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Performance Analysis of Intelligent Controllers in Pem Fuel Cell Voltage Tracking

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Abstract: The main criteria to be kept in mind while designing any application using fuel cell is the Voltage Control under sudden load variations. As a standard practice the output voltage of a fuel cell is controlled and maintained to the reference by introducing Intelligent Controllers. This paper shows the performance analysis of various intelligent controllers that can track the output voltage of fuel cell. In this paper, the state space model of Proton Exchange Membrane Fuel cell is considered for analyzing various controllers. Additionally the transient response of the fuel cell is analyzed and compared for the different controllers. The performance of the controllers is evaluated by estimating the time response characteristics of the system and also by calculating the system errors.

Key words: Feedback · Intelligent systems · Neural Networks · Optimal Control · Renewable energy Source

INTRODUCTION

With the increase in green house gas emissions due to exorbitant usage of fossil fuels, many research works are carried out with an aim to find an alternative solution for energy generation with minimal green house gas emissions features. Due to the inherent advantages of Proton Exchange Membrane Fuel cell (PEMFC) [1] like minimal pollutant discharge, high efficiency, increased lifetime and high power density, it is considered as a significant renewable energy source and alternate to fossil fuel as compared with fossil fuels and other types of fuel cells [2].

PEM Fuel Cell consists of electrodes anode and cathode separated by an electrolyte called proton exchange membrane. The hydrogen pumped in the anode splits into protons and electrons, of which the protons are allowed to flow through the thin membrane and the negative electrons reach the cathode through an external circuit to generate electric current. At the cathode, electrons and protons combine with oxygen to generate water and heat as by-product [1-3].

However for a PEMFC to achieve the desired performance and for utilizing in any applications, the required output voltage has to be maintained to a predefined desired proportional under sudden load variations. Hence the requirement of an intelligent controller is inevitable and mandatory in a PEMFC to control and maintain the required output voltage as per the varying load requirements.

To design an intelligent Controller the knowledge of the input/output variables in a fuel cell system is essential. The relationship between the different critical variables required to run the PEMFC system are important and the same is attained by modeling a fuel cell system. In this paper the accurate model of the PEMFC is described by considering the State space Model of the fuel cell [20].

Neural Networks based Controllers are widely used to control the terminal voltage of a dynamic fuel cell model and the simulation results registered improved performance in tracking the voltage [4-8]. Fuzzy controls are also applicable to the fuel cell system to track the output voltage since fuzzy linguistics helps to evidently define the relationship between the different variables of fuel cell [9]. PID controllers are also widely used to control fuel cell output voltage due to their simple structure and reliability. PID Controllers follow integer order derivatives. Since the real world is fractional everywhere and many studies related to the fractional orders in the field of Science and Engineering are evolved [10-15] recently. Several Optimization techniques like Evolutionary programming, Genetic Algorithms are used to tune the controller parameters to accomplish better performance in a fuel cell [16-19].

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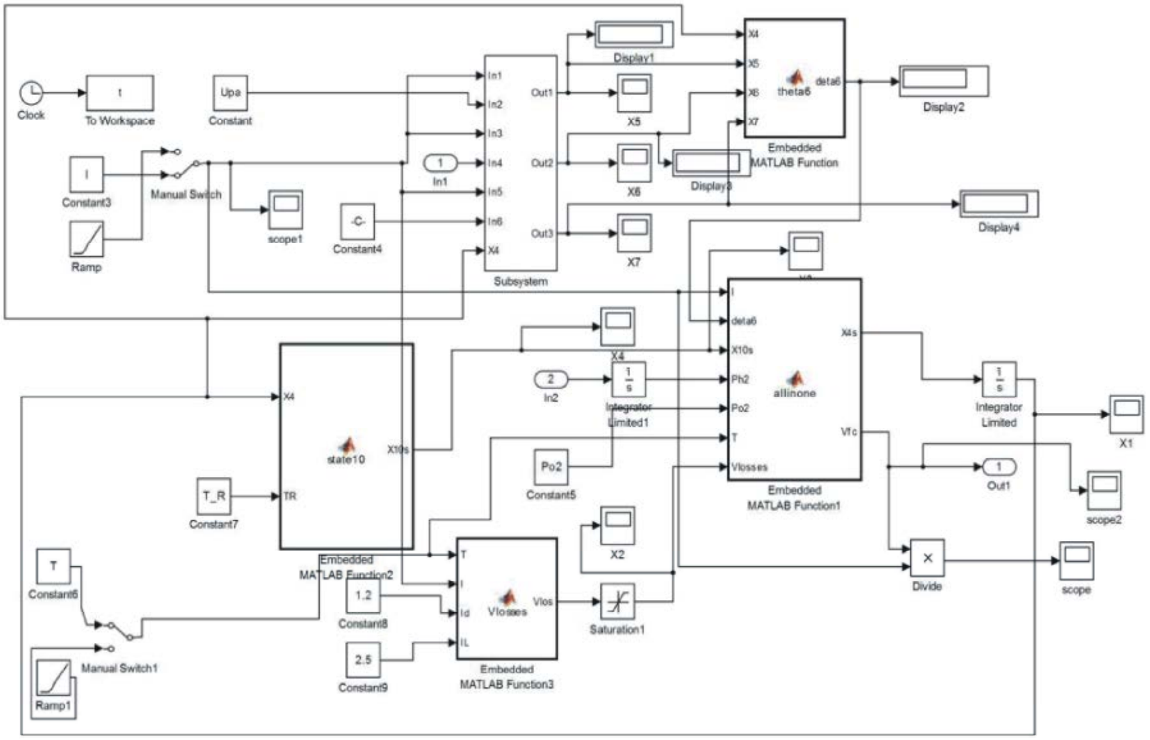

Fig. 1: State Space Model of PEM Fuel Cell

In this paper, various intelligent controllers are applied to track the fuel cell voltage under load variations. This paper considers the state space model of PEMFC for analyzing the voltage tracking. Although several models like steady state models ,empirical models, dynamic models of fuel cells are existing, the state space model facilitates control algorithm implementation [20] along with unambiguous relation between the input and output variables of fuel cell.

Paper is organized as follows: In Section II PEM fuel cell state space model is explained in brief. In Section III the various intelligent controllers and their design are discussed. Section IV compares the performance analysis of the various controllers.

PEM Fuel Cell State Space Model: The performance of PEM Fuel cell depends on various system parameters and it is characterized as:

$$V = \text{func}\ (I, PO_2, PH_2, qH_2, qO_2, \lambda, T) \tag{1}$$

where, I is the current density, PO_2 is the Partial Pressure of Oxygen, PH_2 is the partial pressure of hydrogen, qH_2, qO_2 are the flow rates of hydrogen and oxygen respectively, ë is the humidity or moisture content in the Membrane and T is the cell temperature. The correlation among the variables of the fuel cell is highly non linear. Therefore a nonlinear model is necessary to perform the analysis of PEMFC.

Hence a nonlinear state space model is considered for analysis in this paper [20].The output voltage of PEM fuel cell is

$$V_{pemfc} = V_{oc} - V_{loss} \tag{2}$$

$V_{oc}$is the open circuit voltage of a fuel cell and V_{loss} is the irreversible voltage losses in a fuel cell. The open circuit output voltage of the PEM fuel cell is given in (3).

$$V_{oc} = n_{stack} E_{ref}^{cell} + \frac{n_{stack} RT}{2F} \ln\left(\frac{P_{H_2} P_{O_2}}{P_{H_2o}}\right) \tag{3}$$

where n_{stack} is the number of PEM Fuel cell stacks, E_{ref}^{cell} is the reference potential at standard operating conditions (V), T is the stack temperature(K), F is Faradays Constant (C/mol), R is Universal gas constant [J/(molK)], P_{H2} is the partial pressure of Hydrogen(atm), P_{O2} is the partial pressure of Oxygen(atm) and P_{H2}^{o} is the partial pressure of Water(atm).

Activation loss, Ohmic loss and Concentration loss are the three types of voltage losses associated with the PEM fuel cell. This irreversible voltage loss is represented as;

$$V_{loss} - V_{active} + V_{ohm} + V_{conc} \quad (4)$$

where, V_{active} is the activation loss due to the slow-moving electrode kinetics and it is represented as;

$$V_{active} = \frac{RT}{2F} \ln\left(\frac{1}{I_d}\right) \quad (5)$$

V_{ohm} ohmic loss is associated with the movement of protons through the electrolyte and electrons through internal electronic resistance and it is represented as;

$$V_{ohm} = V_A^O + V_C^O + V_M^O \quad (6)$$

V_A^O is the voltage across anode (volts), V_C^O is the voltage across cathode (volts) and V_M^O is voltage across the thin membrane (volts).

V_{conc} is the concentration loss due to the formation of concentration gradient of reactants at the outer shell of electrodes and it is represented as:

$$V_{conc} = \frac{RT}{eF} \ln(1 - \frac{1}{I_L}) \quad (7)$$

where, e is the number of electrons and IL is Limiting current(A).This model also considers the humidification or moisture content, thermodynamic energy balance and double layer effects in the PEM fuel cell [20].

Controller Design: This paper aims to maintain the fuel cell output voltage to a predefined desired value by comparing with the reference value as per varying load requirements .Whenever any load fluctuation occurs, the power demand or the operating point changes proportionally alters the chemical reaction process of the fuel cell by controlling the critical variables.

Hence positive control over these process and variables is required to regulate the output voltage of fuel cell. In this paper ,intelligent controllers based on Neural Networks, PID, Fractional order PID are used to control the fuel cell output voltage. An optimization technique named Harmony search is applied to minimize the error function by optimally tuning the FPID controller parameters and that show better performance compared to other techniques.

Table 1: NARMA L2 Specifications

Network Architecture	
No. of Delayed Plant inputs	3
No. of Delayed Plant outputs	2
Sampling Interval(sec)	0.01
Size of Hidden layer	9
Training Data	
Training Samples	1000
Maximum Plant input	4
Minimum Plant input	-1
Maximum Plant Output	Infinity
Minimum Plant Output	0
Training Parameters	
Training Epochs	100
Training Function	trainlm

Neural Network Controller: A Multi Layer Feed Forward Network is considered to regulate the fuel cell output voltage and Back Propagation algorithm is employed to minimize the error [6]. The error is generated by comparing the reference voltage V_{ref} and the output stack output voltage V_{fc} .When the actual fuel cell output voltage differs from the reference voltage an error signal is generated which is back propagated through the network. By adjusting the weights the error can be minimized [24].

In this paper, NARMA L2 Controller [18] with back propagation neural network containing with a hidden layer of 9 neurons is considered to control the voltage variations. To maintain constant output the neural network is trained with Levenberg – Marquardt Algorithm (trainlm function) [7]. During the training the error function is minimized by increasing the epochs. In this paper the number of epochs used to train the network taken as 100. Table 1. Shows the specifications of Neural Network Plant Model using NARMA L2 Controller.

Fractional Order Pid Controller: In industrial automation, the conventional PID Controller is extensively used to control any input/output variables due to its simple arrangement. The transfer function of an Integer Order PID Controller is specified as;

$$G_{PID}(s) = \frac{U(s)}{E(s)} = K_p + K_I(s)^{-1} + K_D(s) \quad (8)$$

where E(s) is error, U(s) is controller Output, K_p, K_I and K_D are Proportional, Integral and Derivative Time constants.

$$U(t) = K_P \varepsilon(t) + K_I (D_t)^{-1} \varepsilon(t) + K_D D_t \varepsilon(t) \quad (9)$$

where U(t) is the control signal, $\varepsilon(t)$ is the error signal generated by comparing the plant output with the reference signal and it is given as $\varepsilon(t) = V_{ref} - V_{fc}$.

The conventional PID controllers rectify the error between the reference value and the measured value from the plant output by giving a remedial action to the plant input which regulate the process consequently. The parameters of PID Controller is chosen to minimize the difference between the reference and the fuel cell voltage. The values of the PID Controller parameters are given as: $K_p = 10$, $K_I = 0.001$, $K_D = 0.0001$.

The conventional PID Controller can be further improved by including Fractional values. The transfer function for a Fractional Order PID Controller is specified as;

$$G_{PPID}(s) = \frac{U(s)}{E(s)} = K_p + K_I(s)^{-\lambda} + K_D(s)^{\delta} \tag{10}$$

where λ and δ are Fractional Integral and derivative Constants respectively.

$$U(t) = K_P\varepsilon(t) + K_I(D_t)^{-\lambda}\varepsilon(t) + K_D D_t^{\delta}\varepsilon(t) \tag{11}$$

where $\varepsilon(t)$ is the error signal.

The values of the PID Controller parameters are given as: $K_p = 5$, $K_I = 0.2$, $K_D = 1$. The λ and δ have a value that varies between 0 and 1. The Fractional Order PID controller is also characterized as P I $^{\text{ë}}$ D $^{\text{ª}}$ Controller

Harmony Search Algorithm: Harmony search algorithm is a random search technique to find out the perfect state of harmony. It is a type of evolutionary algorithm developed based on the harmony generated by musicians [21-23]. In Harmony search algorithm, an individual solution is called as Harmony and it is represented as an N -dimensional vector. The initial population of harmony vectors are generated randomly and stored in a location called Harmony Memory (HM). A new harmony is thus generated from the elements in the HM by memory consideration operation or by doing random re-initialization or pitch adjustment operation. At the end, the HM is updated by comparing the new candidate harmony and the worst harmony vector in the HM. The worst harmony vector is replaced by the new candidate vector in case it is better than the worst harmony vector in the HM. The above process is repeated until a termination criterion is achieved. Harmony Search Algorithm can be easily implemented with less adjustive parameters and has quick convergence.

In order to achieve best possible control, the controller has to be tuned optimally [25]. In this paper Harmony search technique is used to find the optimal values of fractional order PID controller parameters. Fig. 2 shows the block diagram of Harmony search Optimized FPID Controller.

The FPID Controller consists of integer order parameters K_p, K_I, K_D and non-integer or fractional values of λ and δ. The objective of using Harmony search optimization is to minimize the error function by selecting optimal controller parameters. The algorithm terminates either if the objective function is obtained or if maximum number of iterations is attained.

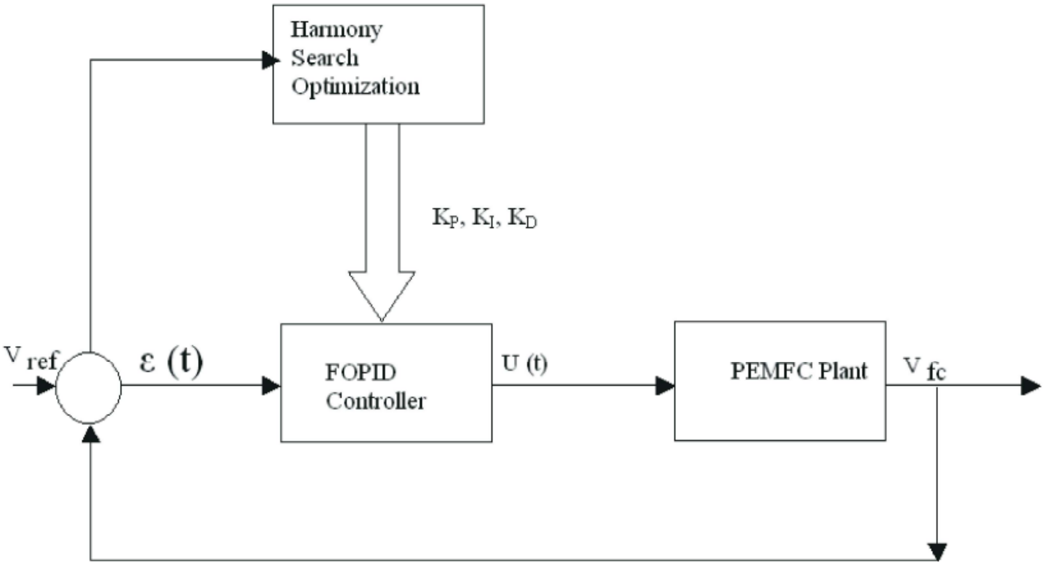

Fig. 2: Block Diagram of HS Optimized Fractional Order PID Controller

The selection of the parameters as mentioned below has yielded better optimization of fuel cell output voltage tracking using Harmony Search algorithm. Harmony Memory Size(HMS) is set as 10, bandwidth as 0.2, Harmony memory consideration rate as 0.95 and pitch adjustment rate as 0.6. The number of iterations is set as 5 and the parameters of the controller is given as: K_p = 3.3758, K_I = 0.6079, K_D = 0.2096.

RESULTS AND DISCUSSIONS

In this paper simulations are carried out using Matlab Simulink with the state space model of PEM fuel cell and the PEM fuel cell parameters are listed out in Table 2. The time response characteristics of the controller is evaluated and analyzed to compare the performance of the controllers.

The performance of the controllers is also analyzed by computing the system errors. They are Integral Squared Error (ISE), Integral Absolute Error (IAE) and Integral Time-weighted Absolute Error (ITAE) as explained below:

Integral Squared Error (ISE): The system performance is measured by integrating the square of the system error over a fixed interval of time. ISE integrates the square of the error over time.

$$ISE = \int \varepsilon^2(t)dt \tag{12}$$

Integral Absolute Error (IAE): IAE integrates the absolute error over time. It does not add weightage to any of the errors in a systems response.

$$IAE = \int |\,\varepsilon(t)\,|\, dt \tag{13}$$

Integral Time-Weighted Absolute Error (ITAE): ITAE integrates the absolute error multiplied by the time over time. This adds weightage to errors which extends for a long time much more heavily than those at the initial period of the response.

$$ITAE = \int t\,|\,\varepsilon(t)\,|\, dt \tag{14}$$

where ε(t) is the error created by comparing reference voltage V_{ref} and fuel cell output voltage V_0.

In order to control the fuel cell output voltage the PEM fuel cell model is tested by comparing with a reference step signal that varies from 0-50V. Simulation results of the output voltage obtained by comparing NN, PID and FPID given in Fig. 3. shows that FPID tracks the reference voltage closely by a value of 49.9993V. Fig. 4 shows that as the optimization technique Harmony Search is applied to FPID Controller, it improves the performance of FPID controller by tracking the reference by a value of 49.9998V.

Table 2: Parameters of Pem Fuel Cell Model

Symbol	Parameter	Value
A_S	Area of a cell	$3.2\text{x}10^{-2}$ m^2
E_O^{Cell}	Reference Potential	1.23V
C_{FC}	Specific Heat Capacity	500J/(mol K)
F	Faradays Constant	96487C/mol
M_{FC}	Total mass of PEM Fuel cell Stack	44Kg
n_s	Number of PEM Fuel cell stacks	48
V_a	Volume of Anode	10^{-3} m^3
V_c	Volume of Cathode	10^{-3} m^3
R	Universal Gas Constant	8.31J/(molK)
h_s	Convective heat transfer Coefficient	37.5W/(m^2.K)
a,b,a_0	Constants in Tafel Equation	a=-3.08x10^{-3}V/K b=9.724x10^{-5}V/K a_0=1.3697V
C	Capacitance due to charge formation in the double layer	10F
K_I K_T	Constant in computation of R_0	K_I=1.871x10^{-3}Ω/A K_T=-2.37x10^{-3} Ω/K

The Time response characteristics of the various controllers are compared as shown in Table 3. From the comparison it is clear that HS optimized FPID Controller tracks the reference voltage more closely compared with other FPID, PID and NARMA-L2 NN Controller. Also HS–FPID controller converges or settles to the reference voltage quickly compared to other controllers.

The system errors like ISE, IAE and ITAE of various intelligent controllers like HS-FPID, FPID, PID, NARMA L2 NN Controllers are evaluated and compared and given vide Fig. 5-10. From the comparisons given in Figs. 5-7 FPID controller shows better performance to track the fuel cell output voltage by minimizing the system errors with PID and NARMA L2 NN Controller. But the Harmony search optimization introduced to FPID Controller achieves better performance than FPID Controller by reducing system errors.

The system errors of the various controllers is compared as given in Table 4 the system errors due to load oscillations are calculated and from the table it is understood that HS optimized FOPID Controller produces less error values.

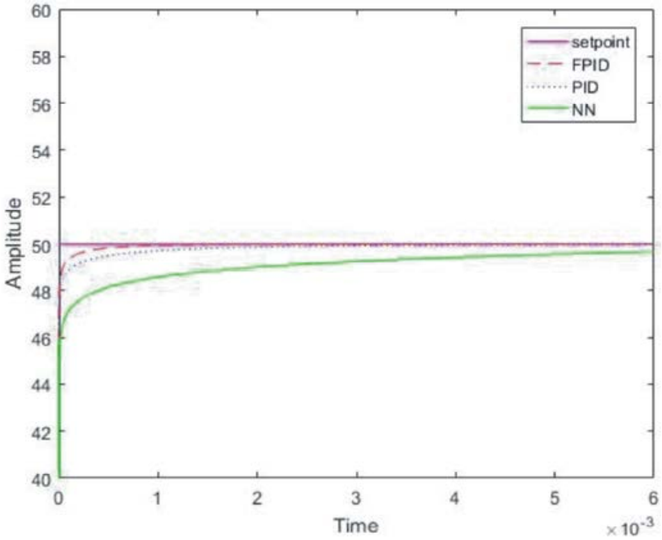

Fig. 3: Comparison of FPID Controller Voltage Tracking with NN and PID Controller

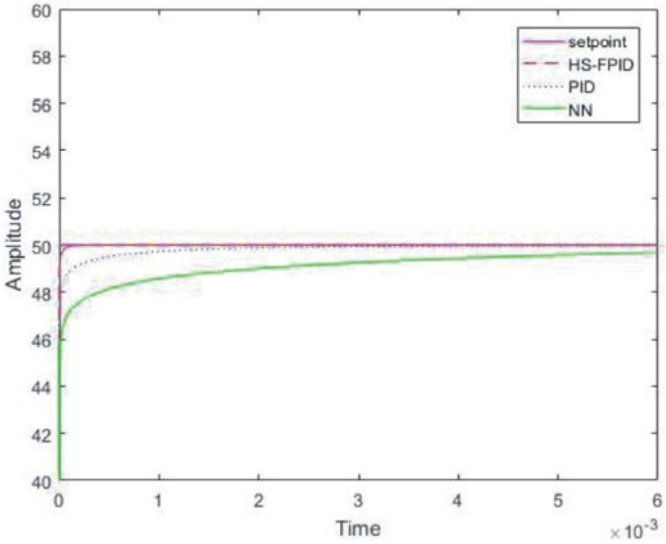

Fig. 4: Comparison of Harmony Search- FPID Controller Voltage Tracking with NN and PID Controller

Table 3: Time Response Characteristics

Parameters	NN Controller	PID Controller	FPID Controller	HS-FPID Controller
Peak Voltage	49.678V	49.9912V	49.9993V	49.9998V
SettlingTime	6.3176e-04s	2.5409e-04s	7.6807e-04s	5.201e-05s
Rise Time	0.0032s	6.2626e-04s	1.9382e-04s	1.1591e-5s
Settling Min:	49.2953V	49.5774V	49.5858V	49.5915V
Settling Max:	49.6780V	49.9912V	49.9993V	49.9998V

Table 4: Comparison of System Errors

System Errors	NN Controller	PID Controller	FPID Controller	HS-FPID Controller
ISE	1.3205e+05	1.9945e+03	195.395	32.1909
IAE	8.2341e+03	1.0309e+03	309.8342	27.8098
ITAE	11.3824	1.0266	0.1167	0.0027

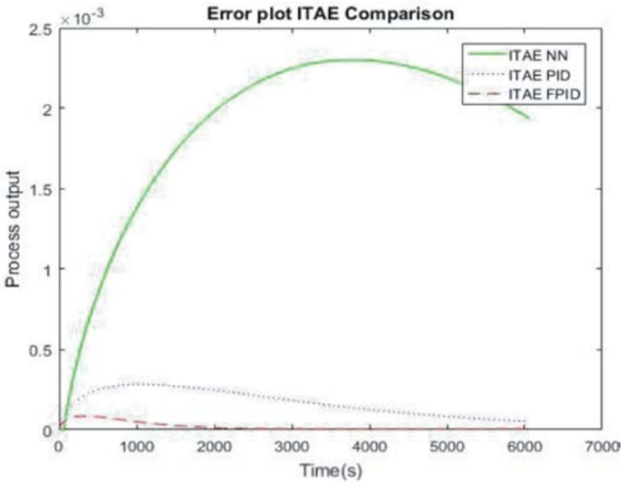

Fig. 5: Comparison of ITAE of FPID with NN and PID

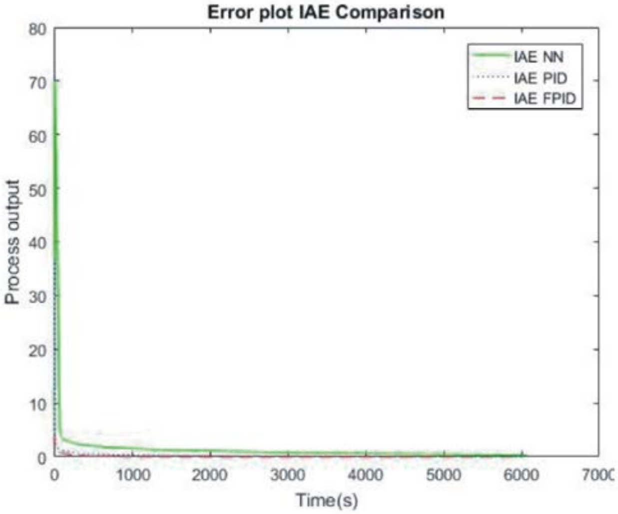

Fig. 6: Comparison of IAE of FPID with NN and PID

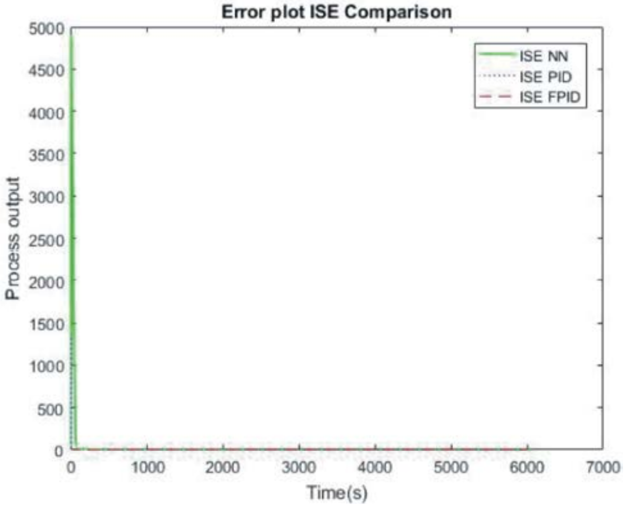

Fig. 7: Comparison of ISE of FPID with NN and PID

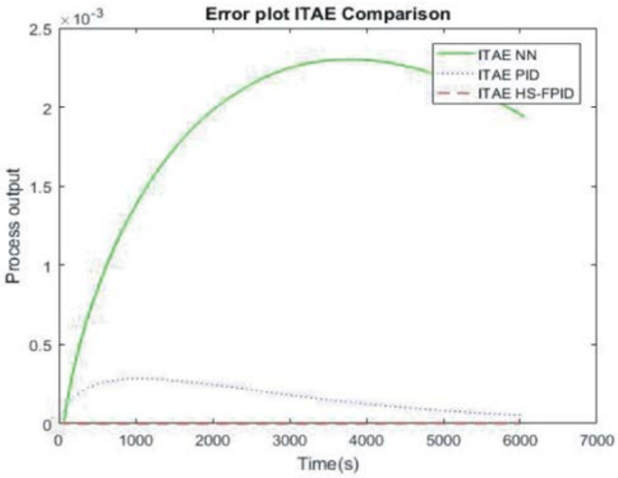

Fig. 8: Comparison of ITAE of HS-FPID with NN and PID

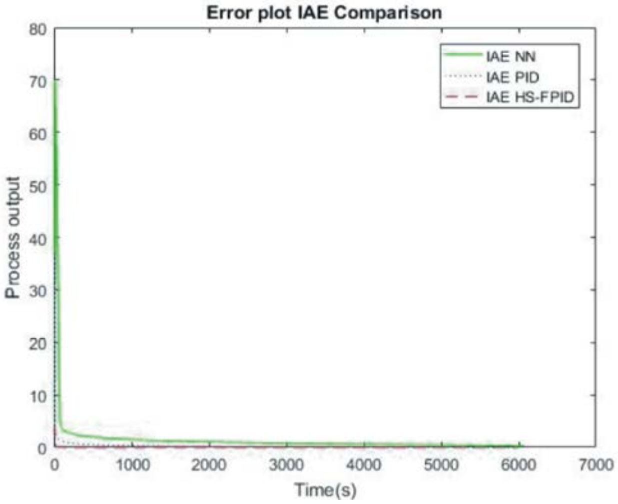

Fig. 9: Comparison of IAE of HS-FPID with NN and PID

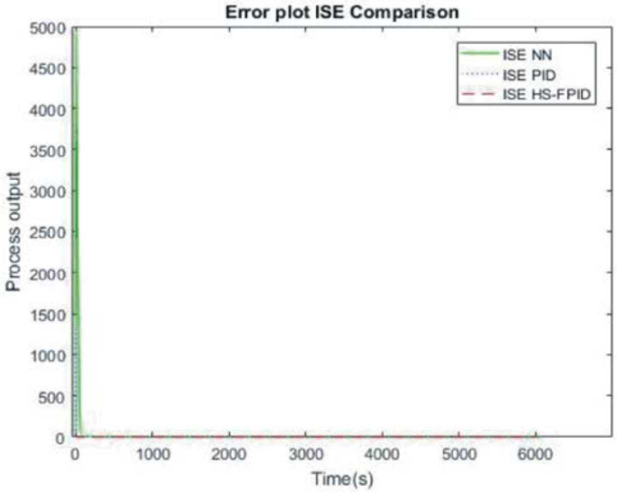

Fig. 10: Comparison of ISE of HS-FPID with NN and PID

CONCLUSION

In this paper, performance analysis of various intelligent controllers required for voltage tracking in PEM Fuel cell under load fluctuations are analyzed. The performance of the intelligent controllers are also analyzed by evaluating the time response characteristics and system errors .From the performance comparison, it is obvious that Harmony search optimization incorporated Fractional Order PID Controller displayed better output voltage characteristics than Neural and classical controllers . It is also evident that optimal controller takes less settling time which helps the system to converge rapidly as compared with other controllers.

REFERENCES

1. Ali T-Raissi, Arundhati Banerjee, 1997. Current Technology of Fuel Cell Systems Energy Conversion Engineering Conference, IECEC-97, Proceedings of the 32nd Intersociety, 3: 1953-1957.
2. Samrat P., Nandikesan, Surajeet Mohanty, M. Shaneeth and K.P. Kamlakaran, 2012. Control strategy for PEM Fuel Cell Power Plant, IEEE I International Conference on Power and Energy in NERIST(ICPEN)2012, pp: 1-3, 2012.IEEE. 978-1-4673-1669-9/12.
3. Mohamed Ali, E.A. and A. Abhudhahir, 2011. A Survey of the Relevance of Control Systems for PEM Fuel cells, IEEE International Conference on Computer, Communication and Electrical Technology-ICCCET 2011, pp: 322-326. ICCCET.978-1-4244-9394-4/11.
4. Karimi, M., M. Imanzadeh, P. Farhadi and N. Ghadimi, 2012. Voltage Control of PEMFC using a New Controller Based on Reinforcement Learning, International Journal of Information and Electronics Engineering, 2(5): 752-756, September 2012, DOI.10.7763/IJIEE.2012.V2.200.
5. Rezazadeh, A., A. Askarzadeh and M. Sedighizadeh, 2011. Adaptive Inverse Control of Proton Exchange Membrane Fuel cell using RBF neural Network, International Journal of Electrochemical Science, 6: 3105-3117, August 2011
6. Mansour, A.M., N.H. Saad and A.A. Sattar, 2012. Maximum Power Point tracking of Ten parameter Fuel cell Model, Journal of American Science, 8(8): 941-946, July2012. Available: http://www.jofamericanscience.org.
7. Rezai, M. and M. Mohseni, 2013. A Predictive Control Based on Neural Network for dynamic Model of Proton Exchange Membrane Fuel Cell", J. Fuel cell Science and Technology Vol.10, No.3, June 2013. Available: http://fuelcellscience.asmedigitalcollection.asme.org/
8. Masoud Salehi Borujeni and Hassan Zarabadipour, 2014. "Fuel cell Voltage Control using neural network based on model predictive control", 2014 Iranian Conference on Intelligent Systems (ICIS), April 2014. 10.1109/IranianCIS.2014.6802609.
9. Liping Fan and Yi Liu, 2012. Fuzzy Logic based Constant power control of a Proton Exchange Membrane Fuel Cell, PRZEGLAD ELEKTROTECHNICZNY (Electrical Review), pp: 72-75, 2012.R. 88 NR 5b/2012
10. Jun-Yi-Cao and Bing-Gang Cao, 2006. Design of Fractional Order Controller Based on Particle Swarm optimization, International Journal of control, Automation and System, 4(6): 775-781.
11. Yang Quan Chen, Ivo Petras and Dingyu Xue, 2009. "Fractional order Control-A Tutorial", 2009 American Control Conference AACC, June 2009, pp: 1397-1411. WeC02.1. 978-1-4244-4524-0/09.
12. Ramiro S. Barbosa and Isabel S. Jesus, 2013. Comparitive Study of Fuzzy integer and Fractional PID Controller, 39th Annual Conference of the IEEE Industrial Electronics Society, IECON 2013 , pp.3392-3397 10.1109/IECON.2013.6699673.
13. Rinku Singhal, Subhransu Padhee, Gagandeep Kaur, 2012. Design of Fractional Order PID Controller for Speed Control of DC Motor, International Journal of Scientific and Research Publications, 2(6): 1-8, June 2012.Available: www.ijsrp.org.
14. Yanzhu Zhang and Jingjiao Li, 2011. Fractional Order PID Controller Tuning Based on Genetic Algorithm, 2011 IEEE International Conference on Business Management and Electronic Information, pp: 764-767, June 201110.1109/ICBMEI.2011.5920371.
15. Bettayeb Maamar and Mansouri Rachid, 2014. "IMC-PID Fractional Order filter Controllers design for integer order systems", ISA Transactions Elsevier. pp. 1620-1628, June 2014. Available: http://dx.doi.org/10.1016/j.isatra.2014.05.007
16. Farhadi, P. and T. Sojoudi, 2014. PEMFC Voltage Control Using PSO-Tuned PID Controller, Proceedings of IEEE NW Russia Young Researches in Electrical and Electronics Engineering Conference 2014, pp: 32-35. DOI:10.1109/ElConRusNW.2014.6839194.

17. Ali Shamel, Noradin Ghadimi, 2016. Hybrid PSTOTVAC/BFA technique for tuning of robust PID Controller of fuel cell voltage, Indian Journal of Chemical Technology, 23: 171-178.
18. Mahsa Khoeiniha, Hassan Zarabadipuour, 2012. Optimal Control Design for Proton Exchange Membrane Fuel cell via Genetic Algorithm , Int. J. Electrochem., Sci., pp: 6302-6312, 7(2012).Available at:www.electrochemsci.org.
19. Akbar Houshyar, Mehdi Mohammadi, Ramtin Rasouli Nezhad and Noradin Ghadimi, 2012. Designing PID controller for fuel cell voltage using Evolutionary Programming Algorithms", , J. Basic. and Applied Scientific Research, 2(2): 1981-1987, 2012. Available:www.textroad.com
20. Sachin V. Puranik, Ali Keyhani and Farshad Khorrami, 2010. State Space Modelling of Proton Exchange Membrane Fuel cell, IEEE Transactions on Energy Conversion, 25(3): 804-813, September 2010. DOI:10.1109/TEC.2010.2047725.
21. Bilbao, M.N., J. Del Ser, Z.W. Geem, S. Gil-Lopez, Landa-Torres, D. Manjarres and Salcedo-Sanz, 2013. A Survey on the Applications of the harmony search algorithm, Engineering Applications of Artificial Intelligence, 26(8): 1818-1831, 2013. http://dx.doi.org/10.1016/j.engappai.2013.05.008.
22. Normah Kassim, Shahril Irwan Sulaiman, Ismail Musirin, 2014. Harmony search Based Optimization of Artificial Neural Network for Predicting AC Power from a photovoltaic system.", IEEE 8th International Power Engineering and Optimization Conference(PEOCO2014). DOI:10.1109/PEOCO.2014.6814481.
23. Alireza Askarzadeh, Alireza Rezazadeh, An Innovative global Harmony Search Algorithm for parameter identification of a PEM fuel cell model, IEEE Transactions on Industrial Electronics, 59(9): 3473-3480. DOI:10.1109/TIE.2011.2172173
24. Vinu, R. Varghese Paul, 2015. Robust Optimized Artificial Neural Network Based PEM Fuelcell Voltage Tracking, Advances in Intelligent Systems and Computing, Springer, 424: 79-91, December 2015.DOI:10.1007/978-3-319-28031-8.
25. Vinu, R. Varghese Paul, 2016. Harmony Search Optimized Fractional Order PID Controller for Voltage Control of Fuel cell Asian Journal of Research in Social Sciences and Humanities, 6(10): 815-829, October 2016 .DOI NUMBER:10.5958/2249-7315.2016.01055.8.