A Comparative Study of FF-PID and Fuzzy-PID Control for Anode Pressure Stability in PEM Fuel Cells

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ABSTRACT

The anode hydrogen supply subsystem is one of the fuel cell subsystems responsible for hydrogen supply and for the stability of the anode inlet pressure. This study focuses on the control of the anode hydrogen subsystem in an Open Cathode PEM Fuel Cell (OCPEMFC). The proposed control strategy is PID feedback control with compensation, where the compensation uses two different algorithms, namely empirical equation-based and fuzzy logic. The two different algorithms will be compared to determine which control system performs better. The manipulated variable is the hydrogen supply flow rate through the control valve. Experiments were conducted at a laboratory scale where the OCPEMFC was operated under dynamic load. Some performance indicators used in this paper include the tracking of the hydrogen supply flow rate, as well as the accuracy and stability of the anode inlet pressure under dynamic load. The experimental results prove that FF-PID performs slightly better than Fuzzy-PID, with a very small difference. However, Fuzzy-PID is proven to be more suitable for dynamic load applications that require smooth actuation and stack protection.

Keywords-OCPEMFC; anode hydrogen supply; feedback-feedforward; fuzzy-PID

I. INTRODUCTION

A fuel cell is an electrochemical device that converts chemical energy to electrical energy through electrolytic reaction. The hydrogen supply is one of the subsystems of the fuel cell system that is responsible for regulating the hydrogen supply and its pressure at the anode, which affects the output voltage [1] and hydrogen utilization rate [2]. Hydrogen pressure stability is an important variable in fuel cell systems. Excessive hydrogen anode pressure fluctuations can reduce the hydrogen utilization rate [3] and affect the fuel cell stack's working life [4]. For this reason, an appropriate control strategy is needed to maintain the stability of the anode hydrogen supply pressure or anode inlet pressure, and also ensure that the hydrogen demand or consumption is met.

The hydrogen supply (fuel consumption) determines hydrogen utilization [5] or Hydrogen Excess Ratio (HER). Various system configurations and control strategies have been proposed for the hydrogen supply subsystem. The primary target of these strategies is to increase hydrogen utilization and maintain the stability of the HER at a predetermined value. The configurations for fuel cell system hydrogen supply can be carried out in three modes: flow-through mode, dead-end mode, and recirculation mode [6].

Authors in [7] implemented a feedback structure with a fuzzy logic algorithm to regulate hydrogen pressure in flow-through mode. Hydrogen pressure was regulated by manipulating the hydrogen supply flow rate through the common-rail injector. The results showed that fuzzy logic resulted in smaller fluctuations than PID control. Authors in [8] developed a control scheme for controlling hydrogen pressure deploying the Fuzzy Logic PI Control and Feed-Forward Compensation (FLPIF) method. The latter is used to maintain stability and prevent drops or overshoots in hydrogen pressure caused by disturbance signals in the form of purge activation and load current. The results showed that FLPIF had better performance than PI control and fuzzy logic PI control. However, the gain constant value used in feed-forward compensation must be precisely tuned. Therefore, a testing scheme under different conditions is required to obtain the optimal gain constant value.

Authors in [9] investigated the nonlinear behavior of the hydrogen delivery model. A MIMO Model Predictive Control (MPC) scheme based on feedback linearization in recirculation mode was introduced with the aim of improving control accuracy in managing HER and anode pressure. A similar approach was also employed in [10], regulating HER and anode pressure, using a multivariable controller with nonlinear MPC. The application of control schemes, such as MPC, in fuel cells can show better performance but requires complex mathematical modeling. Controlling the hydrogen supply in fuel cells operating in recirculation mode has been the subject of many previous studies. However, this strategy is generally used in fuel cells with large capacities or above 1kW to increase the efficiency of hydrogen supply consumption. Nevertheless, hydrogen recirculation can lead to a decrease in the purity of the hydrogen supply, which necessitates certain strategies to overcome this issue.

Although the hydrogen supply subsystem has been extensively investigated and has shown much progress, the control strategy of the hydrogen supply subsystem still requires further research. Previous researchers have implemented strategies for controlling hydrogen supply using a feedback control structure, specifically by controlling the anode inlet pressure or HER as the control variable. Feed-forward control has also been implemented, but only as a compensation where precision was required in determining the gain constant value for this compensation.

Therefore, in this study, the proposed control strategy is focused on the anode hydrogen supply subsystem. For the control variable, the proposed control strategy is used to maintain the stability of the anode inlet pressure by manipulating the hydrogen flow rate through the control valve. Specifically, this paper will present a feedback-feed-forward control strategy. In the feedback control structure, PID control is used to ensure the stability of the anode inlet pressure relative to the reference pressure. Meanwhile, the feed-forward control structure is used to handle disturbances, which in this case are the stack current (load). To achieve this objective, the developed feed-forward control algorithm is an estimator algorithm is used to produce an estimation or prediction of the required hydrogen flow rate.

Two different algorithms are proposed in this paper. The first algorithm is an empirical equation obtained from curve fitting the relationship between hydrogen consumption and stack power. The second algorithm is fuzzy logic, which is designed to generate an estimate of the hydrogen flow rate demand based on stack voltage and current. Fuzzy logic was utilized for its ability to process dynamic or nonlinear variables [11], its relatively low computational complexity, and its robustness [12]. Fuzzy logic has been widely used fuel cell energy management systems [13]. This study experimentally tests and compares the performance of two control strategies: FF-PID (PID feedback with empirical equation feed-forward) and Fuzzy-PID (PID feedback with fuzzy logic feed-forward), based on several dynamic performance indicators. Its main contributions are:

- It proposes two different feed-forward designs: (i) a curve-fitting equation between stack power and hydrogen consumption, and (ii) a fuzzy logic-based estimator that utilizes stack voltage and current as an alternative approach with low computational complexity.
- It provides the first experimental evidence comparing both strategies' performance under dynamic load scenarios in a hydrogen supply configuration that uses only a control valve (without a recirculation pump).
- It offers insights into the trade-offs between algorithm complexity, pressure stability, and hydrogen savings, enabling researchers and practitioners to select the optimal approach based on constraints of cost, space, and additional power.

II. SYSTEM DESCRIPTION

In this experiment, the fuel cell used was a commercial OCPEMFC stack from Horizon Fuel Cell Technologies (model H-500) with a capacity of 500W. The manufacturer's system included a controller, but its function was limited to managing fan speed and the purge valve, leaving the hydrogen supply to be regulated by a manual valve. Therefore, in this experiment, a variable valve was installed to regulate the flow rate and pressure of the hydrogen supply. The H-500 fuel cell model specifications are shown in Table I and its characteristic curve is depicted in Figures 1 and 2 [14]. From this characteristic curve, the OCPEMFC operating range can be grouped into three types: small (purple), medium (red), and large (green). Furthermore, it is implied that the greater the load current, the lower the voltage; so, the relationship between these two variables is inversely proportional. Meanwhile, the relationship between hydrogen flow rate and power is directly proportional.

One of the performance indicators investigated in this paper is HER$\left(\lambda_{H_2}\right)$, defined as [15]:

$$\lambda_{H_2} = \frac{Q_{\sup}}{Q_{react}} \tag{1}$$

$$Q_{react} = \frac{NI}{2F} \tag{2}$$

where Q_{sup} is the flow rate hydrogen supply (mol/s), Q_{react} is the hydrogen reaction (mol/s), N is the number of cells, I is the stack current, and F is the Faraday constant.

By referring to the characteristic curves in Figures 1 and 2, and applying (1) and (2), the HER characteristics of the H-500 fuel cell are obtained, as presented in Figure 3, where it is revealed that the HER value drops at a load of 300 W and 500 W. Additionally, some minor HER instability is observed, though its magnitude is relatively small. Since the HER value should ideally be stable at all load levels, the average HER value of the H-500 fuel cell is 1.1. This value will be adopted as a reference for performance analysis in this experiment.

TABLE I. SPECIFICATIONS OF OCPEMFC H-500

Parameter	Value
Number of cells	24
Rated power	500W
Performance	14.4V@35A
External temperature	5 to 30oC
Max stack temperature	65oC
Hydrogen pressure	0.45-0.55 bar
Flow rate max output	6.5 L/min
Efficiency of stack	40% @14.4V
Humidification	Self-humidified

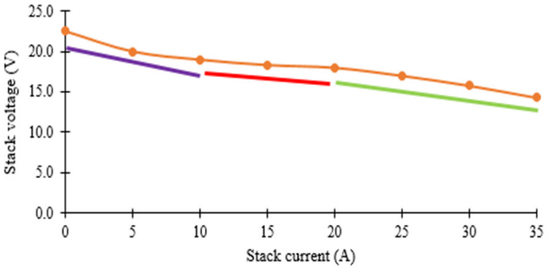

Fig. 1. Characteristic curve for stack voltage of OCPEMF H-500.

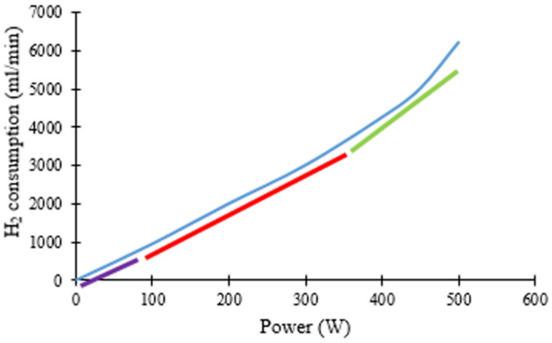

Fig. 2. Hydrogen consumption of OCPEMFC H-500.

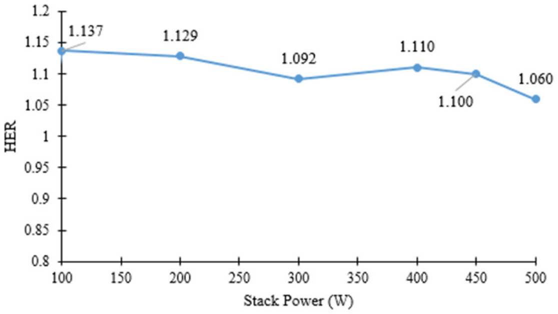

Fig. 3. HER for OCPEMF H-500.

To support the proposed control strategy, this experiment uses a variable valve device module called Mass Flow Control (MFC). The module consists of a control valve and a hydrogen gas flow rate sensor, which functions as a controller for the hydrogen supply flow rate from the hydrogen tank to the fuel cell inlet anode. The MFC module's control valve is controlled by providing a 0-5 V analog signal input to the port, representing the desired hydrogen gas flow rate set point. The flow rate sensor then reads the actual gas flow rate, displayed on the MFC's LCD, and outputs it to the output port as a 0-5 V analog signal (Figure 4).

The schematic diagram and a photograph of the experimental setup are shown in Figures 4 and 5, where the installed sensors include pressure, temperature, current, and voltage sensors. Current and voltage sensors are used to read the load or stack power, while the pressure sensor is used to read the anode inlet pressure. Hydrogen supply control is achieved by regulating the flow rate and pressure from the hydrogen tank to the anode inlet port via an MFC. The Microcontroller (MCU) is responsible for sending the hydrogen supply flow rate set point signal to the MFC module. According to Figure 2, the required hydrogen consumption (flow rate) depends on the stack power; thus, current and voltage sensor readings are performed in real-time by the MCU. As for the test load, several light bulbs were used via a DC to AC inverter, which was controlled by a dimmer module to generate dynamic multi-step loads.

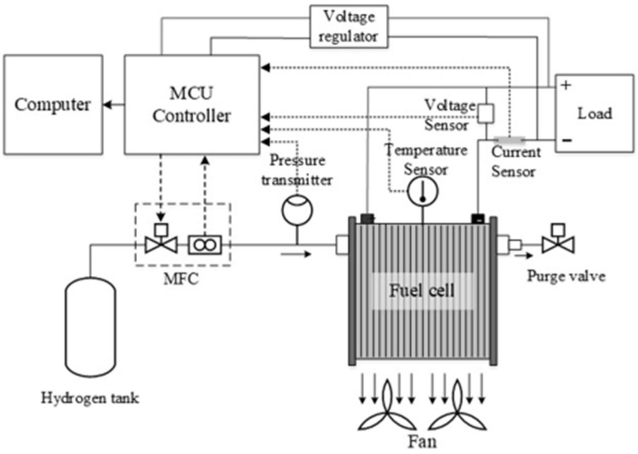

Fig. 4. A schematic of the experimental setup

To determine the performance of the proposed control strategy, several dynamic tracking indicators are applied as follows:

- Maximum tracking error (ΔE_{max}), Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Steady State Error (STE):

$$E_{\max} = \max\left|y(k) - y_{ref}(k)\right| \tag{3}$$

$$\text{MAE} = \frac{1}{n}\sum_{k=1}^{n}\left|y(k) - y_{ref}(k)\right| \tag{4}$$

$$\text{RSME} = \frac{1}{n}\sqrt{\sum_{k=1}^{n}\left(y(k) - y_{ref}(k)\right)^{2}} \tag{5}$$

$$\mathrm{STE} = \frac{\max y(k) - y_{ref}}{y_{ref}} x100\% \qquad (6)$$

- Fluctuation or stability is expressed in the ripple coefficient (C_r):

$$C_r = \frac{y_{\max} - y_{\min}}{\bar{y}} x100\% \qquad (7)$$

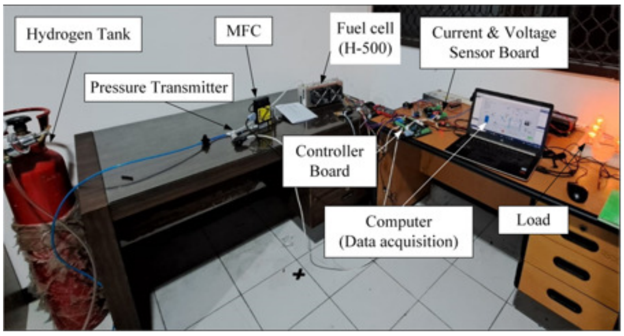

Fig. 5. A photograph of the experimental setup.

III. METHOD

This section describes the implementation stages of the feedback-feed-forward control strategy carried out experimentally on a 500 W OCPEMFC. The control variable is the anode inlet pressure, and the manipulated variable is the hydrogen supply flow rate through the control variable valve (MFC).

A. Control Structure

In the feedback control structure, PID control is used to ensure that the actual anode inlet pressure matches the reference pressure (Figure 6). With only the feedback structure, excessive fluctuation of hydrogen anode pressure occurs with a ripple coefficient of 90.9% (Figure 7), so it is necessary to add compensation techniques. In this study, there are two compensation techniques that will be tested. The first is compensation with an algorithm in the form of an empirical equation that shows the relationship between hydrogen supply consumption (flow rate) and stack power. The second is the fuzzy logic algorithm. Fuzzy logic is used to generate an estimate of the hydrogen supply flow rate demand based on stack voltage and current.

The output signal from the feedback and feed-forward controls UFL is the sum of UCOMP and UP (Figure 8). Control signal UFL is a 0-5 V analog signal that represents the value of the hydrogen supply reference flow rate.

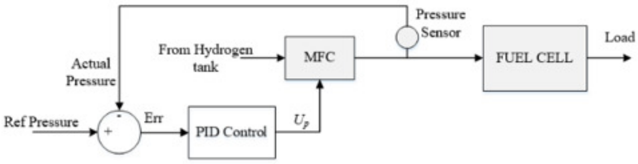

Fig. 6. Diagram blok of feedback control.

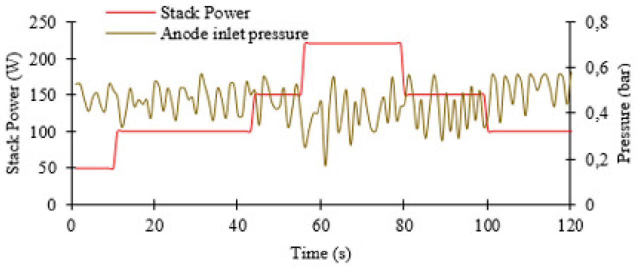

Fig. 7. Anode inlet pressure respon of PID feedback control.

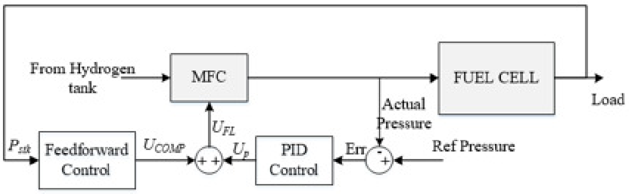

Fig. 8. Diagram blok of feedback-feed-forward control.

B. Compensation Algorithm

As explained above, two compensation algorithms were tested. The first used an empirical equation derived from the characteristic curve in Figure 2. The experiment was conducted in the operational region below 400 W, where Figure 2 shows a linear relationship between the hydrogen flow rate and stack power. So, the mathematical equation for feed-forward control is formulated as:

$$Q = 0.0106 P_{stack} - 0.07 \qquad (8)$$

where Q is the required hydrogen supply flow rate and P_{stack} is the stack power. Compared to the characteristic curve in Figure 2, the deviation (MAE) of the empirical equation in (8) is 5.7%.

The second compensation algorithm is fuzzy logic, which uses an approach by dividing the OCPEMFC into three operating areas, as displayed in Figures 1 and 2. For the membership function, it is designed using three variables, two inputs (stack voltage and current) and one output, namely the hydrogen supply flow rate. Each membership function is grouped into three sets, small (S), medium (M) and big (B), as shown in Figures 9-11. The linguistic numeric for each membership function set is determined based on the V-I polarization curve (Figure 1) and the hydrogen supply flow rate demand (Figure 2).

The formulation of fuzzy rules, as depicted in Table II, is based on the characteristic curve. For example, if the current is small and the voltage is small, then the hydrogen supply is small. The impossible event, namely small current versus small voltage or large current versus large voltage, will result in a small hydrogen supply decision. When the current is medium and the voltage is low, a large hydrogen supply is provided to avoid voltage drops. Meanwhile, when the current is low and the voltage is medium, a medium hydrogen supply is provided to meet the demands of a small load.

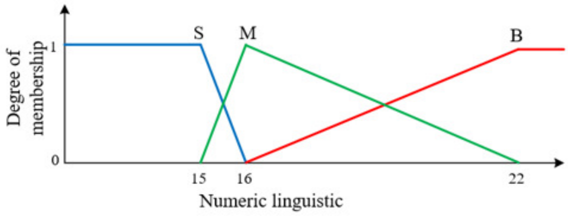

Fig. 9. Membership function of stack voltage.

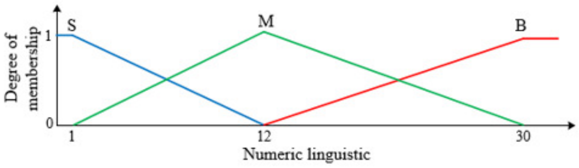

Fig. 10. Membership function of stack current.

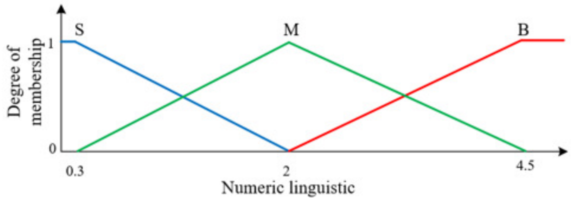

Fig. 11. Membership function of flow rate hydrogen supply.

TABLE II. FUZZY RULE FOR HYDROGEN

Output		**Stack voltage**		
		S	**M**	**B**
Stack current	**S**	S	M	S
	M	B	M	M
	B	B	B	S

IV. RESULTS AND DISCUSSION

To evaluate the performance of the proposed control strategy, the performance of two control algorithms, FF-PID and Fuzzy-PID control, will be compared. The focus of the testing is the ability to track the load and the stability of the anode inlet pressure under a dynamic load. The test scenario examined the response of the two compensation algorithms when subjected to a multi-step dynamic load. The fan, which functions as a coolant and oxygen supply, was operated at maximum speed to avoid disrupting the OCPEMFC's performance.

The gain parameters in the PID feedback control were determined by trial and error, where the proportional gain was 0.1, the integral gain was 0.01, and the derivative gain was 0.5. Monitoring and data collection were carried out by recording data from sensors installed on the fuel cell via a computer, as shown in Figure 12.

Regarding the results of the hydrogen supply flow rate test, both control algorithms produced a response in which the hydrogen flow rate successfully tracked the sudden load changes (Figures 13 and 14). However, when the load was below 10 A, both control algorithms had a similar response, in that the actual hydrogen supply flow rate was often lower than the reference flow rate. The dynamic performance indicators, when compared to the reference flow rate, showed that FF-PID control was better than Fuzzy-PID control, as displayed in the flow rate tracking indicator (MAE = 0.12, RMSE = 0.01) in Table III, and in its smaller flow rate fluctuation, as illustrated in Figures 13 and 14. From these results, the actual HER value is obtained, as shown in Figure 15. When the load is less than 5 A, the HER of the fuzzy-PID control is better than that of the FF-PID. This result proves that the fuzzy-PID controller is superior at maintaining the HER at low loads but is less effective in accurately tracking the hydrogen flow rate. In addition, fuzzy PID produces a less fluctuating HER response (with a ripple coefficient of 41.56%) compared to FF-PID (with a ripple coefficient of 71.37%).

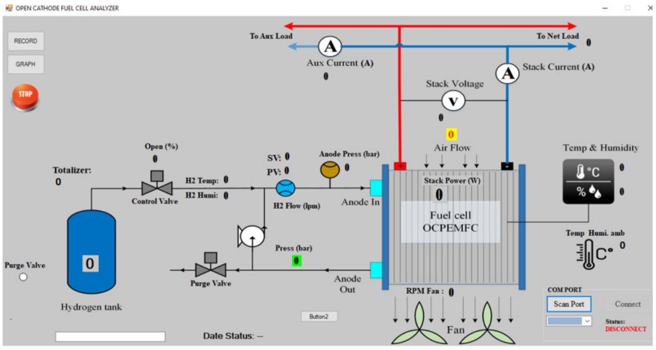

Fig. 12. Graphical user interface for fuel cell analyzer.

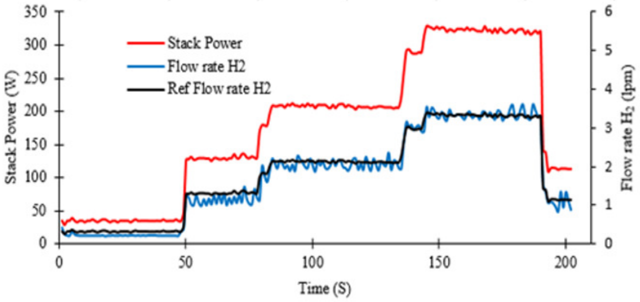

Fig. 13. Flow rate H_2 response of the FF-PID controller.

The anode inlet pressure reference value was set at 0.45 bar. Testing was conducted to determine the accuracy and stability of the anode inlet pressure under dynamic load. As presented in Figures 16 and 17, and Table III, the FF-PID and fuzzy-PID control algorithms achieved SSEs below 5%, with values of 2.22% and 4.44%, respectively. The FF-PID was more precise in tracking the reference value, as indicated by its smaller MAE and RMSE, and a half fuzzy SSE. This is consistent with the curve-fitting method's characteristic of rapidly converging to the set-point after the disturbance subsides. However, Fuzzy-PID successfully reduced pressure fluctuations (ripple coefficient decreased by ±16%).

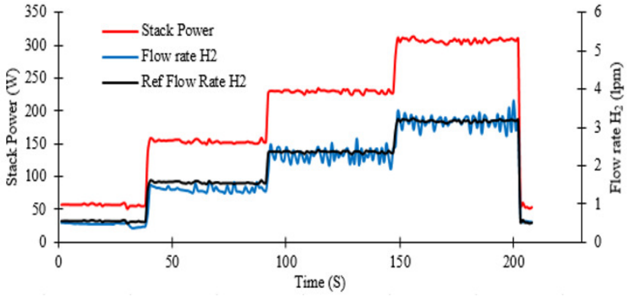

Fig. 14. Flow rate H_2 response of the Fuzzy-PID controller.

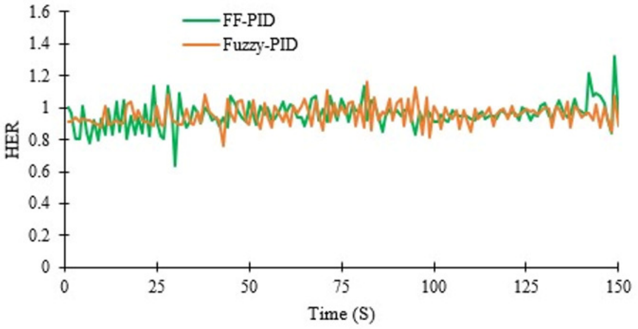

Fig. 15. Actual HER response of both controllers.

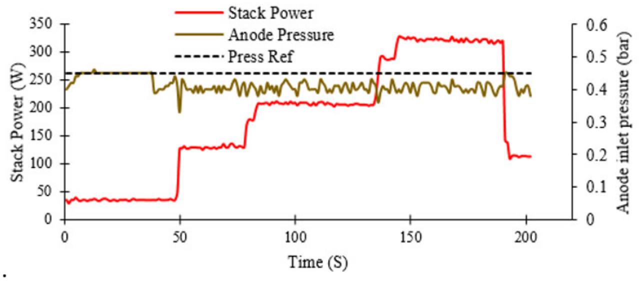

Fig. 16. Anode inlet pressure response of the FF-PID controller.

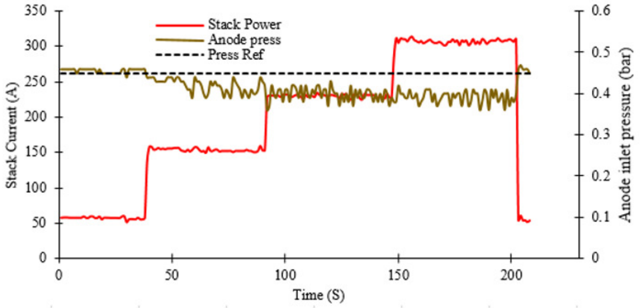

Fig. 17. Anode inlet pressure response of the Fuzzy PID controller

TABLE III. CONTROLLER PERFORMANCES UNDER DYNAMIC LOAD

Indicator of dynamic performances	FF-PID	Fuzzy-PID
MAE of flow rate H_2	0.12	0.14
MAE of anode pressure	0.037	0.038
RMSE of anode pressure	0.001	0.003
Ripple coefficient of anode pressure (%)	31.49	26.54
SSE of anode pressure (%)	2.22	4.44

V. CONCLUSIONS

The anode hydrogen supply subsystem is an important part of the Open Cathode PEM Fuel Cell (OCPEMFC) because it is related to the demand for hydrogen supply consumption and the stability of the anode pressure when the OCPEMFC is operated at dynamic load. This study presents the results of experimental testing from a 500 W OCPEMFC, comparing the performance of two control algorithms (FF-PID and fuzzy-PID) on a feed-forward control structure with compensation. Overall, FF-PID offers the best average accuracy, indicated by slightly lower Mean Absolute Error (MAE) and Root Mean Square Error (RMSE) of discharge and anode pressure—but causes larger overshoot, undershoot, and pressure ripple coefficients, resulting in rougher valve operation and a risk of starvation during load surges. In contrast, Fuzzy-PID can dampen fluctuations and shorten the settling time by almost half, keeping the Hydrogen Excess Ratio (HER) and anode pressure within safe limits, but leaving a steady-state bias of ±0.02 bar and a slightly higher discharge MAE, which impacts hydrogen consumption. Thus, Fuzzy-PID is more suitable for dynamic load applications that demand smooth actuation and stack protection, while FF-PID remains a viable option for stationary systems with relatively constant loads or when computational limitations are a priority—provided that ripple needs to be dampened using filtering or retuning.

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