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Fuel Cell Powered Bidirectional DC-DC Converter with Fuzzy Logic Controller for Electric Vehicle Applications

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ABSTRACT

This paper focuses on Air Breathing Fuel Cell (ABFC) as an alternate power source for electric vehicles (EV). An empirical model of ABFC has been developed with MATLAB/Simulink Software. In this paper, a bidirectional DC-DC Converter by using fuzzy controller is designed and simulated. The structure of the proposed converter is very simple and has higher step-up and step-down voltage gains than the existing bidirectional DC-DC converter. Finally, a 14/42 V converter circuit in closed loop mode is designed and simulated using fuzzy control technique.

Keywords:-Air Breathing Fuel Cell (ABFC); Electric Vehicle (EV); DC-DC Converter; Fuzzy Logic Controller.

1. INTRODUCTION

Fuel cell powered Electric Vehicle is being investigated as an alternative application for conventional internal combustion engine vehicle [1].Fuel Cell is an electro chemical device which converts fuel and oxidant into DC electricity [2].Fuel cell is characterised by high electrical efficiency and zero/low pollutant emission. Only water, heat and electricity are the products of electrochemical reaction in the fuel cell.

Cells that take up oxygen, for the cathode reaction, from ambient air by passive means are known as “air-breathing” fuel cells [3]. In the ABFC, hydrogen and oxygen are fed at anode and cathode respectively as reactants. The electrons transfer from the anode to the cathode through the external circuitry of the fuel cell. Hydrogen ions transfer across the membrane internally from the anode to the cathode to complete the current flow as shown in Figure 1.

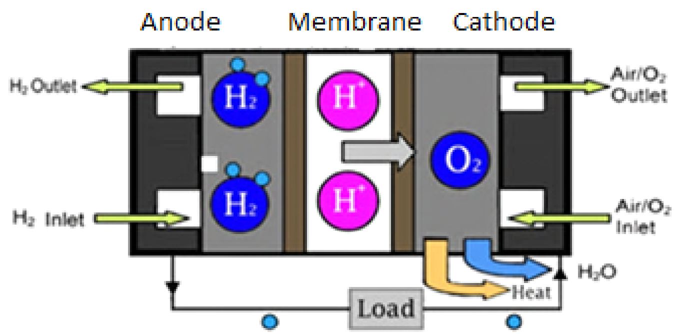

Figure1.Work process and reaction principle of an ABFC

Anode side reaction - $2H_2 \rightarrow 4H^+ + 4e^-$

Cathode side reaction - $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Overall reaction - $2H_2 + O_2 \rightarrow 2H_2O$ + Electricity + Heat

In addition to the fuel cell model, the other significant components of the overall system include a bidirectional DC-DC converter and its associated Fuzzy controller. A Bidirectional DC-DC converter allows the transfer of power between two dc sources in either direction. These bidirectional dc-dc converters are increasingly needed in applications like hybrid electric vehicle energy systems, DC uninterrupted power supplies, fuel cell hybrid power systems, photovoltaic hybrid power systems and battery chargers. The bidirectional DC-DC fly back converters has a very simple structure, but the active switch suffer a high voltage stresses due to the leakage inductance of the transformer [4, 5]. The coupled inductor type converters can provide high step-up and step-down voltage gains but the circuit configuration in more complicated[6]. The multilevel type converter requires more switches to achieve high step-up and step-down voltage gains and the circuit becomes more complicated [7].

The step-up and step-down voltage gains of the conventional bidirectional dc-dc converter are low due the effect of power switches. To achieve the high step-up and step-down voltage gains, a novel bidirectional dc-dc converter is proposed as shown in Figure2. The proposed converter employees a coupled inductor with same winding turns on primary and secondary sides.

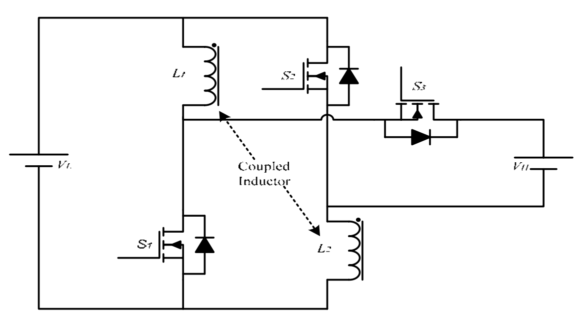

Figure 2. Proposed Bidirectional DC-DC Converter

The paper is organized as follows. Section II describes the mathematical modelling of the ABFC using MATLAB/Simulink. In Section III, the voltage mode control of the proposed converter is described. In Section IV, Results are discussed. Finally, Section V concludes the dynamic response of the proposed converter in closed loop mode using fuzzy logic controller.

2. NOTATION

Indexes:

D Switching duty cycle of DC–DC converter

E Open circuit voltage,(V)

G Gibbs free energy of formation per mole

H Enthalpy of formation per mole

S Entropy of formation per mole

I Current density,(mA Cm^{-2})

C_p Molar specific heat capacity at constant pressure [$JK^{-1}mol^{-1}$]

R Area-specific resistance,(KΩ Cm^2)

T Temperature,(K)

Constants:

F Faraday constant, the charge of one mole of electrons (96,485 C)

i_n Internal current density,(mA Cm^{-2})

i_o Exchange current density,(mA Cm^{-2})

P Pressure, (bar)

R Molar gas constant, (8.314 $JK^{-1}mol^{-1}$)

A Charge transfer coefficient

Γ Concentration of hydrogen

B Concentration of oxygen

Δ Concentration of steam

3. MODELLING OF THE OVERALL ABFC SYSTEM

The ABFC system model implemented in the paper consists of different sections. The overall system consists of the following sections:

- MATLAB model of the ABFC Stack.

- MATLAB model of a Bi-directional DC–DC converter with fuzzy controller.

The block diagram of the proposed scheme is shown in Figure 3. The design and modelling of each section is presented in detail in the succeeding sections. Simulation results are presented at each stage.

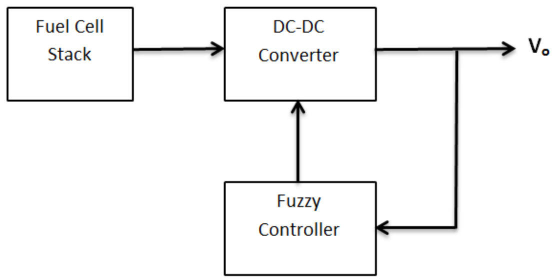

Figure 3. Block diagram of the proposed scheme.

4. MATHEMATICAL MODELLING OF THE ABFC

The analytical model of the ABFC can be represented by a set of mathematical equations. Gibbs free energy (Δg) is the net electrical work done by the system and is expressed in terms of the enthalpy of formation, temperature and the entropy of formation [13] represented by Eq (1).

$$\Delta g = \Delta h - T\Delta s \qquad (1)$$

For a fuel cell, the change in the enthalpy of formation and the change in entropy were modelled according to the mathematical Eqs (2) and (3).

$$\Delta h = h_{H_2O} - h_{H_2} - \frac{1}{2} h_{O_2} \qquad (2)$$

$$\Delta s = s_{H_2O} - s_{H_2} - \frac{1}{2} s_{O_2} \qquad (3)$$

However, h and s are expressed as functions of temperature as represented in Eqs (4) and(5).

$$h_T = h_{298.15} + \int_{298.15}^{T} C_p dT \qquad (4)$$

$$s_T = s_{298.15} + \int_{298.15}^{T} \frac{1}{T} C_p dT \qquad (5)$$

The molar specific heat at constant pressure (C_p) for steam, hydrogen and oxygen, respectively are given by the mathematical Eqs (6) - (8).

$$\mathbf{C_{p,Steam}} = \mathbf{143.05 - 58.04T^{0.25} + 8.2751T^{0.5} - 0.036989}\mathrm{T} \quad (6)$$

$$\mathbf{C_{p,hydrogen}} = \mathbf{56.505 - 22222.6T^{-0.75} + 116500T^{-1} - 560700T^{-1.5}} \quad (7)$$

$$\mathbf{C_{p,oxygen}} = \mathbf{37.432 - 2.0102 \times 10^{-5}T^{1.5} + 17850T^{-1.5} - 2368800T^{-2}} \quad (8)$$

The standard potential of a hydrogen/oxygen fuel cell at standard STP (25^{o}C and 1 atm) is 1.229V. Activation losses, ohmic losses, and Concentration losses are the three types of irreversible losses present in ABFC,due to which the actual cell potential drops from its equilibrium potential.The output voltage of the single cell ABFC is given by Eq (9).

$$\mathbf{V_{Cell} = E_{nernst} - \Delta V_{Act+crossover} - \Delta V_{Ohm} - \Delta V_{Conc}} \quad (9)$$

$$\mathbf{E_{nernst}} = \frac{-\Delta g}{2F} + \frac{RT}{2F}\ln\left(\frac{\gamma\beta^{\frac{1}{2}}}{\delta}P^{\frac{1}{2}}\right) \quad (10)$$

It is assumed that pure hydrogen and oxygen are used as reactants (i.e. γ= β= 1). The adopted equations which describe Activation losses, ohmic losses, and Concentration losses respectively are represented by equation (11)- (13) [7].

$$\Delta \mathbf{V_{act+fuelcrossover}} = \frac{RT}{2\alpha F}\ln\left(\frac{i+i_n}{i_o}\right) \quad (11)$$

$$\Delta \mathbf{V_{ohm}} = \mathbf{ir} \quad (12)$$

$$\Delta \mathbf{V_{conc}} = \mathbf{mexp(ni)} \quad (13)$$

The model built in MATLAB using the Eqs (1) – (13) is shown in Figure 5. The values of simulation parameters taken from the literature [8-14] and are tabulated in Table 1. The simulated polarisation curve was plotted for a range of current densities and at an operating temperature of 30^{o}C, as shown in Figure4and variation of cellvoltage of an ABFC for different cell temperatures is shown in Figure 6.

Table 1. Parameters of ABFC model

Parameter	**Value**
M	0.00003 V
N	0.008 cm^2 mA^{-1}
R	0.0002 KΩ cm^2
i_n	3 $mAcm^{-2}$
i_o	1 $mAcm^{-2}$
A	0.25

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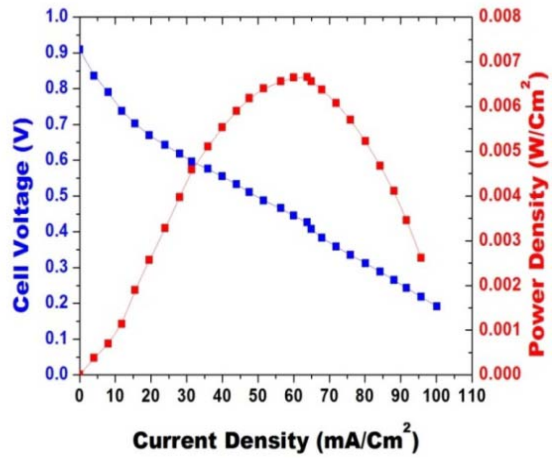

Figure 4.Polarization curve for an ABFC operating at 30°C

The operating voltage of a fuel cell ranges between 0.5 and 0.6 V [15]. According to Figure 3, that voltage range is produced within a current density range of approximately 40– 60 mA/cm^2. Thus, for the implemented Simulink model, an operating current density of 50mA/cm^2 was selected in order to produce a reasonable operational voltage for the fuel cell. Subsequently, it was found that for a current density of 50mA/cm^2, and an exchange current density of 1 mA/cm^2, the resulting operational voltage is 0.5656 V per fuel cell. Figure 6 presents a comparison between polarisation plots for three values of cell temperatures 30°C, 50°C, and 60°C to demonstrate the correctness of the simulation results. Theoretically, the cell voltage will be lower over the operating current density with increased cell temperature. This behaviour is observed in the Simulink model predictions. In this paper, we are using a 25 cell ABFC stack to obtain the required voltage of 14V for bi-directional DC-DC converter.

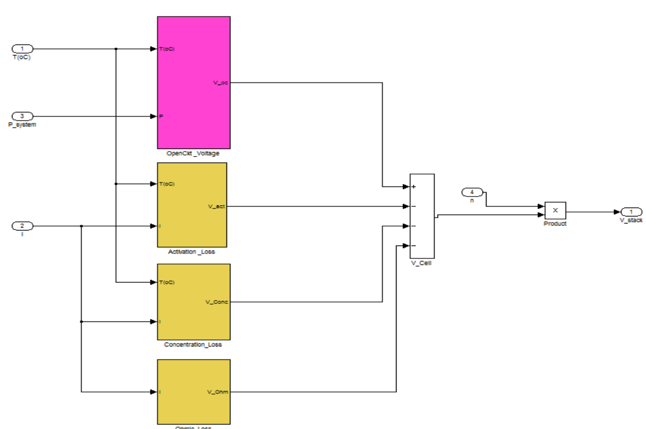

Figure 5.Scheme of the model developed in MATLAB in order to simulate stack behaviour

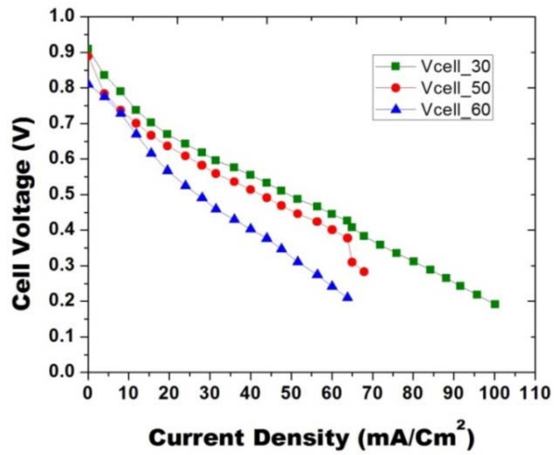

Figure-6. Cell voltage of an ABFC for different cell temperatures.

5. VOLTAGE MODE CONTROL OF THE PROPOSED CONVERTER WITH FUZZY CONTROLLER

The design parameters, MATLAB/Simulink Models of the proposed converter with Fuzzy controller are discussed in this section. The integrated MATLAB/Simulink model of the proposed converter by using fuzzy controller is shown in Figure 7. The design parameters of the proposed converter are shown in Table 2.

Table 3. Rule base for fuzzy logic controller

‘e’ / ‘Δe’	**NB**	**NS**	**ZE**	**PS**	**PB**
NB	NB	NB	NB	NS	ZE
NS	NB	NB	NS	ZE	PS
ZE	NB	NS	ZE	PS	PB
PS	NS	ZE	PS	PB	PB
PB	ZE	PS	PB	PB	PB

The Fuzzy Logic controller is designed with the help of membership functions as shown in Figure 8 and with linguistic rules as tabulated in Table 3.

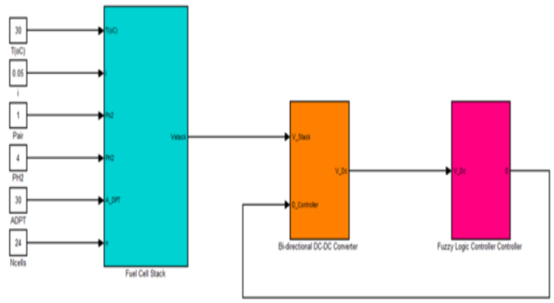

Figure 7. The integrated MATLAB/Simulink model of the proposed system

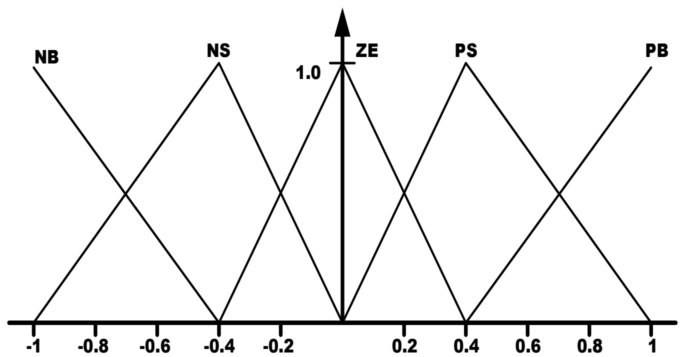

Figure 8. Membership functions error, change of error and output variable.

5. RESULTS AND DISCUSSIONS

The Simulink Model of the Proposed Converter with Fuzzy logic controller is shown in Figure 9. The output voltage shown in Figure 10 undergoes a zero transient voltage deviation at t=0.5 sec as shown in Figure 11. The output current waveform is shown in Figure 12.

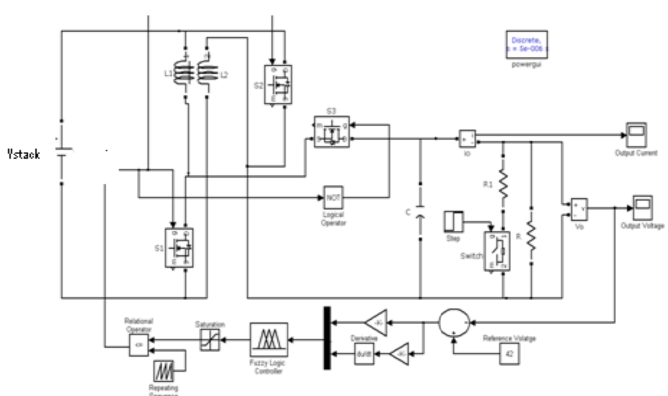

Figure 9. Simulink Model of the Proposed Fuel Cell powered Bi-directional DC–DC Converter with Fuzzy logic controller.

Table 4. Design Parameters of the proposed converter

Mode of Operation	**Step-up**	**Step-down**
Input	14v	42v
Output	42v	14v
Frequency	50KHz	50KHz
Power	200W	200W
Inductance	15.5μH	15.5μH
Capacitance	330 μF	330 μF

Figure 10. Output Voltage Waveform of the proposed converter when a step change in load from 0.47A to 5.2A at t=0.5sec.

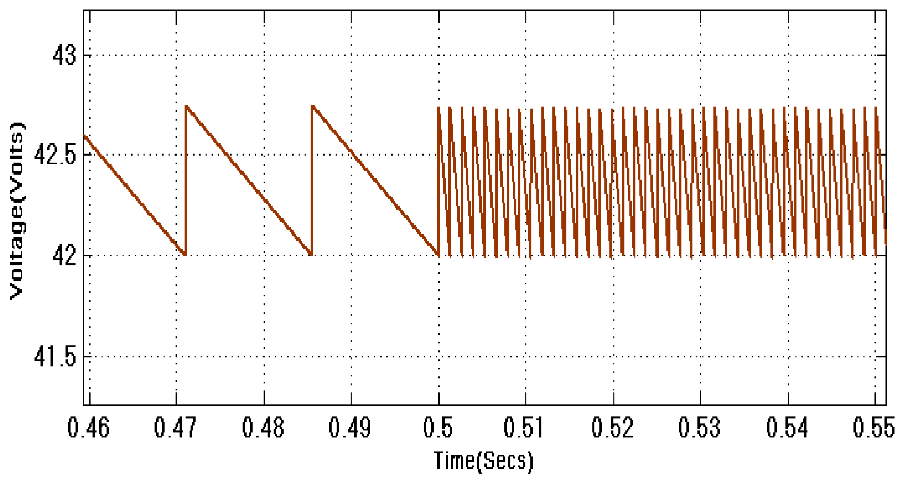

Figure 11. Transient Voltage Deviation of Output Voltage waveform of the proposed converter at t=0.5sec.

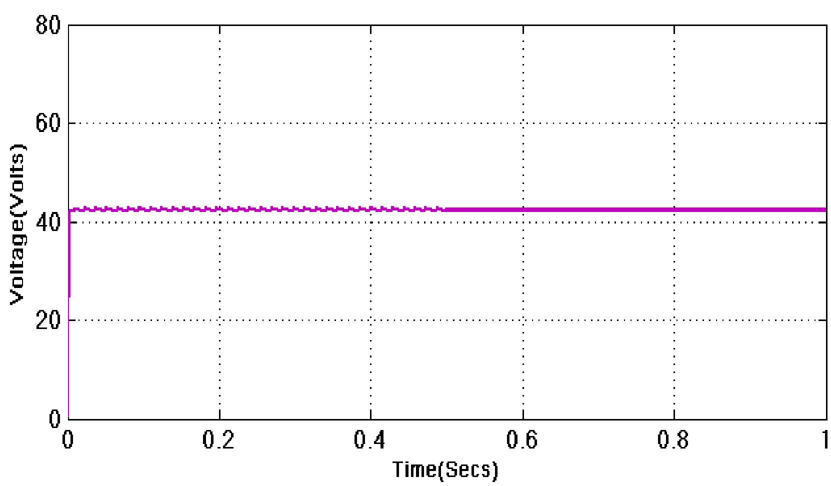

Figure 12.Output Current Waveform of the proposed converter when a step change in load from 0.47A to 5.2A at t=0.5sec

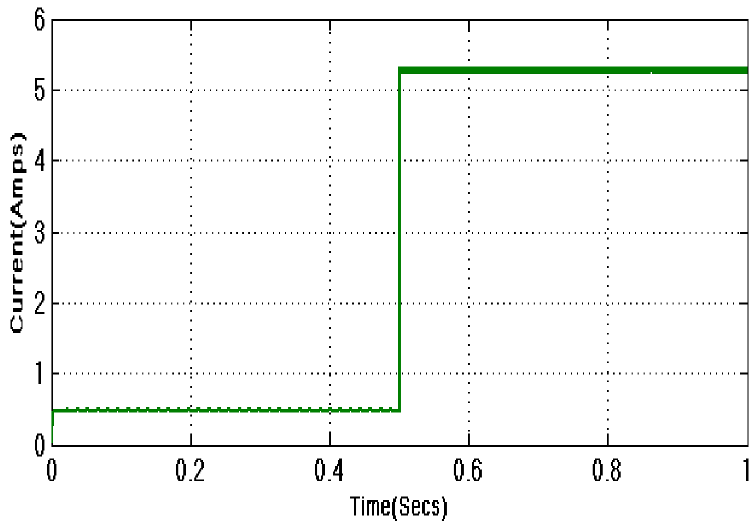

Table 5. Comparison of Steady state and dynamic performance

Mode of Operation	Transient voltage dip (from desired value 42V) for a step change in load	Transient settling time for a step change in load	Steady state voltage ripple
Open Loop	8.33%	0.015sec	2.6%
Fuzzy Logic Controller	0%	0 sec	1.6%

The steady state and dynamic performance comparison for the proposed converter in open loop and closed loop modes in terms of steady state voltage ripple, transient voltage deviation and transient settling time are tabulated in table 5.

6. CONCLUSION

The paper presented empirical model of an air breathing fuel cell. Also, a bidirectional DC-DC converter with fuzzy controller is designed and simulated. The dynamic performance of the proposed converter by using fuzzy controller is better than the open loop performance in terms of steady state voltage ripple, transient voltage deviation and transient settling time. It is observed for a step change in output current from 0.47A to 5.2A at t =0.5s, the transient voltage dip vanishes from 8.33% in open loop and steady state voltage ripple is reduced from 2.6% to 1.6%.

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