

Application of PEM Fuel Cell for Stand-alone Based on a Fuzzy PID Control

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Abstract

Due to increasing concerns on environmental pollution and depleting fossil fuels, fuel cell (FC) has received considerable attention as an alternative to the conventional energy systems. Fuel cells have numerous stand-alone and grid-connected applications. This paper presents the control of the stand-alone application based on fuzzy PID (FPID) controller. The aim of the paper is to achieve the control of the fuel cell for stand-alone with suitable power conditioning unit (PCU) that consists of the two stages of DC/DC converter and DC/AC inverter. An analysis of cascade structure based on FPID controller for a single phase inverter is done and comprises two feedback control loops. The inductor current and capacitor voltage are measured and feedback to the inner loop and the outer loop, respectively. The analytical models of the h PEM fuel cells is designed and simulated by developing a detailed simulation software using Matlab, Simulink and SimPowerSystems Blockset for portable applications. The PEM fuel cell model is validated with Nexa™ Power Module MAN5100078 by Ballard Power Systems at 80°C. In this paper shown that the proposed controller shows a robust behavior and good transient response.

Keywords: PEM Fuel Cell, Fuzzy PID, DC/DC Converter, DC/AC inverter, Stand-alone application

1. Introduction

In the last decades, the traditional methods from burning fossil fuels have Environmental problems derived from the CO₂ emissions such as climatic change and urban air pollution, and fossil fuels dependence, should encourage actions in several fields in order to minimize them [1]. Nowadays, fuel cell technology is considered as a suitable alternative in several applications. Hydrogen may be an alternative to gasoline, gasoil and biofuels for the automotive sector [1].

Polymer Electrolyte Membrane (PEM) FCs, has many advantages such as small size, weight and ease of construction [2], are ideal to be used in stand –alone applications. PEM fuel cells are a good source of energy for supply stationary-state power, but cannot answer changes of load as fast as it will be taken. The main disadvantage of fuel cells is load current variations and extreme load fluctuations that cause voltage fluctuations and power problems at the time. This problem can be solved with using the proper power converters and control strategies.

The fuel cells have numerous applications such as stand-alone and grid-connected. Therefore, the power conditioning unit is needed for processing of the raw power output from the fuel cell in order to make it usable. The power conditioning unit might have a DC/DC converter to increase the output voltage of DC and DC/AC single-phase inverter converts DC voltage to AC voltage.

In the year 2012, Liu et al. Single phase sine inverter with the high-frequency links for small wind power system in order to improve the reliability and efficiency of energy conversion offered and designed a fuzzy self-tuning PID controller for inverter proposed [2].

In previous research, there are many control techniques for producing pure sinusoidal output voltage with low total harmonic distortion (THD) and fast dynamic response. Initially, a conventional controller, of Proportional and Integral-Time Derivative (PID) for single-phase inverter was presented [3]. Many low-cost methods for discrete time by microcontrollers are designed, such as [4], sliding mode control, and [5-7] deadbeat-based control, in order to increase the inverter system features. In addition, various methods have been reported for inverter control systems, including control based on neural networks [8], the controller based on fuzzy logic [9].

Discrete methods such as sliding mode, sliding mode control and deadbeat-based control to deal with the uncertainty has been implemented, but the discrete methods has hardware implementation problem.

In the conventional PI and PID method are now used in approximately 90% of industrial control loops worldwide, according to facilitate the implementation of the method. However, conventional PID controllers are insufficient to control processes with complexities such as time delay, significant oscillatory behavior, parameter uncertainty and disturbances. The necessary conditionings for implementation of the conventional PI and PID controllers are the tuning parameters and additional functionalities including anti-windup, feed forward action, and set-point filtering [10]. Fuzzy control is an intelligent, cost-effective nonlinear control. The combination of a PID with a fuzzy control strategy means that PID control has nonlinear characteristics. Fuzzy control strategy makes more sense to enhance conventional PID's performance by making up for the areas in which the PID gains do not do so well. The fuzzy self-organizing controller readjusts the PID gains in real-time to improve the process output response and act as adaptive PID, during the system operation under parameter uncertainty and disturbances [10].

This study aims to model a stand-alone application consists of a PEMFC as the primary energy source, DC/DC boost converter and voltage source DC/AC inverter. The output voltage of PEMFC is unregulated DC voltage, which fluctuates with load variations. The fuel cell is modeled as the main and unregulated input source and the boost DC/DC converter is used to regulate an output voltage of the PEM fuel cell system to 215V. The boost DC/DC converter is controlled by a feedback controller based on a fuzzy PID.

The control structure of single phase inverter is consisted of two loops and has been arranged in a cascaded structure. The control structure is comprised of two loops such as inductor current as the inner loop and output voltage as the outer feedback loop as cascade controller. Control law is based on the design of current mode fuzzy PID controller.

In this paper, a stand-alone system based on fuel cell as the primary energy source and voltage source inverter is proposed using fuzzy PID controller to produce a quality sinusoidal output voltage and a control strategy using fuzzy PID controller is presented for DC/DC boost converter. The proposed single-phase inverter is suitable for residential power generation, especially for stand-alone applications. The control technique also has strong robustness and excellent dynamic and static characteristics.

In this research, the fuzzy PID control strategies are designed for DC/DC converter and DC/AC inverter. The proposed fuzzy PID controller automatically changes the gains of K_p , K_i and K_d with any load variations. The fuzzy self-organizing controller (as fuzzy PID) is a robust controller and improves the process output response in the system operation with parameter variations and load disturbances.

The paper is organized as follows: Section 2 presents dynamic modeling of PEM. Section 3 introduces structure of power conditioning unit (PCU). The DC/DC converter design and control process is introduced in section 4. The AC/DC inverter design and control are presented in section 5. Section 6 presents fuzzy control design and implementation. The simulation results that validate the developments in section 7 are shown. Finally, in section 8 some Conclusions are presented.

2. PEM Fuel Cell Dynamic Model

The PEMFC model proposed in Ref. [11] and Ref. [12, 13] is modified for this research. The PEMFC model presented is made using the relationship between output voltage and partial pressure of oxygen, hydrogen and water. q_{H_2} is hydrogen molar flow(mol/s). The relationship between the molar flow of hydrogen gas through the valve with its partial pressure is expressed as [11]:

$$\frac{q_{H_2}}{P_{H_2}} = k_{H_2} = \frac{k_{an}}{\sqrt{M_{H_2}}} \quad (1)$$

where k_{an} is valve constant of anode and M_{H_2} represents hydrogen molar mass. There are three important factors for hydrogen molar flow such as: hydrogen input flow, hydrogen output flow, and the reaction hydrogen flow [12, 13]. The relationships between these factors are presented in the following equations:

$$\frac{d}{dt} P_{H_2} = \frac{RT}{V_{an}} (q_{H_2}^{in} - q_{H_2}^{out} - q_{H_2}^r) \quad (2)$$

Where V_{an} is volume of the anode side. The relationships between hydrogen reacted flow rate and the fuel cell current according to the basic electrochemical relationship is given by [11, 12]:

$$q_{H_2}^r = \frac{N I_{fc}}{2F} = 2K_r I_{fc} \quad (3)$$

Where K_r is a modeling constant. The s domain of the hydrogen partial pressure is attended by applying Laplace's transform and using Equation. (1) and (3) in the following [11, 12]:

$$P_{H_2} = \frac{1/K_{H_2}}{1 + \tau_{H_2} s} (q_{H_2}^{in} - 2K_r I_{fc}) \quad (4)$$

Where

$$\tau_{H_2} = \frac{V_{an}}{K_{H_2} RT} \quad (5)$$

Similarly above method, the oxygen partial pressure and water partial pressure can be calculated.

The ideal standard potential of a PEM fuel cell is 1.229 V (25°C and 1 atm) with liquid water product. The actual fuel cell potential is decreased from its equilibrium point because of irreversible voltage losses occurring in fuel cell systems. Several sources contribute to irreversible losses in a practical fuel cell. The losses which are often called polarization over voltage, originate from three sources such as activation polarization, ohmic polarization and concentration polarization [14-16]. These losses results in a cell voltage for a fuel cell that is less than its ideal potential:

$$V_{cell} = E - losses \quad (6)$$

Thermodynamic potential E is defined from a Nernst equation in expanded form as [15, 16]:

$$E = 1.229 - 0.85 \times 10^{-3} (T - 298.15) + 4.3085 \times 10^{-5} \times T \times (\ln P_{H_2} + \frac{1}{2} \ln P_{O_2}) \quad (7)$$

The parametric equations for the over voltage due to activation, internal resistance and concentration are as follow:

2.1. Activation Over Voltage

This loss is caused by the slowness of the reactions taking place on the surface of the

electrodes [15].

$$V_{act} = N \frac{RT}{2\alpha F} \ln\left(\frac{i}{i_o}\right) \quad (8)$$

2.2. Ohmic Over Voltage

This voltage drop is the straight forward resistance to the flow of electrons through the material of the electrodes and various interconnections [15, 17].

$$V_{ohmic} = N I_{fc} r \quad (9)$$

2.3. Concentration Over Voltage

This voltages drop results from the change in concentration of the reactants at the surface of the electrodes as the fuel is used.

$$V_{conc} = N m \exp(n I_{fc}) \quad (10)$$

The combined effect of thermodynamics, mass transport kinetics and ohmic resistance determines the output voltage of the cell as [14-17]:

$$V_{cell} = E - V_{act} - V_{ohmic} - V_{conc} \quad (11)$$

A fuel cell stack consists of several cells in series to increase the voltage from fuel cell. In the following equation, N is the number of cells in series. Fuel cell stack voltage was described by:

$$V_{stack} = N V_{cell} \quad (12)$$

The proposed specific characteristics of PEM fuel cell is represent in Table.1. The PEMFC model parameters used in this study are in Table 2. Figure 1 shows the model of the PEMFC, which is realized as a variable voltage source and then integrated into the overall system.

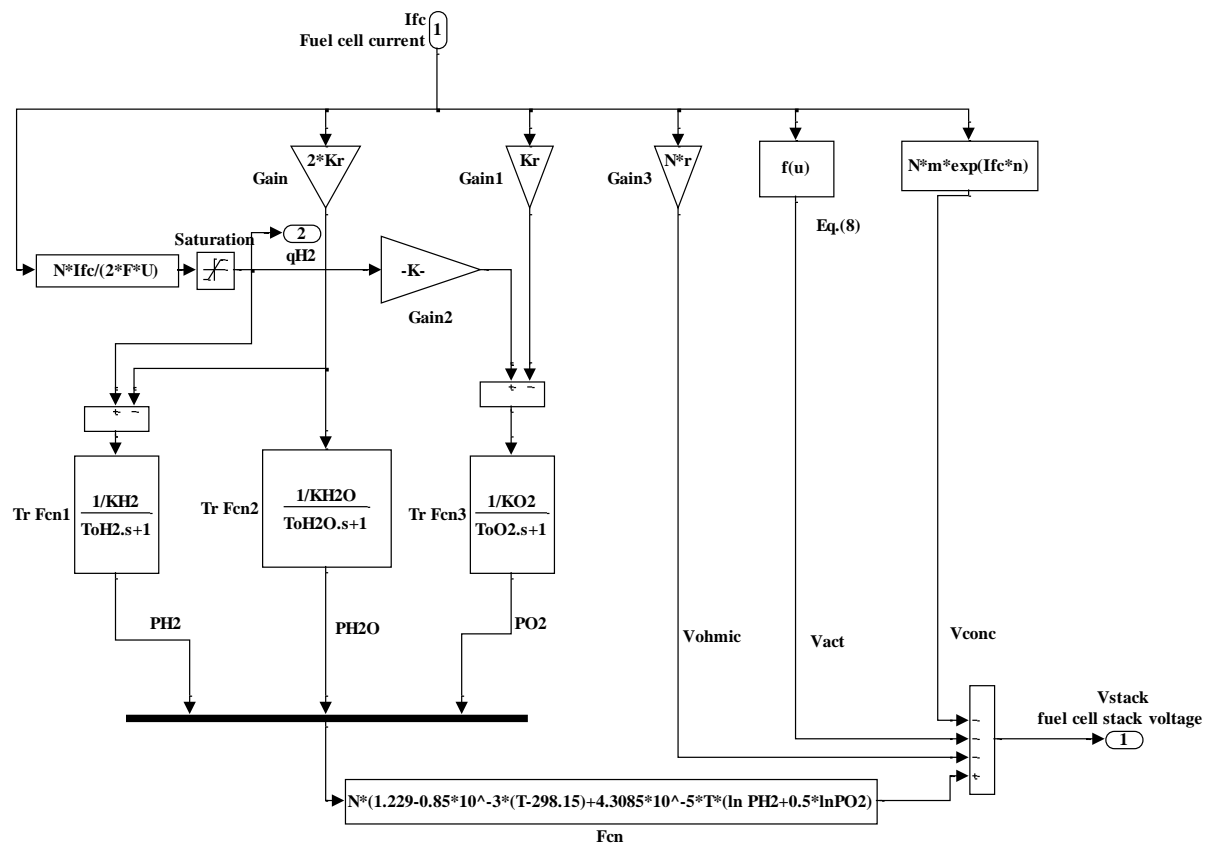


Figure 1. PEM fuel cell system dynamic model

3. Power Conditioning Unit (PCU) and Control Strategy

The power conditioning unit converts the raw power into useable power for different applications. The PCU, controls frequency and maintains harmonic in acceptable level. The overall structure will be consisted of a boost followed by a DC/AC inverter, and the system inverter is as a load for a convert DC/DC boost. Boost converter, is an interface with inverter and FC. Figure 2 shows the structure of the PCU with the DC/DC boost converter and DC/AC inverter stage. There are intermediate stages in Figure 2 that includes filters for harmonics suppression and filtering out of the unwanted current and voltages at the output of the DC/DC converter and the DC/AC inverter. Power obtained from the inverter is injected into the network. Inverter acts as a grid interface. The system can be used as a stationary system (stand-alone) after the DC/DC converter.

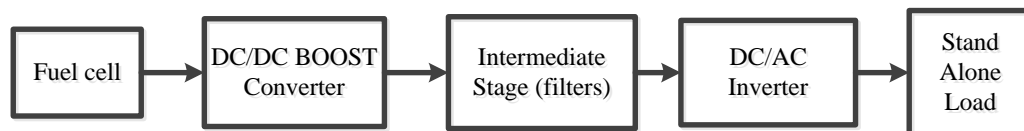


Figure 2. Structure of power conditioning unit

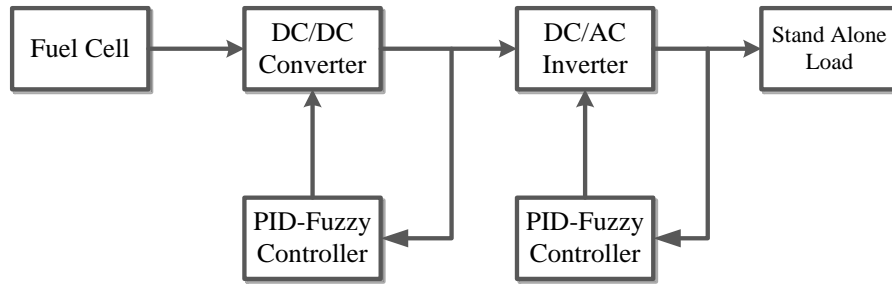


Figure 3. Control strategy of DC/DC converter and AC/DC inverter

With fluctuations in load, FC output voltage is unregulated DC voltage. Then the boost converter controls DC voltage and inverter acts as a grid interface. The PCU is shown with control strategies and there are two separate control loops to control the DC/DC converter and inverter DC/AC based on fuzzy PID (Figure 3). Pulse-width modulation technology is used in the boost converter, while sine pulse-width modulation technology is used in inverter.

4. DC/DC Boost Converter and Control Strategy

In the polarization curve can be seen that the increase in current, FC voltage would be reduced, so unregulated terminal voltage cannot be connected directly to the DC bus and cannot make use of inverter DC/AC for stand-alone and residential applications. However, using of fuel cell in the nonlinear region damaged the membrane electrolyte assembly (MEA). Therefore, the fuel cell stack is used at linear work area. Figure 4 shows a closed-loop system of DC/DC boost converter.

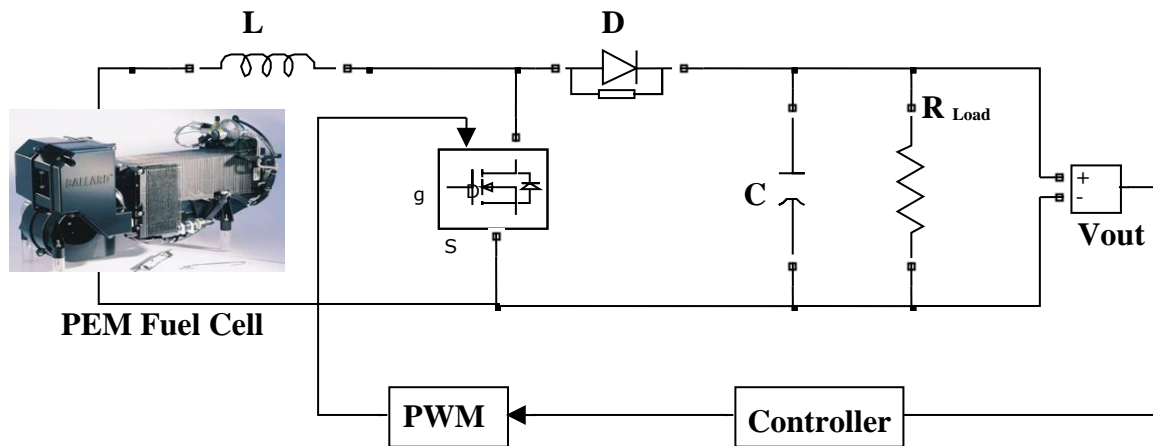


Figure 4. Structure of the DC/DC boost converter with feedback

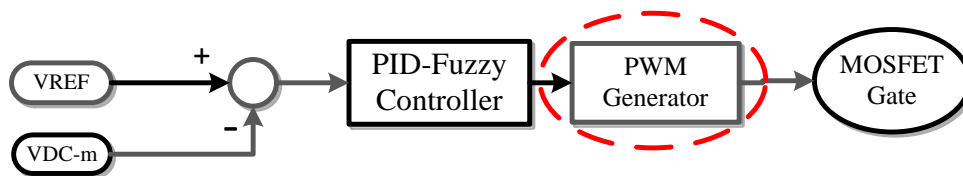


Figure 5. Block diagram of the boost control loop

Output voltage of the boost converter with DC reference voltage is compared, and the error signal and change in error are generated. Error and change in error are fed as input to Fuzzy logic PID controller. FPID based on the inputs, and the rules base in fuzzy interface engine generated control signal. FPID will change duty ratio value to achieve the desired voltage at the output of DC/DC converter. Changing of the duty ratio is changed pulse width modulation (PWM) that pulses fed to the switch in the DC/DC converter circuit. Figure 5 shows a control loop block diagram of the boost converter.

5. Single-Phase Inverter DC/AC and Control Strategy

The purpose of using the inverter is the production a sinusoidal output voltage, stable and smooth waveform regardless of the type of load. The main key to achieve this require is the use of control feedback [18]. The circuit diagram of the single phase inverter is shown in Figure 6.

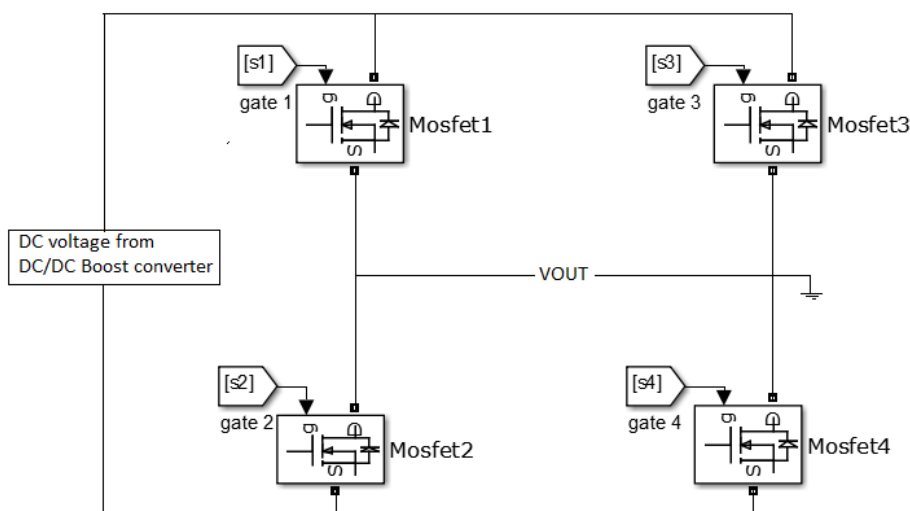


Figure 6. The circuit diagram of single phase inverter

Single phase full bridge inverter consists of two arms as shown in Figure 6, which consists of four switching elements (S1, S2, S3, S4) with four diodes anti-parallel (D1, D2, D3, D4). When two of the switches S1 and S4 are switched on, the output voltage same as DC bus voltage is +Vdc and Similarly, other two switches S2 and S3 are switched on, the output voltage is -Vdc. The output voltage of the DC/DC converter is filtered and is given to the inverter to produce an output (voltage/current) AC for connecting to a stand-alone load.

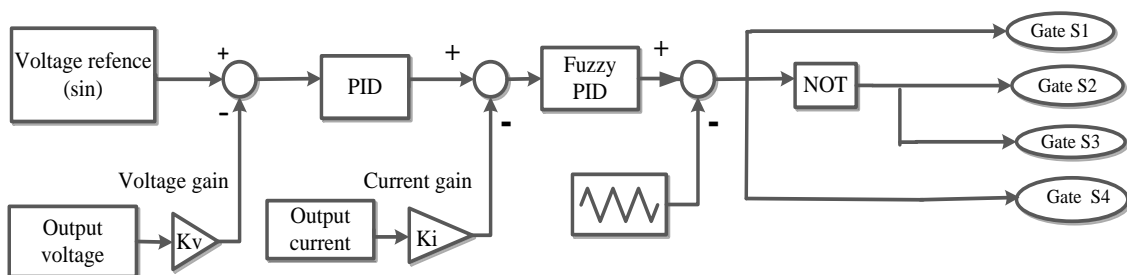


Figure 7. Control diagram of single phase inverter

Figure 7 shows the control diagram for single phase inverter. The inverter has two control loop, the inner loop (current) and outer loop (voltage) which both are controlled by a separate controller. At first, the feedback signal of is compared with a reference voltage signal, and the generated error signal is the input of conventional PID. Then, the control signal obtained from the conventional PID is compared with the feedback output current and is used as the input of fuzzy PID. Finally, generated control signal is compared by a saw tooth wave and PWM signal is generated. Produced PWM signal is sent to the inverter switches.

6. Fuzzy Logic Control

Using fuzzy logic for solving the practical problems which cannot properly be resolved by the techniques of classical control is the main issue for the theory of fuzzy logic. Fuzzy controller does not need the accurate mathematical model of the controlled objects; it is based upon the control decision table to decide the size of the amount of control [19]. In order to solve the problems that brought about through load-mutation and nonlinear loads, the combination of conventional PID control and advanced control strategies is an effective solution for solving above problems. The aim of combining the conventional PID controller with fuzzy controller is to produce fuzzy self-tuning PID controller. Fuzzy controller relates its output to the input through the use of IF-THEN rules. IF part, determines the certain conditions. The THEN part, determines the values to the output variable to achieve optimum output for controller [19, 20]. In this paper, the fuzzy PID is designed for either the inverter and for a boost DC/DC converter. Figure 8 illustrates the diagram of the fuzzy controller. The fuzzy controller has two inputs such as $e(t)$, $\dot{e}(t)$ and three outputs. PID coefficients are K_p , K_i and K_d .

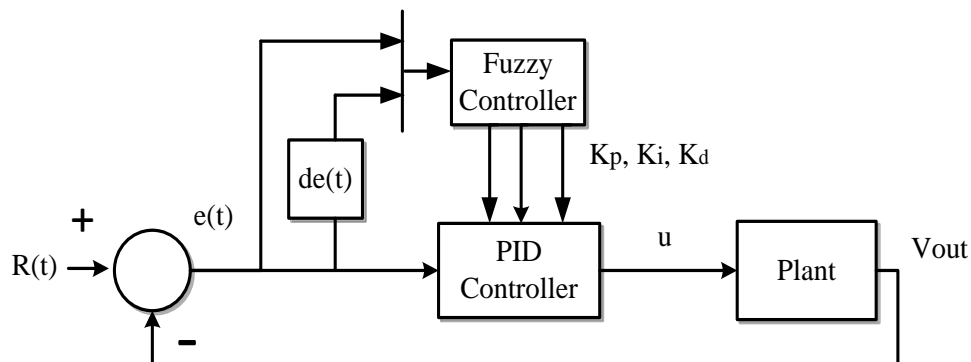


Figure 8. Diagram of fuzzy PID control

6.1. Design of FPID Controller for the Inverter

The conventional two input variables of fuzzy PID, namely the error $e(t)$ and, the change of error $\dot{e}(t)$ and three outputs K_p , K_i and K_d . These inputs produce optimal control signal based on fuzzy rules to control the output of the inverter DC/AC.

Input fuzzy variables based on linguistic are expressed as follows: NB (Negative Big), NM (Negative Medium), NS (Negative Small), ZE (Zero), PS (Positive Small), PM (Positive Medium) and PB (Positive Big).

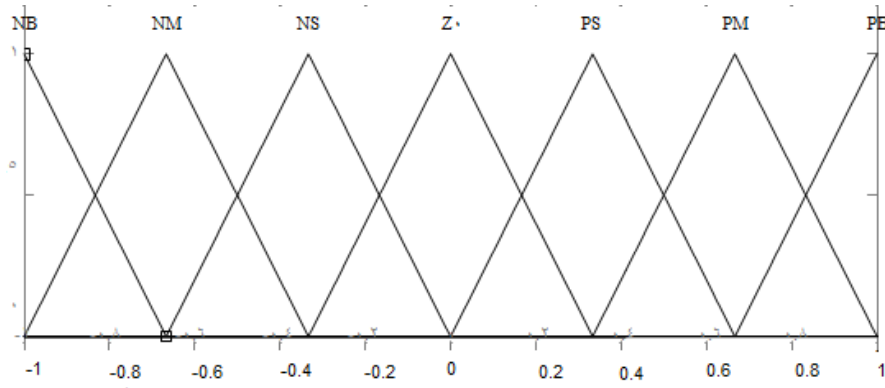


Figure 9. Fuzzy membership function of $e(t)$

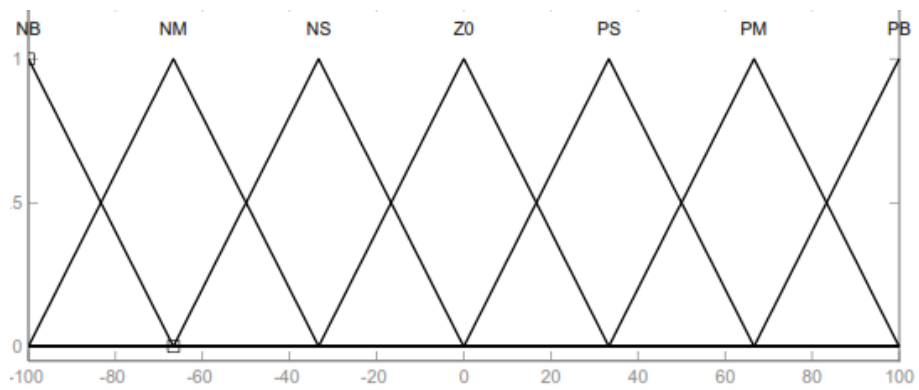


Figure 10. Fuzzy membership function of $\dot{e}(t)$

The input membership functions are shown in Figures 9 and 10. The output fuzzy variables are expressed as follows:

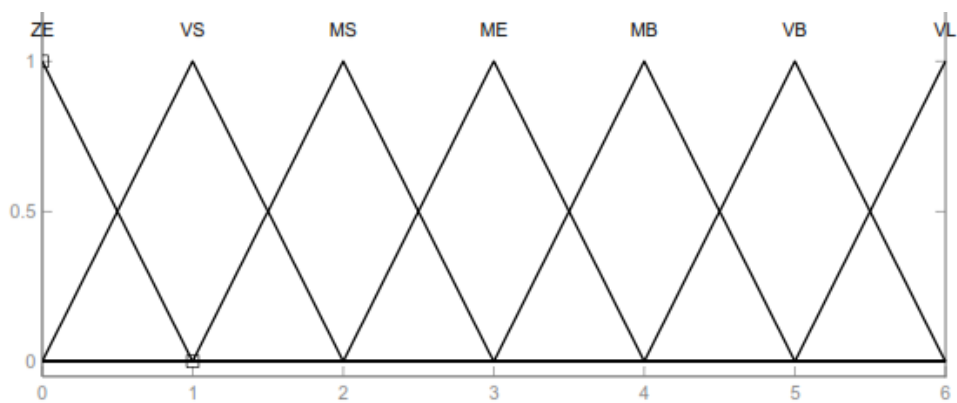


Figure 11. Fuzzy membership function of K_p

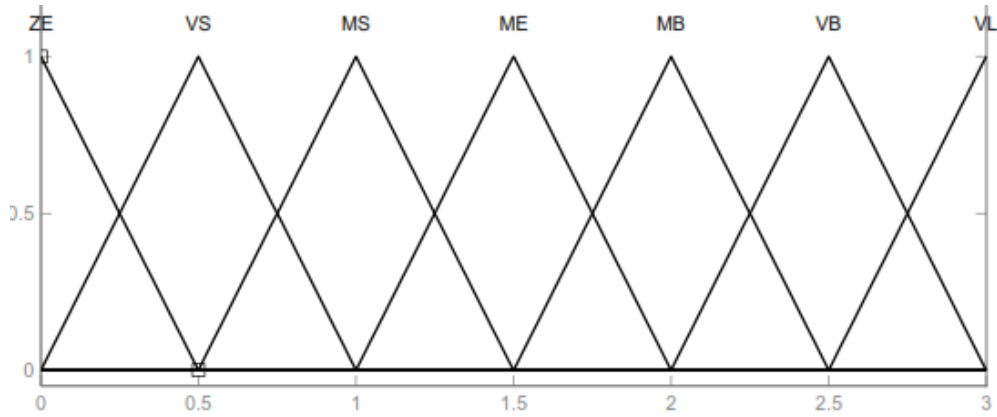


Figure 12. Fuzzy membership function of K_i and K_d

ZE (Zero), VS (Very Small), MS (Medium Small), ME (Medium), MB (Medium Big), VB (Very Big) and VL (Very Large). The output membership functions are shown in Figures 11 and 12.

Fuzzy rules for the form of "If ... Then" stated that a total of $7 \times 7 = 49$ rule base was available for each output. Rule base tables based on experience and trial-and-error test are obtained at Table 3, Table 4 and Table 5. For example: One of the rules in Table 3 is as follows:

If " $E = NB$ and $EC = PB$ Then $K_p = ME$ ".

This statement indicates that the error (E) is negative big, and change of error (EC) is positive big. In this instance, the error changes are a major and the error decreases rapidly. Thus K_p output is medium.

6.2. Design of Fuzzy PID Controller for Boost Converter

Design of the fuzzy controller for the boost DC/DC converter is similar in terms of rule base and membership function. However, the inputs ranges are different together but the outputs ranges are similar to inverter and do not change such as:

$$e(t) = \{-100, 100\}, \quad \dot{e}(t) = \{-100, 100\}$$

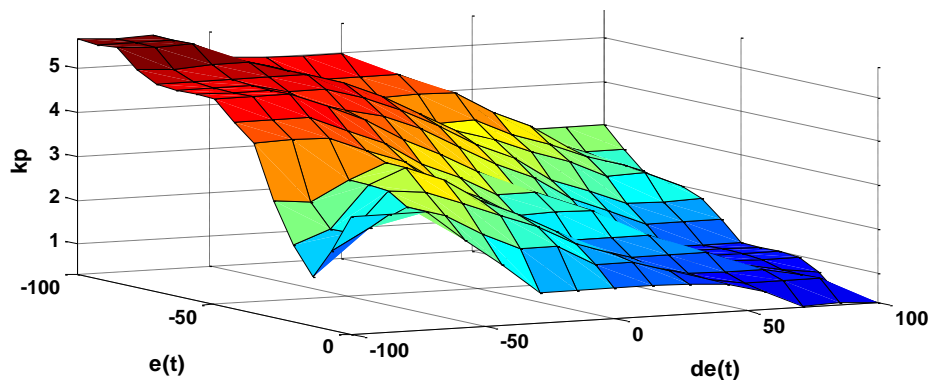
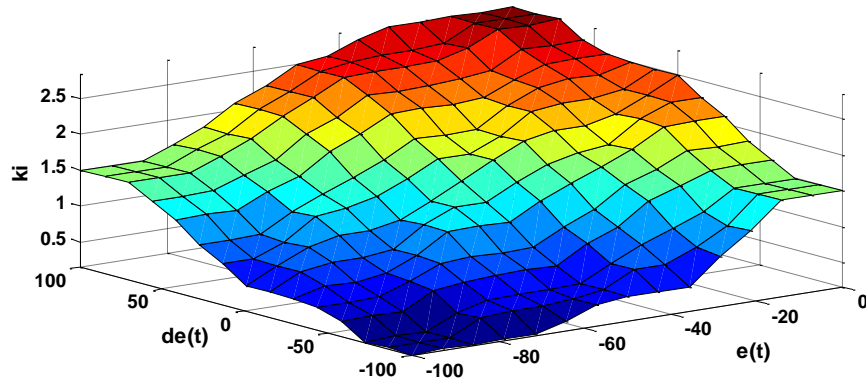
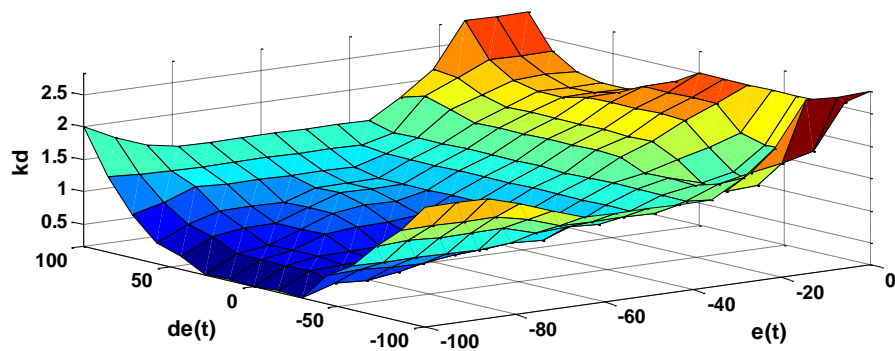


Figure 13. Fuzzy surface for K_p

Figure 14. Fuzzy surface for K_i Figure 15. Fuzzy control surface for K_d

The overall levels of an output system (K_p , K_i and K_d) that based on the inputs ($\dot{e}(t)$, $e(t)$) systems are shown in Figures 13, 14 and 15. In this project, the system has two inputs and surface plot for each of the outputs is three-dimensional. Axis x, y for the two input and axis z for output.

7. Simulation

For the validation of the PEMFC model, were prepared and tested Nexa™ Power Module MAN5100078 by Ballard Power Systems at 80°C [21]. Figure 16 displays the validation of PEMFC model using experimental data obtained for Nexa™ Power Module. The rated net power of Nexa™ Power Module is 1200 W with DC voltage range of 22-50 VDC and rated current 46 A. It can clearly be seen that the developed model performs similar response characteristics with the experimental studies. Figure 16 represents experimental and simulated data for cell temperature 80°C at ambient pressure. Moreover, it can clearly be seen from Figure 16 that the developed model performs similar results compared to experimental studies under different operating conditions.

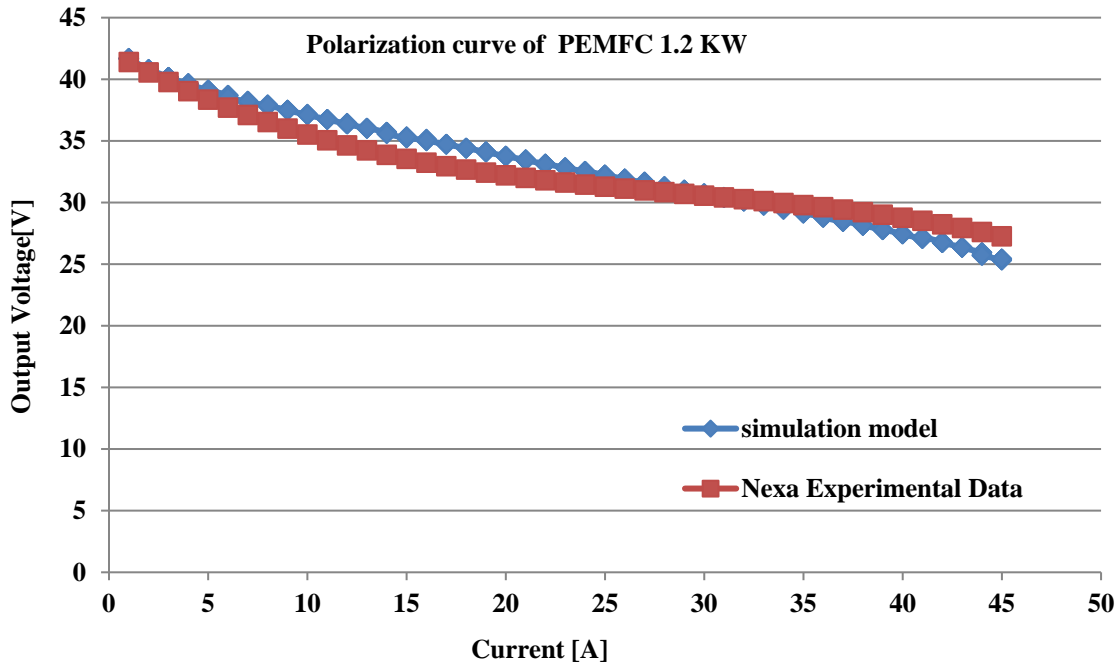


Figure 16. Experimental validation of PEMFC model under different current

7.1. Simulation of Fuzzy PID Control for Single-Phase Inverter

To simulate the inverter with a fuzzy PID, in the inner loop instead of the conventional PID, fuzzy PID is used. Figure 17 shows subsystem of fuzzy PID controller. In this simulation, a fixed amount of proportional gain or (P) equals 0.34 and integral gain (I) is 70.

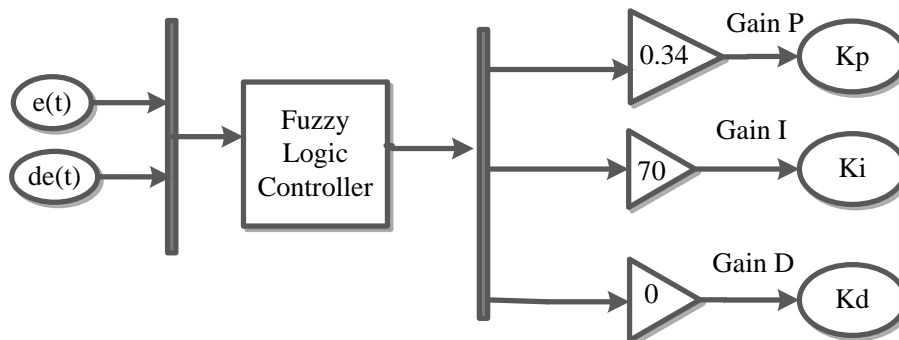


Figure 17. Subsystem of fuzzy PID controller

Output figure of fuzzy PID inverter is the sine wave in the interval $[-100,100]$ and is shown in Figure 18. The errors in inner loop and outer loop are shown in Figures 19, 20. Furthermore, the close-loop step response of FPID and PID controller for single-phase inverter is shown in Figure 21.

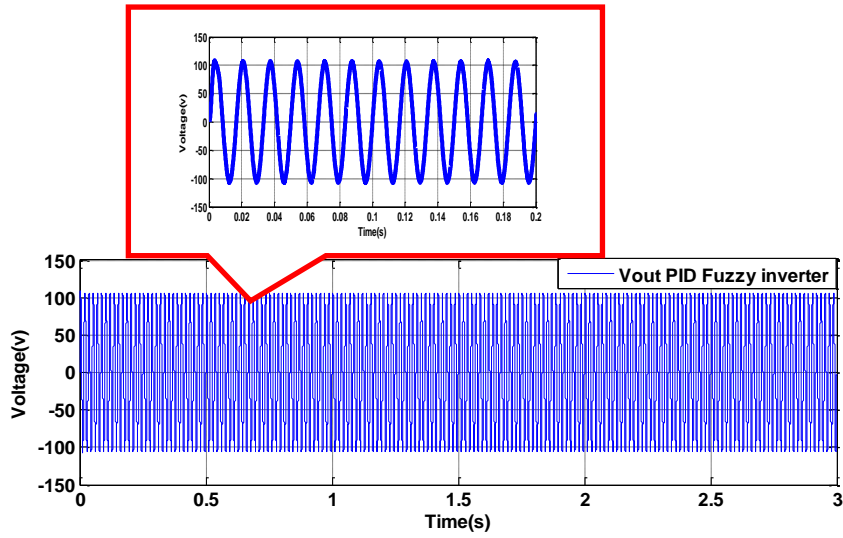


Figure 18. Output signal of inverter with fuzzy PID

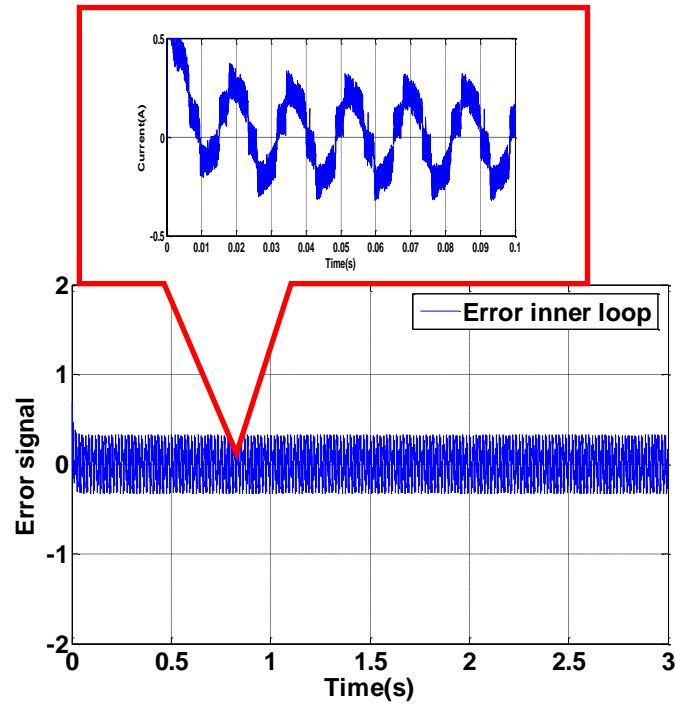


Figure 19. Error signal for inner loop in inverter with fuzzy PID

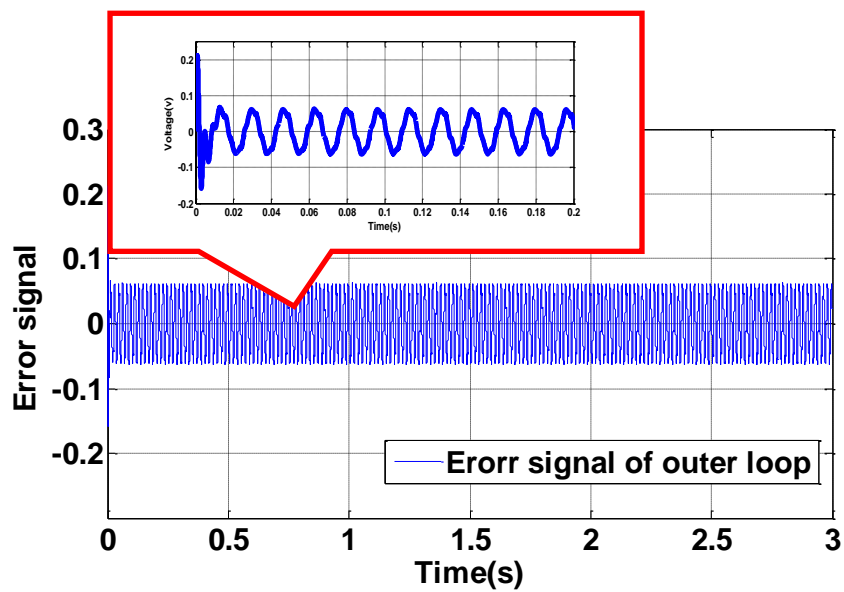


Figure 20. Error signal for outer loop in inverter with fuzzy PID

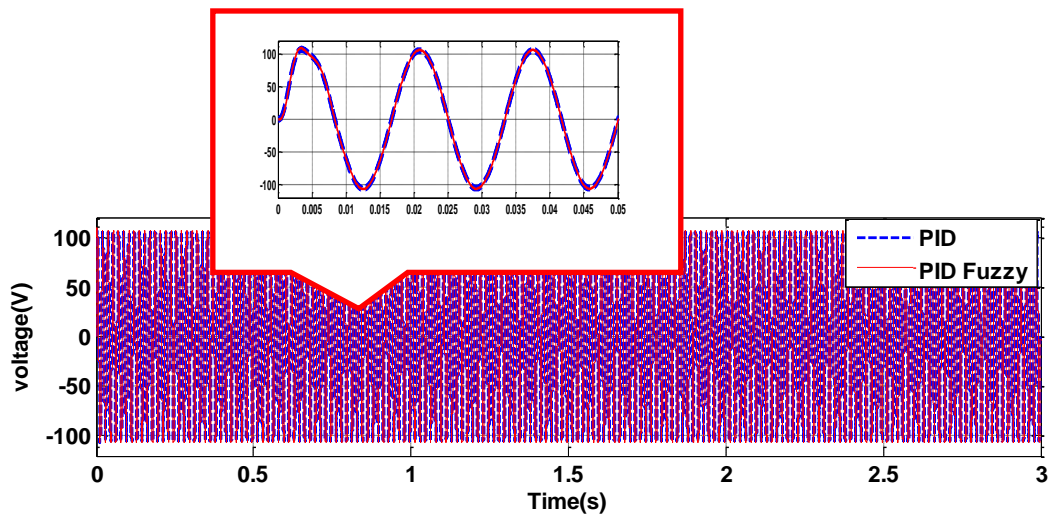


Figure 21. Close-loop response of FPID and PID controller for inverter

7.2. Simulation of DC/DC Boost Converter with Fuzzy PID

According to Figure 4, a fuel cell system (150V DC) is used as the main input source and the boost converter is used to increase the DC voltage level to 215V DC. The DC/DC boost converter and a control system based on FPID according to the output voltage and the desired voltage (150 V DC) is used.

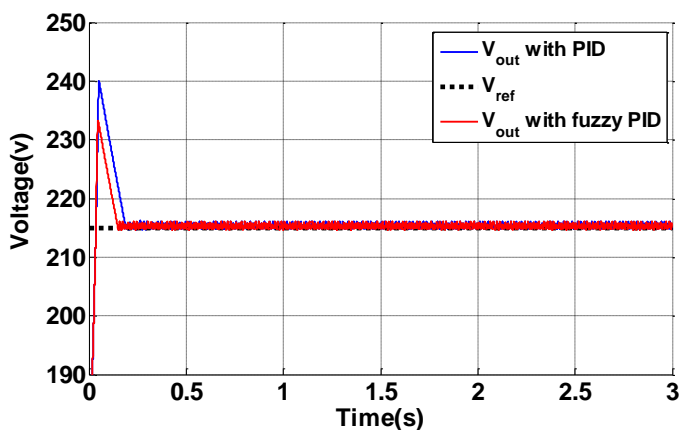


Figure 22. Close-loop step response of FPID and PID controller of boost converter

The simulation block diagram is similar to Figure 17. However, a P gain is 0.001 and constant value of I is equal to 10^{-5} . The close-loop step response of FPID and PID controller for boost converter is shown in Figure 22. Tracking output to the reference value is approximately 0.23 second. In fact, the fuzzy PID simulation output has reached earlier the desired value and tracking has done faster.

7.3. The Effect of the Controller in Wide Range of the Load Variation

The effect on the controller against a wide range of the load variation as an external disturbance is investigated using the proposed controller. During simulation, the load is changed from 5Ω to 3Ω in first second. Figures of 23- 25 are depicted, simulation results of load variations. When a load is reduced, the output voltage at the boost converter with changing the duty cycle is established. Figure 23 shows the inverter output voltage than by changing the resistance load from 5Ω to 3Ω , also the output is the sine with amplitude $[-100, 100]$. Figure 24 shows the inverter output current. Figure 25 shows the output voltage of the boost converter that by the changing load, still voltage output tracks the 155 V in first second, but the tracking has a little fluctuation because the severe current of load.

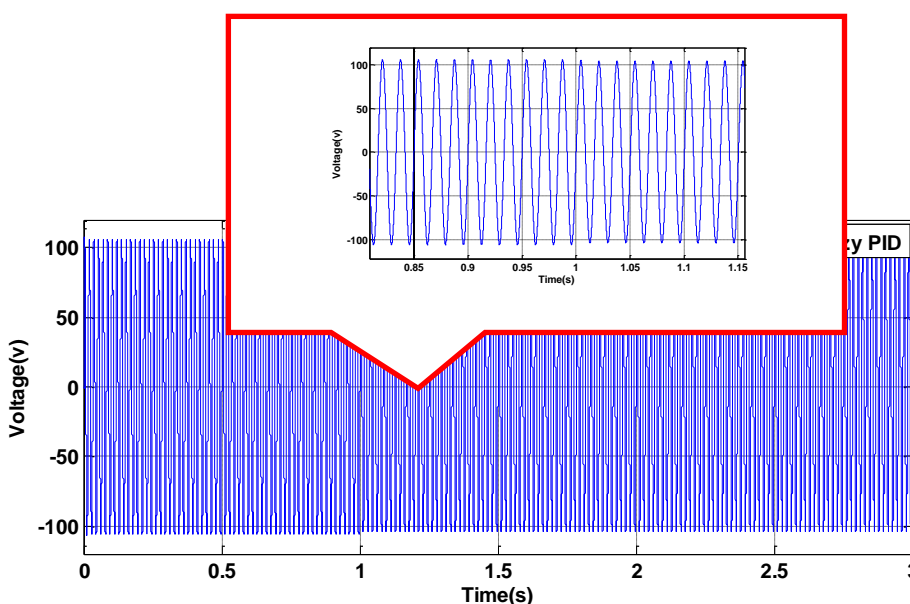


Figure 23. Inverter output voltage with the changing load from 5Ω to 3Ω

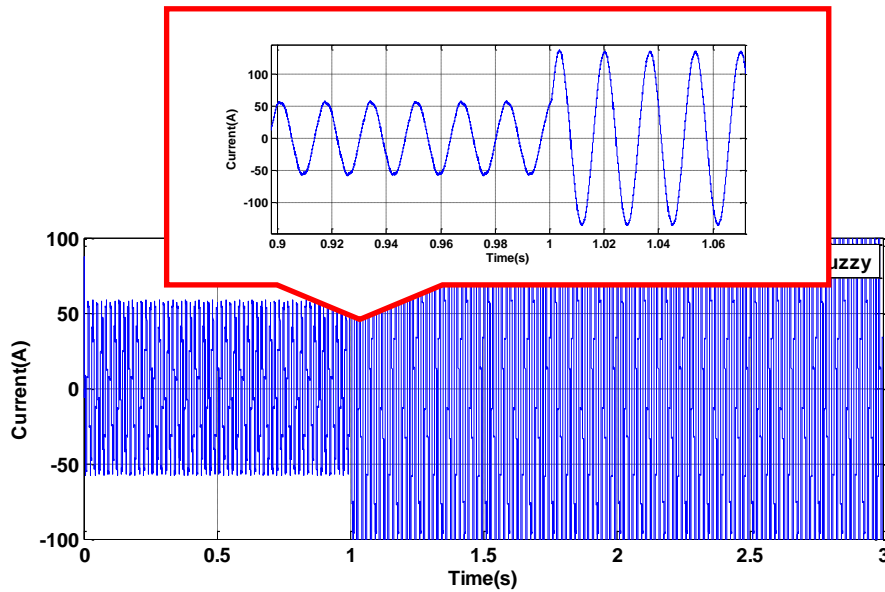


Figure 24. Inverter output current with the changing load from 5 Ω to 3 Ω

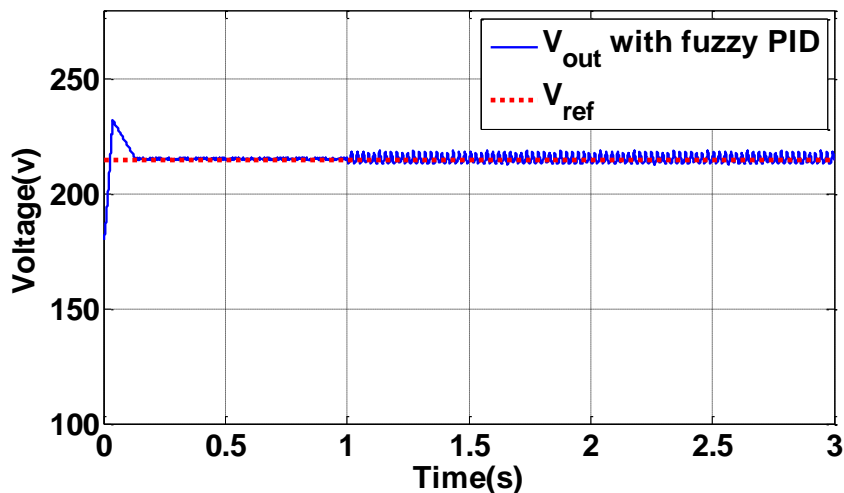


Figure 25. Voltage boost output with changing load to 3 Ω

8. Conclusion

This paper introduces a stand-alone system based on PEMFC and fuzzy logic PID is used to control PCU. due to, the output voltage of the fuel cell system has a voltage variation in response to the load fluctuations and the fuel cell produces an unregulated voltage due to its internal dynamics. A DC/DC boost converter is used to regulate the output voltage of PEMFC. By controlling the duty ratio, regulated voltage at output DC/DC converter is achieved. The fuzzy logic based-proportional-integral-derivative is used to design the controllers of DC/DC and DC/AC. Without trial and error as in the conventional PID controller design, PID coefficients of the FLPID controller are automatically and simultaneously tuned by a fuzzy controller. The proposed integrated fuzzy PID controller automatically adjusts the coefficients K_p , K_i and

K_d with any changes of load. The FPID is a nonlinear controller and overcome inherent disadvantages such as parameter uncertainty, disturbances and uncontrollable large overshoot.

A single-phase sinusoidal inverter for fuel cell system is proposed. The cascade structure is proposed of inductor current as the inner loop and output voltage as the outer feedback loop. The simulation results show that a proper SPWM control switching with the fuzzy PID controller has been generated to control the inverter MOSFETs. This proves that the fuzzy PID controller demonstrates very good efficiency and offers robustness characteristics in tracking the output voltage at the desired value. However, further studies are promising to confirm the applicability of the results to the practical implementation, a hardware control.

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