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Optimal lead-lag controller designing for reduction of load current total harmonic disturtion and hanmonic with voltage control using honey bee mating optimization (HBMO)

Hamdi Abdi[1] and Ramtin Rasoulinezhad[2]*

[1]Electrical Engineering Department, Faculty of Engineering, Razi University, Kermanshah, Iran.
[2]Department of Electrical Engineering, Science and Research Branch, Islamic Azad University, Kermanshah, Iran.

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Increase in world demand load has resulted in new distributed generation (DG) that has entered into the power system. One of the most renewable energies is fuel cell, which is connected to power system using a power electronics interface in microgrid or standalone condition. The highest problem of this switching interface based DGs is the power quality (PQ) and harmonics of currents. Also, the voltage of the DGs should be controlled in islanding condition. In this paper, we present a Lead-Lag optimal controller for controlling one of the most important types of fuel cell, namely proton exchange membrane fuel cell (PEMFC) in islanding mode operation for reducing PQ problems and voltage control. At first, the introduction and implementation of the PEMFC is present and next, during system load variations the proposed controller is designed. The controller should be designed against the demand load variations of fuel cell. Here, the lead-lag controller is used when its coefficients are optimized based on honey bee mating optimization (HBMO). In order to use this algorithm, at first, the problem is written as an optimization problem which includes the objective function and constraints, and then to achieve the most desirable controller, HBMO 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.

Key words: Power system, fuel cell.

INTRODUCTION

Rising of fossil fuel cost and their probable depletion, air pollution, global warming phenomenon and severe environmental problems that 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 a 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 (Alireza and Alireza, 2011).

PEMFC is composed of cathode, anode and electrolyte between the anode and cathode. Hydrogen gas (H_2), which is obtained from methanol (CH_3OH), is inserted into the end of the anode blade and oxygen or air at the end of the positive electrode of the cell (cathode) (Mo

*Corresponding author. E-mail: chibueze.nnaji@unn.edu.ng, Tel: +234(0)8030967563.

Zhigun et al., 2005).

In the previous literature, various models have been developed for the PEMFC system dynamic modeling, analysis, control and operation. A type of fuzzy controller that controls the fuel cell output voltage is considered by Mo Zhigun et al. (2005). BP and RBF networks control strategy for voltage and current control of the fuel cell is used by Yanjun et al. (2006). The development of a computer model for simulating the transient operation of a tubular solid oxide fuel cell (SOFC) is described by David et al. (1999). The power quality in an FC-based on power system is affected by the harmonic contents of the current waveform injected to the load / grid by the inverter and also by the harmonic currents produced by the non linear loads connected to the system (Tanrioven and Alam, 2006). In addition, the harmonics injected by the inverter would increase in the FC connected to a distribution generation DC bus with devices such as photovoltaic and wind turbines. 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 by Michael et al. (2001). Analytical detailed active and reactive power output of a stand-alone PEM fuel cell power plant (FCPP) is controlled (El-Sharkh et al., 2004). The validity of the analysis in this paper is verified when the model is used to predict the response step changes in the active load and reactive power demand and actual active and reactive load profile.

The ripple current propagation path is analyzed by Changrong and Jih-Sheng (2007), who derived its linear AC model. Equivalent circuit model and ripple current reduction with passive energy storage and advanced active control technique are then proposed to incorporate a current control loop in the DC–DC converter, which is used for this goal. A fully integrated modeling approach that lends itself to parallelism is introduced by Abdelkrim et al. (2010). Simulation time reduction with parallel computing is achieved with this modeling. Gemmen (2003) suggested that the ripple current be limited to less than 10%. Passive energy storage compensation method was suggested and tested extensively by Schenck et al. (2005). Active compensation with external bidirectional DC–DC converter method was suggested by Novaes and Barbi (2003) and Monti et al. (2002). These methods require externally added components or circuits and are not preferred.

To produce electrical energy from the fuel cell, it is essential that the output voltage of cell be kept constant for different loads to supply high quality power to the loads. Also the Power Quality (PQ) problems should be solved in islanding mode operation of fuel cell. . In this paper, a simple Lead-Lag controller is proposed for fuel cell voltage control, reducing the current Total Harmonic Distortion (THD) and Current Harmonic (CH) reduction. The proposed controller is design based on HBMO algorithm. In order to achieve the optimal Lead-Lag controller at first, the problem is converted to optimization problem and then is solved by using HBMO algorithm. The main goal of this optimization problem is to regulate the voltage of PEM. The advantages of the proposed control are as follows: 1- controllers are simple, 2- its robustness against load changes, 3- has the desired control features, 4- has fast transient response and 5- has zero steady error.

Dynamic model of the fuel cell

Firstly, to study the dynamic behavior of the fuel cell, the scheme, structure and modeling of the fuel cell should be done. Figure 1 shows the schematic model of the fuel cell system proposed as voltage controller that is applied in this paper. The mass of the anode and cathode in the figure is considered as a sole compression of anode and cathode (Noradin et al., 2012). The dynamic model of the PEMFC system is based on Akbar et al. (2012). The equal output voltage of the PEMFC system is extracted by deducing the voltage drops from the regressive voltage. Equation (1) expresses how to calculate the fuel cell output voltage (Noradin et al., 2012).

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

Where, V_s is the accumulated fuel cell outandut 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} results from the mass transfer of oxygen and hydrogen. $E_{reversable}$ in equation (1) is calculated through the following Equations (1) and (10).

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

Where, T is the cell 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,

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

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

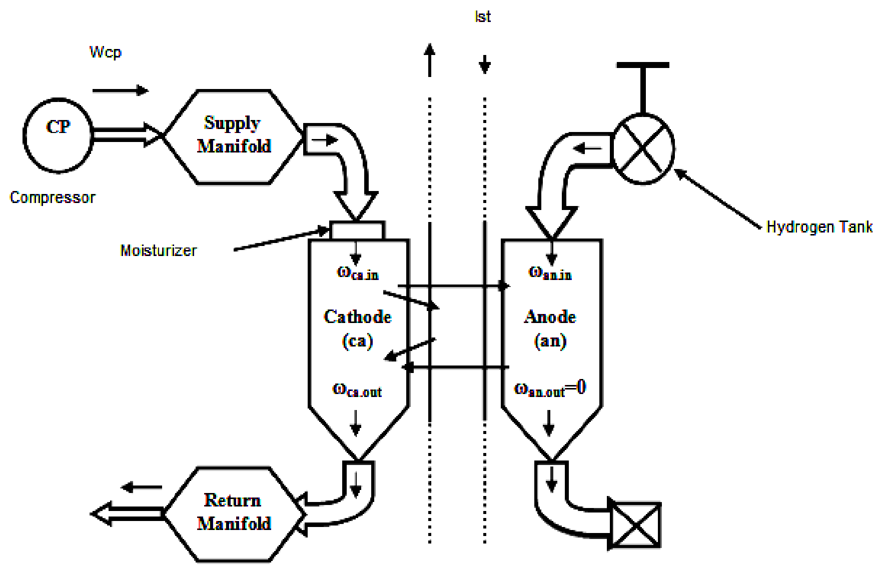

Figure 1. Schematic diagram of fuel cell.

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 whose 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,

$$P_{N_2}^{channel} = \frac{0.79}{0.21} PO_2 \quad (5)$$

All the amounts used in this article are the same with data available in the work of Noradin Ghadimi, (2012).

Honey bee mating optimization

Honey bee is a social insect that can survive only as a member of a community or a colony. The colony inhabits an enclosed cavity. A colony of honey bees consist of a queen, several hundred drones, 30,000 to 80,000 workers and broods during the active season. A colony of bees is a large family of bees living in one bee-hive. The queen is the most important member of the hive because she is the one that keeps the hive going by producing new queen and worker bees (Taher, 2011). Drones' role is to mate with the queen. Tasks of worker bees are several such as: rearing brood, tending the queen and drones, cleaning, regulating temperature, gathering nectar, pollen, water, etc. Broods arise either from fertilized (represent queen or worker) or unfertilized (represent drones) eggs. The HBMO Algorithm is the combination of several different methods corresponded to a different phase of the mating process of the queen. In the marriage process, the queens mate during their mating flights far from the nest. A mating flight starts with a dance performed by the queen who then starts a mating flight during which the drones follow the queen and mate with her in the air. In each mating, sperm reaches the spermatheca and accumulates there to form the genetic pool of the colony. The queen's size of spermatheca number equals to the maximum number of matings of the queen in a single mating flight is determined. When the queen mates successfully, the genotype of the drone is stored. At the start of the flight, the queen is initialized with some energy content and returns to her nest when her energy is within some threshold of zero or when her spermatheca is full. In developing the algorithm, the functionality of workers is restricted to brood care, and therefore, each worker may be represented as a heuristic which acts to improve and/or take care of a set of broods. A drone mates with a queen probabilistically using an annealing function (Yannis et al., 2011):

$$P_{rob}(Q,D) = e^{-\frac{\Delta(f)}{s(t)}} \quad (6)$$

Where Prob (Q, D) is the probability of adding the sperm of drone D to the spermatheca of queen Q (that is, the probability of a successful mating); Δ (f) is the absolute difference between the fitness of D (that is, f (D)) and the fitness of Q (that is, f (Q)); and S (t) is the speed of the queen at time t. It is apparent that this function acts as an annealing function, where the probability of mating is high when both the queen is still in the start of her mating–flight and therefore her speed is high, or when the fitness of the drone is as well as the queen's. After each transition in space, the queen's speed, S(t), and energy E(t) decay using the following equations:

$$S(t+1) = \alpha \times s(t)(2) \quad (7)$$

$$E(t+1) = E(t) - \gamma \quad (8)$$

Where α is a factor and γ is the amount of energy reduction after each transition. Also, Algorithm and computational flowchart of HBMO method to optimize the PEM controller parameters is presented in Figures 2 and 4. Thus, HBMO algorithm may be constructed in the following five main stages:

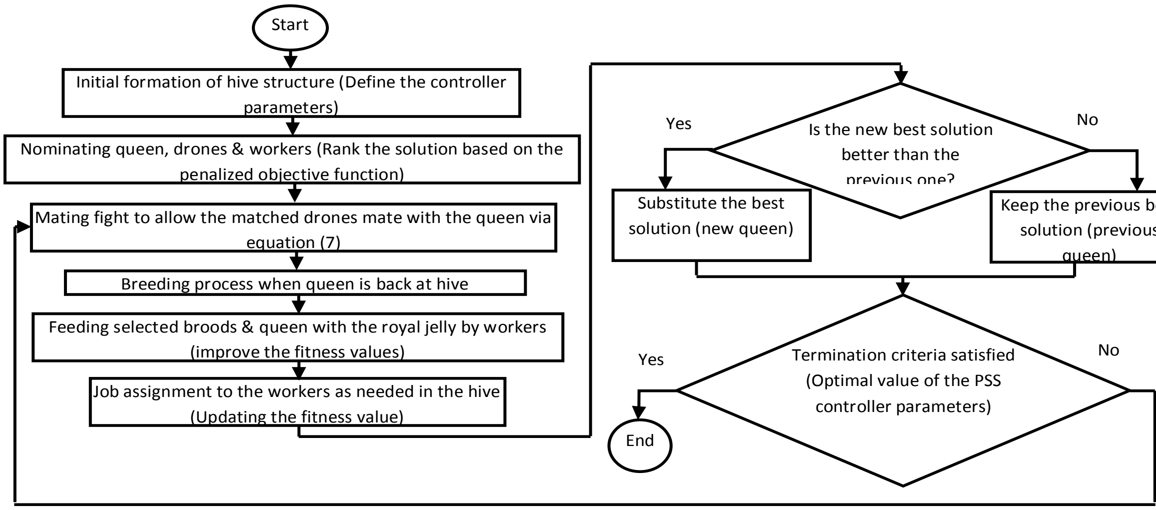

Figure 2. Algorithm and computational flowchart of HBMO.

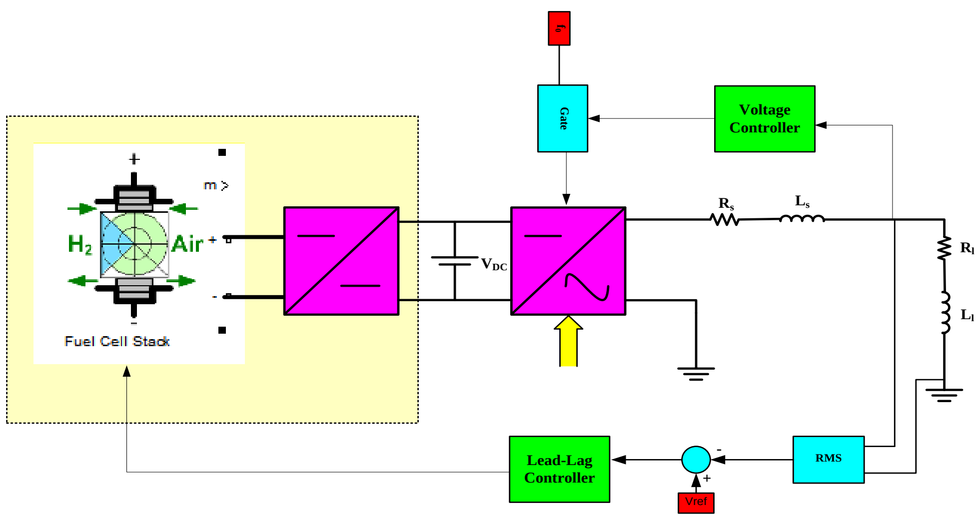

Figure 3. Single line diagram of DG, local load, controller and grid.

(i) The algorithm starts with the mating–flight, where a queen (best solution) selects drones probabilistically to form the spermatheca (list of drones). A drone is then selected from the list at random for the creation of broods.
(ii) Creation of new broods by crossover ring the drones' genotypes with the queen's.
(iii) Use of workers (heuristics) to conduct local searches on broods (trial solutions).
(iv) An adaptation of workers' fitness based on the amount of improvement achieved on broods.
(v) Replacement of weaker queens by fitter broods.

Study system description

Schematic diagram of an electronically coupled PEMFC, DG unit is depicted in Figure 3. In this figure, DG unit is connected to load via a low pass filter R_t, L_t and VSC. Parameters of the system are listed in Table 1.

Table 1. Parameters of DG, local load and grid.

Parameter	Value
R	3.8 Ω
Rt	0.075 mΩ
Lt	15 μH
VSC rated power	5 kW
PWM carrier frequency	1,980 HZ
f0	50 HZ
Nominal Load voltage	110 V (rms)

This system should be working in islanding mode. Depending on the load value, voltage of local load may be increased or decreased and even it may approach instability. Although, in the case of rated load, the voltage and the frequency would remain in nominal value.

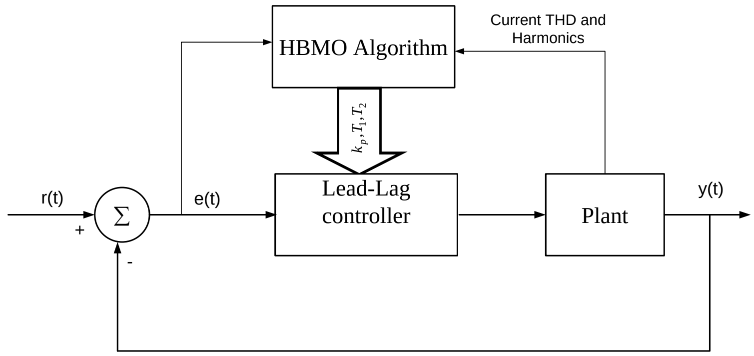

Figure 4. Schematic of the proposed controller designing.

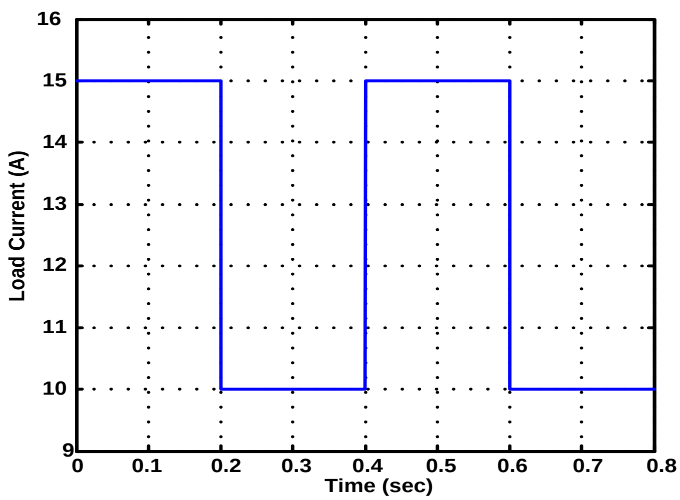

Figure 5. Worst case of load variation of PEMFC.

Also, based on load current, the harmonic current can be produced. Thus, it is necessary for system, different controller appropriate for improving system performance.

Using HBMO to adjust controller parameters

Due to the development of system controllers, the conventional controllers are used widely in power system applications. Applying conventional controllers is simple against the new controllers of power systems (Akbar et al., 2012). The Lead-Lag controllers are widely used in most cases of power system controllers which compensate very well. One of the highest benefits of these controllers is the easily implemention in analog and digital systems. If these controllers are designed optimally, indubitable they become one of the most implemented controllers in modern systems. This paper introduces a new optimal Lead-Lag controller, which is used by HBMO algorithm for designing the controller of proton exchange membrane fuel cell in order to control OD voltage and improve the PQ. The overall controller schematic is shown in Figure 4.

Lead-Lag general controller is expressed in Equation (9) in which the controller k_p, T_1, T_2 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 is not viable to be implemented because this system is an absolute nonlinear. So these methods would have no efficient performance in the system.

$$G_c(s) = k_p \frac{1+sT_1}{1+sT_2} \tag{9}$$

In order to design an optimal controller using HBMO for the fuel cell from the load current curve, we consider the worst condition for load design controllers for these conditions. Figure 5 depicts the worst condition for a load current in the system for voltage equal to 200V. At first, the problem should be written as an optimization problem and then by applying the proposed optimization method, the best Lead-Lag controller is achieved. Selecting objective function is the most important part of this optimization problem. This is because choosing different objective functions may completely change the particle's variation state. In optimization problem, we considered the voltage error signal, total harmonic distortion of current and 3rd harmonic of current in order to achieve the best controller.

$$J = \int_{tstart}^{tsim} \left[\left|V_{ref} - V_{out}\right| + \left|THD_i\right| + \left|I_h^{3th}\right| \right] dt \tag{10}$$

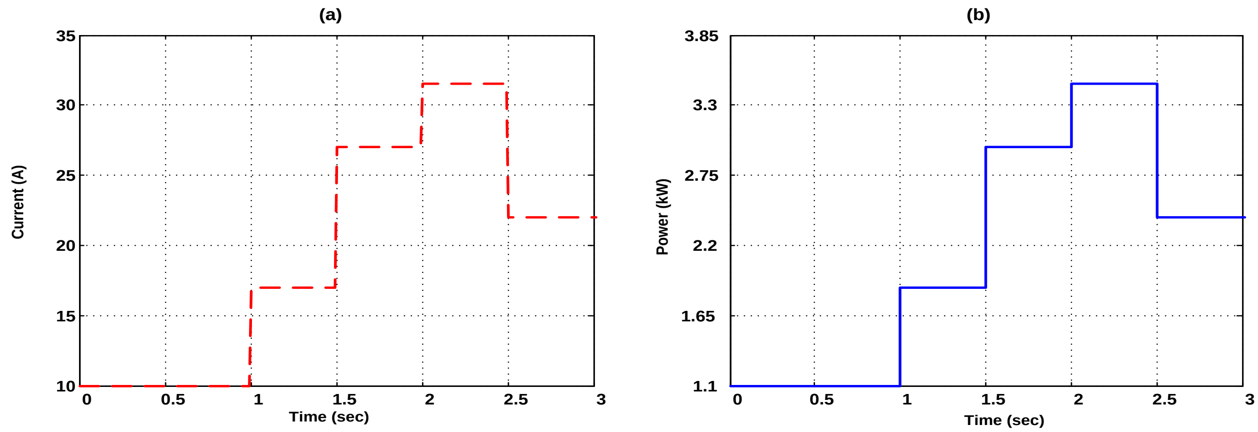

Figure 6. Load variation considering constant voltage for the fuel cell a) current b) demand power.

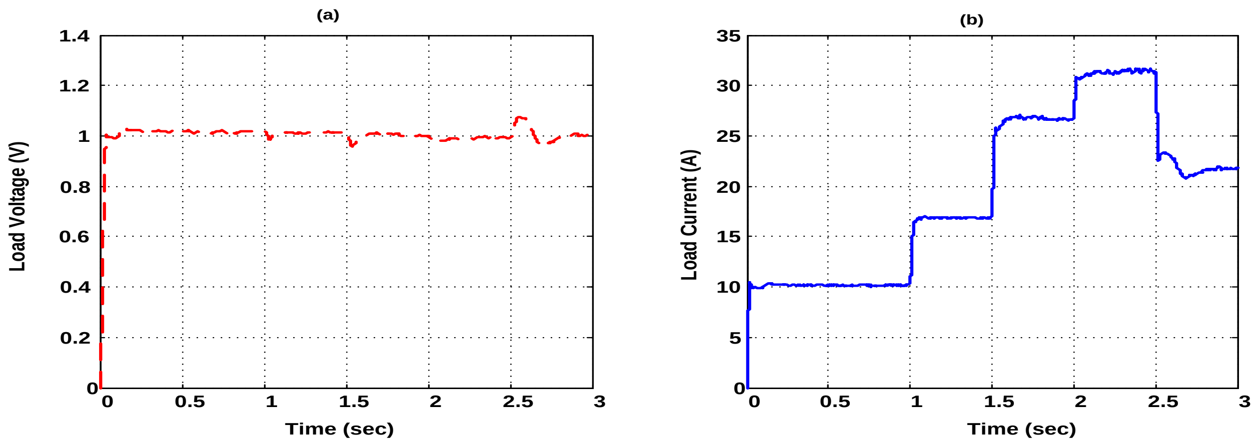

Figure 7. the results of proposed controller for load changing condition a) output voltage and reference voltage b) anode and cathode gas pressure with load current.

Where, *tsim* is the simulation time in which objective function is calculated, V_{out} is the real output voltage and V_{ref} is the reference voltage, THD_i is the current total harmonic distortion and $\left|I_h^{3th}\right|$ is the 3rd current harmonics. We are reminded that when 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. Problem constraints should be expressed as:

$$\begin{aligned} &Minimize\, J \text{ subject to} \\ &k_p^{\min} \le k_p \le k_p^{\max} \\ &T_1^{\min} \le T_1 \le T_1^{\max} \\ &T_2^{\min} \le T_2 \le T_2^{\max} \end{aligned} \tag{11}$$

Where, T_1, T_2 are in the interval [0.01 2] and k_p in the interval [1 500]. In this problem, the number of particles, the dimension of the particles, and the number of repetitions are selected as 40, 3, 80, respectively. After optimization, results are determined as:

$$k_p = 134.1 \,, T_1 = 0.077 \,, T_2 = 1.7240 \tag{12}$$

Simulation results

The load curve variation for fuel cells is considered in order to show good performance of the proposed algorithm. Desired load current is plotted in Figure 6(a) and in Figure 6(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 32 amperes and its variations are considered to show the performance of the proposed controller in transient times. Simulation output results obtained from the proposed algorithm which is expressed in Equation (12) are shown in Figures 7, 8 and 9. Figure 7(a) depicts PEMFC's

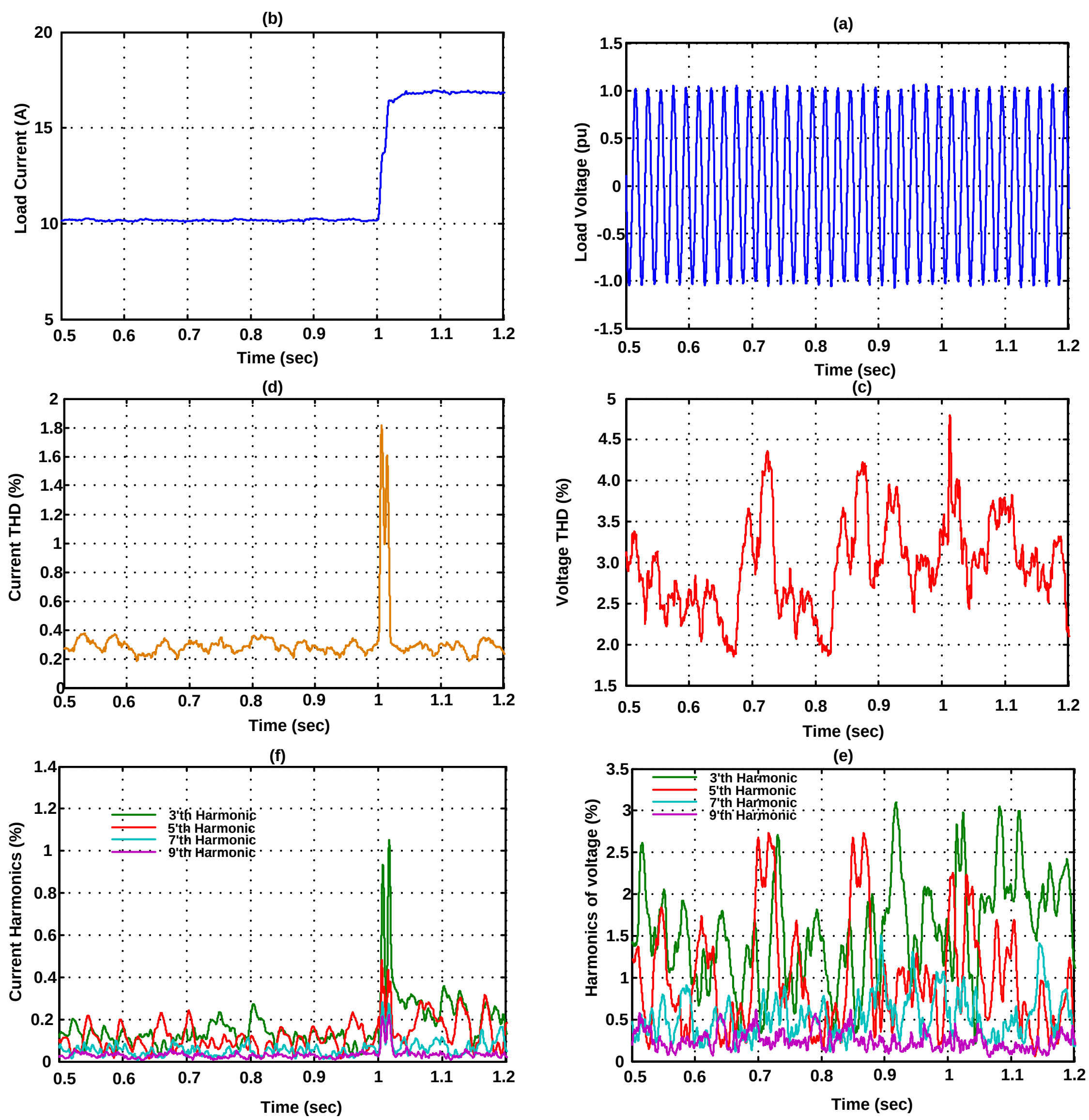

Figure 8. Transient response in load changing using proposed controller a) reducing of demand power b) increasing of demand power.

output voltage which is about 1 pu. Figure 7(b) shows the variation of load current of demand load that reaches the reference current signal. 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 1 pu and this shows good performance of the proposed controller albeit simplicity. Also, according to an 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 load voltage and current are plotted in increasing load variation condition, respectively. From the figure, it is obvious that the proposed controller can control the load voltage. Figure 8(c) and (d) show the THD value of voltage and current, respectively. It can be seen that, the THD of the voltage is lesser than 5% and THD of current is lesser than 2%. The harmonics of voltage and currents are plotted in Figure 8(e) and (f), respectively. These results have shown the high efficiency of the proposed algorithm. At t=2.5 s, reducing step in load switching occurrs. Figure 9 depicts the results of the proposed algorithm for this condition. Figure 9(a) and (b) show the load voltage and current in reducing load variation condition, respectively. From the figure, it is obvious that the proposed controller can control the load voltage. The THD value of voltage and current is plotted in Figure 9(c) and (d), respectively. It

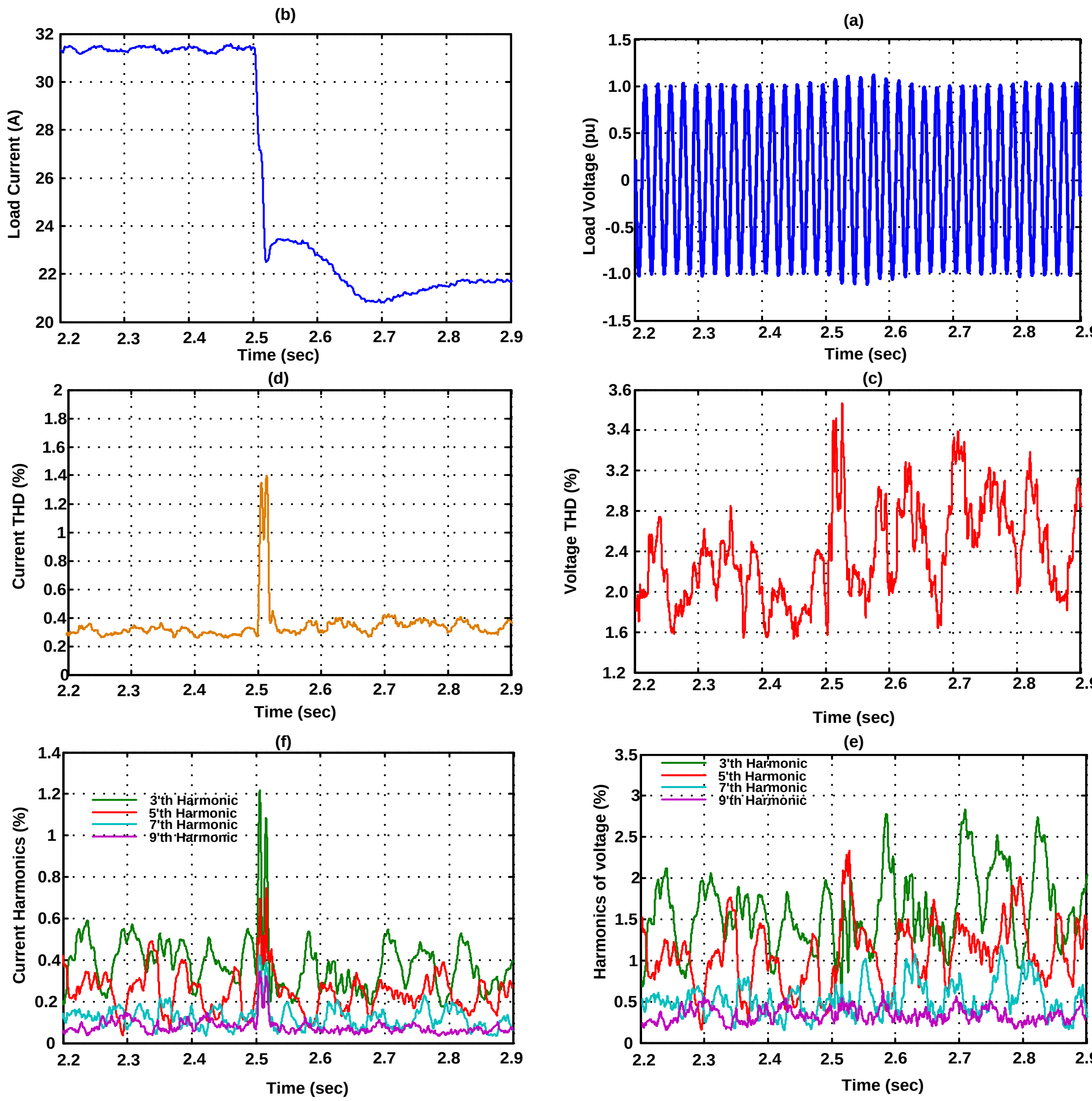

Figure 9. Transient response in applying the disturbance in anode and cathode gas.

can be seen that, the THD of the voltage is lesser than 3.6% and THD of current is lesser than 1.4%. The harmonics of voltage and currents are plotted in Figure 9(e) and (f), respectively. From these results, one can say the proposed controller is an optimal controller for PEMFC system.

CONCLUSION

Optimal controller designing for voltage control and power quality improvement using HBMO based Lead-Lag controller was proposed in this paper. For simplicity, easy implementation, high efficiency features of the Lead-Lag controller, this controller is chosen in this paper. To obviate the problem of the previous controller HBMO algorithm was utilized to design the Lead-Lag controller to have the most optimized state. In solving this problem, the problem was first written in the form of the optimization problem in which its objective function was defined and written in time domain; and then the problem was solved using HBMO algorithm. The objective function contains three parts, namely: voltage error signal, total harmonic distortion of current signal and the 3rd harmonic signal of current. The most optimal mode for gain coefficient and controller zero and pole was determined using the algorithm.

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