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FUZZY LOGIC IMPLEMENTATION OF PEM FUEL CELL BASED FOUR PHASE INTERLEAVED BOOST CONVERTER

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ABSTRACT

This paper implements the fuzzy logic control technique for the modeling of the PEM (Proton Exchange Membrane) fuel cell interfaced with a four-phase coupled IBC (Interleaved Boost Converter). In the modeling part of the PEM fuel cell, a fuzzy logic controller (FLC) is used to control, the flow rate of methane in the reformer and then output voltage of IBC is maintained constant by incorporating a FLC. The modeling, control and simulation is achieved for PEM fuel cell interfaced with four-phase coupled IBC. MATLAB simulink and fuzzy logic toolbox are used to check the proposed control algorithms.

Key words: PEM fuel cell, 4 Phase coupled IBC, Fuzzy logic control, Hydrogen flow rate.

INTRODUCTION

Most of the researchers are still developing the efficient fuel cell for commercial usage[1]. The fuel cell power supply is extended to residential, industrial areas, road vehicles, airport utility vehicles, transport aircrafts by replacing Auxiliary Power Source (APS). The fuel cell consists of number of cells connected in series forming a stack and it is fed by the gases of hydrogen, oxygen and coolant to the cells. By adding appropriate catalyst to the fuel cell, hydrogen, oxygen are transformed into electrical power, water and heat[2]. Among the variety of fuel cells, PEM fuel cell shows most attraction with its advantages such as fast response, high power density, low temperature and zero emission. So, PEM fuel cell is selected for this research. At first dynamic modeling of PEM fuel cell is achieved. The FLC is used to control the flow rate methane in the reformer. It's used to control the hydrogen flow rate of PEM fuel cell. The Gaussian type membership function is used for inputs and output. For fuzzification max-min interface method is used. For defuzzification centroid method is used. After implementation of FLC control system to the PEM fuel cell, it interfaced with the four phase coupled IBC to improve the output voltage.

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Interleaved boost converter is a better solution, for fuel cell system due to increased efficiency, low electromagnetic emission, high transient response & high reliability, reduced weight and size. In the structure of IBC, use of coupled inductor reduces the converter volume, size and weight. Therefore, FLC is implemented for PEM fuel cell based four phase coupled IBC, to control the output voltage value accurately. The Gaussian type membership function is used for inputs and output. For fuzzification max-min interface method is used. For defuzzification centroid method is used.

Fuel cell model

The dynamic model of PEM fuel cell is discussed in this section. The relationship between output voltage and partial pressure of hydrogen and oxygen is taken into account in this model[3]. The molar flow of hydrogen through the valve and its partial pressure inside the channel can be related as shown in Eqn. (1).

$$\frac{q_{H_2}}{P_{H_2}} = K_{H_2} \qquad \ldots(1)$$

Hydrogen molar flow can be categorized as hydrogen input flow, hydrogen output flow and hydrogen flow during the reaction[4]. It can be related as –

$$\frac{d}{dt} P_{H_2} = \frac{RT}{V_{an}} (q_{H_2}in - q_{H_2}out - q_{H_2}r) \qquad \ldots(2)$$

V_{an} is the volume of the anode channel.

The partial pressure and input flow rate of the fuel cell is given in Eqn. (3), (4) & (5).

$$P_{H_2} = \frac{1/K_{H_2}}{1+\tau_{H_2}S}(q_{H_2}in - 2K_r I) \qquad \ldots(3)$$

$$P_{O_2} = \frac{1/K_{O_2}}{1+\tau_{O_2}S}(q_{O_2}in - K_r I) \qquad \ldots(4)$$

K_r is defined as the relativity between the rate of reactant hydrogen and fuel cell current[5].

$$q_{H_2}{}^{r} = \frac{N \times I}{2FU} = 2K_r I \qquad \ldots(5)$$

where N is the number of cells in the stack. F is the Faraday's constant. I is the stack current. K_r is the constant value of the modeling.

Output voltage of a single cell can be defined as Eqn. (6) & (7).

$$V_{fc} = E_{nernst} - V_{act} - V_{ohm} - V_{conc} \quad \ldots(6)$$

E_{nernst} is the reversible voltage. V_{act} is voltage drop due to activation of anode and cathode. V_{ohm} is the ohmic voltage drop. V_{conc} is the voltage drop due to concentration of the reacting gases are given in Eqn. (8), (9), (10) & (11). E_{nernst} is the no load voltage[7].

$$E_{cell} = nV_{fc} \quad \ldots(7)$$

n is the number of cells connected in series & forming a stack.

$$E_{nernst} = \frac{\Delta G}{2F} + \frac{\Delta S}{2F}(T - T_{ref}) + \frac{RT}{2F}[\ln(P_{H_2}) + \frac{1}{2}\ln(P_{O_2})] \quad \ldots(8)$$

ΔG is the change in Gibb's free energy(J/mol), F is the constant of Faraday (96.487 C), ΔS is the change of entropy (J/mol), R is the universal constant of the gases (8.314 J/Kmol), P_{H_2} and P_{O_2} are the partial pressure of the hydrogen and oxygen (atm), respectively. T is the cell operating temperature, T_{ref} is the reference temperature.

$$V_{act} = -[\varepsilon_1 + \varepsilon_2 T + \varepsilon_3 T \ln(CO_2) + \varepsilon_4 \ln(I_{stack})] \quad \ldots(9)$$

I_{stack} is the cell operating current. ε_i represents the parametric co-efficient of the each cell model, CO_2 is the concentration of the oxygen.

$$V_{ohmic} = I_{stack}(R_m + R_c) \quad \ldots(10)$$

R_c is the resistance to the transfer of protons through the membrane.

$$V_{conc} = \frac{-RT}{eF}\ln\left[1 - \frac{I}{I_z}\right] \quad \ldots(11)$$

e is the number of participating electrons and I_z is the limiting current. By using the above equation, the simulink model of the PEMFC is realized.

Four phase coupled interleaved boost converter

It is necessary to boost the fuel cell voltage, to connect the fuel cell to an external power system. To increase the output voltage and to regulate the output voltage the boost converter plays an important role[2-5]. Higher efficiency can be achieved by splitting the output current into n paths. Because it reduces I^2R losses and inductor losses. IBC with coupled inductor to give the benefits such as reduced core and winding losses. Fig.1 shows the schematic diagram of four phase IBC with directly coupled inductors.

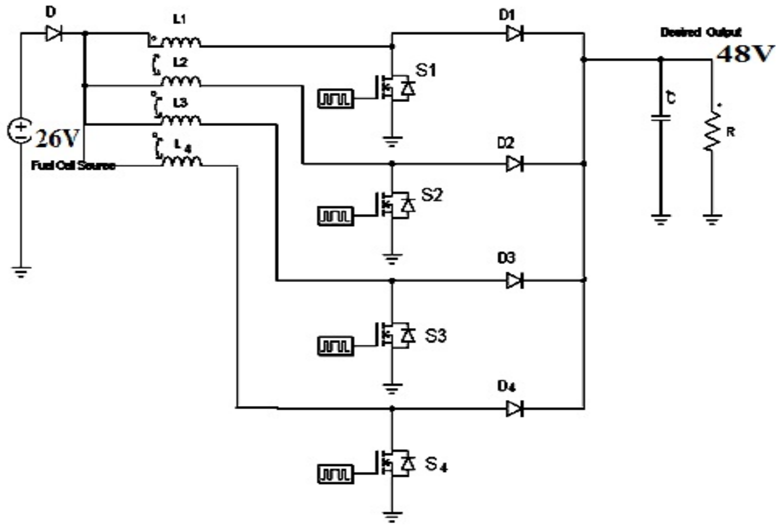

Fig. 1: Circuit diagram of a 4 phase direct coupled IBC

The gating pattern of the switches of the 4 phases are shifted by 360/n (360/4 for n=4), which is equal to 90 degrees.

Design methodology for direct coupled IBC

In interleaved design the inductors and diodes should be identical in each channels. Output power is channeled through n power paths. Where n is number of phases. The main steps involved in the design of coupled IBC's are[5-7]:

(i) Selection of inductor values.

(ii) Decision of duty ratio and number of phases.

(iii) Selection of power semiconductor switches.

(iv) Design of output filter.

(i) Selection of coupled inductors

The equivalent inductance for direct coupled IBC

$$L_{eq} = \frac{V_{in}DT}{\Delta I_{phase}} \qquad ...(12)$$

Where V_{in} is the input voltage, D is the duty ratio, ΔI_{phase} is the phase ripple current.

$$\Delta I_{phase} = \frac{V_{in}DT}{L} \times \frac{1+\alpha+2\alpha\frac{D}{1-D}}{1+\alpha-2\alpha^2} \qquad ...(13)$$

α is the coupling co-efficient (0.61). The self inductance of the coupled inductor can be expressed as –

$$L = \frac{1+\alpha\frac{D}{1-D}}{1+\alpha-2\alpha^2} \times L_{eq} \qquad ...(14)$$

The mutual inductance L_m can be found as –

$$L_m = \alpha \times L \qquad ...(15)$$

The leakage inductance L_k can be defined as,

$$L_k = (1-\alpha) \times L \qquad ...(16)$$

The input current ripple is –

$$\Delta I_{in} = \frac{V_{in}DT}{L} \times \frac{(1-\alpha)\left(1-\frac{2D}{1-D}\right)}{1+\alpha-2\alpha^2} \qquad ...(17)$$

(ii) Selection of duty ratio and phases

Duty ratio value can be selected as 0.52 and the number of phases can be selected as 4, to produce reduced input current ripple and to keep the inductor current ripple within limits.

(iii) Selection of power devices

To construct 4-phase IBC, suitable power semiconductor devices can be selected, such that it has the main benefits of lower ON state resistance, lower conduction losses and high switching operation[8,9]. The maximum voltage developed across the switching device is given by –

$$V_{switch} = Vin \times \frac{1}{(1-D)} \quad \ldots(18)$$

(iv) Output Filters

To reduce peak to peak ripple output voltage, a capacitor is needed as filter at the output[10]. The value of capacitance is given by –

$$C = \frac{V_o DT}{R\,\Delta V_o} \quad \ldots(19)$$

R is the load resistance, V_o is the output voltage & T is the switching period.

Fuzzy logic implementation to control hydrogen flow rate:

The cost of the controller design and implementation is relatively low in the fuzzy logic based control method. It also achieves high performance/cost ratio[11]. Fuzzy set theory has Linguistic Variables for fuzzy inferencing. Linguistic variables defined by fuzzy sets.

In fuzzy based control system, 2 inference methods are normally available. Mamdani fuzzy systems and Sugeno fuzzy systems.

Fuzzy control system provides better control technique compare to the other methods, because it is non linear and adaptive in nature and it provides robust performance under parameter variations and load disturbances[12-14].

(i) Reformer Model

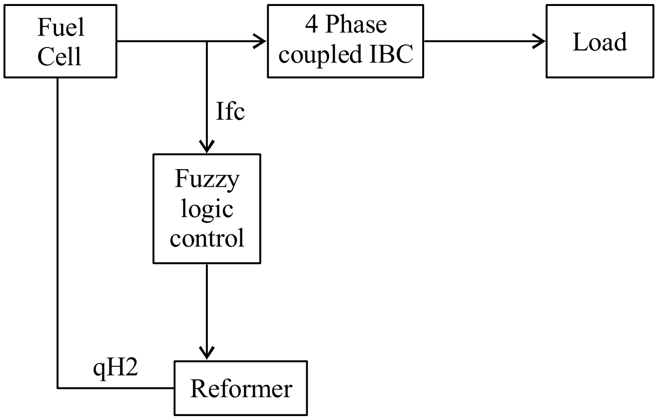

Fig. 2: Block diagram of fuzzy logic implementation to control hydrogen flow rate

A simple model of reformer is introduced to generate hydrogen through reformer. In the reformer section, sample & hold, summer and flow rate switch are used to control the hydrogen flow rate, which is directly proportional to the fuel cell current. Hydrogen prepared by economically, the most important process of removal of hydrogen from hydrocarbons[15]. Commercial bulk hydrogen is usually produced by the steam reforming of the natural gas. At high temperature (1000-1400 K) steam reacts with methane to yield carbon monoxide and H_2.

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad \ldots(20)$$

The mathematical form of the reformer model will be,

$$\frac{q_{H_2}}{q_{methane}} = \frac{CV}{\tau_1 \times \tau_2 S^2 + (\tau_1 + \tau_2)\, S + 1} \quad \ldots(21)$$

CV = 2, is the conversion factor (Kmol of hydrogen produced by Kmol of Methane). $\tau_1 = \tau_2 = 2$ are reformer time constants.

To implement the fuzzy logic controller for PEM fuel cell, 2 parameters should be monitored and regulated. These parameters are hydrogen flow and fuel cell current. A feedback from stack current is considered to control the hydrogen flow from the fuel cell[15-17].

In this method the controller is conventional fuzzy controller[18]. It has one input of error i.e., hydrogen flow rate e(k) and other input of change of error ce(k). The output of the controller is the hydrogen flow rate in terms of duty ratio.

$$e(k) = q_{H_2} + q_{meth\ ref} - q_{H_2O} \quad \ldots(22)$$

$$ce(k) = e(k) - e(k-1) \quad \ldots(23)$$

$$u_{H_2}(k) = u_{H_2}(k-1) + \rho \Delta u_{H_2}(k) \quad \ldots(24)$$

Q_{H_2} is the hydrogen flow from the current feedback signal, which is proportional to the load. $Q_{meth\ ref}$ is the methane reference signal, Δu_{H_2} (k) is the change of duty ratio inferred by fuzzy controller and ρ is the gain factor of the controller.

The linguistic terms for error, change of error and control are NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZO (Zero), PB (Positive Big), PM (Positive Medium), PS (Positive Small). By using these linguistic terms 7*7 fuzzy rules are framed as under.

Table 1: Fuzzy rules to control hydrogen flow rate

MFs	**NB**	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	NS	ZO
NM	NB	NB	NB	NM	NS	ZO	PS
NS	NB	NB	NM	NS	ZO	PS	PM
ZO	NB	NM	NS	ZO	PS	PM	PB
PS	NM	NS	ZO	PS	PM	PB	PB
PM	NS	ZO	PS	PM	PB	PB	PB
PB	ZO	PS	PM	PB	PB	PB	PB

The membership functions for input and output are Gaussian type. The error, change of error and control are represented by the membership function as shown in Fig. 3, 4, 5.

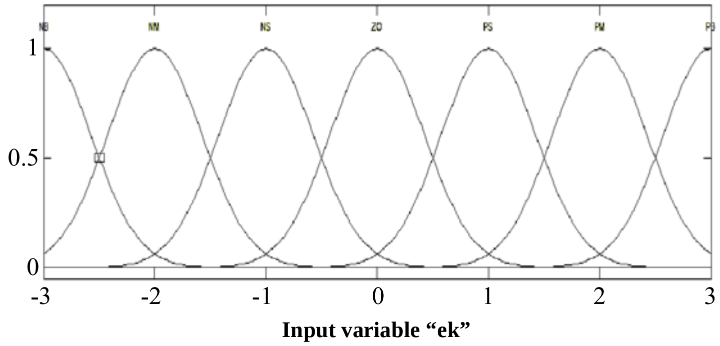

Fig. 3: The membership function for input 1

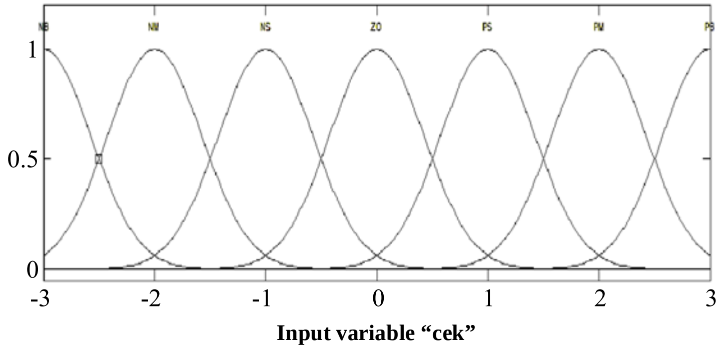

Fig. 4: The membership function for input 2

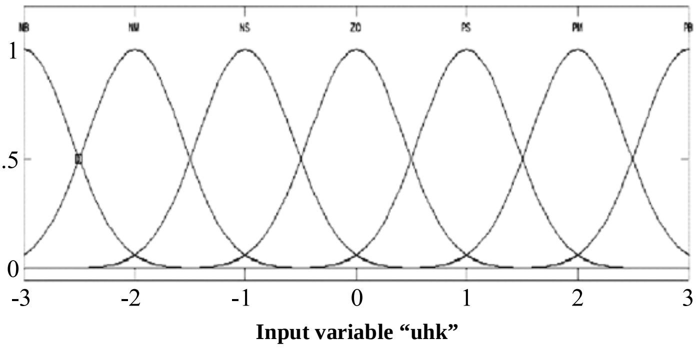

Fig. 5: The membership function for output

In defuzzification centroid method is used. So the output value can be determined by center of gravity of the output membership function[19].

$$\Delta u_{H_2} = \frac{\sum_{i=0}^{n} \mu_{ci}(u_{H_{2i}}) \times u_{H_{2i}}}{\sum_{i=0}^{n} \mu_{ci}(u_{H_{2i}})} \quad \ldots(25)$$

The inference method used is developed from the minimum operation function rule as a fuzzy implementation function. The Min-Max method is utilized here. The control surface is presented in Fig. 6.

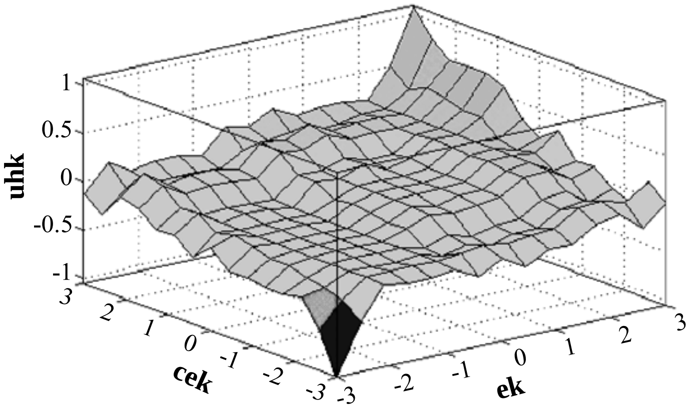

Fig. 6: The control surface to control the hydrogen flow rate

Fuzzy logic implementation to control the output voltage of IBC

In the second part FLC is implemented in the 4 phase IBC itself to control the output voltage of the fuel cell based 4 phase IBC.

In this part, fuzzy set theory uses linguistic variables for fuzzy inferencing. Mamdani fuzzy systems are used here[20-25]. The inputs are error e(k) (i.e, rated output voltage of the coupled IBC), change of error is ce(k), the output of the controller is –

$$e(k) = V_{oref} - V_o \qquad \ldots(26)$$

$$ce(k) = e(k) - e(k-1) \qquad \ldots(27)$$

$$u_{V_o}(k) = u_{V_o}(k-1) + \rho\Delta u_{V_o}(k) \qquad \ldots(28)$$

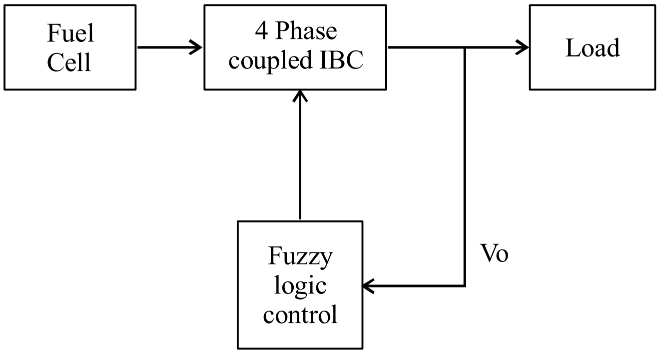

Fig. 7: Block diagram of FLC implementation to control the output Voltage of IBC

For error, change of error the linguistic terms are NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZO (Zero), PS (Positive Small), PM (Positive Medium), PB (Positive Big)[26-32]. By using these linguistic terms 7*7 fuzzy rules are framed as under.

Table 2: Fuzzy rules to control the output voltage of IBC

MFs	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZO
NM	NB	NB	NB	NM	NS	ZO	PS
NS	NB	NB	NM	NS	ZO	PS	PM
ZO	NB	NM	NS	ZO	PS	PM	PB
PS	NM	NS	ZO	PS	PM	PB	PB
PM	NS	ZO	PS	PM	PB	PB	PB
PB	ZO	PS	PM	PB	PB	PB	PB

The gaussian type membership functions are used for inputs & output. The membership functions for error, change of error & control are presented in the Figs. 8, 9, 10, 11.

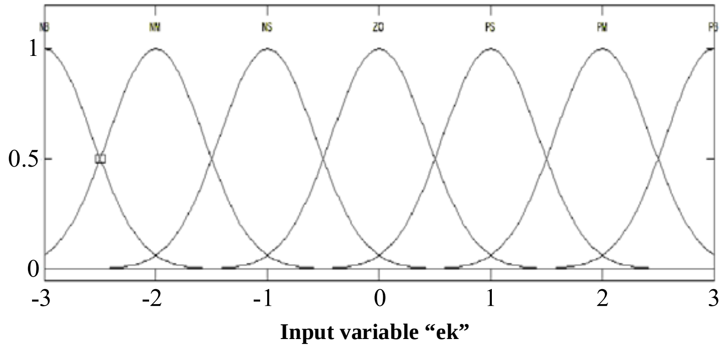

Fig. 8: Membership function for input 1

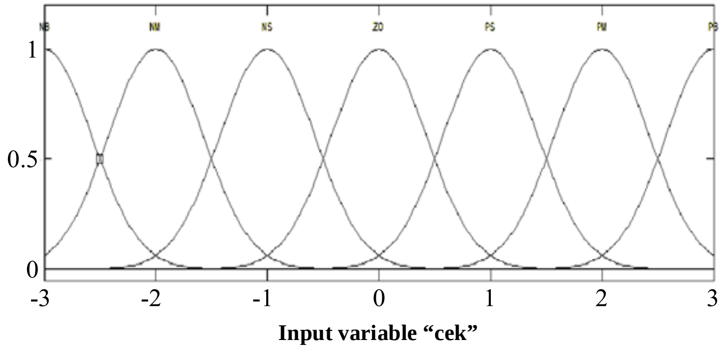

Fig. 9: Membership function for input 2

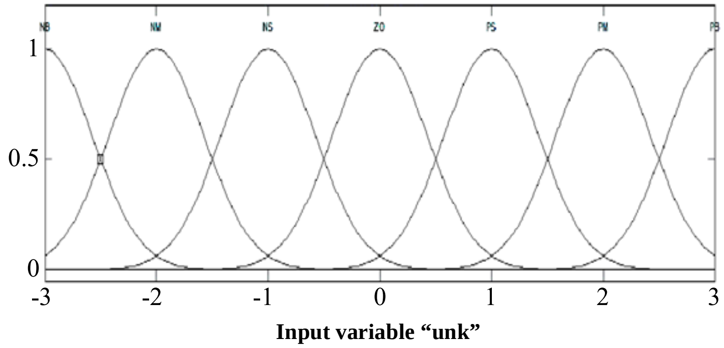

Fig. 10: Membership function for output

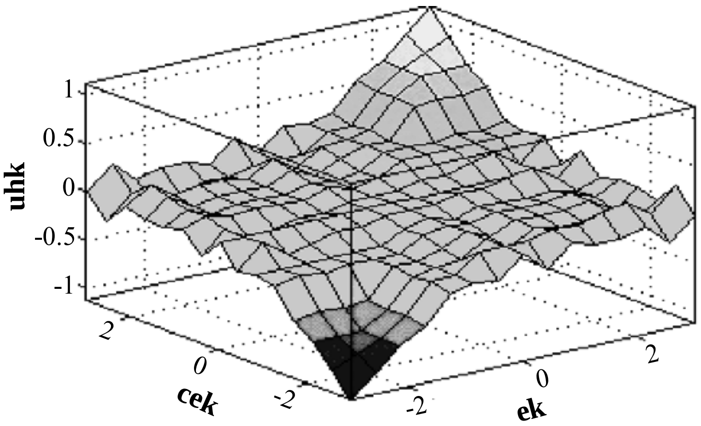

Fig. 11: The control surface to control the IBC output Voltage

The centroid method is used for defuzzification. So the output value can be found out by center of gravity of the output membership function & it's given by the expression,

$$\Delta u_{V_o} = \frac{\sum_{i=0}^{n} \mu_{ci}(u_{V_{oi}}) \times u_{V_{oi}}}{\sum_{i=0}^{n} \mu_{ci}(u_{V_{oi}})} \qquad \ldots(29)$$

The inference method used is Min-Max method and the control surface is presented here.

Simulation results

The simulations of fuzzy logic implementations are achieved in two different ways.

(i) At first hydrogen flow rate of fuel cell is controlled by fuzzy control system. Then fuel cell voltage can be improved by 4 phase coupled IBC. So the fuel cell output voltage, IBC output voltage, IBC output voltage ripple and IBC output current simulations are presented in Fig. 12, 13, 14, 15.

(ii) At second part fuel cell output voltage improved by 4 phase coupled IBC. In the IBC itself, fuzzy logic was implemented to control the output voltage of the IBC. So the IBC output voltage, IBC output ripple & output current simulations are presented in the Fig. 16, 17.

(a) Fuzzy controller to control hydrogen flow rate

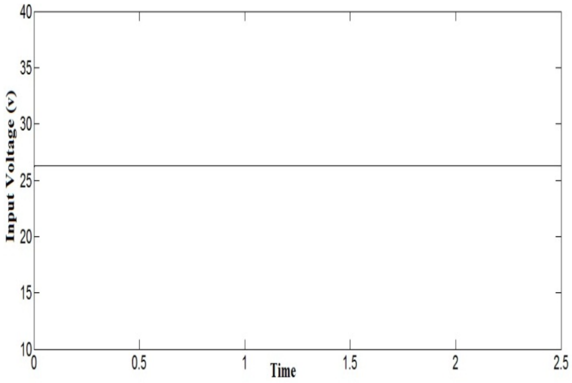

Fig. 12: IBC input voltage

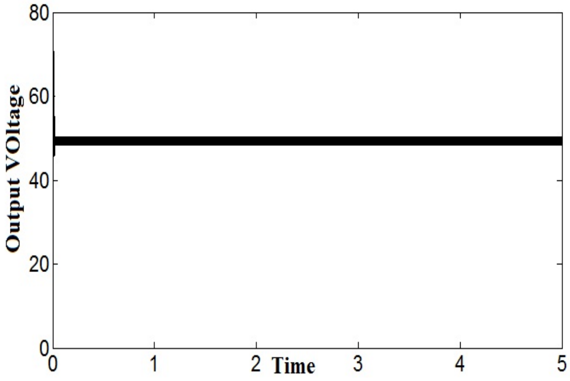

Fig. 13: IBC output voltage

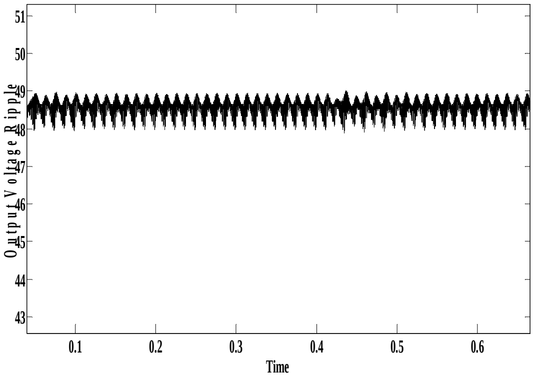

Fig. 14: IBC output voltage ripple

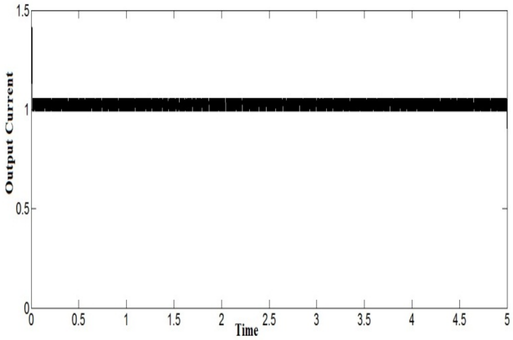

Fig. 15: IBC output current

(b) Fuzzy controller to control IBC output voltage

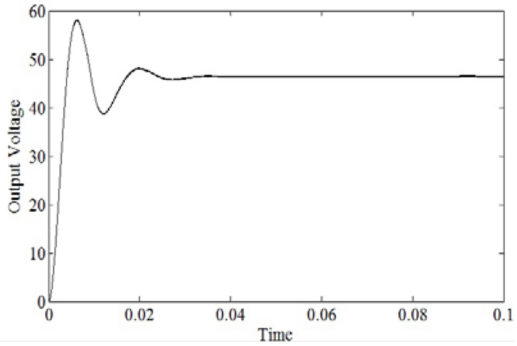

Fig. 16: IBC output voltage

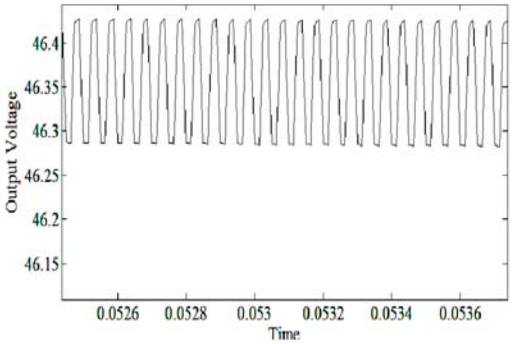

Fig. 17: IBC output ripple

Table 3 shows the ripple of IBC with and without fuzzy logic controller. It is found that with fuzzy controller, both the input current ripple and output voltage ripple are reduced.

Table 3: Ripple calculation for IBC

Parameters	Fuzzy based IBC	IBC without fuzzy controller
Output Voltage ripple (V)	0.018	0.014
Input current ripple (A)	0.0135	0.19
Inductor current ripple (A)	0.00068	0.22

CONCLUSION

Modeling, control and simulation study is carried out to control the flow rate of hydrogen in fuel cell and to control the output voltage of 4-phase coupled IBC. To control the hydrogen flow rate, dynamic fuel cell model and reformer model is implemented. A fuzzy controller is used to control the flow rate of methane in the reformer, output voltage of the four-phase coupled IBC. With fuzzy control, the output voltage ripple and input current ripples are reduced compared to the conventional IBC.

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