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Pressure Regulation in Proton Exchange Membrane Fuel Cell using Direct Active Fuzzy Non-Linear Controller

Mohamed Ali E A[1], Manivanna Boopathi A[2], Abudhahir A[3] and Subha Velappan [4]

[1] Department of ECE, National College of Engineering, Tirunelveli, India
[2]Instrumentation and Chemical Division, Bahrain Training Institute, Isa Town, Kingdom of Bahrain
[3]Department of EEE, Veltech MultiTech Dr.Rangarajan Dr.Sakunthala Engineering College, Chennai, India
[4]Department of CSE, Manonmaniam Sundaranar University, Tirunelveli, India

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Abstract: A Direct Active Fuzzy Nonlinear Controller (DAFNLC) has been designed to control the pressures of supplied reactants to both Cathode and Anode of a Proton Exchange Membrane Fuel Cell (PEMFC). This controller also ensures that the pressure difference across the membrane is maintained within the prescribed limit in order to improve the life of PEMFC. A control oriented Multi input-Multi output model in the state space has been used for PEMFC. An integral controller in association with a state feedback is employed which is termed as Non-linear controller. A Fuzzy Logic component has been used to fix the gains of both integral and state feedback controller modes and thereby the controller is named as DAFNLC. It is a well-known fact that the irregular supply of reactants to both the Anode and Cathode sides of the PEMFC and large pressure difference across the membrane will eventually lead to decreased life time of the Fuel cell. Hence, it is aimed in this paper to develop and deploy an efficient control strategy which will increase the longevity of the Fuel cell by maintaining the reactant flows to both cathode and anode sides and the pressure difference across the membrane at the desired value, irrespective of the fixed and changing load conditions. The simulation experiments have been performed in MATLAB-SIMULINK environment and the obtained results have proven that the proposed DAFNLC performs much better than the controllers used in the earlier research published works.

Keywords: PEMFC, Pressure regulation, Hydrogen Flow Rate, Oxygen Flow Rate, Direct Active Fuzzy Non-Linear Controller

1. Introduction

Electrical energy is produced from chemical energy without any combustion process involved in Fuel cells and hence the Fuel cells are electrochemical devices. Water and heat are the by-products of this electrochemical reaction which happens in Fuel cells. PEMFCs have received wide attraction among the researchers albeit there are many types of Fuel cells being in use in variety of applications, since they have attractive features such as compact in size, very less weight, least operating temperature, more power, emission free, high current, faster start up, etc. All these features and being portable make the PEMFC a best candidate for applications such as stationary and automotive energy sources. However, the issues such as operational cost, lastingness and the ability to withstand wear, etc. make the PEMFCs still not affordable in the above-mentioned applications [1]. Developing a suitable and effective controller to control its parameters can help to improve the life and performance of the PEMFC and hence its affordability [2].

Developing an accurate mathematical model of PEMFC is one of the primary and key aspects in the PEMFC research. Many mathematical models have been developed for PEMFC by the researchers earlier by modelling the Fuel cell subsystems and its output voltage. Three stack voltage models namely Amphlett et al. [3], Larminie & Dicks [4] and Kim et al. [5] have been taken in to consideration by Saadi et al. [6] in order to analyse their performance for various changing load conditions. The results of this study showed that the results of experiments of Amphlett model were more accurate than the other two models. On the other hand, the model proposed by Kim et al. exhibited less than 2% of error in 400 W condition. Besides these, the third model by Larminie and Dicks was found to be not affected by any changes in load current. Another model was proposed by Pukrushpan et al. [7], with an objective of maintaining the flow rate of reactant to the cathode of the cell at the desired value. Further, a model was proposed by Na et al.

E-mail address: ea_mdali2003@yhoo.co.in, arumugamboopathy@gmail.com, abudhahir74@yahoo.co.in, subha_velappan@msuniv.ac.in

[8] using the approach of exact linearization in order to design a non-linear controller for PEMFC. This model was further extended by employing the approach of feedback linearization [9].

By maintaining the partial pressures of the reactants at both cathode and anode sides of the fuel cell at the desired level, the endurance and pursuance can be considerably enhanced [10]. In actual fact, the output of the fuel cell stack can be increased by increasing the partial pressures of the reactants supplied to the cathode and anode and thereby the power density and efficiency can also be improved with the reduced need for humidification. However, this leads to a need of spending more power by the compressor [5]. There are many control schemes presented by the early researchers for this purpose including Non-linear controller [9], PI controllers in various forms [11]-[16], Controller with state feedback [17], Linear–quadratic–Gaussian controller [18], Linear–quadratic regulator controller [19], Controller using Neural Network [20] and Variable structure Sliding Mode Controller [14]. In order to achieve a smooth operation and effectiveness of PEMFC, the controller should be selected appropriately [21].

This research has two main aims which will get rid of degradation of PEMFC. Firstly, the partial pressures of reactants supplied to the cathode and anode should be accurately maintained at the required value. Secondly, the difference between the pressures of reactants across the membrane should be always maintained at less than 0.5atm. These two tasks should be accomplished in the PEMFC irrespective of uncertainties such as static and dynamic changes in load conditions. The improper selection of controller's gain parameters leads to instability, slow recovery and worst performance of the system. Hence, the controller with improper gain values collapse the smooth operation of the process. Fuzzy logic gives a non-analytic alternative option to the classical control theory and it is a robust and efficient tool for any complex processes and the processes for which precise model is not possible. By utilizing defined rules, the fuzzy logic technique can be tuned effortlessly to enhance the Fuel cell system performance.

The proposed DAFNLC accomplishes these tasks successfully. The results of simulations and comparison of performance of DAFNLC and other existing controllers are presented in this paper to substantiate the effectiveness of the proposed controller.

The contents of this paper are organized in the following way. The mathematical and simulation models of PEMFC are presented in section II. In the section III, the scheme and details of the proposed DAFNLC are presented in detail. The section IV gives the detailed insight of simulation results and performance comparison of existing and proposed controller. Finally, it is concluded with the scopes for future research in the section V.

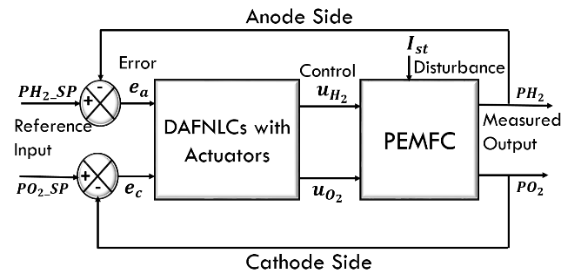


Figure 1. Proposed DAFNLC scheme for pressure regulation of PEMFC

2. DYNAMIC MODEL OF A PEMFC

There are umpteen number of mathematical models for PEMFCs, being used by researchers. In this research, the accurate and efficient stack voltage model and state space dynamic models presented in [7-8, 14-16] are taken in to consideration. However, certain modifications have been made to the models. These modifications are, including a charge double layer, considering the activation losses in both sides, considering the stack temperature not as a constant but as a variable one. Also, the model is built as a 500Watt PEMFC. The mathematical model of the fuel cell system being considered for this research, its various system parameters and their values are as same as those presented earlier in [7], [8], [14]-[16].

The stack voltage model is the mathematical model of a stack containing many PEMFC cells connected in series. On the other hand, the state space model of PEMFC is a Multi Input-Multi Output nonlinear dynamic model. The partial pressures of Hydrogen and Oxygen which are supplied to Anode and Cathode respectively are taken as state variables in addition to the water in the cathode. With these three state variables, the flow rates of Hydrogen and Oxygen are considered as control input and the load current as disturbance.

3. DIRECT ACTIVE FUZZY NON-LINEAR CONTROLLER (DAFNLC)

The schematic diagram of proposed DAFNLC is depicted in Fig. 1. The role of Fuzzy logic is to fix the values of the gains of the controller appropriately and adjust if and when required. Deploying Fuzzy logic with the nonlinear controller considerably improves the robustness of controller. Further, maintaining the partial pressures of reactants at set-point and pressure difference across the membrane at less than 0.5atm, helps to effectively stave off the reactant starvation in cathode and anode and thereby improves the longevity of the PEMFC.

Since there are two sides of the PEMFC to be controlled, there are two controllers employed. The errors in cathode and anode sides of the PEMFC are named as e_c and e_a respectively. The error e_c and e_a are measured as,

$$e_c = (PH_2\_SP) - (PH_2)$$
$$e_a = (PO_2\_SP) - (PO_2) \quad (1)$$

TABLE I.
FUZZY LINGUISTIC VARIABLES FOR DAFNLC

Input		Output	
NL	Negative Large	PVL	Positive Very Low
		PS	Positive Small
NS	Negative Small	PMS	Positive Medium Small
ZE	Zero	PM	Positive Medium
PS	Positive Small	PML	Positive Medium Large
PL	Positive Large	PL	Positive Large
		PVL	Positive Very Large

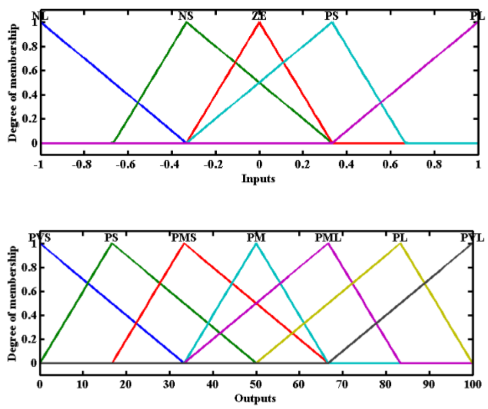


Figure 2. Membership functions of DAFNLC

Where, PH_2_SP and PO_2_SP are the set-points in anode and cathode respectively. PH_2 and PO_2 are the actual pressure of Hydrogen and Oxygen at anode and cathode respectively.

These two controllers produce the actuating signals as given in Equation 2.

$$u_{H_2} = K_{pH_2} e + K_{iH_2} \dot{e}$$
$$u_{O_2} = K_{pO_2} e + K_{iO_2} \dot{e} \quad (2)$$

The Fuzzy Logic component of the proposed DAFNLC is designed with two inputs, error and rate of change of error, defined in the range of [-1,1] and the two outputs which are the gains of Non-linear controller, (K_p and K_i) for both hydrogen and oxygen sides, are defined in the range of [0,100]. For defuzzification of fuzzy outputs, the centroid method is used. Both the fuzzy inputs are designed by triangular membership functions with five memberships and both the fuzzy outputs are designed by triangular membership functions with seven memberships as given in TABLE I and Fig. 2. Further, the fuzzy rule base is presented in TABLE II. The proposed DAFNLC control scheme is presented in Fig. 3.

4. RESULTS AND DISCUSSION

In order to assess the effectiveness of the proposed DAFNLC, simulation experiments have been performed in MATLAB-SIMULINK version 8.1 (R2013a).

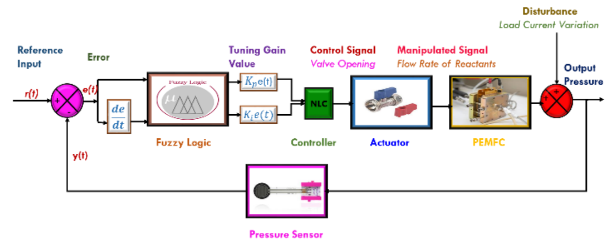


Figure 3. Proposed DAFNLC control for PEMFC

First the simulation models of stack voltage model and state space dynamic models of cathode and anode are built. Then the simulation model of proposed DAFNLC is built. Since there are two dedicated controllers to be employed in cathode and anode of PEMFC, two separate DAFNLCs are used in cathode and anode sides.

The simulations are performed by using the proposed DAFNLC with various set-points and different load conditions such as static and dynamic loads and the results are obtained. Further, the simulations were also performed by employing the existing controllers such as PI controller (PI), Non-Linear Controller (NLC) and Direct Active Fuzzy PI Controller (DAFPI) with the same set of set-points and load conditions. The obtained results are compared in different aspects such as their dynamic responses, time domain specifications and performance indices. The simulation results of all the four controllers namely PI, NLC, DAFPI and DAFNLC, for different conditions mentioned above are presented below one by one. Eight different factors namely the Current output, Power output, Stack voltage, Flow rates of Hydrogen and Oxygen, Pressures of Hydrogen and Oxygen and the pressure difference between cathode and anode sides are taken in to consideration for the performance comparison.

A. Condition-1: Set point: 3atm; Static load - 1 ohm

The responses for condition-1 are presented in Fig. 4 below. It is seen from the figures that the DAFNLC exhibits a considerably lesser settling time than the other three controllers in current output, voltage output, power output and reactants flow rates. In addition, the proposed controller maintains the partial pressures of reactants in either side of the PEMFC very well at 3atm. As far as the pressure difference across the membrane, the proposed DAFNLC maintains it very close to zero than the other controllers in a very short time.

To substantiate the excellent performance of proposed DAFNLC, time domain specifications namely the rise time (t_r), peak time (t_p), settling time (t_s) and maximum peak overshoot ($\%M_p$) are found out from the responses of partial pressures of reactants by all four controllers and tabulated in TABLE III.

TABLE II. FUZZY RULES

Error (e)	Change in Error (de)										
	K_p						K_i				
		NL	**NS**	**ZE**	**PS**	**PL**		**NL**	**NS**	**ZE**	**PS**	**PL**
	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

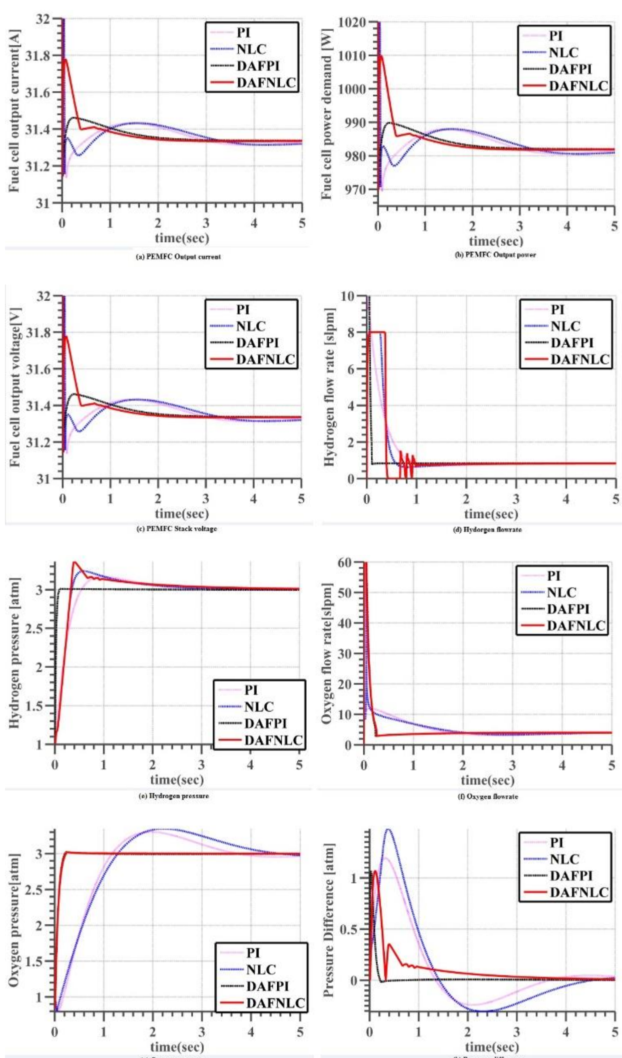
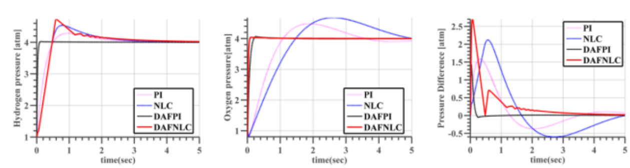


Figure 4. Responses of PEMFC for condition-1

TABLE III. TTIME DOMAIN SPECIFICATIONS OF RESPONSES OF PARTIAL PRESSURES FOR CONDITION -1

CONTROLLER	P-H_2				P-O_2			
	t_r(s)	t_p(s)	t_s(s)	M_p(%)	t_r(s)	t_p(s)	t_s(s)	M_p(%)
PI	0.37	0.98	2.33	5.56	0.72	1.96	3.65	11.42
NLC	0.24	0.58	2.25	7.91	0.86	2.22	4.32	12.39
DAFPI	0.08	0.18	0.13	0.49	0.21	0.39	0.40	1.45
DAFNLC	0.24	0.39	2.43	11.70	0.12	0.25	0.20	0.67



(a) Hydrogen pressure (b) Oxygen pressure (c) Pressure difference

Figure 5. Responses of PEMFC for condition-2

B. Condition-2: Set point: 4atm; Static load - 1 ohm

In this stage of simulations, the desired pressure of reactants in cathode and anode is set to 4atm with the same static load of 1 ohm.

Responses of the controllers on maintaining the pressure of Hydrogen and Oxygen and the pressure difference across the membrane are shown in Fig. 5. It again proves that the DAFNLC exhibits a faster and better response than the other controllers.

C. Condition-3: Set point: 5atm; Static load - 1 ohm

In the third condition, the desired value of reactant pressures is considered as 5atm with all other conditions remain same as in condition-2.

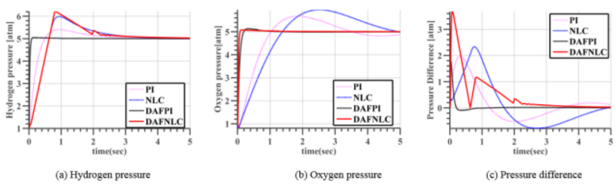


Figure 6. Responses of PEMFC for condition-3

Though the DAFPI performs slightly better than DAFNLC in maintaining the Hydrogen pressure and Pressure difference, the DAFNLC succeeds in maintaining the Oxygen pressure.

D. Condition-4: Set point: 3atm; Dynamic load

In this condition of simulations, the static load of 1 ohm is replaced by a dynamically changing load condition. The nature in which the load changes is shown in Fig. 7. As seen in Fig. 7, the changes in load are step in nature.

Except the nature of load change, all other conditions are kept as same as in condition-1. However, it is obvious that the time domain specifications considered in condition-1 cannot be considered when the load is dynamically changing. Hence, performance indices namely Integral Absolute Error (IAE), Integral Squared Error (ISE), Integral Time-weighted Absolute Error (ITAE) and Integral Time-weighted Squared Error (ITSE) are measured from the responses of all the four controllers, instead of the time domain specifications. The results of simulations are presented in Fig. 8. In these responses, certain portions are zoomed and presented for better visibility of differences.

It can be seen from the responses that the performance of DAFNLC is much better than the other controllers except on current output, power output and stack voltage responses where all the four controllers perform almost same. Further, from the Fig. 8, it is evident that the proposed DAFNLC maintains the pressure difference across the membrane as very near to zero when comparing with the other three controllers.

The values of IAE, ISE, ITAE and ISTE measures are determined for all the four controllers and presented in TABLE IV. This table also shows that the proposed DAFNLC is much better performing than the other controllers.

E. Condition-5: Set point: 4atm; Dynamic load

In this simulation, the set-points for Hydrogen and Oxygen pressures are set to 4atm with the same dynamic load change as considered in condition 4. The responses are given in Fig. 9.

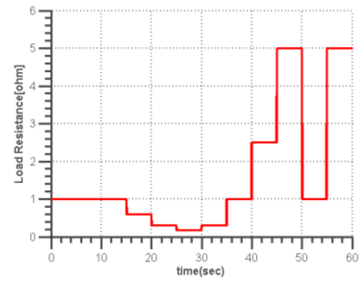


Figure 7. Dynamic Load

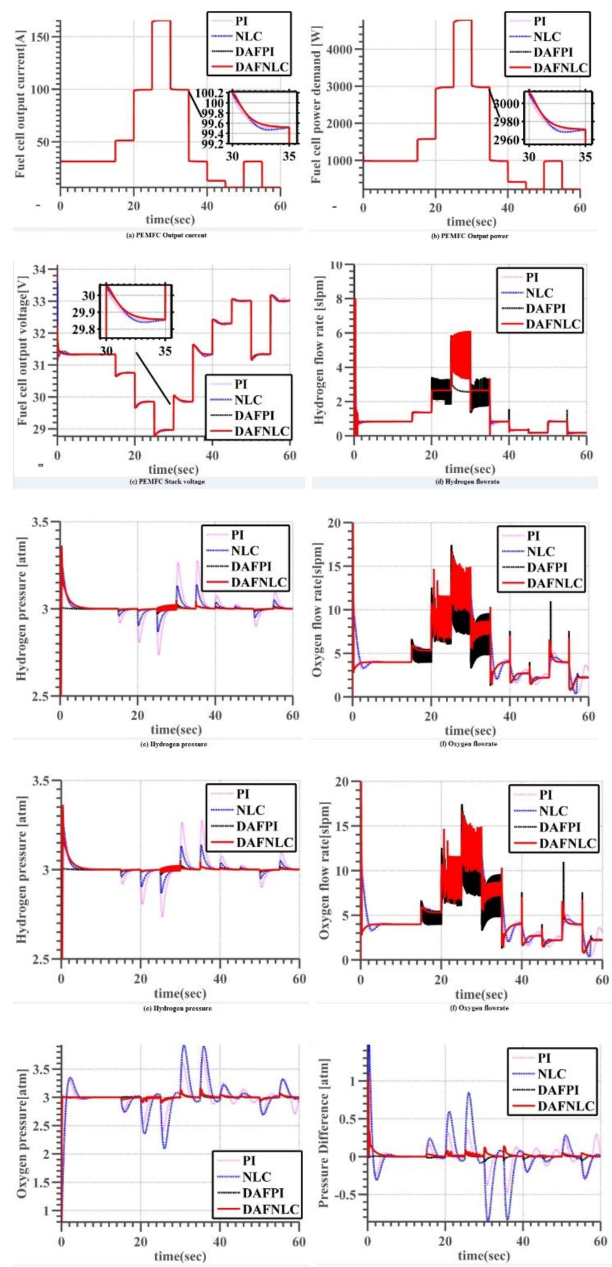


Figure 8. Responses of PEMFC for condition-4

TABLE IV. PERFORMANCE INDICES UNDER DYNAMIC LOAD

CONTROLLER	P-H₂				P-O₂			
	IAE	ISE	ITAE	ITSE	IAE	ISE	ITAE	ITSE
PI	2.42	0.73	60.08	7.73	8.04	3.96	235.9	71.3
NLC	1.44	0.58	26.86	1.6	10.7	6.33	292.12	138.51
DAFPI	0.51	0.10	14.62	0.26	1.43	0.45	41.05	3.10
DAFNLC	0.84	0.54	5.68	0.12	1.09	0.21	32.39	1.45

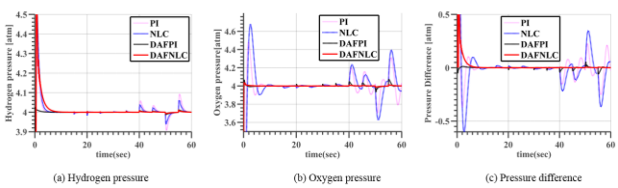


Figure 9. Responses of PEMFC for condition-5

These results show an encouraging performance by the proposed controller exhibiting no oscillations in all responses unlike the other controllers. Also, the errors are maintained at zero in all three controls.

F. Condition-6: Set point: 5atm; Dynamic load

In the final set of simulations, the set-point is changed to 5atm with the existing dynamic load change condition. The results of simulation for the control of reactant pressures and pressure difference are shown on Fig. 10.

As in the conditions 4 and 5, the proposed DAFNLC shows an excellent performance for the condition 6 too. All three responses show that the proposed controller is superior to the remaining three controllers in the control of pressures and pressure difference, without any oscillations and faster response.

The results presented in Table III and Table IV are obtained through simulations. The measures such as Rise time (t_r), Peak time (t_p), Settling time (t_s) and Maximum Peak Overshoot (%M_p) presented in Table III are obtained by simulations for all the four controllers namely, PI, NLC, DAFPI and DAFNLC. These measures are used to assess and compare the performance of these controllers. However, these measures will not have any sense when the load keeps changing continuously as shown in Fig. 7. Hence, the error measures such as IAE, ISE, ITAE and ITSE are obtained for the changing load conditions. The obvious fact is that the least values of all these performance measures represents a better performance of the controller. Hence, these measures are presented in Table III and Table IV to prove that the proposed DAFNLC perform much better than the other three controllers.

PI controllers are proposed in [22] to maintain the value of hydrogen excess ratio at 1.5 and oxygen excess ratio at the value of 2, by assuming that the fuel cell stack temperature is uniform and constant and reducing the deviation between the partial pressure of reactants can improve the performance and life of PEMFC. However, this assumption will not be true in the case of dynamic change in load condition.

Further, PI, Fuzzy Logic and Neural Network-based controllers are proposed in [23] to track the fuel cell stack output power (P_{ref}) for dynamic change in load condition. It is to be noted that the partial pressures of hydrogen at anode and oxygen at cathode are not considered as a control variable. Because of this, the results show large deviations of more than 1atm partial pressure most of the time which will severely affect the membrane and deteriorate the life of the PEMFC.

In this research, both the above mentioned conditions are taken in to consideration and proved with results that the proposed DAFNLC is more efficient and effective in dealing these conditions.

5. CONCLUSION

A robust controller named Direct Active Fuzzy Non-Linear Controller (DAFNLC) is proposed for control of PEMFC. For the simulation studies, a nonlinear Multi Input Multi Output dynamic model of PEMFC has been used. Simulations were performed in MATLAB-SIMULINK. The controllers already reported in literature

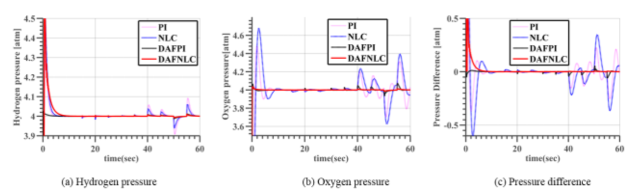


Figure 10. Responses of PEMFC for condition-6

namely PI controller (PI), Non-linear Controller (NLC), Direct Active Fuzzy PI Controller (DAFPI) were taken for consideration in order to substantiate the performance of the proposed controller. Various conditions such as different set-points of reactant pressures, different load conditions such as different values of static loads and dynamically changing load were considered for simulations. The pressure difference across the membrane was also taken for performance assessment of DAFNLC. The comparison of results of the proposed controller with existing controllers in all conditions being considered are presented and verified that the proposed controller is superior to the other controllers. Further, the time domain specifications and error measures were also determined and presented to emphasize the effectiveness of the proposed DAFNLC. Various other factors such as output current, power, stack voltage and reactant flow rates were also considered to prove the superior behaviour of DAFNLC. Though the proposed DAFNLC exhibits much better performance in almost all conditions, there are few situations where it exhibits overshoots which keeps this research still to be pursued further. Also, it also gives avenues for future research by including certain uncertainties present in the PEMFC such as charge double layer, activation losses in both sides, stack temperature, etc., which were assumed during the mathematical modelling as not affecting the performance of PEMFC.

In the proposed PEMFC model, the membrane water content and stack temperature are assumed to be uniform and constant. Hence, an attempt may be made to extend these control algorithms to maintain the water balance and temperature inside the stack. Further, this work can be extended by applying the proposed controllers in a hybrid photovoltaic/wind/fuel cell power system along with the inverter and storage battery to supply the power for all the stationary and automobile applications.

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Prof. E.A.Mohamed Ali is working as Associate Professor in the Department of Electronics and Communication Engineering. He received B.E. (Electrical and Electronics Engineering) from Manonmaniam Sudaranar University, India in 2000. He received his Master Degree in Applied Electronics from Madurai Kamaraj University, India in 2001. He has published 20 papers in National and International Journals and conferences.

Dr. A.Manivanna Boopathi received B.E. (Instrumentation and Control) from Madurai Kamaraj University, India in 1997. He received his Master in Control System Engineering degree from Jadavpur University, Kolkata, India in 2002. He received his Ph.D. from Anna University, Chennai, India in 2016. He has published 18 papers in National and Internataional Journals and conferences. Presently, he is a faculty member in Instrumentation and Chemical Division, Bahrain Training Institute, Isa Town, Kingdom of Bahrain. His areas of interest include Nonlinear control, Adaptive control and Data Mining.

Dr. A.Abudhahir is working as Professor in the Department of Electrical & Electronics Engineering. He received B.E. (Instrumentation and Control) degree and M.E.E. (Measurement and Instrumentation) degree in 1996 and 2001 from Madurai Kamaraj University and Jadavpur University, Kolkata respectively. He completed Ph.D. degree at Anna University, Chennai in 2009. He has produced eight doctorates and now guiding five research scholars towards their Ph.D. degree in the areas such as Image processing, Instrumentation, Control systems, Optimization, Nondestructive testing etc. He has published 50 research papers in National and International Journals and conferences. He was one of the active members in the documentation team of National Board of Accreditation (NBA), New Delhi and involved in the process of developing 2013 version accreditation manual which led NBA, New Delhi to become a signatory member in Washington Accord.

Dr. Subha Velappan received B.E. (Electronics and Communication Engineering) from Bharathiyar University, Coimbatore, India, in the year 2000. She received M.E. (Computer Science and Engineering) and Ph.D. from Manonmaniam Sundaranar University, Tirunelveli, India, in 2002 and 2017 respectively. She has published more than 30 papers in National and International Journals and conferences. She is presently working as Assistant Professor in Manonmaniam Sundaranar University. At present, four research scholars are pursuing research towards Ph.D. degree under her guidance in the areas of Data Mining and Image processing. Her areas of current research include Data Mining, Pattern recognition and Soft-computing and optimization techniques for predication of diseases.