AN ADVANCED APPROACH IN DIRECT ACTIVE FUZZY PI CONTROLLER FOR PRESSURE REGULATION IN PEM FUEL CELLS

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Abstract

Maintaining fuel and air flow rates at optimum levels during load variation, start-up and shut down and regulating pressure are the fundamental crisis to be sorted out first for improving the performance and reliability of Proton Exchange Membrane Fuel Cell (PEMFC). In this paper, a Direct Active Fuzzy PI controller is developed and used to regulate the pressure of the reactants on anode and cathode side by controlling the flow rates of the reactants. The simulation results reveal that PEMFCs equipped with the proposed Direct Active Fuzzy PI controller exhibit better transient performances than the simple PI controller and nonlinear controller reported earlier.

Keywords: PEM Fuel Cells, Pressure regulation, Reactant Flow rate, Fuzzy PI Controller.

1. Introduction

The awareness of environmental protection is the need of the hours of twentieth century. With this observation, the scientists, technologist, public and policy makers look for alternative source to carry and convert energy. To substitute the conventional energy converters, Proton Exchange Membrane Fuel Cell (PEMFC) is observed to be the most satisfying and promising device. It is also viewed as the solution to the environmental and energy related problems. In future it will become the suitable energy converter for automotive, stationary and portable applications due to the high energy density at the operating temperatures, quick start-up and zero emission. However, the cost and durability of fuel cell is viewed as the major drawback to replace conventional energy converters [1]. Inadequate supply of Reactants and reactants pressure cause severe damage to the cell membrane and catalyst layer. The performance and life of the stack is mainly concerned with the proper maintenance of the reactant pressure on both side of the electrodes [2]. Control plays a major role to keep the performance and stack life by maintaining the flow rate, partial pressure of reactants, water and thermal management [3]. Many control strategies to keep oxygen excess ratio for avoiding oxygen starvation addressed in literature, ranging from feed forward control [4-6], LQR control [5, 7-8], Fuzzy logic control [9, 10], Neural network control [11, 12], Parameter optimized feed forward fuzzy logic control with feedback PID control [13] and Model predictive control [14, 15].

The impact of partial pressure of the reactants on the performance of the PEMFC is very high than other parameters, because of the fact that the stack voltage depends on the value of partial pressure of the reactants. The main objective of this work is to keep the partial pressure of the reactants at the desired level in order to avoid the detrimental degradation of the life of PEMFC and also hold the pressure difference between the hydrogen and oxygen sides at less than 0.5atm all the times by employing the proposed Direct Active Fuzzy PI controller.

2. Dynamic Model of a PEM Fuel Cell

2.1. PEMFC Stack Voltage Model

A PEMFC stack consists of a multiple number of single cells are connected electrically in series by bipolar plates to produce a reasonable voltage. Each fuel cell has proton exchange membrane which is sandwiched between two electrodes (anode and cathode) that are coated with a platinum catalyst. Fig. 1 shows the whole operation of PEMFC schematically.

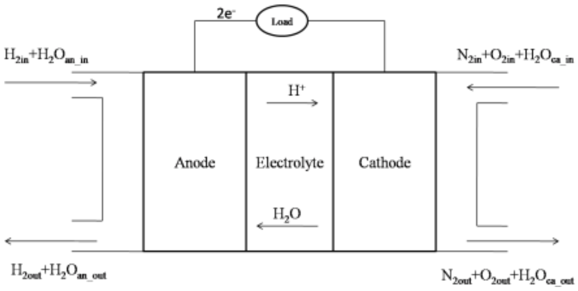


Fig. 1. Schematic diagram of a PEMFC

Hydrogen of 99.9% purity is well humidified and supplied as fuel with stoichiometry of 2, at the anode with the help of a pressure regulator and purging system for the hydrogen component. On the other hand, an air supply system which is composed of air compressor, air filter and flow controllers supplies the humidified air uniformly mixed with nitrogen and oxygen in the ratio of 79:21 with stoichiometry ranges from 2 to 2.5 to the cathode [3].

The fuel cell stack output voltage can be expressed by the following equation,

$$\mathrm{V_{st}} = \mathrm{E_{Nernst}} - \eta_{\mathrm{act}} - \eta_{\mathrm{ohm}} - \eta_{\mathrm{conc}} \tag{1}$$

The reversible thermodynamically predicted stack voltage based on Nernst equation is,

$$\mathrm{E_{Nernst}} = \mathrm{N_{cell}}\left[\mathrm{V_0} + \left(\frac{\mathrm{RT}}{2\mathrm{F}}\right)\ln\left(\frac{\mathrm{P_{H_2}}.\sqrt{\mathrm{P_{O_2}}}}{\mathrm{P_{H_2O_{ca}}}}\right)\right] \tag{2}$$

The activation loss due to the sluggishness in electrochemical reaction on the surface of the electrode, can be described by,

$$\eta_{\mathrm{act}} = \mathrm{N_{cell}}.\frac{\mathrm{RT}}{2\alpha\mathrm{F}}.\ln\left(\frac{\mathrm{I_f}+\mathrm{I_n}}{\mathrm{I0}}\right) \tag{3}$$

The ohmic loss due to the ionic and electrical resistance which is offered by external conductor and membrane, can be expressed by,

$$\eta_{\mathrm{ohm}} = \mathrm{N_{cell}}.\mathrm{I_f}.\mathrm{r} \tag{4}$$

The concentration loss due to reduction in transport of reactants, can be written as,

$$\eta_{\mathrm{conc}} = \mathrm{N_{cell}}.\mathrm{m}.\exp\left(\mathrm{n}.\mathrm{I_f}\right) \tag{5}$$

2.2. PEMFC State Space Dynamic Model

While modeling the PEMFC, the following assumptions have been made to obtain a simplified Multi Input Single Output (MISO) nonlinear dynamic model of PEMFC.

- All gases are ideal.
- Temperature along the entire stack is uniform.
- Reactants in the anode and cathode sides are well humidified.
- Hydrogen with the purity of 99.99% and stoichiometry of 2 is fed to the anode.
- Air uniformly mixed with nitrogen and oxygen in the ratio of 79:21 with stoichiometry ranges from 2 to 2.5 is supplied to the cathode.
- The excess condensed liquid water humidifies the reactants when their humidity drops below 100% [4, 5, 6, 16, and 17].

Nonlinear MISO dynamic model of PEMFC system is developed based on ideal gas law and mass conservation principle as,

$$\dot{x_1} = \frac{RT}{\mathrm{V_{an}}}\left(\left\{1 - \frac{x_1}{\mathrm{P_{an}}}\right\}u_1 + \{-2k_rA_c + 2k_rA_cx_1\}u_3\right) \tag{6}$$

$$\dot{x_2} = \frac{RT}{\mathrm{V_{ca}}}\left(\left\{1 - \frac{x_2}{\mathrm{P}_{ca}}\right\}u_2 + \{-k_rA_c + 2k_rA_cx_2\}u_3\right) \tag{7}$$

$$\dot{x_3} = \frac{RT}{\mathrm{V_{ca}}\mathrm{P}_{ca}}\left(x_3u_2 + \{2k_rA_c - 2k_rA_cx_3\}u_3\right) \tag{8}$$

Three state variables being considered here are, the partial pressure of reactants to be controlled and water at cathode side. The control input is the flow rates of reactants and the disturbance of the PEMFC system is the load current.

States:

$$[x_1x_2x_3] = [\mathrm{P_{H_2}P_{O_2}P_{H_2O_{ca}}}] \tag{9}$$

Inputs:

$$[u_1u_2u_3] = [\mathrm{H_{2in}O_{2in}}i_{FC}] \tag{10}$$

3. Proposed Direct Active Fuzzy PI Controller

The Partial pressure of Hydrogen at the anode and Oxygen at the cathode for PEMFC system under different load condition is regulated through the control of mass flow rate of Hydrogen and Oxygen at anode and cathode respectively. The proposed Direct Active Fuzzy PI control scheme is shown in Fig. 2. This controller regulates the Partial pressure of Hydrogen and Oxygen by controlling the inlet flow rates of Hydrogen and Oxygen on the both sides.

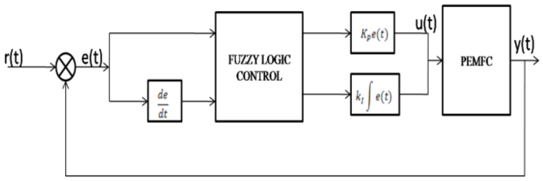


Fig. 2. Direct Active Fuzzy PI controllers for pressure regulation of PEMFC

Controllers such as Sliding Mode controllers have been extensively used for nonlinear systems and systems with uncertainties [18, 19]. Besides this, adding a Fuzzy component with a controller improves its robustness [19, 20] and makes it adaptive for inaccurate and imprecise nonlinear systems [21 - 23].

The proposed direct active fuzzy PI controller is designed with two inputs, error and rate of change of errors ("rate") defined in the range of [-1,1]. Two outputs K_p, K_i are defined in the range of [0, 50] and fifty fuzzy control rules, as shown in Fig. 3.

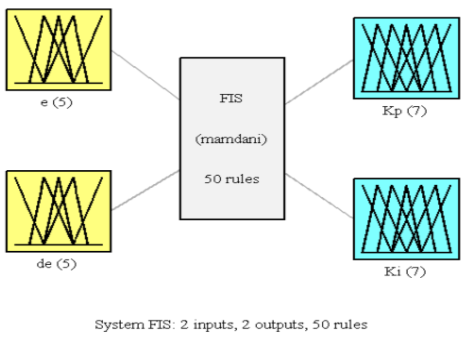


Fig. 3. Schematic diagram of fuzzy logic control

The fuzzy sets “error” and “rate” are assigned with five triangular fuzzy memberships, denoted by NL (Negative Large), NS (Negative Small), ZE (Zero), PS (Positive Small), and PL (Positive Large). The fuzzy set outputs K_p, K_i are assigned with seven triangular fuzzy memberships, represented by PVL (Positive Very Low), PS (Positive Small), PMS (Positive Medium Small), PM (Positive Medium), PML (Positive Medium Large), PL (Positive Large), PVL (Positive Very Large). These memberships are shown in Fig. 4.

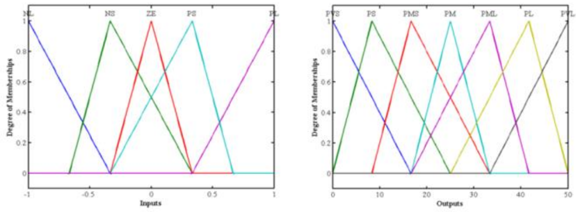


Fig.4. Membership functions of fuzzy PI component

The control rules for assigned linguistic variables are given in Table 1. Defuzzification of output variable has been obtained by centroid method. Here, the values of PI controller parameters Kp and Ki are regulated by the optimal output of fuzzy logic control.

Table 1. Fuzzy PI rule base for gain parameters K_p and K_i

	Change in Error (de)											
	K_p						**K_i**					
		NL	NS	ZE	PS	PL		NL	NS	ZE	PS	PL
Error (e)	NL	PVL	PML	PVS	PML	PVL	NL	PM	PMS	PS	PMS	PM
	NS	PVL	PML	PVS	PML	PVL	NS	PM	PMS	PS	PM	PM
	ZE	PVL	PML	PS	PML	PVL	ZE	PM	PMS	PVS	PMS	PM
	PS	PVL	PL	PMS	PL	PVL	PS	PM	PMS	PS	PMS	PM
	PL	PVL	PVL	PMS	PVL	PVL	PL	PM	PMS	PS	PMS	PM

4. Results and Discussion

The simulation models of PEMFC Stack voltage model, State space dynamic model, and the proposed Direct active Fuzzy PI controller have been developed in MATLAB-SIMULINK, version 8.1 (R2013a). In order to maintain the Hydrogen and Oxygen pressures at the desired levels under static and dynamic load conditions, the PI controller gain adjustments are made by the Fuzzy logic component of PI controller. Three different set-points of partial pressure of the hydrogen at anode and oxygen at cathode, have been considered for the simulation experiments (3atm, 4atm and 5atm). Two separate direct active fuzzy PI controllers have been employed for static and dynamic load conditions.

Any prolonged deviation in reactant pressure from the set-point will lead to severe damage on membrane and thereby affecting the life of PEMFC. Hence, it is very much essential to maintain a constant reactant pressure on both sides of the Polymer Electrolyte Membrane. In addition to maintaining the constant partial pressure of Hydrogen and Oxygen, it is also ensured that the differences between these pressures are maintained at the smallest possible level. This helps to improve the life of PEMFC stack.

The obtained simulation results of proposed controller for various conditions being considered have been compared with the results of PI controller and nonlinear controller reported in [3]. The comparisons are shown in graphically and also tabulated for various conditions being considered. For the simulation experiments, the static load is set as 1 ohm and the dynamic load change is considered as given in Fig. 5.

4.1. Static load conditions

Simulations are carried out with the load conditions being considered as static. The static load considered for the simulations is 1 ohm for three different set-points of 3atm, 4atm and 5atm for both Hydrogen and Oxygen partial pressures. The results of simulations are given in Figures 6, 7 and 8. The figures show the comparison of responses of proposed controller with early reported PI and Non-liner controllers [3].

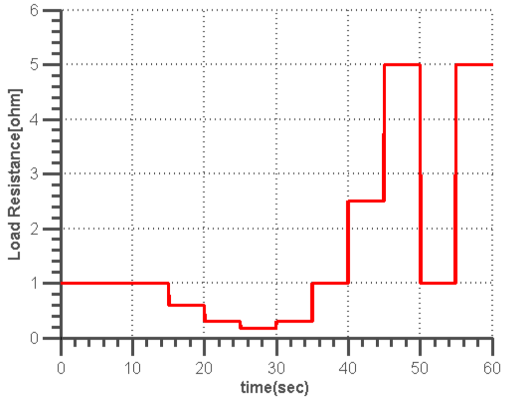


Fig. 5. Dynamic load condition considered for simulation

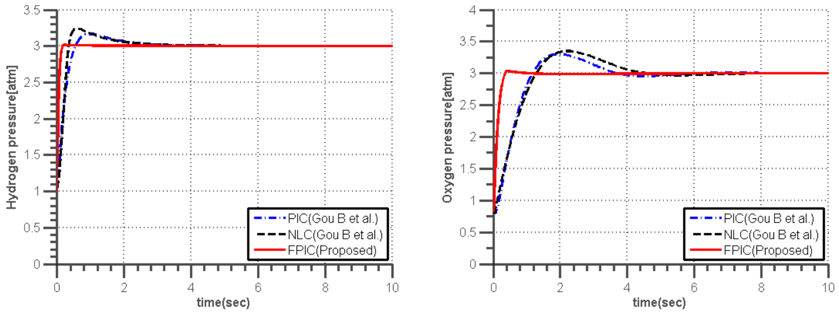


Fig. 6. Hydrogen and Oxygen pressure responses of PEMFC under static load (Set-point = 3atm)

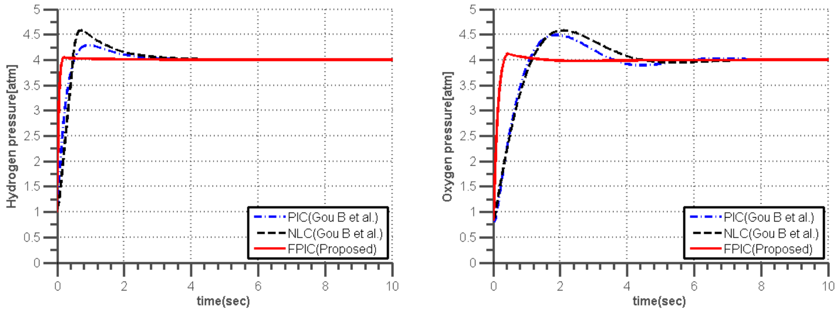


Fig. 7. Hydrogen and Oxygen pressure responses of PEMFC under static load (Set-point = 4atm)

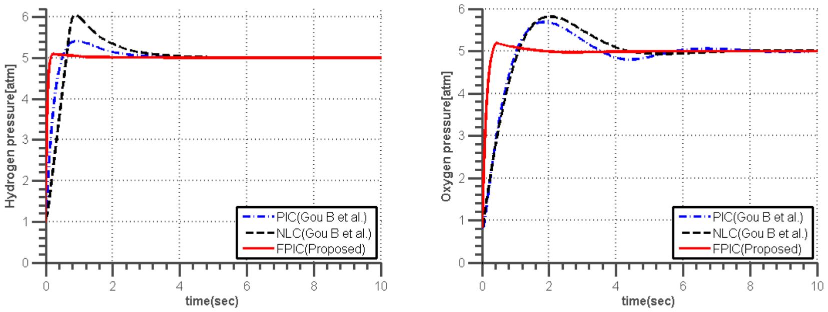


Fig. 8. Hydrogen and Oxygen pressure responses of PEMFC under static load (Set-point = 5atm)

From the responses in Figures 6, 7, and 8, it is found that the proposed direct active fuzzy PI controlled system exhibits a much better response with a negligible amount of overshoot, no understood, faster rising time and more improved settling time than that of PI controller and Non-linear. Further, the time domain specifications extracted from the responses are consolidated and presented in Table 2.

Table 2 Time domain specifications of controllers under static load conditions

Controller	P_{H2}=3atm			P_{H2}=4atm			P_{H2}=5atm		
	t_r(s)	t_s(s)	M_p(%)	t_r(s)	t_s(s)	M_p(%)	t_r(s)	t_s(s)	M_p(%)
PIC	0.37	2.36	5.59	0.35	2.42	7.20	0.34	2.45	8.18
NLC	0.24	2.30	7.99	0.36	2.86	14.52	0.47	3.30	20.88
FPIC	0.09	0.14	0.51	0.09	0.13	1.25	0.09	0.36	1.86
.Controller	P_{O2}=3atm			P_{O2}=4atm			P_{O2}=5atm		
	t_r(s)	t_s(s)	M_p(%)	t_r(s)	t_s(s)	M_p(%)	t_r(s)	t_s(s)	M_p(%)
PIC	0.74	3.43	10.14	0.72	5.12	12.35	0.70	5.26	13.85
NLC	0.89	4.12	11.55	0.83	4.04	14.44	0.80	4.00	16.26
FPIC	0.21	0.33	1.31	0.21	0.82	3.16	0.20	1.03	3.97

4.2 Dynamic load conditions

To assess the adaptive nature of the proposed controller, simulations are also carried out with the dynamic load conditions. The dynamic load change profile shown in Fig. 5 is considered for the simulations with three different set-points of 3atm, 4atm and 5atm for both Hydrogen and Oxygen partial pressures, as in the case of static load conditions. The simulation results of proposed controller, compared with that of PI and Non-liner controllers [3], are given in Figures 9, 10 and 11. PV Module is used to observe the solar radiation as much as maximum as possible. The PV module comprise of number of solar cells or photovoltaic cells. On the other hand wind energy is observed by means of wind generators. Both renewable energy resources are being saved by battery as DC source. We need AC source to drive motor so DC is converted by means of inverter circuit. Switching of inverter are the another problem. As seen in Fig. 5, the load change happens at 0, 15, 20, 25, 30, 35, 40, 45, 50, 55 seconds. Figures 9, 10 and 11 show that the proposed Direct active fuzzy PI controllers exhibit a negligible amount of overshoot, faster rise time and quick settling of partial pressure of the reactants when compared to the other controllers. Hence, it is evident that direct active fuzzy PI controllers perform much better during dynamic load changes also.

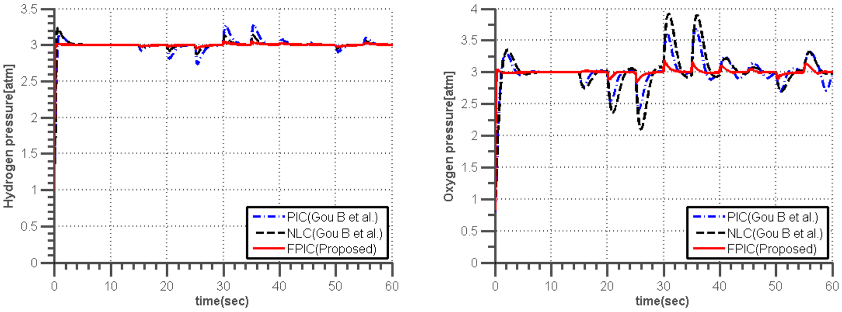


Fig.9. Hydrogen and Oxygen pressure responses of PEMFC under dynamic load (Set-point = 3atm)

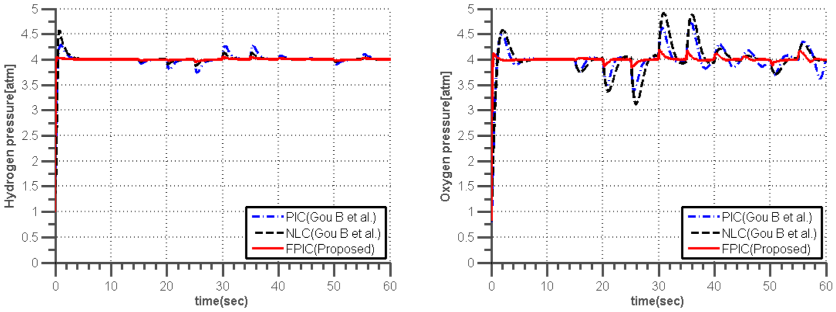


Fig.10. Hydrogen and Oxygen pressure responses of PEMFC under dynamic load (Set-point = 4atm)

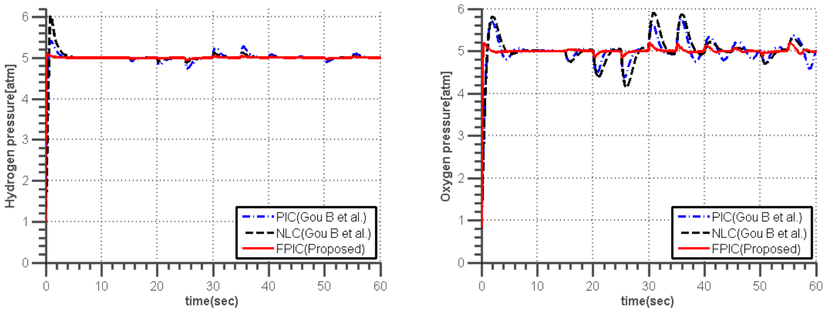
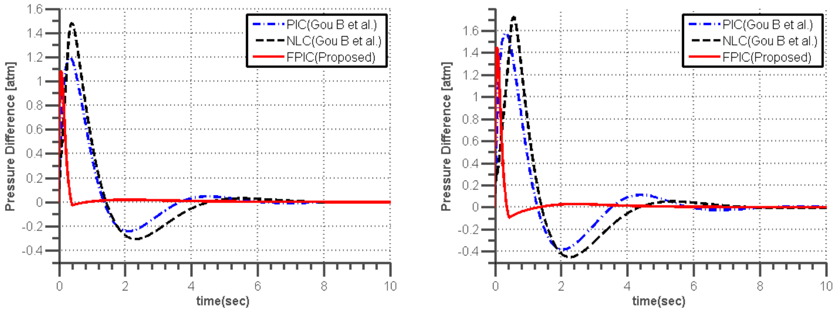
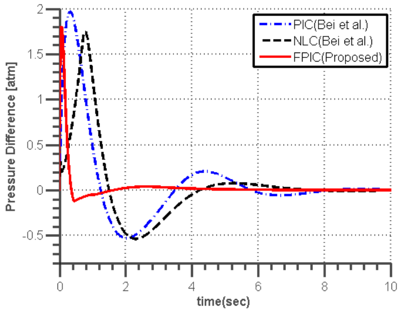


Fig. 11. Hydrogen and Oxygen pressure responses of PEMFC under dynamic load (Set-point = 5atm)



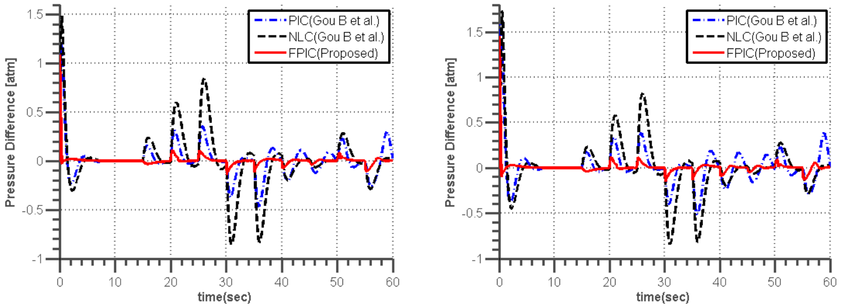
(a) Set-point = 3 atm

(b) Set-point = 4 atm



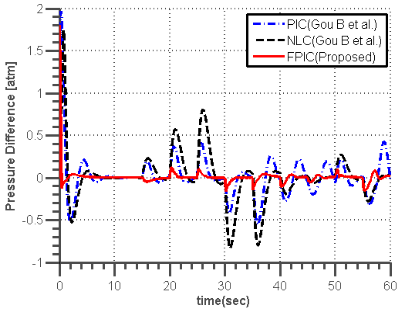
(c) Set-point = 5 atm

Fig.12 Pressure difference between reactants at anode and cathode (static load condition)



(a) Set-point = 3 atm

(b) Set-point = 4 atm



(c) Set-point = 5 atm

Fig. 13 Pressure difference between reactants at anode and cathode (dynamic load condition)

4.3. Reactant pressure difference

To protect the membrane from severe damage and thereby to ensure the long life of PEMFC stack, the pressure difference between the reactants at anode and cathode has to be maintained as low as possible. This is also well accomplished by the proposed controller, by maintaining the pressure difference at values less than 0.1atm, as seen in figures 12 and 13 for both static and dynamic load conditions respectively and various set-points being considered.

5. Conclusion

The effectiveness of a PEMFC is mainly concerned with the proper control of humidity, pressure of the reactant supply, temperature, and fuel and air flow rate. The pressure regulation is the predominant role of control system. In this paper, a Direct Active fuzzy PI controller is designed and proposed for a MISO nonlinear dynamic model of

PEMFC. The proposed controller is used for regulation of fuel and oxygen pressures by regulating the mass flow rate of the reactants. The results show better responses under static and dynamic load conditions for various set-points compared to the conventional PI controller and Non-linear controller reported in literature earlier. Because of its effectiveness the proposed direct active fuzzy PI control strategy can be incorporated to the design of an overall control scheme for PEMFC in addition to stack voltage control, control of water and heat management, fuel processor and the air compressor.

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