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A Novel Approach for the Design of Controllers with Interleaved Boost Converter

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***Abstract*—**Themomentous increase in exigency of electric energy is forced us to find various source of generations like solar, wind, hydraulic and clean energy like fuel cell. Low cost, high efficiency, compactness, portability and environmentally clean energy has enhanced the research on fuel cell. One of the factor which affects the life time of the fuel cell is ripple content presents in the current. In order to supply high voltage and low current applications, fuel cell is used to integrate with boost converter. But to improve the performance and lifetime of fuel cell, interleaved boost converter is employed. Also to supply for constant load the output voltage has to be maintained at a particular value. To attain this controllers are exploited. The conventional PI controller and smith predictive controller are designed for fuel cell fed interleaved boost converter in order to track the output voltage and to improve the transient time.The results depict the validity of the design procedure and the potential of the proposed method.

***Keywords*—*Conventional PI controller, Smith Predictive Controller, Interleaved Boost Converter, Fuel Cell*.**

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I. INTRODUCTION

The ever increasing demand for electrical energy and the intense competition between electric companies in the new electric utility market has intensified research in alternative sources of electrical energy that are reliable and cost effective. And to meet the power requirement continually in the future, the development of clean energy generation becomes very important task. The fuel cell, as a renewable energy source, is considered one of the most promising sources of electric power. Fuel cells are not only characterized by higher efficiency than conventional power plants, but they are also environmentally clean, have extremely low emission of oxides of nitrogen and sulphur and have very low noise.

Due to high energy efficiency, ultra-low emission, compactness, high power density, solid electrolyte, long life, low corrosion, low temperature, fast response, low noise and zero emission proton exchange membrane (PEM) fuel cells are considered great alternatives for distribution source of energy from low-temperature fuel cells include the alkaline fuel cell (AFC), and solid polymer fuel cell (SPFC) or proton exchange membrane fuel cell (PEMFC).The medium-temperature class has the phosphoric acid fuel cell (PAFC). The high-temperature class has the molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC) [1].

In order to supply a constant of high voltage and low current loads, the output of low voltage and high current from the fuel cell has to be boosted by some DC/DC converter. The boost converters usually employed to boost up the output voltage. Using the simple boost converter circuit will introduce more ripple content in input current. Sharp increase and decrease in input content will reduce the performance and also the life time of the catalyst of fuel cell. To avoid this problem interleaved boost converter is employed. Paralleling the N number boot converter circuit will make the interleaved boost converter. The input current is divided into N number of paths so the ripple at the output side is reduced drastically. When the load is varied or when the input level to the fuel cell is reduced then the output voltage reduced correspondingly. So this setup may not be able to supply for constant load like grid.

M. uzunoglu et al. [4] developed a dynamic model considered the partial pressure of hydrogen, oxygen and water as three state equations with ohmic and activation loss.Jay T. Pukrushpan [3] developed a dynamic model considering partial pressure of oxygen, hydrogen, nitrogen, water in both anode and cathode, supply manifold pressure and air flow rate through the compressor as dynamic states and also considered all losses with concentration loss depends upon the partial pressure of oxygen. HaipingXu et al [6] developed a interleaved boost converter for fuel cell distributed generation system. Omar Hegazy [7], [8] has designed the multilevel interleaved boost converter for hybrid electric vehicle system. Hang. C. C [13] has analyzed the smith predictive controller and its applications.This paper proposes control methods to track the output voltage at a particular level. Conventional PI controller and Smith Predictive controller are the proposed controllers for fuel cell fed interleaved boost converter. These controllers will track the output voltage to the referred value.

The design procedure and performance analysis of each controller has been compared and the optimal controller had been proposed in this paper.

This paper is organized as follows. Section II presents the basics of the PEM fuel cell. Section III presents the interleaved boost converter. Section IV presents the basics of voltage mode controllers. Section V presents the mathematical modelling of voltage mode conventional PI controller. Section VI presents the mathematical modelling of smith predictive controller. Section VII presents the simulation results and comparison of both controllers. Section VIII presents the conclusion.

II. PROTON EXCHANGE MEMBRANE FUEL CELL

Proton exchange membrane fuel cells, also known as polymer electrolyte membrane (PEM) fuel cells (PEMFC)[3], are a type of fuel cellbeing developed for transport applications as well as for stationary fuel cell applications and portable fuel cell applications. Their distinguishing features include lower temperature/pressure ranges (50 to 100 °C) and a special polymer electrolyte membrane. PEM fuel cells are the most popular type of fuel cell, and traditionally use hydrogen as the fuel[1],[2].

A. *Operation and Basic Principles of Fuel Cell*

The electrolysis is the hydrogen and oxygen are recombining and an electric current is being produced. The hydrogen fuel is being burnt or combusted in the simple reaction.

$$2H_2 + O_2 \rightarrow 2H_2O \qquad (1)$$

At the anode of an acid electrolyte fuel cell, the hydrogen gas ionizes, releasing electrons and creating H+ ions (or protons).

$$2H_2 \rightarrow 4H^+ + 4e^- \qquad (2)$$

This reaction releases energy. At the cathode, oxygen reacts with electrons taken from the electrode and H+ ions from the electrolyte, to form water

$$O_2 + 4e^- + 4H^+ \rightarrow 2H_2O(3)$$

For both these reactions to proceed continuously, electrons produced at the anode must pass through an electrical circuit to the cathode. Also, H+ ions must pass through the electrolyte. An acid is a fluid with free H+ ions, and so serves this purpose very well. Certain polymers can also be made to contain mobile H+ ions are called Proton exchange membrane, as an H+ ion is also a proton.

B. *Open Circuit Voltage*

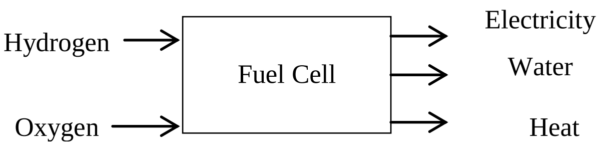


Fig. 1 Fuel Cell Inputs and Output

Electrical work done = charge × voltage = −2FE joules

If the system is reversible (or has no losses), then this electrical work done will be equal to the Gibbs free energy released. So

$$\Delta\overline{G}f = -2FE \qquad (4)$$

$$E = \frac{-\Delta\overline{G}f}{2F} \quad (5)$$

C. *Losses Presents in Fuel Cell*

1. Activation losses

These are caused by the slowness of the reactions taking place on the surface of the electrodes. This voltage drop is highly non-linear.

2. Fuel crossover and internal current

This energy loss results from the waste of fuel passing through the electrolyte.

3. Ohmic losses

This voltage drop is the straightforward resistance to the flow of electrons through the material of the electrodes and the various interconnections, as well as the resistance to the flow of ions through the electrolyte.

4. Mass transport or concentration loss

These result from the change in concentration of the reactants at the surface of the electrodes as the fuel is used. The reduction in concentration is the result of a failure to transport sufficient reactant to the electrode surface, this type of loss is also often called mass transport loss.

D. *Polarization Curve Model*

Stack voltage of the PEMFC is given by the following equation [3],

$$V_{stack} = V_{reversible} - V_{activationloss} - V_{ohmicloss} - V_{concentrationloss} (6)$$

Where ,$V_{reversible}$ = Reversible voltage.
$V_{activationloss}$ = Activation loss.
$V_{ohmicloss}$ = Ohmic loss.
$V_{concentrationloss}$ = Concentration loss.

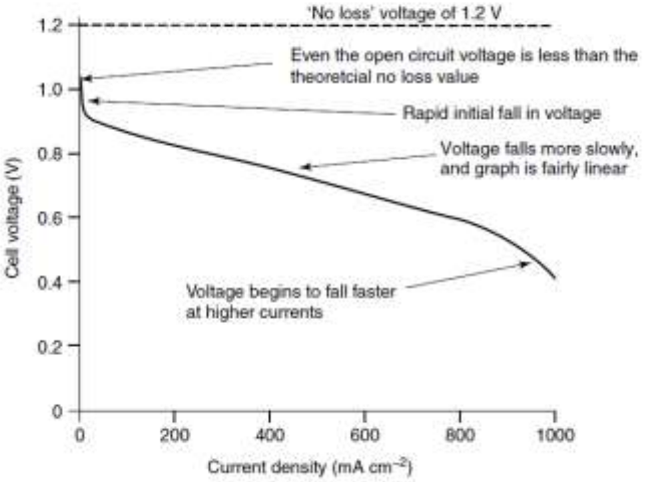


Figure: 2 VI Characteristics of Fuel Cell

III. INTERLEAVED BOOST CONVERTER

Number of boost converters connected in parallel is called as interleaved boost converter. It shares the common source and common load. That is the source current is shared between the numbers of converters connected in parallel [9], [10].

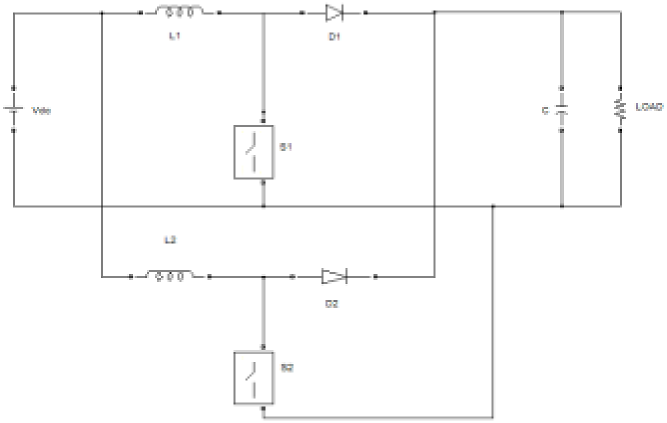


Fig. 3 Interleaved Boost Converter

So the current stress on the single converter is reduced by interleaving. Therefore the ripple at the current is reduced automatically by providing the $2\frac{\pi}{n}$ phase shift between the numbers of converters connected in parallel. Where n is the number of converter connected in parallel. And each converter is rated for equal power rating.

TABLE I INTERLEAVED BOOST CONVERTER PARAMETERS

Parameters	value
L	6.3 mH
R	6 Ω
C	127 mF
F	50 kH
V_{in}	35 V
D V_o	51.38 % 72 V

Fig.4 Basic block diagram of the system

TABLE IIComparison of Number of Phases of theInterleaved Boost Converter Ripple Content Values

No.of Phases/Parameters	1 Phase	2 Phase	3 Phase	4 Phase
Output Voltage Ripple in [V]	1	0.07	0.033	0.0323
Output Current Ripple in [A]	0.164	0.0132	0.013	0.00033
Input Current Ripple in [A]	3.72	0.8	0.6	0.3
Inductor Current Ripple in [A]	3.67	3.66	3.67	3.7

Table 2 shows the drastic reduction in the input current, which increases the lifetime and performance of the fuel cell.

IV. VOLTAGE MODE CONTROLLER

To track the output voltage at a particular referred value, output feed controllers has to be implement[12]. The first step in designing the conventional PI controller is to get the error signal by comparing the output voltage with the reference value. And the controlled error signal is obtained by passing the error signal to the conventional PI controller.

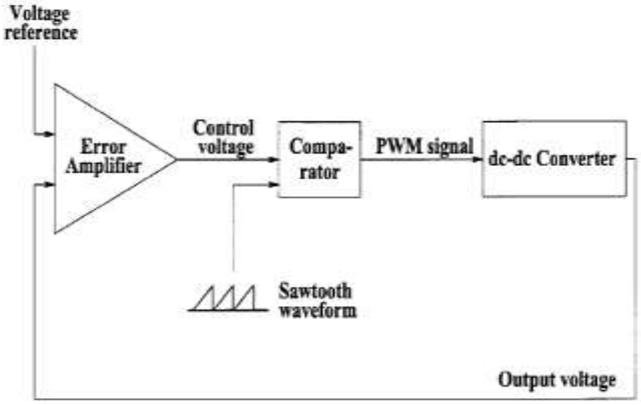


Figure: 5 Block diagram of ILBC with voltage mode controller

The error amplifier may be any type of controller like P, PI, PID and SMITH Predictive Controller. This error amplifier produces the control signal which is then compared with the constant amplitude of saw tooth waveform in order to generate the PWM pulse signals to the switch. The duty ratio of PWM signal depends on the value of the control voltage.

The frequency of the PWM signal is the same as frequency of the saw tooth waveform.

V. MATHEMATICAL MODELLING OF ILBC WITH VOLTAGE MODE CONTOLLER

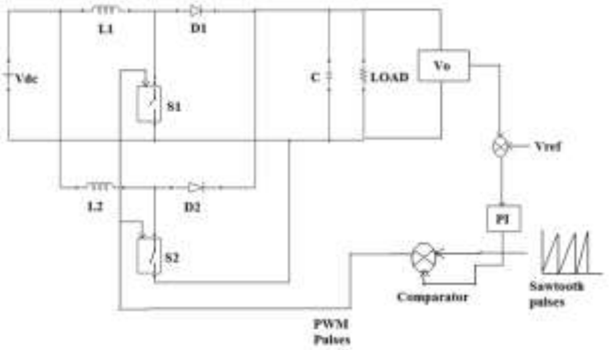


Fig.6 ILBC with Voltage Mode Controller

A. *Transfer Function Of Interleaved Boost Converter*

The controller design needs a system transfer function and its poles and zeros. By analyzing the system with root locus technique the PI or PID controller is designed by using the pole placement method.

Equations which defines the small signal model of the two phase interleaved boost converter[6],[7]

Current $\hat{i}_1$ equation,

$$\left(s+\frac{r_1}{L}\right)\hat{i}_1=\left(\frac{D-1}{L}\right)\hat{V}_0+\frac{V_0}{L}\hat{d} \qquad (7)$$

Current $\hat{i}_2$ equation,

$$\left(s+\frac{r_2}{L}\right)\hat{i}_2=\left(\frac{D-1}{L}\right)\hat{V}_0+\frac{V_0}{L}\hat{d} \qquad (8)$$

Voltage V equation,

$$\left(s+\frac{1}{RL}\right)=\left(\frac{1-D}{C}\right)\hat{i}_1+\left(\frac{1-D}{C}\right)\hat{i}_1+\frac{(I_1+I_2)}{C}\hat{d} \qquad (9)$$

By using the signal flow graph technique and block diagram reduction technique the transfer function between the V_o and $\hat{d}$ is obtained as,

$$\frac{Vo}{\hat{d}}=\frac{2V_o(1-d)R-sLRI-IRr}{s^2LRC+s(L+RCr)+r+2R(1-d)^2} \qquad (10)$$

While analyzing the poles and zeros of the above transfer function it is found that there is a zero on the right hand side. So the ILBC is a non minimum phase system. The conventional PI controller cannot be designed for non minimum system.

B. *Important Factor Found From Analysis*

1. Two phase interleaved boost converter is a non minimum phase system.
2. Conventional controller cannot be designed for an ILBC system.
3. But the controller with the tuned PI controller is working fine for the ILBC system in simulation and also in the hardware.
4. The following Voltage mode controller's PI controller is designed with such tuning method. That is the Kp and Ki values of the PI controller is tuned continuously and for the particular value of the integral and proportional gain the output is regulated to the reference value.

VI. MATHEMATICAL MODELLING OF SMITH PREDICTIVE CONTROLLER FOR ILBC

The smith predictive controller is the type of predictive controller for the system with pure time delay. It has been implemented by O. J. M. Smith in 1957,[13].

A. *Design procedure of Smith Predictive Controller for ILBC*

1. Convert the system into FOPDT system and get G(s) and e^{-k}.
2. Design a controller C(s) for the system G(s).
3. Get a closed loop transfer function H(s) for C(s) and G(s).
4. Now multiply the e^{-k} with H(s) and get a new closed loop transfer function for the system with time delay.
5. By solving the terms get a new controller

$$C_1(s)=\frac{C(s)}{1+C(s)G(s)(1-e^{-k})}$$

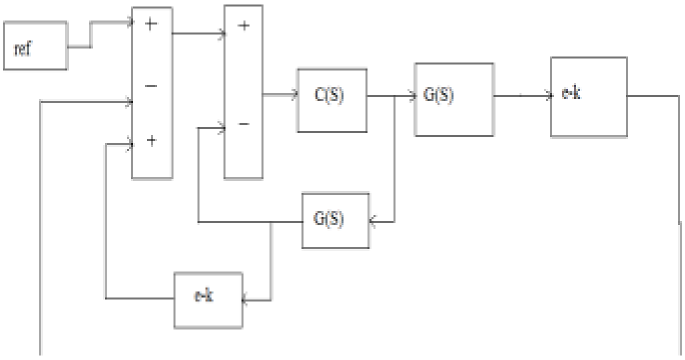


Fig.7 Implementation of Smith Predictive Controller $C_1(s)$

First Order Plus Dead Time System For Interleaved Boost Converter

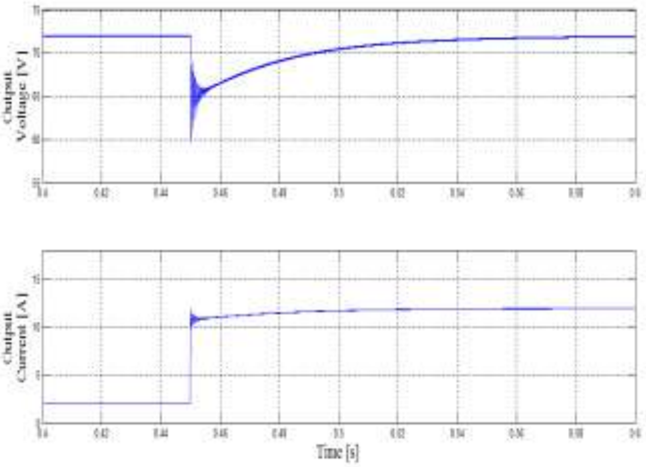
$$\text{FOPDT for ILBC}\quad=\frac{405.0678e^{-23.3289}}{1.3889e^{-3}s+1} \qquad (11)$$

$$\text{Designed PI controller} = \frac{1.3889e^{-3}s+1}{s} \tag{12}$$

VII. SIMULATION RESULTS

A. *Voltage mode conventional PI controller for fuel cell fed ILBC system*

a. Step increase from 12.5% to 75% of load current at 0.45 s



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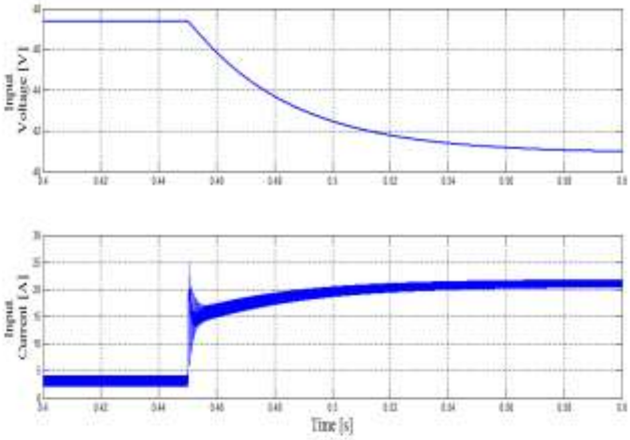

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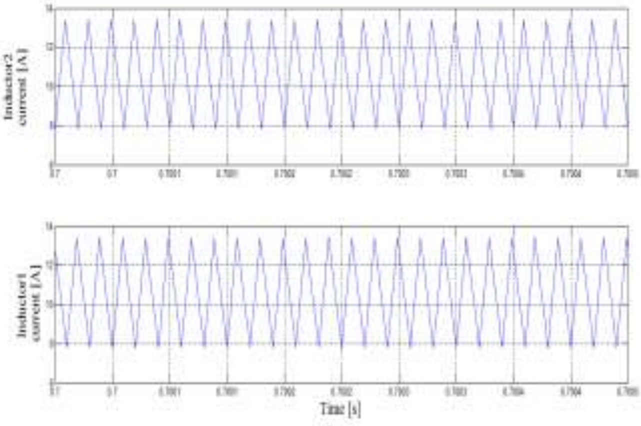
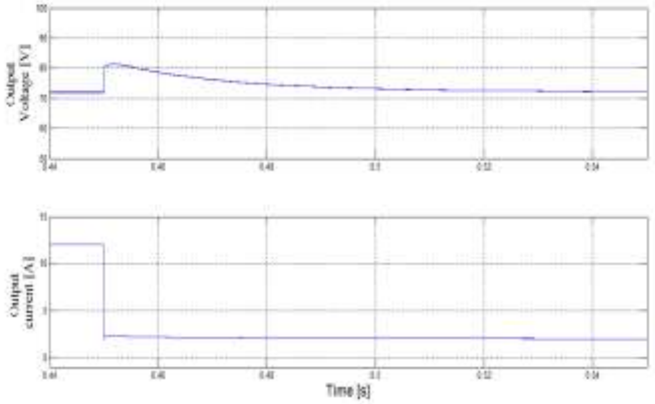


(c)

Fig.8 step increase in load from 12.5% to 75% at 0.45 s, (a) output voltage and current waveforms (b) fuel cell voltage and current waveforms (c) inductor current waveforms.

b. *Step decrease in load at 0.45 s from 75% to 12.5%*



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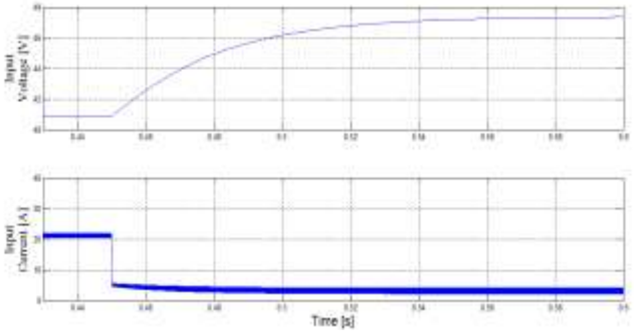
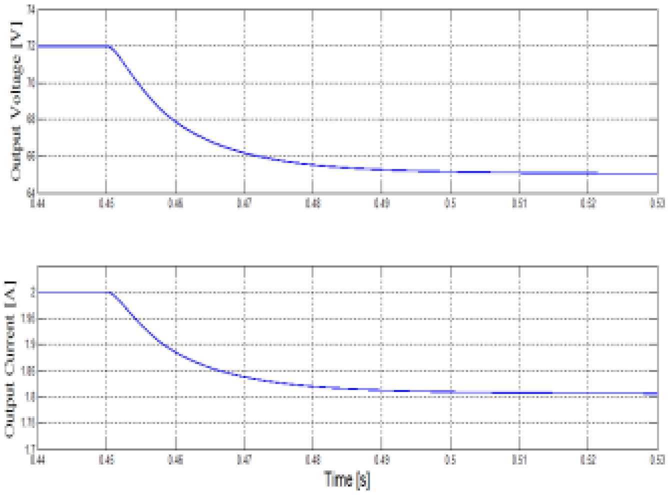


(b)

Fig.9 step decrease in load from 75% to 12.5% at 0.45 s, (a) output voltage and current waveforms (b) fuel cell voltage and current waveforms.

c. *Step change in reference from 72 V to 65 V*



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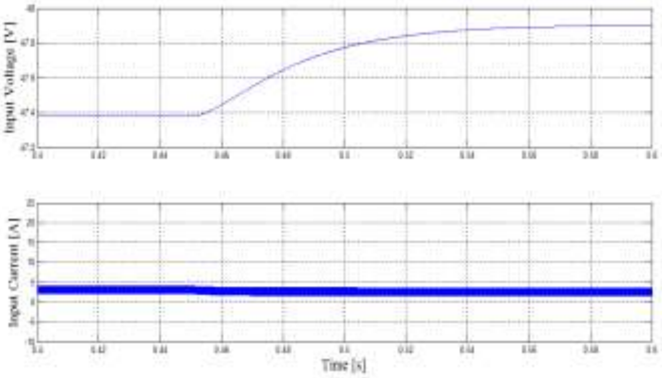


(b)

Figure: 10 Step change in reference from 72 V to 65 V, (a) output voltage and current waveforms, (b) fuel cell voltage and current waveforms

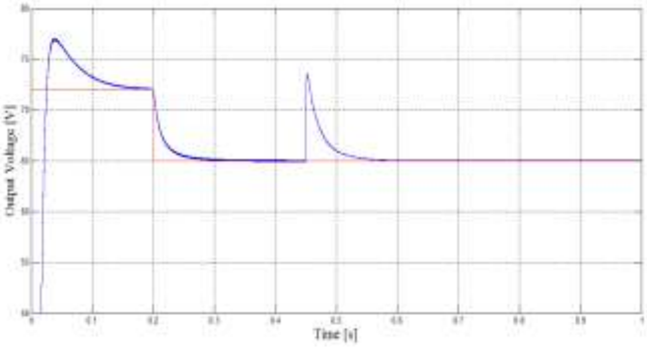
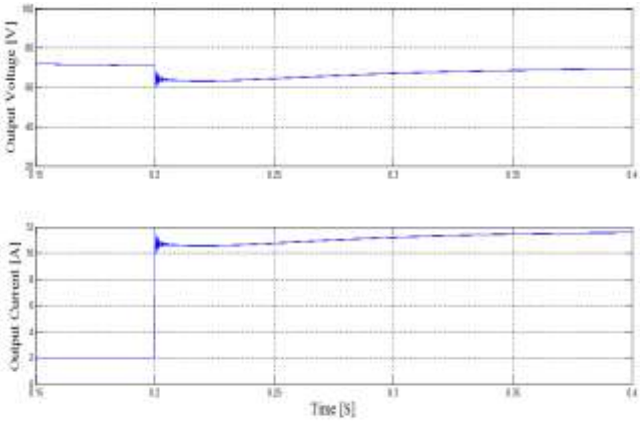


Fig.11 Line and Load regulation tracking of ILBC

B. *Smith Predictive Voltage Mode Controller for Fuel Cell fed ILBC*



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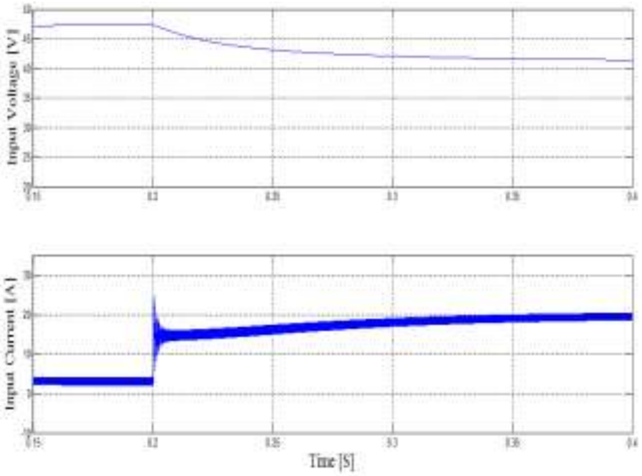

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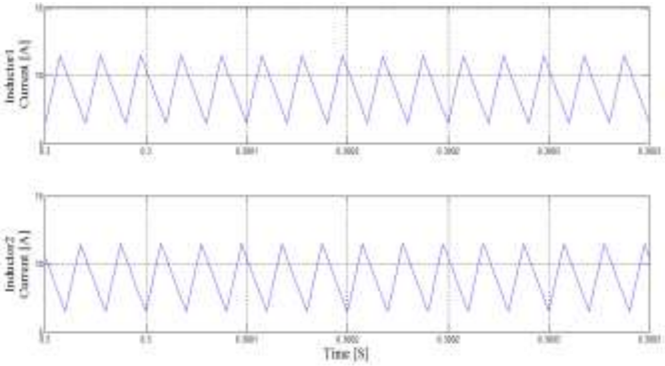
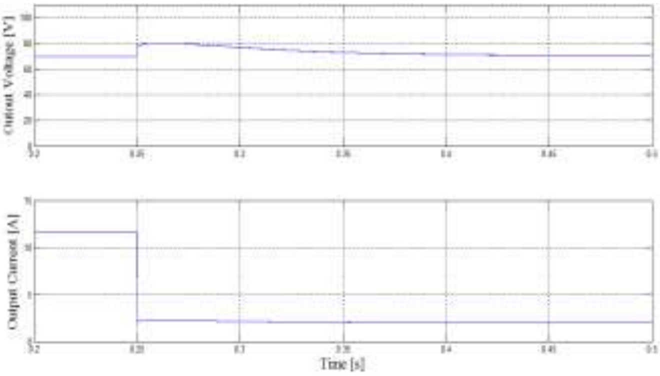
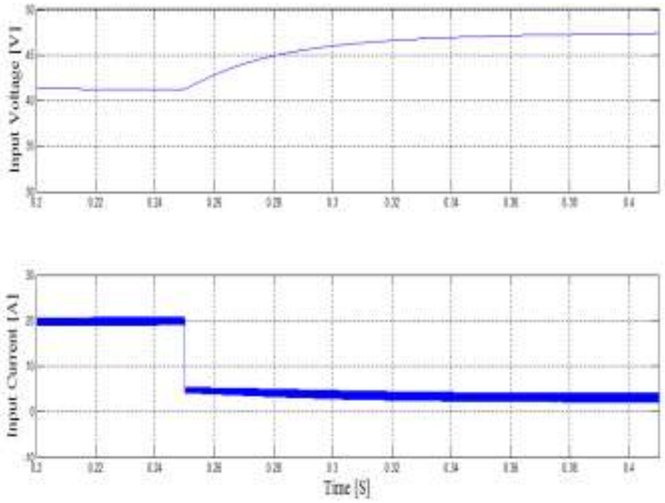


(c)

Fig.12 Step increase in load current from 12.5% to 75%,(a) Output voltage and current waveforms, (b) input voltage and current waveforms, (c) inductor current waveforms.

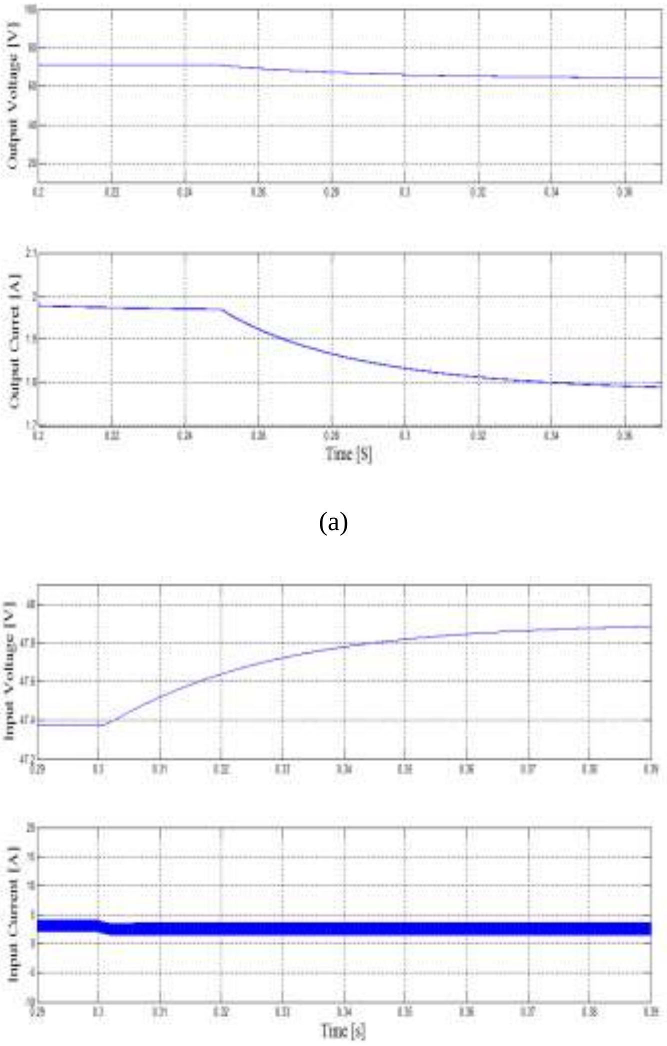


(a)



(b)

Figure: 13 Step decrease in load current from 75% to 12.5%, (a) output voltage and current waveforms, (b) input voltage and current waveforms



(a)

(b)

Figure: 14 step change in reference from 72 V to 65 V,(a) output voltage and current waveforms, (b) fuel cell voltage and current waveforms.

Table: 3 Comparisons of Voltage Mode PI Controller and Smith Predictive Controller

TYPE OF CONTROLLER/ PARAMETERS		VOLTAGE MODE PI CONTROLLER	SMITH PREDICTIVE CONTROLLER
STEP DECREASE IN LOAD CURRENT FROM 75% TO 12.5%	PEAK VOLTAGE [V]	9.8	9
	TRANSIENT TIME [m S]	100	155
	OUTPUT CURRENT RIPPLE [A]	0.018	0.015
STEP INCREASE IN LOAD CURRENT FROM 12.5% TO 75%	PEAK VOLTAGE [V]	12.5	11
	TRANSIENT TIME [m S]	150	160
	OUTPUT CURRENT RIPPLE [A]	0.00175	0.0012
STEP CHANGE IN REFERENCE VOLTAGE FROM 72V TO 65V	TRANSIENT TIME [m S]	60	125
	OUTPUT CURRENT [A]	0.00119	0.00113

VIII. CONCLUSION

This paper gives an exhaustive description procedure of a new Smith Predictive controller applied for interleaved boost converter. Design of voltage mode controller for ILBC system is obtained by using the smith predictive control. And this method overcomes the problem of conventional PI controller design. Performance of smith predictive controller is better than the PI controller performance. Due to presents of delay in the system transient time is more. The simulation results and performance analysis of both the controllers are compared in this paper.

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