Bulletin of Electrical Engineering and Informatics
Vol. 3, No. 4, December 2014, pp. 229~238
ISSN: 2089-3191

Optimal PID Controller Designing for Voltage Control of Fuel Cell

Seyed-Jalal Seyed-Shenava, Omid Khezri
Technical Engineering Department, University of Mohaghegh Ardabili, Ardabil, Iran

Abstract

This paper is proposed a PID optimal controller in order to control of one of the most important types of fuel cell, namely proton exchange membrane fuel cell (PEMFC). At first, the introducing and implementation of PEMFC is present and next, during system load variations the proposed controller is designed. The controller should be designed against the load variations for keeping in a fixed value of Fuel cell output voltage. Here, the PID Controller is used which its coefficients are optimized based on Invasive Weed Optimization (IWO). In order to use this algorithm, at first, problem is written as an optimization problem which includes the objective function and constraints, and then to achieve the most desirable controller, IWO algorithm is applied to solve the problem. Simulation results are done for various loads in time domain, and the results show the efficiency of the proposed controller in contrast to the previous controllers.

Keywords: *maximum 5 keywords from paper*

1. Introduction

Rising of fossil fuels cost and their probable depletion, air pollution, global warming phenomenon and severe environmental problems is caused distributed energy sources have gained the attention of many nations in producing electricity. High efficiency and very low emissions can be satisfied in fuel cell-based power generation systems. Moreover, fuel cells have superior dynamic response, good stability and low noise. Proton exchange membrane fuel cell (PEMFC) can be a great alternative for power generating sources in the coming years, especially in the automotive, distributed power generation, and portable electronic applications [1].

PEMFC is composed of cathode, anode and electrolyte between the anode and cathode. Hydrogen gas (H2), which is obtained from the methanol (CH3OH), is inserted to the end of the anode blade and oxygen or air to the end of the positive electrode of cell (cathode) [2].

In the previous literature, various models have been developed for the PEMFC system dynamic modeling, analysis, control and operation. In [2], a type of fuzzy controller to control the fuel cell output voltage is considered. BP and RBF networks control strategy for voltage and current control of the fuel cell, is used in [3]. The development of a computer model for simulating the transient operation of a tubular solid oxide fuel cell (SOFC) is described in [4]**.** The electrochemical and thermal parts of the model were developed and verified separately before they were combined to form the transient model. The model includes the electrochemical, thermal, and mass flow elements that affect SOFC electrical output. A nonlinear lumped-parameter mathematical model of direct reforming carbonate fuel cell stack is considered in [5]. In ref [6], analytical details active and reactive power output of a stand-alone PEM fuel cell power plant (FCPP) is controlled. The validity of the analysis in this paper is verified when the model is used to predict the response step changes in the load active and reactive power demand and actual active and reactive load profile.

The ripple current propagation path is analyzed in ref [7] which its linear ac model is derived. The equivalent circuit model and ripple current reduction with passive energy storage with an advanced active control technique is then proposed to incorporate a current control loop in the dc–dc converter is used to this goal. A fully integrated modeling approach that lends itself to parallelism is introduced in [8]. Simulation time reduction with parallel computing is achieved with this modeling. Reference [9] suggested that the ripple current be limited to less than 10%.

Received June 25, 2014; Revised September 12, 2014; Accepted October 3, 2014

Passive energy storage compensation method was suggested and tested extensively in [10]. Active compensation with external bidirectional dc–dc converter method was suggested in [11], [12]. These methods require externally added components or circuits and are not preferred.

To produce electrical energy from fuel cell, it is essential that the output voltage of cell kept constant for different loads to supply high quality power to the loads. But fuel cell output voltage changes for different loads. In this paper a simple PID controller is proposed for fuel cell voltage control. The proposed controller is design based on IWO algorithm. In order to achieve the optimal PID controller at first, the problem is converted to optimization problem and then is solved by using IWO algorithm. The main goal of this optimization problem is voltage regulation of PEM. About the advantages of the proposed control, we can point followings: 1- controllers are simple 2- being robustness against load changes 3- having the desired control features 4- fast transient response 5- zero steady error.

2. Dynamic model of the fuel cell

At first, in order to study the dynamic behaviour of the fuel cell, the schematic, structure and modeling of the fuel cell should be done. Figure 1, shows the schematic model of the fuel cell system that proposed voltage controller will be applied in this paper. The mass of the anode and cathode in the figure are considered as a sole compression of anode and cathode [13].

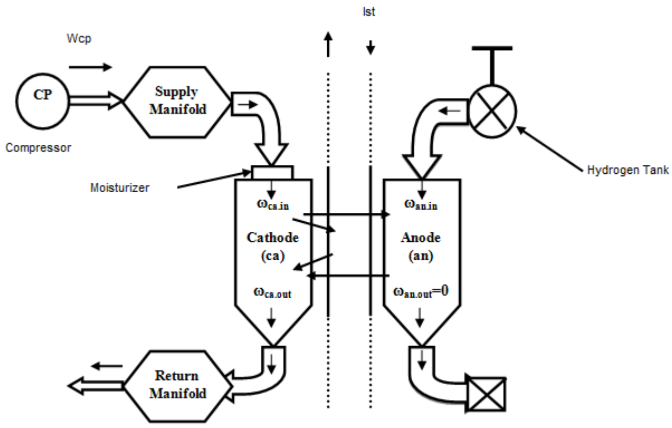

Figure 1. Schematic diagram of fuel cell

The dynamic model of the PEMFC system is considered according to the reference [14]. The equal output voltage of the PEMFC system is extracted usig deducing the voltage drops from the regressive voltage. Equation (1) express how to calculate the fuel cell output voltage [15].

$$V_s = n(E_{reversable} - V_{act} - V_{ohmic} - V_{con}) \qquad (1)$$

Where, V_s is the accumulated fuel cell output voltage in volts, n is the existing cells in the accumulated fuel cell, V_{act} is the voltage drop resulting from anode and cathode activity in volts, V_{ohmic} is the ohmic voltage drop in volts, which is a certain amount of resistance in the transfer of electrons and protons in the electrolyte between the anode and cathode. V_{con} is resulting from the mass transfer of oxygen and hydrogen. $E_{reversable}$ in equation (1) is calculated through the following equations [1] and [9].

$$E_{reversable} = 1.229 - 0.85\times10^{-3}(T - 298.15) + 4.3085\times T \times [\ln(PH_2 + 0.5\ln(PO_2)] \qquad (2)$$

Where, T is the cells temperature in Kelvins, PH_2, PO_2 are effective partial pressure (atm) of hydrogen and oxygen gases respectively that can be calculated by the following equation.

$$PO_2 = P_c - P_{H_2o}^{sat} - P_{N_2}^{channel} \exp\left(\frac{0.291\left(\frac{i}{A}\right)}{T^{0.932}} \right) \tag{3}$$

$$PH_2 = 0.5 P_{H_2o}^{sat} \left(\frac{1}{\exp\left(\frac{1.635\times\left(\frac{i}{A}\right)}{T^{1.334}} \right) \cdot \left(\frac{P_{H_2o}^{sat}}{P_a} \right)} - 1 \right) \tag{4}$$

Where, P_a and P_c are the anode and cathode inlet pressure in atmospheres, A is the effective electrode area in Cm^2, i is the current of each cell in amperes, $P_{H_2o}^{sat}$ is the amount of saturated steam pressure that its value depends on the fuel cell. $P_{N_2}^{channel}$ is the partial pressure of N_2 in the cathode gas flow channels in atmospheres which can be calculated by the following equation.

$$P_{N_2}^{channel} = \frac{0.79}{0.21} PO_2 \tag{5}$$

All amounts used in this article, are the same data available in the reference [13].

3. Invasive Weed Optimization

IWO algorithm is motivated by a common phenomenon in agriculture, which is colonization of invasive weeds. According to the common definition, a weed is any plant growing where it is not wanted. Any tree, vine, shrub, or herb may qualify as a weed, depending on the situation; generally, however, the term is reserved for those plants whose vigorous, invasive habits of growth pose a serious threat to desirable, cultivated plants. Baker and Stebbins [41] mentions that a plant is called weed, if in any specified geographical area, its population grows entirely or predominantly in situations markedly disturbed by man (without, of course, being deliberately cultivated plants).

Weeds have shown very robust and adaptive nature, which turns them to undesirable plants in agriculture. The algorithm is simple but has shown to be effective in converging to the optimal solution by employing basic properties, e.g. seeding, growth and competition, in a weed colony [40]. The reported results are compared with other recent evolutionary-based algorithms: genetic algorithms, memetic algorithms, particle swarm optimization, and shuffled frog leaping. The results are also compared with different versions of simulated annealing, which are simplex simulated annealing and direct search simulated annealing. The performance of IWO has a reasonable performance for all the test functions.

IWO starts with a population of NP D-dimensional parameter vectors or weeds representing the candidate solutions. We shall denote subsequent generations in IWO by G = 0, 1, …, G_{max}. We represent the *i-th* vector of the population at the current generation as:

$$X_{i,G} = [x_{1i,G}, x_{2i,G}, x_{3i,G}, ..., x_{di,G}] \quad (6)$$

The initial population (at G = 0) should cover the entire search space as much as possible by uniformly randomizing individuals within the search space constrained by the prescribed minimum and maximum bounds:

$$X_{\min} = [x_{1,\min}, x_{2,\min}, x_{3,\min}, ..., x_{d,\min}] \quad (7)$$

And

$$X_{\max} = [x_{1,\max}, x_{2,\max}, x_{3,\max}, ..., x_{d,\max}] \quad (8)$$

The plants will produce seeds depending on their relative fitness which will be spread out over the problem space. Each seed, in turn, will grow into a flowering plant. Thus, if S_{max} and S_{min} denote the number of seeds produced by plants with best and worst fitness respectively then seed count of plants will increase linearly from S_{min} to S_{max} depending on their corresponding fitness values. The number of seeds produced by the i-th weed $X_{i,G}$ is therefore given by,

$$S_{i,G} = \left[\frac{F_{\max,G} - F\left(X_{i,G}\right)}{F_{\max,G} - F_{\min,G}} \left(S_{\max} - S_{\min}\right) \right] \quad (9)$$

where $F_{\max,G}$ and $F_{\min,G}$ are the maximum and minimum fitness values at the G-th generation of the weed colony.

The produced seeds are randomly distributed over the D dimensional search space by random numbers drawn from a normal distribution with zero mean but with a varying variance. However, the standard deviation (SD), σ , of the normal distribution decreases over the generations from an initial value, max, to a value, min, and is determined by the following equation,

$$\sigma = \left(\frac{G_{\max} - G}{G_{\max}} \right)^n . \left(\sigma_{\max} - \sigma_{\min}\right) + \sigma_{\min} \quad (10)$$

where σ is the SD at the current generation and G_{max} is the maximum number of iterations while n is the non linear modulation index. This is the adaptation property of the algorithm.

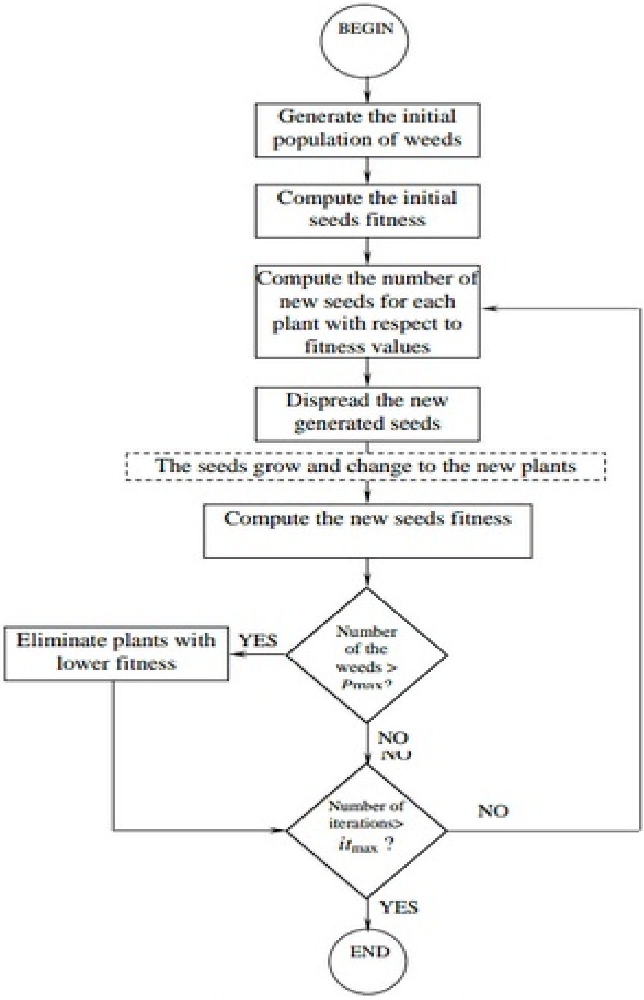

Figure 2. Algorithm and computational flowchart of IWO

4. Using IWO to Adjust Controller Parameters

Due to develop of system controllers, the conventioal contreollers are used widely in power system applications. Making applicable of conventional controllers is simple againist the new controllers of power systems [14]. The PID controllers are widely used in most cases of power systems controllers which compensat very well. One of the most benefits of these controllers is the easily implemention in analog and digital systems. If these controllers are designed optimaly, indubitable they become one of the most implimanted controllers in modern systems. This paper introduce a new optimal PID controller, which is used of IWO algorithm to designing the voltage controller of proton exchange membrane fuel cell. The overall controller schematic is shown in Figure 3.

PID general controller is expressed in equation (9) which the controller k_p, k_i, k_d parameters should be optimized using the proposed algorithm. In the load variations, it is obvious that the transient mode of the PEMFC system depends on the controller parameters. The conventional controller designing method are not viable to be implemented because this system is an absolute nonlinear system. So these methods would have not efficient performance in the system.

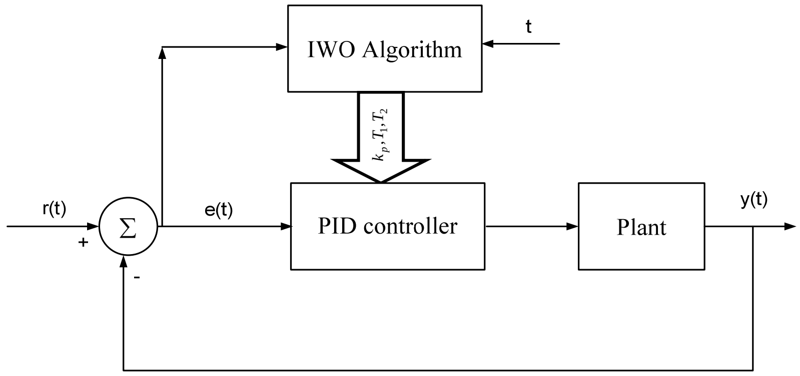

Figure 3. Schematic of proposed controller desining

$$G_c(s) = k_p + \frac{k_i}{s} + k_d s \tag{9}$$

In order to design controller optimal controller using IWO for the fuel cell from the load current curve, we consider the worst condition for load design controllers for these conditions. Figure 4, depicts the worst condition for load current in the system for voltage equal to 200V.

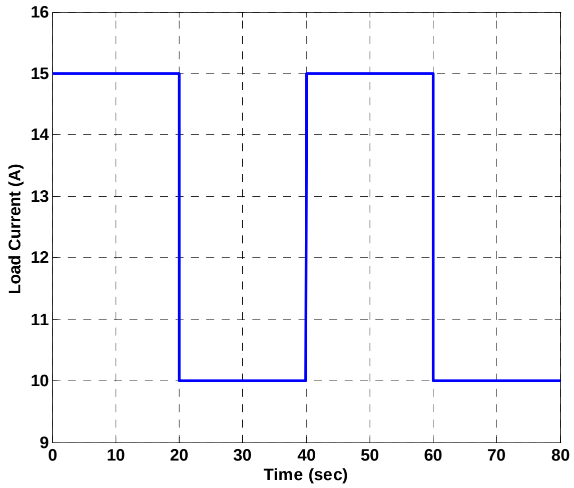

Figure 4. Worst case of load variation of PEMFC

At first, problem should be written as an optimization problem and then by appliyning the proposed optimization method, the best PID controller is achieved. Selecting objective function is the most important part of this optimization problem. Because, choosing different objective functions may completely change the particles variation state. In optimization problem we considered the error signal of voltage in order to achieved the best controller.

$$J = \int_0^{t=tsim} \left| v_{out} - v_{ref} \right| dt \tag{10}$$

Where, *tsim* is the simulation time in which objective function is calculated, the v_{out} is the real output voltage and v_{ref} is the reference voltage. We are reminded that whatever the objective function is a small amount in this case the answer will be more optimized. Each optimizing problem is optimized under a number of constraints. At this problem constraints should be expressed as.

$$\begin{aligned} &Minimize\ J\ subject\ to \\ &k_p^{\min} \le k_p \le k_p^{\max} \\ &k_i^{\min} \le k_i \le k_i^{\max} \\ &k_d^{\min} \le k_d \le k_d^{\max} \end{aligned} \quad (11)$$

Where, k_p, k_i, k_d are in the interval [0.01 200].

In this problem, the number of particles, dimension of the particles, and the number of repeatations are selected 40, 3, 80, respectively. After optimization, results are determined as below:

$$k_p = 86.66\ , k_i = 11.21, k_d = 0.386 \quad (12)$$

5. Simulation Results

The load curve variation for fuelcell is considered in order to show good performance of the proposed algorithm. Desired load current is plotted in Figure 5(a) and in Figure 5(b), the amount of fuel cell power demand or load power variation is displayed. Desired load is considered under the constant output voltage, while the current is changing between the range of 10 to 15 ampers, and the number of its changes are considered more to show the performance of the proposed controller.

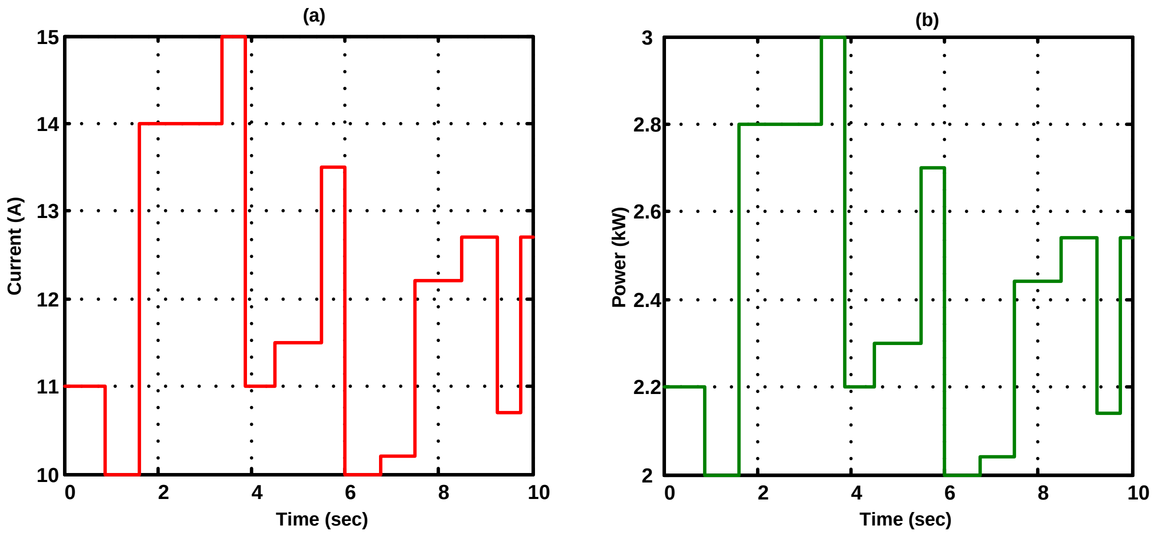

Figure 5. Load variation considering constant voltage for the fuel cell a) current b) demand Power

At first, using try and error designing the parameters is determined as:

$$k_p = 25.6\ , k_i = 4.2, k_d = 0.02 \quad (12)$$

This parameters is applied in fuel cell system and the results for two transient time is shown in Figure 6(a) and (b). in Figure (a), the results of load reducing at t=1.6 s is depicted. The results shows that the peak of voltage is 10 volt and settling time in about 0.08 second. Also these results is extracted from Figure 6 (b) which shows the results for increasing of the demand loads.

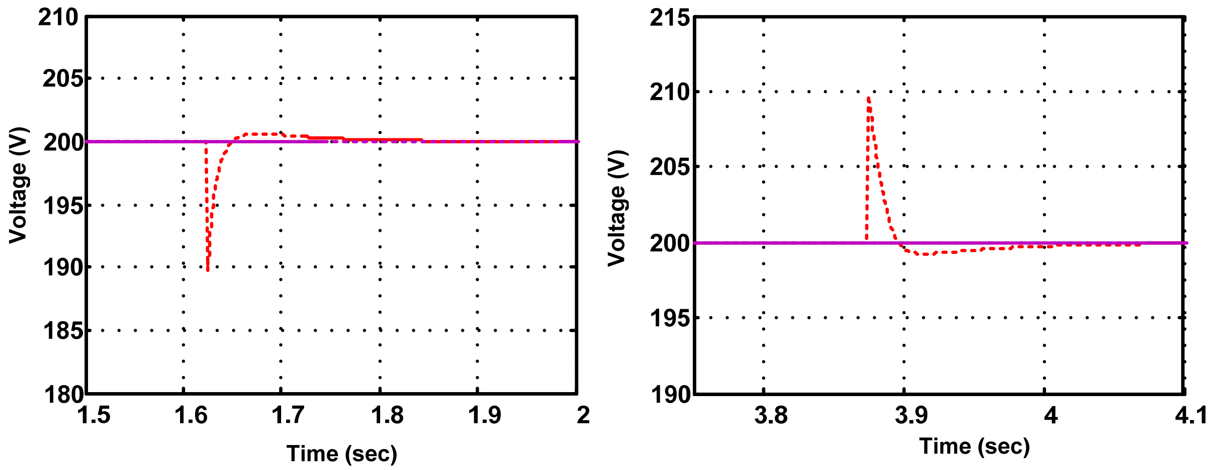

Figure 6. Transient response in load changing a) reducing of demand power b) increasing of demand Power

In second condition, simulation output results obtained from the proposed algorithm which is expressed in equation (12) are shown in Figure 7 and 8. Figure 7(a) depicted PEMFC's output voltage and reference voltage and Figure 7(b) is shows the gas pressure in anode and cathode with load current of demand load. From this Figure, it can be seen that by changing load current, gas pressure in the anode and cathode change quickly to keep stable the output voltage of the fuel cell at the desired voltage and this show good performance of the proposed controller albeit simplicity. Also, According to output voltage of load and reference voltage, it is obvious that controller response is appropriate and it could follow the reference voltage properly. In Figure 8 (a) and (b), the output voltage of load and reference voltage is plotted in reducing and increasing load variation condition, respectivily. The results shows that the peak of voltage is 8 volt and settling time less than 0.01 second. Also these results is extracted from Figure 8 (b), too.Which the high efficiency of the proposed algorithm shown clearly.

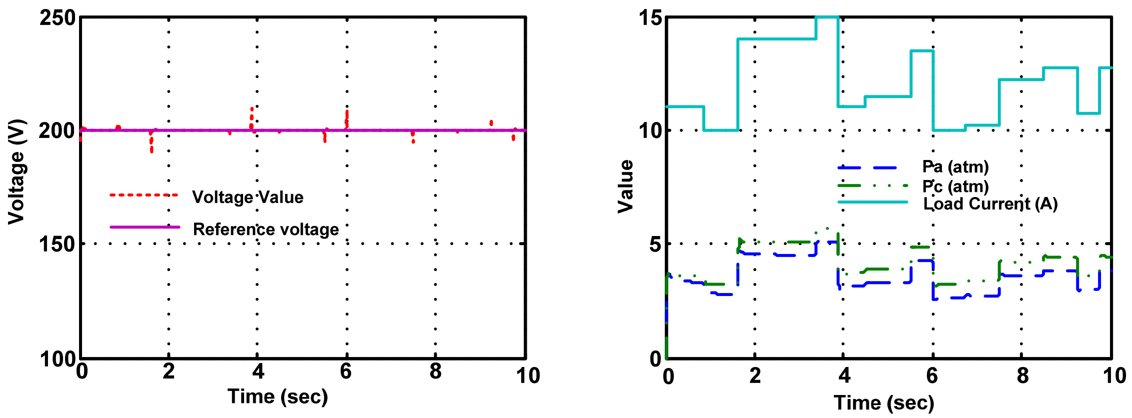

Figure 7. The results of proposed controller for load changing condition a) output voltage and refrence voltage b) anode and cathod gas pressure with load current

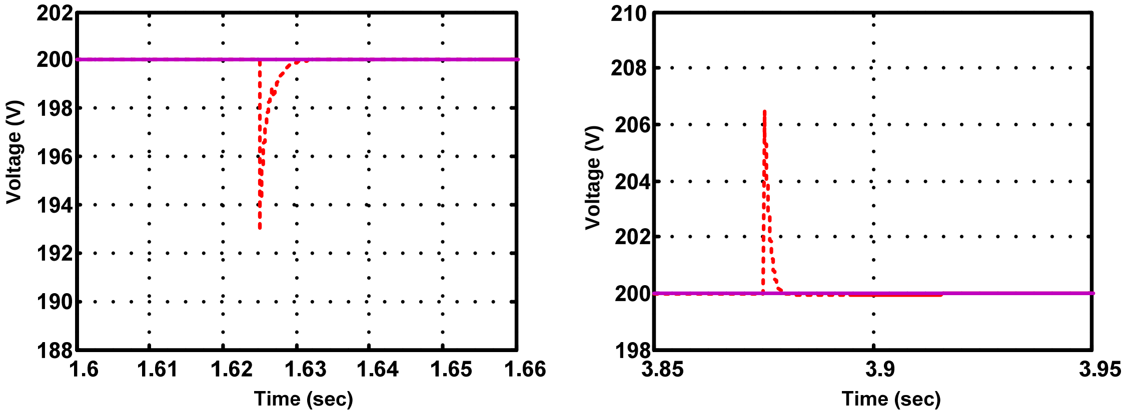

Figure 8. Transient response in load changing using proposed controller a) reducing of demand power b) increasing of demand Power

In the oder condition, at time t=5s the disturbance is applied to anode and cathod pressures. The results of these disturbance response is present in Figure 9. From of Figure 9, in is obvious that the controller can be rejected the disturbance and cantroller can be set the error value of voltage signal in steady state to zero. Also, in transient condition the good results is visible from of this Figure.

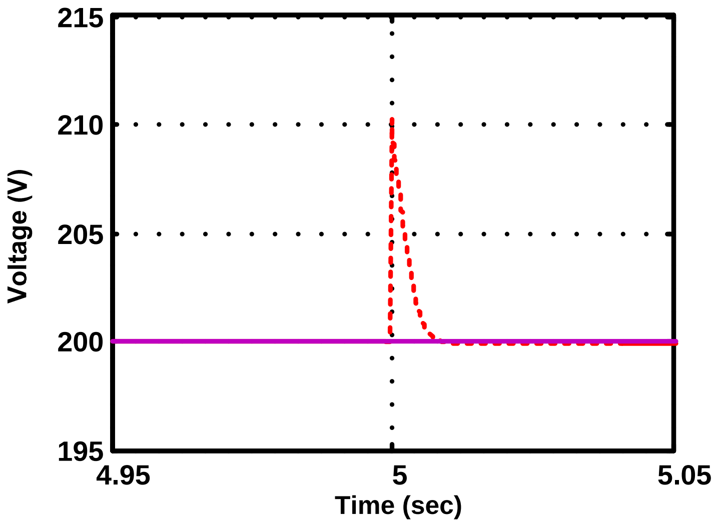

Figure 9. Transient response in applying the disturbance in anode and cathod gas

6. Conclusion

A new optimal controller designing based on IWO and PID controller to control the fuel cell output voltage was proposed in this paper. In order to simplicity, easly implimantation, high efficiency features of the PID controller, this controller is chosen in this paper. Which, it can be obviate the problem of the previous controller IWO algorithm was utilized to design the PID controller to have the most optimized state. In solving this problem, at first problem was written in the form of the optimization problem which its objective function was defined and written in time domain and then the problem has been solved using IWO algorithm. And the most optimal mode for gain coefficient and controller zero and pole were determined using the algorithm.

References

[1] Alireza Askarzadeh, Alireza Rezazadeh. Artificial immune system-based parameter extraction of proton exchange membrane fuel cell. *Electrical Power and Energy Systems*. 2011; 33: 933–938.
[2] Mo Zhigun, Zhu Xinjian and Cao Guangyi "Design and Simulation of Fuzzy Controller for PEMFCs" *IEEE Conference*. 2005: 220-224.
[3] Yanjun Li, Houjun Wang, Zhijian Dai. "Using Artificial Neural Network to Control the Temperature of Fuel Cell". *IEEE Conference*. 2006: 2159-2162.
[4] David J Hall, R Gerald Colclaser. Transient Modeling and Simulation of a Tubular Solid Oxide Fuel Cell. *IEEE Transactions on Energy Conversion*. 1999; 14(3): 749-753.
[5] Michael D Lukas, Kwang Y Lee, and Hossein Ghezel-Ayagh. An Explicit Dynamic Model for Direct Reforming Carbonate Fuel Cell Stack. *IEEE Transactions on Energy Conversion*. 2001; 16(3): 289-295.
[6] MY El-Sharkh, A Rahman, MS Alam, AA Sakla, PC Byrne, and T Thomas. Analysis of Active and Reactive Power Control of a Stand-Alone PEM Fuel Cell Power Plant. *IEEE Transactions on Power Systems*. 2004; 19(4): 2022-2028.
[7] Changrong Liu, and Jih-Sheng Lai. Low Frequency Current Ripple Reduction Technique with Active Control in a Fuel Cell Power System with Inverter Load. *IEEE Transactions on Power Electronics*. 2007; 22(4): 1429.
[8] Abdelkrim Salah, Jaafar Gaber, Rachid Outbib, Olivier Serres, and Hoda El-Sayed, Modeling and Simulation of PEM Fuel Cell Thermal Behavior on Parallel Computers, *IEEE Transactions on Energy Conversion*. 2010; 25(3): 768-777.
[9] RS Gemmen. "Analysis for the effect of inverter ripple current on fuel cell operating condition". *J. Fluids Eng*. 2003; 125(3): 576–585.
[10] M Schenck, K Stanton, and JS Lai. "*Fuel cell and power conditioning system interactions*". in Proc. IEEE Applied Power Electronics Conf., Austin, TX. 2005: 114–120.
[11] YR Novaes and I Barbi. "*Low frequency ripple current elimination in fuel cell systems*". in Proc. Fuel Seminar Special Session on Fuel Cell Power Conditioning, Miami, FL. 2003: 21–27.
[12] A Monti, E Santi, F Ponci, D Franzoni, D Patterson, and N Barry. "*Fuel cell based domestic power supply-a student project*". in Proc. IEEE Power Electronics Specialists Conf., Cairns, Australia. 2002: 315–320.
[13] Noradin Ghadimi. Genetically tuning of lead-lag controller in order to control of fuel cell voltage. *Scientific Research and Essays*. 2012; 7(43): 3695-3701.
[14] Akbar Houshyar, Mehdi Mohammadi, Ramtin Rasouli nezhad, Noradin Ghadimi. Designing PID Controller for Fuel Cell Voltage Using Evolutionary Programming Algorithms. *J. Basic. Appl. Sci. Res*. 2012; 2(2): 1981-1987.
[15] Noradin Ghadimi, Mohammad Marefati and Rasoul Ghadimi. Adjusting Parameters of Lead Lag Controller Using Simulated Annealing to Control Fuel Cell Voltage. *Research Journal of Information Technology*. 2012; 4(1): 23-26.