REDUCTION OF INVERTER OUTPUT CURRENT RIPPLE IN CONNECTION OF FUEL CELL TO THE POWER NETWORK

H. R. IZADFAR AND S. GHOLAMI KHARKESHI

Abstract. In this paper, a method is introduced which reduces the harmonic distortion of the inverter output current, connecting the fuel cell to the AC load. Using FUZZY LOGIC-PI (FLPI), the controlling method is engaged in optimum tuning of the PI controller coefficients of this converter. This converter has only one DC-AC boost inverter and simultaneously has the task of increasing voltage level and generating the AC power. In order to control the inverter output voltage, an internal current control loop and an external voltage control loop are used. Designing the control of each loop is done separately based on FLPI controller. Simulation results for proposed fuel cell energy system in the presence of this controller imply good performance of FLPI and suitable mitigation of inverter output current ripple.

1. **Introduction**

Nowadays, environmental and economic concerns have caused an increasing interest in renewable energies besides the fossil fuels. Small scale power generation technologies improve power quality and increase reliability. Variety of power generation resources provides opportunities for competition in the electricity market more than ever [2, 12, 15].

Some important studies related to renewable energies include such as real-time evaluation of energy management [8], frequency stability enhancement [9], optimum operation and control of distributed generation, power quality enhancement and etc. Fuel cell is one of the distributed generation technologies that can play an important role in power supply through direct conversion of electrochemical energy into electrical energy.

Fuel cells are clean, noiseless and have high efficiency. For these reasons, they are used in various applications and different power levels such as power plants, hotels, office buildings and ships [11, 15].

Among the four main types of fuel cells, proton exchange membrane fuel cell has fast starting, high efficiency, low operating temperature and low pollution [11].

One of the fundamental requirements in a fuel cell plant is the good quality of its voltage and current in terms of harmonic spectrum. Converter type and its control method affect the total harmonic distortion level.

By switching the fuel cell energy system, low frequency component with as twice as the frequency of output voltage (100/120Hz) is flooded into the fuel cell. To

Received: December 2016; Revised: July 2017; Accepted: December 2017
Key words and phrases: Boost Inverter, Dual Loop Control, Fuel Cell, Fuzzy.

improve the efficiency, increase the life time span of fuel cell and to avoid consuming ten percent more fuel, the amplitude of second harmonic component should be limited to 15% and fundamental frequency ripple of system current in the output should be limited to 10% in 10-100% loading [20].

In some researches, two-stage power conditioning systems have been used to connect the fuel cell to the load or the grid [4, 7, 13, 18]. Most of these systems include a stage of increasing dc level and a stage of converting dc to ac which is done using boost converter and inverter, respectively. Various objective functions, such as reducing current distortion, decreasing the cost of converter connecting fuel cell to the grid, etc. have been defined to control this converter [18]. A PI controller is used in most of the converters. However, some papers have used methods such as Fuzzy to adjust its coefficients [13].

Two-stage power conditioning system has a complex and expensive structure and contains more than six switches and diodes, transformer, clamp circuit and active filter. To overcome these disadvantages, one-stage power conditioning system (boost inverter) can be used [5, 6, 22].

This system converts dc power directly into ac power by increasing the voltage level and has lower switching losses and simpler structure. The boost inverter is also controlled in a one-loop [3, 16] or dual-loop [14] control strategy. Ref. [3] has controlled the inverter using sliding mode control and has achieved the good characteristics for transient responses. But generally, this method also suffers from problems such as variable switching frequency, lack of proper control for inductor current and hard constraints for controller coefficients.

A fuzzy-PI logic for control of grid interactive inverter has been introduced in [16]. This boost inverter consists an inverter coupled with a line power transformer and an output filter. Its inverter controlled in a one-loop control strategy. The Inductor current is the control variable. Its method needs a PLL to calculate the output voltage and make the error signal. This method, although produces an appropriate output voltage, but has expensive and complex structure as same as two stage power conditioning systems. These problems are moderated using dual-loop control strategy [14].

Dual-loop control strategy proposed in [14] for the boost inverter has an internal loop for controlling inductor current and an external loop for controlling capacitor voltage. This method has a better performance in transient conditions. PI controller is used in the structure of this control method. In addition to simplicity, PI controller has the ability to provide good and stable responses. However, PI controller does not have a good performance in the uncertain conditions (disturbance and load variations) and the stability of dual-loop control strategy cannot be thoroughly achieved [1, 17]. In the case of uncertain conditions, frequent adjustment of controller coefficients is required. Another disadvantage of this controller is the poor performance in the nonlinear conditions. One of the main methods to overcome these disadvantages is tuning of PID coefficients by a powerful algorithm such as fuzzy logic which is named Fuzzy Logic PID (FLPI) [10].

In this paper, in order to connect the fuel cell to the load, a one-stage boost inverter and dual-loop control strategy based on FLPI are used.

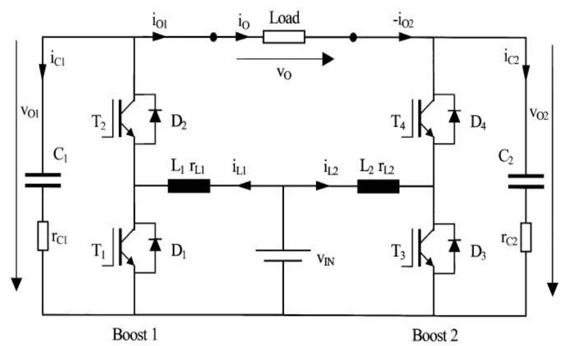

FIGURE 1. Boost Inverter Topology [14]

Inductor current and capacitor voltage are the inputs of fuzzy system. Fuzzy control is used to adjust the PI coefficients correctly. Since the fuzzy control is based on training and does not require the use of mathematical equations of controlled unit, it could be used in a lot of equipment. The combination of PI and Fuzzy controller in dual-loop control strategy will lead to a further mitigation in the output ripple. In this paper similar to [12], FLPI and dual-loop control strategy will be applied to reduce the inverter output current ripple. But unlike it, one-stage boost inverter will be used. Also unlike [16] in proposed method, no need to use line transformer and output filter. Thus with reduction of cost and structure complexity, desirable output energy will be achieved. In the other words, in addition to reduce the hardware, harmonic distortion of the current will be mitigated to an acceptable level.

It will be shown that this strategy has very fast response to sudden load variations and robust again short circuit faults, too.

To achieve these goals the paper is organized as follow. Power conditioning unit is described in section 2. Third section introduces dual-loop control strategy and intended fuzzy controller designs. In section 4, simulation results of proposed method are given. Finally, the relevant conclusions are presented in section 5.

2. **Power Conditioning Unit (PCU)**

Fuel cell is connected to the load via a unified PCU. This system includes only one stage of voltage conversion. The boost inverter is responsible for increasing the level and alternating the voltage simultaneously. This inverter is a combination of two boost DC converters. The output voltage of two converters have a 180-degree phase difference and their difference is an AC voltage waveform greater than the fuel cell DC voltage with a variable duty cycle. Figure 1 shows the structure of the inverter.

The output voltage equations are as below:

$$V_{o1} = V_{dc} + \frac{1}{2} A_1 sin\theta \qquad (1)$$

$$V_{o2} = V_{dc} + \frac{1}{2}A_2 sin\theta \tag{2}$$

$$V_o = V_{o1} - V_{o2} = Asin\theta \tag{3}$$

Where, V_{o1} and V_{o2} are the output voltages of each boost converter and A is the maximum amplitude of output voltage waveform for the boost inverter. The minimum dc bias is obtained by:

$$V_{dc} \geq \frac{A}{2} + V_{in} \tag{4}$$

V_{in} is the output voltage of the fuel cell or the input voltage of the inverter.

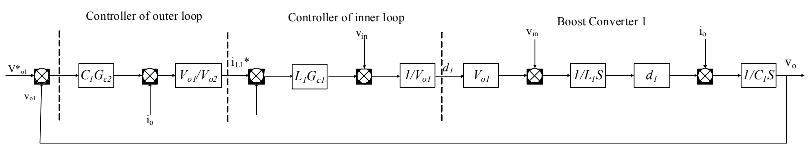

FIGURE 2. Control Strategy for Boost Converter 1

3. Dual-Loop Control Strategy

Output voltage of the boost inverter is controlled by dual-loop control strategy including an internal current control loop and an external voltage control loop as shown in figure 2 [5, 14].

To implement dynamic model of dual-loop control strategy, continuous mode switching model will be used and to achieve the appropriate controllers, linear feedback will be applied to each loop. Each control loop has an integral-proportional compensator.

Equations for the boost converter 1 are:

$$V_{in} - V_{L1} = (1 - d_1)V_{o1} \tag{5}$$

$$i_{c1} + i_0 = (1 - d_1)i_{L1} \tag{6}$$

Where, i_o is the inverter output current and d_1 is duty cycle of the boost converter 1. V_{o1} and i_{c1} are the capacitor voltage and current, V_{L1} and i_{L1} are the inductor voltage and current and V_{in} is the input voltage.

The control variable in the internal loop will be V_{L1}. In this loop, the following equation is established for the cycle. $V_{L1,ref}$ is the control variable and appears as a disturbance. In this equation, the inductor voltage, unlike the output voltage, is negligible. Therefore, it has been ignored [14].

$$(1 - d_1) = \frac{V_{in} - V_{L1,ref}}{V_{o1}} \tag{7}$$

The control variable in the external loop is i_{c1}. The inductor reference current i_{L1} in the external loop is generated by the capacitor reference current $i_{c1,ref}$ and duty cycle as below.

$$i_{L1,ref} = \frac{i_{c1,ref} + i_o}{1 - d_1} \approx \frac{V_{o1}}{V_{in}}(i_{c1,ref} + i_o) \tag{8}$$

Similar equations for control loops are governed in the boost converter 2.

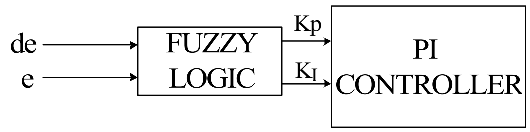

FIGURE 3. Control strategy for Boost Converter 1

4. **Fuzzy Control**

Despite the good performance of dual-loop control strategy in transient conditions, PI compensator applied in the control method has two disadvantages. First, PI compensator coefficients usually need to be set manually for transition to the new situation. Second, PI compensator does not present a good operation for nonlinear and uncertain controlled units such as uncertain loads or disturbance [10].

Fuzzy control is used for problems that cannot be solved by classic methods appropriately. This controller does not need to know mathematical model of controlled unit and acts only based on decision table for control [5, 10, 19, 21]. In this paper, to solve the problems that occur in the presence of nonlinear controlled unit and uncertain factors, a combination of fuzzy controller and PI compensator is used. In this method, using fuzzy logic, PI controller coefficients in each loop will be determined separately. Its scheme is given in Figure 3. This approach is named as FLPI control.

In this structure, e is error signal and obtained by comparing actual values of the inductor current and the capacitor voltage with their reference values as below:

$$e_i = I_L - I_{Lref} \tag{9}$$

$$e_v = V_c - V_{cref} \tag{10}$$

The relationship between input and output in fuzzy controller is performed by IF-THEN rules.

4.1. **Design of Fuzzy-PI Controller for the Bost Inverter.** A FLPI controller is linear if the control surface has the linear shape. Since the purposed system including fuel cell and boost inverter is a nonlinear system, the control surface of FLPI will be nonlinear. This subject will be shown in the next sections.

Membership functions of all input and output variables are selected as Triangular functions. Two input variables for fuzzy controller are error (e(t)) and error variations (de(t)) and its two output variables are coefficients K_P and K_I . Input variables are expressed by 7 linguistic variables as bellow.

NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium), PB (Positive Big).

Output variables will be also defined by 7 linguistic variables as below.

ZE (Zero), VS (Very Small), MS (Medium Small), ME (Medium), MB (Medium Big), VB (Very Big) and VL (Very Large).

Membership functions of the input and output variables have been shown in Figure4 to Figure 7 respectively.

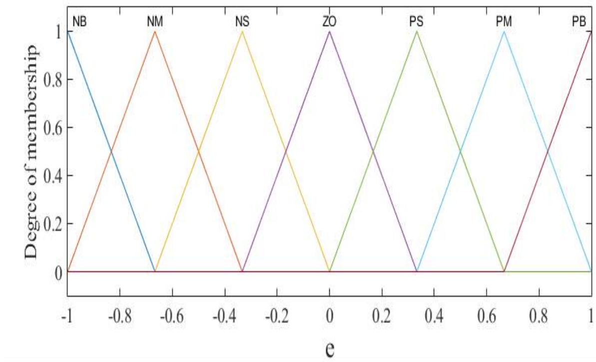

Figure 4. Membership Functions of e

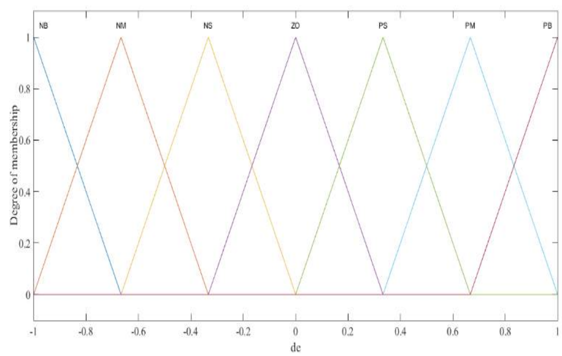

Figure 5. Membership Functions of de

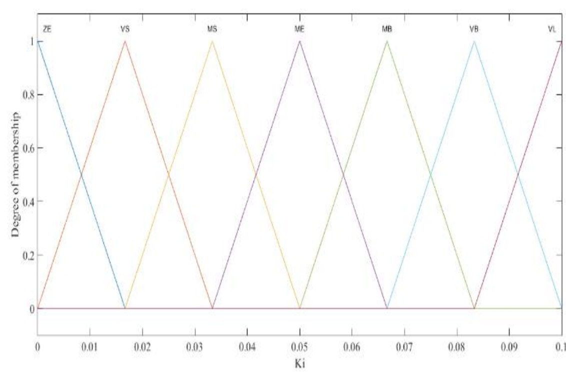

Figure 6. Membership Functions of K_I

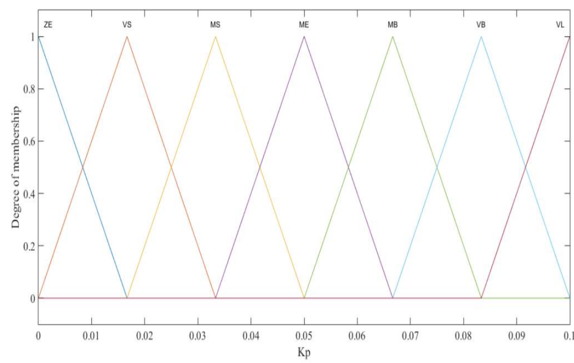

FIGURE 7. Membership Functions of K_P

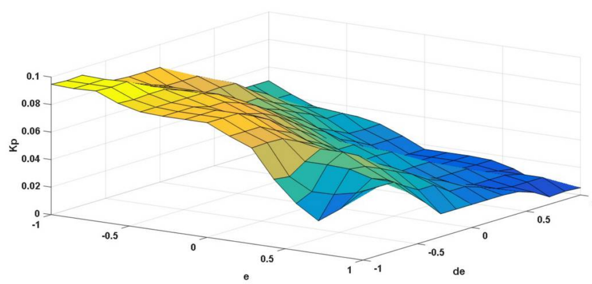

FIGURE 8. Fuzzy Surface for K_P

7 membership functions are defined for each input variable. So, the total number of rules for each output variable will be $7 \times 7 = 49$ rules.

For the inference process, the activation operator is set to be a product, max for the accumulation operator and Center of Gravity as the defuzzifier operator.

Scaling factor for input variables is chosen so that both e and de are located within the range of [-1 1]. The range of output variables of fuzzy controller i.e. K_P and K_I are defined as [0 0.1].

Defined rules for both fuzzy output variables are expressed in the Tables 1 and 2. These rules are based on the examination and experimental methods and have been achieved by trial and error. Fuzzy surfaces for coefficients K_p and K_I are shown in Figure 8 and Figure 9.

5. Simulation and Analysis of the Method

Simulation of the system and proposed method is implemented in MATLAB software. A typical proton exchange membrane fuel cell with the output power of 1.26 KW and characteristics given by Net Stack Company are used in the simulation. DC output voltage of the fuel cell is in the range of 20-42 Volts. Figure 10 shows the polarization curve and output power of the intended fuel cell.

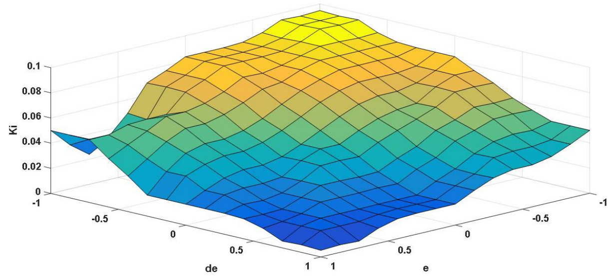

FIGURE 9. Fuzzy Surface for K_I

e / de	NB	NM	NS	ZE	PS	PM	PB
NB	ZE	ZE	VS	VS	MS	ME	ME
NM	ZE	ZE	VS	MS	MS	ME	ME
NS	ZE	VS	MS	MS	ME	MB	MB
ZE	VS	VS	MS	ME	MB	VB	VB
PS	VS	MS	ME	MB	MB	VB	VL
PM	ME	ME	MB	MB	VB	VL	VL
PB	ME	ME	MB	VB	VB	VL	VL

TABLE 1. Fuzzy Roles for K_P

e / de	NB	NM	NS	ZE	PS	PM	PB
NB	MB	MS	ZE	ZE	ZE	VS	MB
NM	MB	MS	ZE	VS	VS	MS	ME
NS	ME	MS	VS	VS	MS	MS	ME
ZE	ME	MS	MS	MS	MS	MS	ME
PS	ME	ME	ME	ME	ME	ME	ME
PM	ME	ME	MB	MB	MB	MB	VL
PB	VL	VB	VB	VB	MB	MB	VL

TABLE 2. Fuzzy Roles for K_I

Simulated model of proposed fuel cell and boost inverter have been presented in Figure 11. In this system, 4 MOSFET as switches, two inductors and two capacitors for the boost converter, one capacitor as a filter to smooth ripples flowed to the fuel cell and one resistor as a load are used.

5.1. **Power Components Design and Simulation Results.** Power components in the proposed system are calculated by the parameters given in Table 3. The following formula can be used to calculate the value of the inductors L_1 and L_2 [6]:

$$i_{L1,max} = \frac{V_{in} - \sqrt{V_{in}^2 - 4R_a K}}{2R_a} \tag{11}$$

$$K = -V_1(t)(\frac{V_2\,(t) - V_1\,(t)}{R_1}) \tag{12}$$

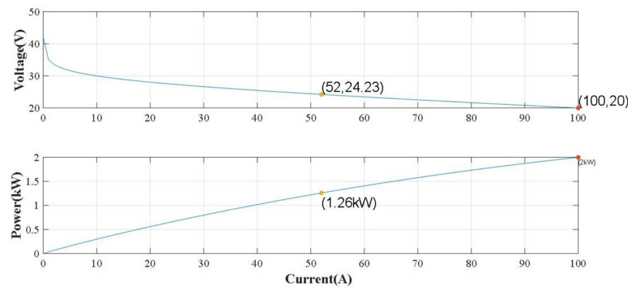

FIGURE 10. Output Voltage and Power of Selected Fuel Cell vs Load Current

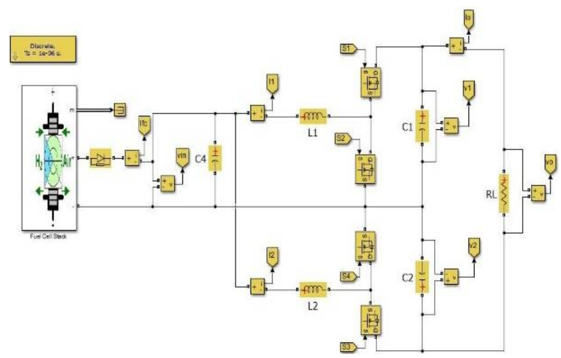

FIGURE 11. Simulated System in MATLAB/SIMULINK

$$\Delta i_{L1}\left(t\right) = \frac{V_{in} - i_{L1}(t)}{L_1}\Delta t \tag{13}$$

$$\Delta V_c\left(t\right) = \frac{V_1\left(t\right) - V_2(t)}{CR_1}\Delta t \tag{14}$$

Inductor and capacitor values of the inverter can be calculated by means of the above equations and data from Table 3. With some calculations, we will have:

$L_1 = L_2 = 200\ \mu H$ and $C_1 = C_2 = 90\ \mu F$.

Figure 12 shows the current flowing through inductors L_1 and L_2 in each boost converter and the output current of the inverter.

DC gain is one of the operating criteria of the boost inverter. This criterion indicates the relation between each converter output voltage, input voltage and duty cycles of the boost inverter in continuous conduction mode. The output voltage of each converter depends to its duty cycle. The relation between voltage and duty cycle are as follow [5].

$$V_{o1} = \frac{V_{in}}{1 - d_1} \tag{15}$$

$$V_{o2} = \frac{V_{in}}{1 - d_2} \tag{16}$$

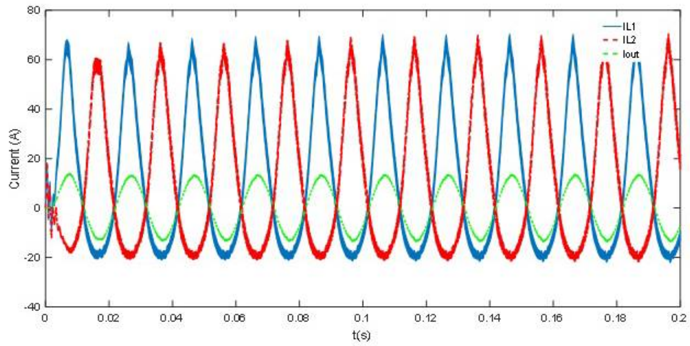

FIGURE 12. Currents of Boost Converters and Inverter

Where d_1 and d_2 are duty cycles of converters.

According to above equations, the ratio of output to input voltage of converters can be shown as follow.

$$\frac{V_{o1}}{V_{in}} = \frac{1}{1-d_1} \tag{17}$$

$$\frac{V_{o2}}{V_{in}} = \frac{1}{1-d_2} \tag{18}$$

Figure 13 shows the value of V_{o1} and V_{o2} with respect to change of duty cycles. Duty cycle of each boost converter changes in the range of 0.18 to 0.82.

The magnitude of harmonic components of the inverter output current is depicted in Figure 14. Total harmonic distortion of the current is 1.22% and within the allowable range. In fact the suggested control strategy can reduce the ripple content in the output current of inverter, considerably.

The fuel cell current ripple should be also in the permissible range to avoid reducing its life. As can be seen from the Figure 15, its THD equals to 12.08% that is allowable value.

Parameter	Value
Fuel Cell output voltage	20-42 VDC
Output voltage	100 V(rms)
Output frequency	50 HZ
Output power	1.26 KW
Switching frequency	20 KHZ
Input voltage	24 V
$X_{L1}=X_{L2}$	10 mΩ
Ra	10 mΩ
Maximum time which a switch remaining on (Δt_1)	42.5 μs
Δi_{Lmax}	0.05 i_{Lmax}
ΔV_c	0.05 V_{1max}
RL	7.9 Ω - 1.26 KW

TABLE 3. Parameters of Conditioning Unit

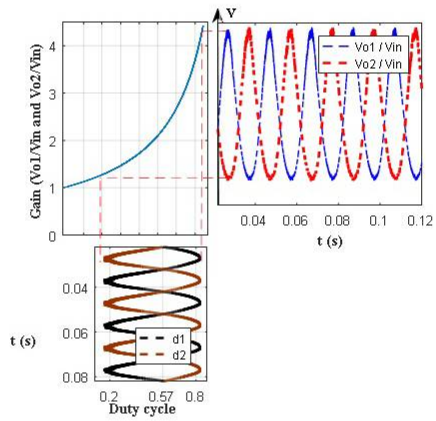

FIGURE 13. Voltages Versus Duty Cycles of Boost Converters

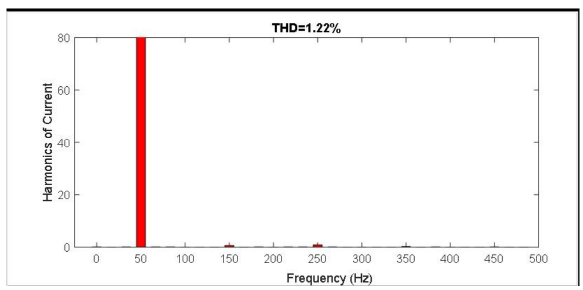

FIGURE 14. Harmonic Components of Output Current

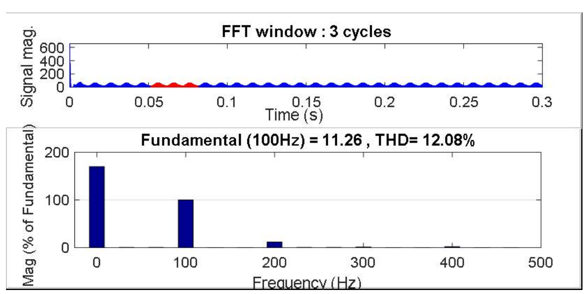

FIGURE 15. Harmonic Components of Fuel Cell Current

In order to better introduce the performance of proposed method, the inverter output variations were studied in two modes including suddenly change of the load and short circuit in the inverter terminal. Figure 16 shows the output voltage in these situations. At the time of t_1, the load value is changed as a step. At the time of t_2, the inverter terminal is short-circuited and the fault is removed in t_3. As can be seen, hardware sets and proposed method are capable of maintaining output quality under variations of the load and circuit condition as well.

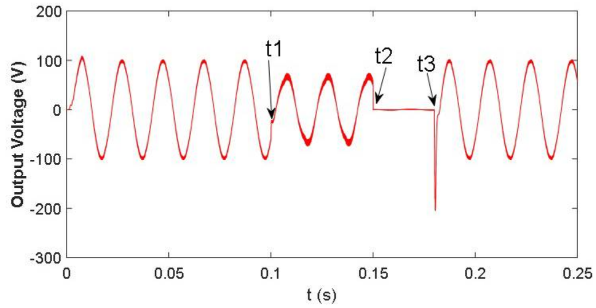

Figure 16. Output Voltage Variations

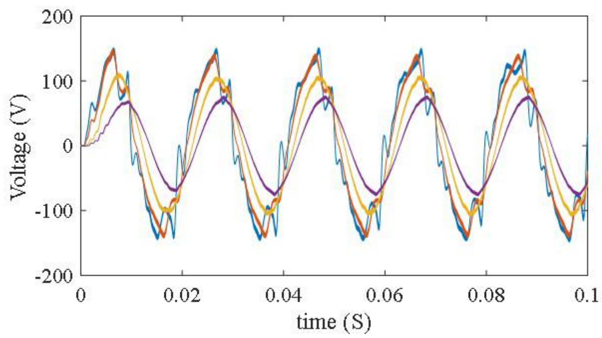

Figure 17. Output Voltage with Respect to Variations of K_P

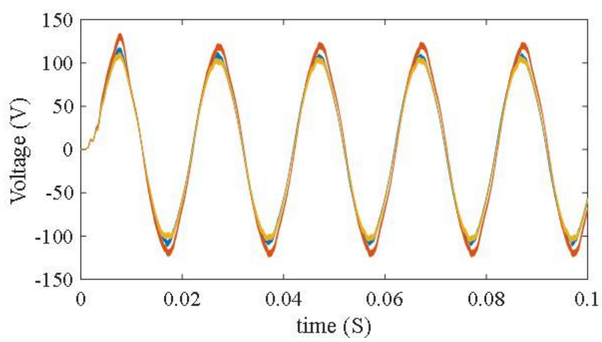

Figure 18. Output Voltage with Respect to Variations of K_I

Since the type of the load is resistive, the harmonic components of the output voltage are similar to output current. This is also true in the case of total harmonic distortion of output voltage and current.

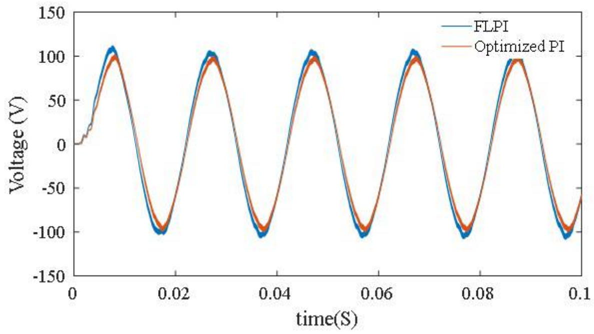

FIGURE 19. Output Voltage with 2 Different Controllers

6. Comparing the Proposed Control Method with Classic PI Controller

In order to better understand the effects of coefficients K_P and K_I on output variables and the role of the proposed controller, output voltage waveforms with respect to K_P variations have been shown in Figure 17. In this analysis, K_I remains to its constant value.

In the next analysis, K_P remains constant and K_I takes different values. Effects of variations of K_I are depicted in Figure18.

Comparing two recent figures, it is clear that the value of K_P is more effective than K_I on output parameter.

In another analysis, instead of FLPI, an optimized classic PI controller is applied to the set of fuel cell and boost inverter. In this design PI coefficients are set to their optimum value.

The results of the proposed method and the optimized PI can be compared in Figure 19. Both methods have very similar results. THD value for the designed PI controller is 2.60%. But as it is mentioned before, PI controller does not have a good performance in the uncertain conditions. In other words, when the operating point changes, the designed PI controller is no longer valid.

The optimum values of PI's coefficients can also be defined by diverse methods such as evolutionary algorithm GA, PSO, etc.

Heuristic optimizing methods usually need more time for computations. For power converters control, which associates with high frequency switching, the real-time implementation control is quite a challenging task.

7. Conclusion

In this paper, using a boost inverter, the output voltage of a fuel cell was converted to the AC form and was connected to the load. To control the inverter output voltage, dual-loop control strategy and PI controller, improved by fuzzy logic, were used. Simple structure of the converter and fuzzy logic used in its control, as well as making a robustness system against load variations, reduced the output current ripple and created a current close to perfect sinusoidal waveform in the load. Two output variables for FLPI were K_P and K_I. The output voltage of the inverter is more sensitive to K_P rather than K_I. Although there are other methods for tuning these coefficients, fuzzy logic provide high quality output parameters in addition to a supply of a fast and robust engine control.

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H. R. Izadfar* , Faculty of Electrical and Computer Engineering, Semnan University, Semnan, Iran

E-mail address: hrizadfar@semnan.ac.ir

S. Gholami Kharkeshi, Msc Student in Electrical and Computer Engineering, Semnan University, Semnan, Iran

E-mail address: s.Gholami@semnan.ac.ir

*Corresponding Author