converter Control Circuit

To control the output voltage of UDC with the varying load conditions, a voltage control loop has been designed and implemented for the UDC as shown in the figure 5. The output of the UDC (or the DC bus voltage) is compared with the reference bus value of 360V and the error function is fed to the PID controller. This error function is used to vary the duty cycle of the PWM generation and hence control the output voltage of UDC.

5.2 Bidirectional Converter Control Circuit

Like UDC control circuit, it is necessary to control the output voltage of the BDC. Since the BDC operates in three different modes namely buck, boost, and shut down, a single control loop is incapable to meet the requirement. Hence, a separate logic circuit has been designed which drives the BDC control circuit to operate in the desired mode of operation. Refer to figure 6.

When EN = 0, $e(t) = V_{buck} - V_{bat}$

When EN = 1, $e(t) = V_{boost} - V_{bus}$

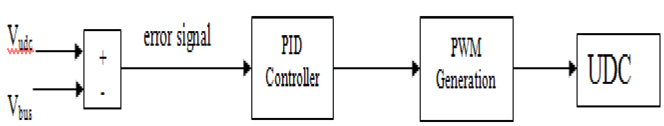

Fig. 5. UDC Control Circuit

5.3 PWM Generation

PWM generation has been used in the control circuits to generate the triggering pulses for the switches used in UDC and BDC. Stepped saw-tooth wave has been used as the carrier wave signal for it is delivering the output with much less ripple content. Switching frequency 100kHz.The reference signal to be compared is the output from the PID controller.

The value of the reference signal changes with change in load or with variation of terminal voltage from the fuel cell or battery. Hence, the duty cycle D is controlled dynamically that leads to effective control of DC load bus voltage.

The MATLAB model of PWM generator is shown in figure 7. Figure 8 and 9 shows the PWM generation for output reference 0.48 and 0.33 respectively.

5.4 Logic Circuit

The logic circuit to determine the operation of BDC control circuit has been designed according to the situation of FC and battery as mentioned under system power flow discussed above. The block diagram is shown in figure 8.

If the BDC should operate in buck mode, EN is at a low level and SD is at a low level. If the BDC should operate in boost mode, EN is at a high level and SD is at a low level. If the BDC should be shut down, SD is at a high level. Then both EN and SD are sent to the BDC control circuit. A logic circuit is designed on the basis of conditions tabulated in table 1. [1]

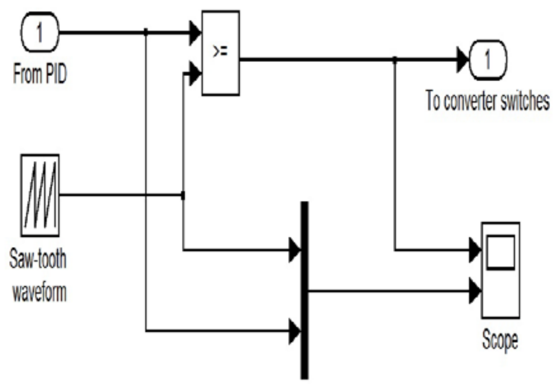

Fig. 7. PWM Generation

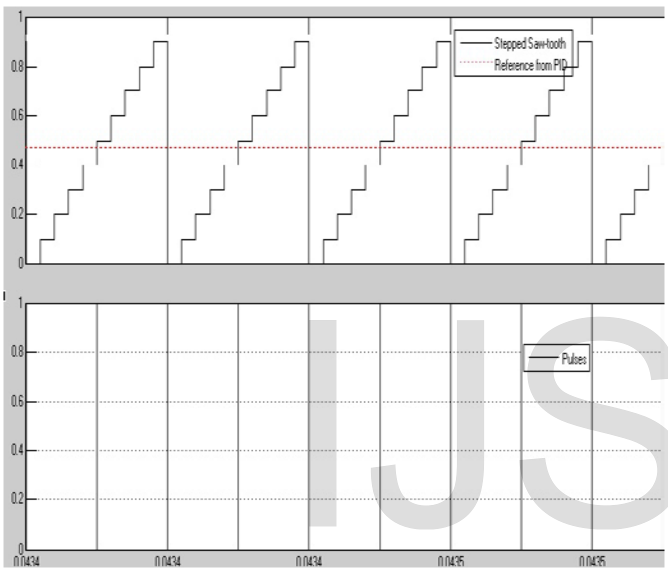

Fig. 8. PWM generation for D=0.48

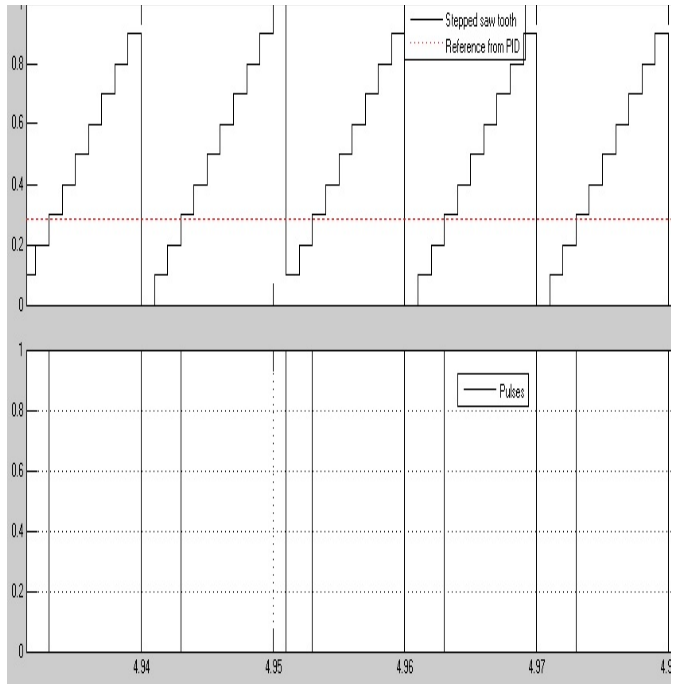

FIG. 9. PWM GENERATION FOR D=0.33

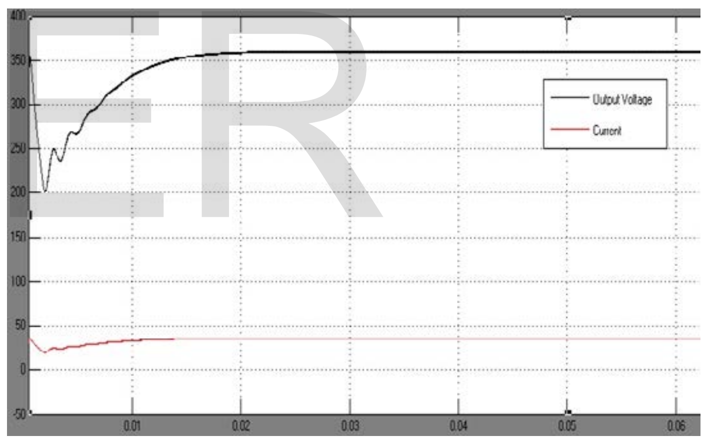

Fig. 10. Voltage and current waveforms for UDC with input voltage 200V.

6. RESULTS AND GRAPHS

Figures 10, 11and 12 shows the output of the UDC circuit simulated in MATLAB. Figure 10 has input voltage of 200 V. Figure 11 shows the output when the input varies from 200 V to 300V. Figure 12 shows the output when the load at DC bus changes from 10Ω to 50Ω. Due to the closed loop feedback, DC load bus voltage reaches the steady state value of 360 V and the corresponding value of current is also shown in the figures. Figure 13 shows the voltage output of BDC and current waveforms for buck and boost mode respectively.

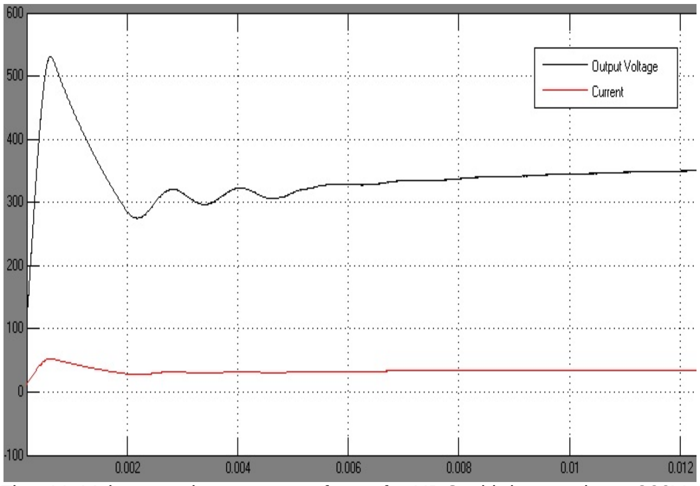

Fig. 11. Voltage and current waveforms for UDC with input voltage 300V.

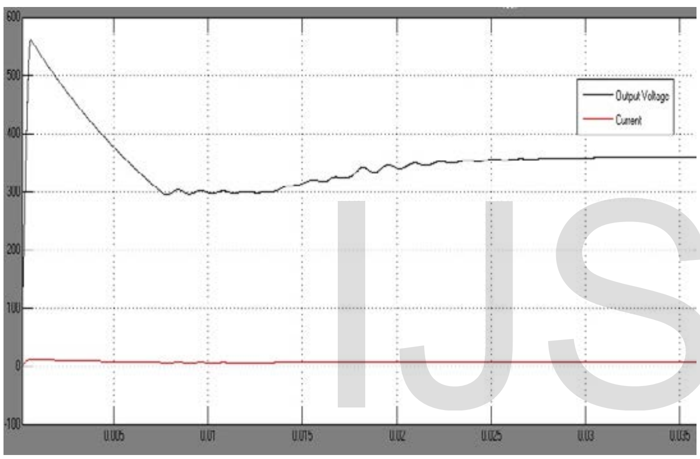

Fig. 12. Voltage and Current waveforms for UDC at load variation of 10Ω to 50Ω

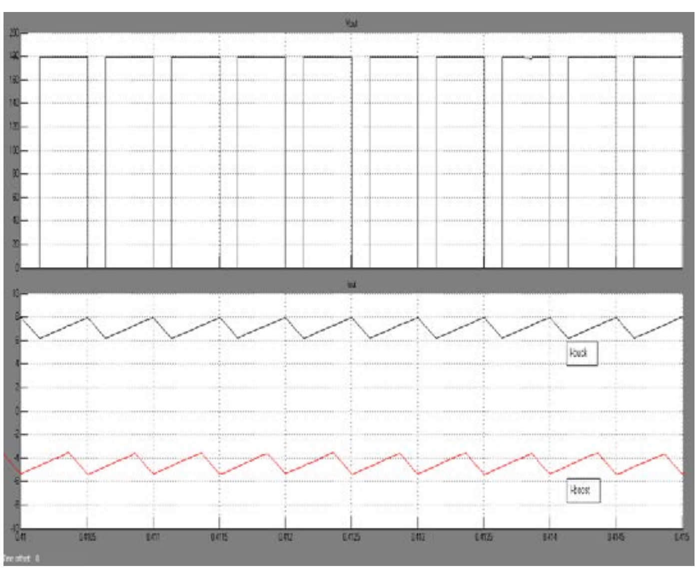

Fig. 13. Voltage and Current waveforms for BDC

7. Conclusion

Control scheme of energy sharing between fuel cell and battery in hybrid fuel cell system is proposed in this paper. The main aim of control scheme is to control mode of operation of BDC in buck, boost or shut down mode depending on conditions of fuel cell and battery. Control is implemented on UDC such that it maintains the bus voltage constant. The experimental results are shown to prove theoretical analysis.

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