

Performance comparison of PEMFC hydrogen reformer with different controllers

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Abstract

The renewable energy technology has become very popular due to major constraint in the existing electrical system such as high electricity demand, increased in fuel prices and concern of environmental pollution. The aims of this project are to develop a complete Proton Exchange Membrane Fuel Cell (PEMFC) model with hydrogen reformer by using MATLAB/Simulink with three different controllers and comparison between the three controllers will be discussed. This project presents the development of methods to solve the problem of PEMFC output voltage by using different controllers which are Proportional Integral (PI), Proportional Integral Derivatives (PID) and Proportional Integral Fuzzy (PI-Fuzzy) controllers. The Ziegler Nicholas tuning method is used to tune PI and PID gains in a Simulink model. It helps the system to achieve a balance between performance and robustness for both controllers. The Mamdani type was used to develop the fuzzy controller in Simulink model. The transient performances that will be discussed are rise time, settling time, maximum overshoot, and percentage of overshoot. The results show that the proposed PI-Fuzzy is better than the conventionally used PI and PID controllers.

Keywords: controller, fuel cell, fuzzy, PEMFC, reformer

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1. Introduction

Renewable energy plays an important roles in reducing environmental problems such as pollutions, greenhouse gas emissions and also decreasing the consumptions of fossil fuels. Fuel cell (FC) is an example of renewable energy technology for power generation that promise clean and sustainable productions of electrical energy. Fuel cell generates electricity by converting chemical energy stored inside the cell directly into electrical energy. Fuel cells eliminate pollution caused by burning fossil fuels because the end products are only electricity and water. If the hydrogen used as inputs comes from the electrolysis of water, then by using fuel cells as electricity source can eliminates greenhouse gases. Since hydrogen can be produced anywhere where there is water and electricity, production of potential fuel can be distributed. Installation of smaller stationary fuel cells leads to a more stabilized and decentralized power grid. Fuel cells have a higher efficiency than diesel or gas engines and most fuel cells operate silently with no moving parts [1], compared to internal combustion engines. There are 4 types of fuel cells in development, which are Phosphoric Acid Fuel Cell (PAFC), Proton Exchange Membrane Fuel Cell (PEMFC), Molten Carbonate Fuel Cell (MCFC) and Solid Oxide Fuel Cell (SOFC) [2]. However, PEMFC is one of the most promising FC with low operation temperature. The Hydrogen gases (H_2) and oxygen from air are needed as an input to PEMFC. The hydrogen gas can be produced from the natural gas such as methanol and ethanol using reformer [3] and also from the electrolysis process. In reformer, a controller is needed to control the hydrogen and also the oxygen gases flow rates before entering the PEMFC stack. PEMFC output voltage is usually takes several periods of time to reach a steady-state level [4] due to the internal reaction inside PEMFC and also due to sluggish performance in hydrogen reformer.

A proper control in reformer will minimize the time taken for the voltage to reach the steady-state condition. Because of that, the PI, PID and PI-Fuzzy controller are used to counter the problems. However, the controller's limitation needs to be considered. For PI

controller, the speed of response will not increase and unable to predict the error in future [5]. Research in [6, 7] show that by implementing PI controller for PEMFC reformer, it will resulted in slow response of the output voltage. For PID controller, when used alone, can give poor performance and the PID loop gains must be reduced so that the control system does not overshoot, oscillate or hunt about the control set point value [8]. In [9], optimal PID controller is used in controlling the fuel flows for PEMFC, however, the slow response at every changes of load current still be the main problem at the hydrogen and oxygen pressures inside the fuel cell. Due to that reason, researchers in [10, 11] develop a reformer controlled by fuzzy controller. However, results show that the FC system takes a little bit of time to reach load demand level and this delay in load following is mainly caused by the reformer due to gas processing response inside the reformer. The slow response problem can be solved by implementing intelligent controller which is the PI-Fuzzy controller to automatically fine-tune the parameters of a conventional PI controller. PI-Fuzzy controller can improve the V-I performance, maintain a constant output voltage and error become small in order to avoid the difficulty caused by that a large number of variables affect the performance of the PEMFC system [12]. This project will compare three different types of controllers used in reformer which are the PI, PID and also PI-Fuzzy in order to get the best output voltage performances of the PEMFC.

2. Research Methodology

2.1. Proton Exchange Membrane Fuel Cell (PEMFC) Modelling

The losses in the fuel cells are identified with the influence output power. In the event that more present is drawn from a cell, the losses will increment. The genuine output voltage of an energy component is decreased by different over voltage losses, to be specific, namely, activation losses due to reaction kinetics (V_{act}), ohmic losses from ionic and electronic resistance (V_{ohm}) and concentration losses due to mass transport (V_{con}). The output voltage of a cell can be characterized as [4, 13]:

$$V_{fuelcell} = V_{nernst} - V_{act} - V_{ohm} - V_{con} \quad (1)$$

the output cell voltage is given by [3]:

$$V_{out} = N_0(E - V_{act} - V_C - V_{ohm}) \quad (2)$$

where, the V_{out} is the output fuel cell voltage, E is the Nernst equation, V_{act} is the activation loss, V_C is the voltage across C (double-layer charge effect), V_{ohm} is the ohm loss and N_0 is the number of cells. The corresponding Nernst given by [8]:

$$E = (1.229 + 0.0085(T - 298.15)) + 4.31 \times 10^{-5} \left[\frac{P_{H_2} \sqrt{P_{O_2}}}{P_{H_2O}} \right] \quad (3)$$

where, P_{H_2} is the partial pressure of hydrogen, P_{O_2} is the partial pressure of oxygen and P_{H_2O} is the partial pressure of water. The fuel cells output voltage is reduced by various over voltage losses, namely, activation losses due to reaction kinetics (V_{act}), ohmic losses from ionic and electronic resistance (V_{ohm}) and concentration losses due to mass transport (V_{conc}). The concentration loss is not considered because the equivalent concentration resistance, R_{conc} is included in the V_C equation as show in (4) [6]:

$$V_C = I - C \frac{dV_C}{dt} (R_{act} + R_{conc}) \quad (4)$$

the concentration resistance can be explain as (5) [6]:

$$R_{conc} = -\frac{RT}{zFI} \ln \left(1 - \frac{I}{I_{limit}} \right) \quad (5)$$

where F is the Faraday constant (96487C), R is the universal constant for gas (8.314 J/Kmol), T is the the operational temperature (343.15K), z is the number of participating electrons and 2 electrons are developed from the hydrogen reaction at the anode in this reaction. C represents the capacitance of double layer charge effect with the value of 4.8F. The activation

loss is brought about by the gradualness of the responses occurring on the surfaces of the anodes and can be communicated by [6],

$$V_{act} = \eta_o + (T - 298)a \quad (6)$$

where, η_o is the empirical constant with 0.4197V and a is the empirical constants with -0.1373 (V/K). The ohmic loss is the voltage drop because of the imperviousness to the stream of electrons through cathodes furthermore the imperviousness to the proton move through electrolytes. The Losses of the fuel cell are consistent in this area and can be depicted by [9]:

$$V_{ohm} = IR_{ohm} \quad (7)$$

R_{ohm} is the equivalent ohmic resistance measured in $\Omega \cdot \text{cm}^2$ [14] and as a function of current and the temperature expressing by [6]:

$$R_{ohm} = 0.01605 - 3.5 \times 10^{-5}T + 8 \times 10^{-5}I \quad (8)$$

Fuel cells need oxygen and hydrogen gases to create electricity. Oxygen needed for fuel cells acquired from the air, which are entered to the cathode. Hydrogen gas is not readily available because it needs to be processed prior to obtain pure hydrogen gas. However, this problem can be solved by using a device called a hydrogen reformer unit. Unfortunately, the efficiency of fuel cells will also be reduced when connected to high load. The hydrogen reformer unit model [6, 9] is built and shown in Figure 1 together with the PEMFC model by consuming (1)-(8) by using MATLAB/Simulink software. Figure 1 shows that reformer will convert fuel which is methane directly into hydrogen and by product gases. The controllers of PI, PID and PI-Fuzzy are used to control the flow rate of methane in the hydrogen reformer unit with appropriate controller including proportional gain (K_p), integral gain (K_i), and differential gain (K_d). From Figure 1, it can be seen that the outputs of the reformer are hydrogen flow rate and also the oxygen flow rate that will be fed into fuel cell model.

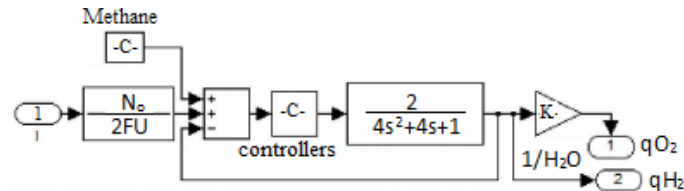


Figure 1. Hydrogen reformer modelling using MATLAB/simulation software [6, 9]

2.2. Ziegler Nichols Tuning Method

Ziegler Nichols is one of the simplest tuning methods for PI and PID controller which promise good results with simple techniques. The purpose of this method is to calculate the value of K_p , K_i and K_d to achieve the best control performances [15-17]. Ziegler and Nichols derived the control parameters based on Figure 2 and from the figure, the parameters of L and T are obtained from the response curve of hydrogen reformer in open loop systems.

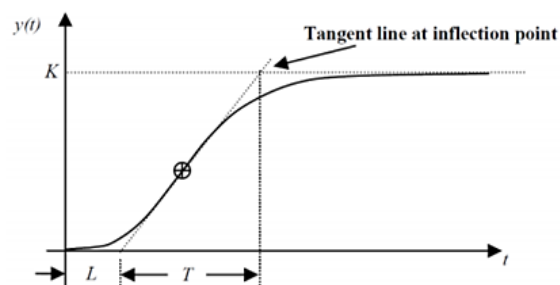


Figure 2. Response curve for ziegler-nichols method [15, 17, 18]

The calculation of K_I and K_D can be described by [15]:

$$K_I = K_P / T_i \tag{9}$$

$$K_D = K_P \times T_d \tag{10}$$

where, the value of K_P , T_i and T_d are obtained shown in Table 1 and the calculated values of parameters for K_P , K_i and K_d for PI and PID controllers for this project are tabulated shown in Table 2.

Table 1. Ziegler-Nichols Tuning First Method

	K_P	T_i	T_d
P	T/L	0	0
PI	0.9 T/L	L/0.3	0
PID	1.2 T/L	2L	0.5L

Table 2. Values of Parameters for K_P , K_i and K_d for PI and PID Controllers

Controller types	K_P	K_I	K_D
PI	9-10	0.6-0.8	-
PID	8-10	0.7-0.8	4-5

2.3. PI-Fuzzy Controller

PI-Fuzzy controller is essentially a rule based controller whose input is obtained from the feedback loop [19] and it has the advantages of conventional PI controller [20]. For PI controller, the control performance depends on the PI gains sensitivity but in case of PI-Fuzzy controller, it operates independently with each other in a control system. In Fuzzy Logic Controller modelling, fuzzification, membership function, rule base, fuzzy inference and defuzzification processes are important [21, 22]. The modelling of PI-Fuzzy controller is shown in Figure 3 to replace the conventional PI and PID controllers where the appropriate membership functions are chosen to cover the whole universe of discourse. Next, the algorithm is implemented in MATLAB with the use of three Member fuzzy inference system which are Mamdani-type with two inputs and one output parameter. The fuzzy logic based controller input signals are the error and also change of error. These signals are control by linguistic variables in this investigation. For the system, three membership functions have been chosen for both inputs (i.e ZE: zero, S: small, B: big), while for the output, five membership functions have been chosen (i.e. ZE: zero, S: small, M: medium, B: big, VB: very big). The interval [0, 1] is considered as the universe of discourse for the two inputs, while for the output the [0, 1] interval is used. Once the input and output variables and MF have been defined, the rule based will be designed according to the decision matrix shown in Table 3. Fuzzy systems based on fuzzy if-then rules is used as approximators due its capability as universal approximators of nonlinear functions [23, 24].

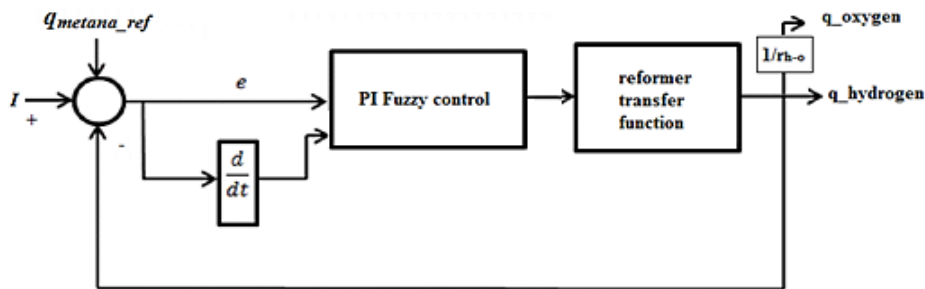


Figure 3. Hydrogen reformer model using PI-Fuzzy controller

Table 3. The Table of Inference Rules

	ZE	S	B
ZE	ZE	ZE	M
S	ZE	S	B
B	M	B	VB

3. Results and Analysis

Figure 4 shows the comparison between the PI, PID and PI-Fuzzy controller used in order to control the molar flows of the gases which will be fed to the PEMFC stack. From the graph, we can see that the hydrogen flow rate shows better performance with PID controller compared to PI, the use of which can overcome the oscillation problem which occurs during the starting point of the simulation [9-11, 25]. By increasing the derivative value, the oscillation at the beginning of the curve will be reduced. However, by implementing PI-Fuzzy controller, no overshoot and delay occurs in the graph and it reaches the steady state condition abruptly. From the result, it shows that PI-Fuzzy controller can counter the problems face by both conventional controllers with no overshoot and no oscillation with a higher hydrogen gas output. Figure 5 shows the output flow rate of oxygen gas produces by the hydrogen reformer using PI, PID and PI-Fuzzy controllers. The graphs shown in Figure 5 have the same behavior as the hydrogen gas with the oscillation problems during the earlier part of the simulation. From the result, PI-Fuzzy controller can counter the problems similar to the hydrogen flow rate output discussed earlier.

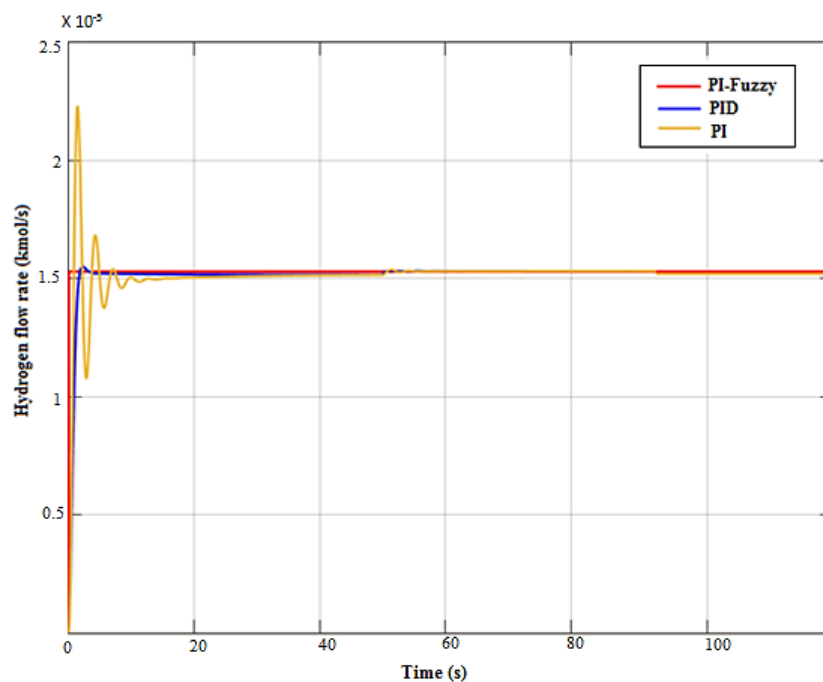


Figure 4. Result of hydrogen gas flow rate output in reformer using PI, PID and PI-Fuzzy controllers

The result of time response from oxygen gas output curve between the three controllers are tabulated as shown in Table 4. It can be seen that the settling time and percentage of overshoot for PID controller are lower than the PI controller. However, by implementing PI-Fuzzy, all the time responses are all zeros with the percentage of overshoot is also zero. The output voltage of the PEMFC is shown in Figure 6. From the graph, the starting voltage by using PI controller is quite faster than the control method using PID. The starting time by implementing PI controller is 1.377s and 2.089s by using the PID. However, by controlling the reformer using the PI-Fuzzy controller, it can reduce the starting time of PEMFC output voltage to 0.438s as shown in Figure 6. The starting time is important to ensure the load received required power instantly. The final analysis is the simulation results on PEMFC output performances subjected to load changes.

The simulation results of the input current and output voltage are shown in Figure 7 (a) and Figure 7 (b), respectively. Figure 7 (a) shows the load current supplied to the fuel cell in which the current varies with the load demand and Figure 7 (b) is the output PEMFC voltage

which depends on the supplied current. From Figure 7 (b), the graph shows that the output voltage is inversely proportional to the input current and this result is in line with the fuel cell characteristic in which the output cell voltage decreases linearly with increasing load. It is noted that the fuel cell takes several time intervals to reach the load demand or the steady state level but by implementing the PI-fuzzy controller, the start-up time is improved. Besides that, the output voltage of PEMFC by using PI-Fuzzy is also higher than the two conventional controllers which are the PI and PID.

Table 4. The result of Time Response from Output Oxygen Gas Curve Between PI, PID and PI-Fuzzy Controller

	PI	PID	PI-Fuzzy
Delay Time (Td)	0.8s	1s	0s
Rise Time (Tr)	1s	1.9s	0s
Settling Time (Ts)	3.5s	1.5s	0s
Peak Time (Tp)	1.9s	2.5s	0s
Percentage of Overshoot (%)	40.7%	3.7%	0%

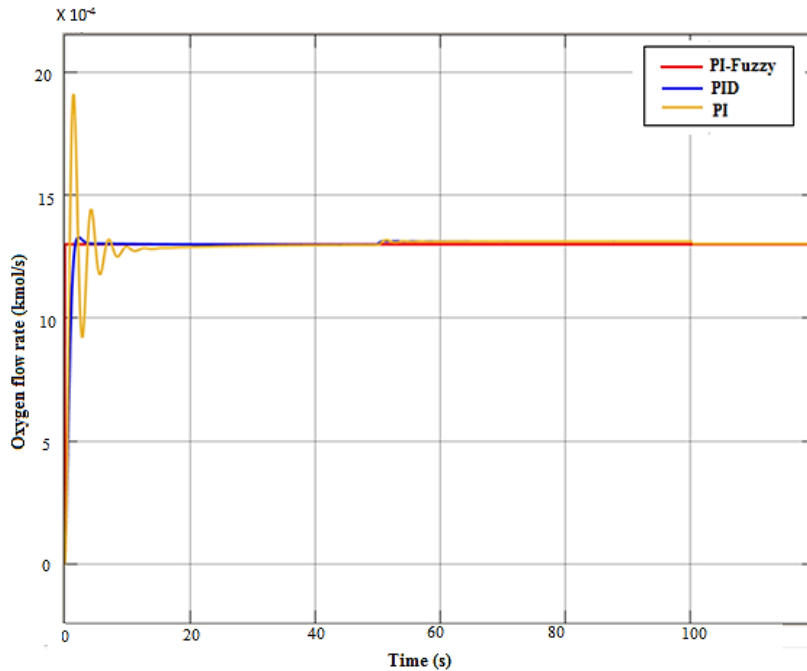


Figure 5. Result of the flow rate output of oxygen gas in reformer using PI, PID and PI-Fuzzy controllers

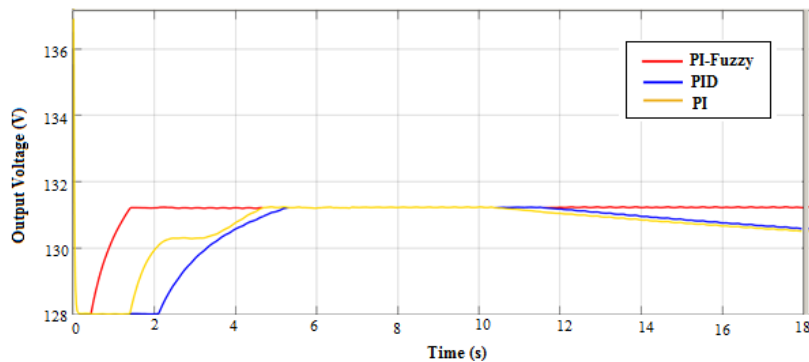


Figure 6. Result of output voltage of PEMFC using PI, PID and PI-Fuzzy controller

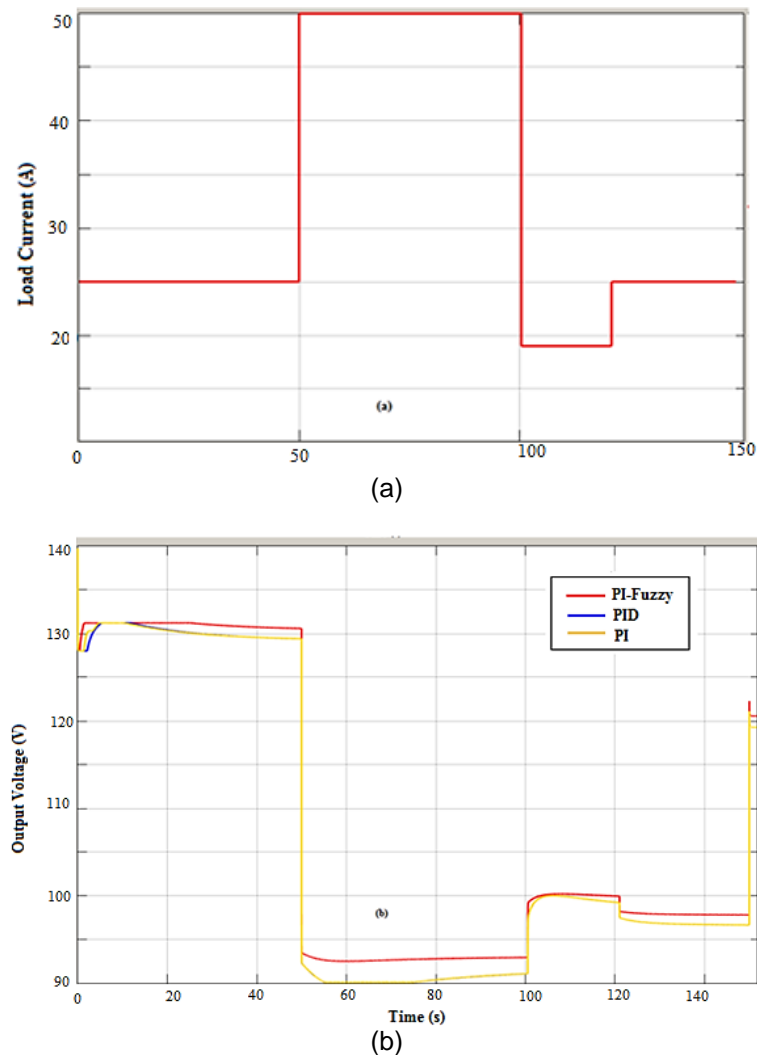


Figure 7. Simulation results (a) load current and (b) fuel cell output voltage

4. Conclusion

This paper compares three types of controllers to control the oxygen and hydrogen flow rates of a reformer before entering the PEMFC model. The main objective of the controller is to reduce the oscillations problem of the hydrogen and oxygen flow rates and thus decreasing the slow start-up time of the FC. From the simulation results, it can be seen that PEMFC outputs meet the fuel cell characteristics in which the output voltage is inversely proportional to the input current. The PEM fuel cell model is considered accurate as it fulfills the load requirement. However, it needs some time to reach the steady state level because it is unable to follow the fast changes in power demand at the starting of the FC operation. However, this main problem is solved by introducing PI-Fuzzy controller in reformer. From the graphs obtained from simulation, it shows that the PI-Fuzzy controller gives the best performances compared to PI and PID controllers. With the existence of PI-Fuzzy controller, it helps the output voltage of PEMFC to operate earlier which means reducing the slower start-up time of the PEMFC. Besides that, the PI-Fuzzy controller can also eliminates all the problems facing by the PI and PID controllers, which are improving the delay time, rise time, settling time, peak time and percentage of overshoot.

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