

Enhancing voltage stability through wavelet-fuzzy control of hydrogen flow in OC-PEM fuel cell

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ABSTRACT

Open cathode proton exchange membrane fuel cells (OC-PEM fuel cells) serve as electricity generators, utilizing hydrogen as an input source. While effective for fixed loads like residential applications, challenges arise in dealing with output voltage fluctuations caused by rapid load changes. These fluctuations not only impact fuel cell performance but also introduce instability in the supplied power. To solve this issue, the study proposes an innovative hydrogen flow control system employing a feedforward wavelet-fuzzy method. The primary goal of this control system is to enhance fuzzy control performance using wavelets, mitigating signal fluctuations and achieving optimal stability in fuel cell output voltage under constant load conditions. Wavelet functions act as filters on the fuzzy control input, minimizing fluctuations and refining the entire process. Additionally, a feedforward system is incorporated to maintain hydrogen flow at the set point value. The proposed control system is implemented on a validated model using experimental data. Performance analysis reveals that the proposed method effectively stabilizes voltage by accelerating the recovery time from disturbances.

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1. INTRODUCTION

Open cathode proton exchange membrane (OC-PEM) fuel cells operate by necessitating a supply of oxygen and hydrogen gas as fuel to generate electrical energy through an electrochemical process [1]. In open cathode-type fuel cells, oxygen is introduced to the cathode via fans, and hydrogen gas is sourced from a pressurized tube [2]. This electrochemical reaction results in electricity production, with the sole byproducts being water and heat, establishing OC-PEM fuel cells as environmentally friendly [3]. OC-PEM fuel cells are versatile, suitable for both fixed and variable loads [4], [5]. In fixed load scenarios, they can efficiently power residential homes or offices, where stable operation is essential to meet consistent power demand [6]. In reality, achieving perfectly smooth output voltage of OC-PEM fuel cell is unattainable, leading to unavoidable undershoot voltage during loading [7]. Undershoot stress stems from insufficient reactants in the catalyst layer, typically observed under loading conditions [8]. When gas diffusion into the catalyst layer lags behind gas consumption through reactions, the reactant concentration becomes unstable,

resulting in fluctuations in output performance [7]. These fluctuations, in turn, disrupt output stability, posing a threat to the reliability and safety of the fuel cell [9]. Severe undershoot behavior can even lead to reverse voltage and contribute to permanent degradation of the fuel cell [10]. Regulating a stable flow of hydrogen gas is one method used to increase the stability of the fuel cell output voltage [11]. Controlling hydrogen flow is critical in maintaining optimal operating conditions and reducing problems such as fluctuations, undershoot and overshoot in fuel cell output voltage [12]. A steady, well-controlled flow of hydrogen helps ensure a consistent supply of reactants to the fuel cell, minimizing variations in electrochemical reactions and contributing to a more stable output voltage [13].

Various control methods, including proportional-integral-derivative (PID) control [14] and fuzzy-PID [15] have been suggested for regulating hydrogen flow in fuel cells. However, the PID control system exhibits limitations in response time and accuracy when applied to highly dynamic non-linear systems [16]. Fuzzy control, while offering potential advantages, necessitates a thorough understanding to establish proper scaling, which can result in suboptimal performance of the control system [17]. Fuzzy control is employed to regulate the flow of hydrogen [18], relying on linguistic rules and fuzzy sets. The inherent ambiguity and subjectivity of linguistic rules can lead to a diminished level of control accuracy in specific situations [19]. Fuzzy controllers frequently encounter challenges in adjusting to unanticipated changes in system dynamics during the rule design phase [20]. Such limitations can impact the controller's effectiveness in managing unforeseen or swiftly changing conditions.

Hence, this paper introduces a novel hybrid control technique aimed at ensuring hydrogen flow stability and achieving voltage stability through the utilization of a wavelet-fuzzy controller. The wavelet component is employed to enhance the performance of fuzzy control by minimizing oscillations in the control input signal. This wavelet, comprising low-pass and high-pass filters, facilitates a rapid process without imposing computational burdens on the control system. The paper is structured into several sections, commencing with an introduction, followed by a method section encompassing the experimental setup, simulation model, and wavelet-fuzzy controller. Subsequently, the results and discussion section critically evaluates the findings. Finally, the conclusions section succinctly summarizes the key insights obtained.

2. METHOD

This section introduces the experimental setup, the simulation model for the OC-PEM fuel cell, and the schematic diagram of the control system. The simulation model was developed using MATLAB Simulink, incorporating mathematical equations pertinent to fuel cells.

2.1. Experimental setup of OC-PEM fuel cell

The fuel cell's performance underwent testing with a hydrogen flow input ranging from 1 to 8 L/min, utilizing an OC-PEM fuel cell with a maximum power capacity of 2.5 kW. Further elaboration on the experiment's parameters is provided in Table 1.

Table 1. Experiment parameters for the OC-PEM fuel cell

Parameters	Value
Number of cells	73 cells
Active area	5.5 cmx29 cm
Thickness	4 mm
Max power	2.5 kW
Temperature	31°C-65°C
Reactants	hydrogen and air
Hydrogen flow rate	1–8 L/min
Cooling	Air (cooling fan)
Fan voltage	48 volt
Purge duration/period	0.5 s/10 s
Oxygen supply	Open cathode

Although the OC-PEM fuel cell can produce up to 2.5 kW of power, this experiment is constrained by device limitations, utilizing a maximum power of 255 W. Hydrogen, supplied to the anode, and oxygen from the air, supplied to the cathode, are crucial for the fuel cell operation. The hydrogen gas supply system incorporates cylinders, regulators, and valves for precise control and delivery. As OC-PEM fuel cells generate heat during electrochemical reactions, a cooling system with three fans maintains optimal operating temperatures. An electrical load, ranging from 1 A to 10 A, is connected to the fuel cell stack to simulate practical power requirements. Various instruments monitor parameters such as voltage, current, temperature, and gas flow rate, providing essential data for performance analysis. Data acquisition systems collect, record,

and process information from these instruments, aiding in the comprehensive understanding of fuel cell behavior under diverse conditions. This experimental setup facilitates the exploration of PEM fuel cell efficiency, durability, and dynamic response, thereby making a substantial contribution to the optimization of fuel cells in this project. For further details, Figure 1 illustrates the components employed in the experiment.

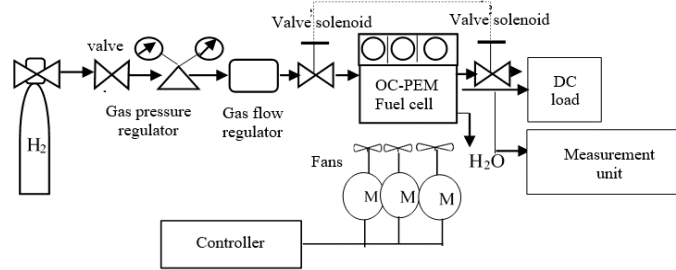


Figure 1. Schematic diagram of the OC-PEM fuel cell

The voltage drop pattern resulting from loading was derived from PEM fuel cell experiments. This pattern is represented by a polynomial as (1):

$$V_L = -(y^2 * 0.3467) + (49.716 * y) - (1724.3) \quad (1)$$

Here, V_L represents the voltage drop, and y denotes the voltage at open circuit voltage. The voltage drop pattern is experimentally obtained by systematically varying the electrical load applied to the fuel cell and measuring the resulting changes in voltage.

2.2. Simulation model of OC-PEM fuel cell

The simulation model for the OC-PEM fuel cell was constructed using MATLAB Simulink, employing mathematical equations as its foundation. The OC-PEM fuel cell simulation model is designed to predict key performance metrics, including voltage, current, and power output. The model aids in pinpointing optimal conditions conducive to achieving maximum power output and efficiency. The output of the fuel cell is typically represented as voltage, as indicated by (2) [21]:

$$V_{FC} = N_{cell} (E_{Nernst} - V_{Act} - V_{Ohmic} - V_{con}) \quad (2)$$

In the context where V_{FC} denotes the output voltage of the fuel cell, E_{Nernst} is the symbol employed to depict the thermodynamic potential and reversible voltage of the fuel cell [22], which equivalently represents its output voltage. Nevertheless, the actual output voltage is diminished owing to diverse voltage losses. These losses encompass activation losses at the anode and cathode (V_{Act}), internal resistance losses (V_{Ohmic}), and losses arising from the mass transfer of the reacting gas (V_{con}) [23]. The calculation for the Nernst voltage (E_{Nernst}) can be expressed using as (3):

$$E_{Nernst} = E^0 + \frac{RT}{2F} [\ln(P_{H_2}) + 0.5 \ln(P_{O_2})] \quad (3)$$

Here, E^0 symbolizes the reference potential, R stands for the universal gas constant, T represents the fuel cell operating temperature, and F denotes the Faraday constant. The voltage drop (V_{act}) arising from the activation of the anode and cathode [24] can be calculated using as (4):

$$V_{act} = -\left(\frac{R \cdot T}{2 \cdot \alpha \cdot F}\right) * \log\left(\frac{i_L}{i_0}\right) \quad (4)$$

The ohmic voltage drop (V_{ohmic}) is associated with the internal electronic resistance within the system and is computed using as (5):

$$V_{ohmic} = -(i_o * r) \quad (5)$$

The voltage drop caused by mass transportation effects, which influence the concentration of the reacting gases, is denoted as V_{con} [25]. It can be described using as (6):

$$V_{con} = -\alpha * i^k * \ln\left(1 - \frac{i_o}{i_L}\right) \quad (6)$$

Static parameters in the OC-PEM fuel cell model are constants or factors that remain relatively stable under steady-state operating conditions. Table 2 displays the static model parameters utilized in this study.

Table 2. Parameters for the static model of OC-PEM fuel cell

Parameter	Value
Number of cells (N_{cell})	73
Max power	2.5 kW
Operating temperature (T)	333 K
Reference potential (E^0)	1.229 V
Universal gas constant (R)	8.314 J/mol
Faraday constant (F)	96485 C/mol
Transfer coefficient (α)	0.5
Limiting current density (i_L)	1.4 A/cm ²
exchange current density (i_0)	10 ⁻⁶ –6.912 A/cm ²
Internal resistance (r)	0.19 Ohm.cm ²

The mathematical equations for dynamic systems start by determining the molar constant value of the hydrogen valve (K_{H_2}) [26].

$$K_{H_2} = \frac{q_{H_2}}{P_{H_2}} = \frac{k_{an}}{\sqrt{MH_2}} \quad (7)$$

The symbol q_{H_2} represents the molar flow of hydrogen, while P_{H_2} signifies the partial pressure of hydrogen. Furthermore, MH_2 is the molar mass of hydrogen, and k_{an} is the anode valve constant. The mathematical equation for the partial pressure of hydrogen gas, represented by the symbol P_{H_2} [27], is as (8):

$$P_{H_2} = \frac{\frac{1}{K_{H_2}}}{1 + \tau_{H_2}s} (q_{H_2}^{in} - 2K_r I) \quad (8)$$

Where the modeling constant is indicated by K_r . The symbol $q_{H_2}^{in}$ represents the flow rate of hydrogen input, while the symbol $\tau_{H_2}s$ represents the hydrogen time constant. The stack current is denoted by the symbol I . To calculate τ_{H_2} use (9):

$$\tau_{H_2} = \frac{V_{an}}{K_{H_2}RT} \quad (9)$$

In (10) can be employed to calculate the reacting hydrogen flow, denoted by the symbol $q_{H_2}^r$.

$$q_{H_2}^r = \frac{N_{cell}I}{2F} = 2K_r \quad (10)$$

The partial pressure of oxygen gas (P_{O_2}) at the fuel cell cathode can be calculated by (11):

$$P_{O_2} = \frac{\frac{1}{K_{O_2}}}{1 + \tau_{O_2}s} (q_{O_2}^{in} - K_r I) \quad (11)$$

The molar flow of hydrogen gas (q_{H_2}) can be determined by (12):

$$q_{H_2} = \frac{N_{cell}I_{stack}}{2FU} \quad (12)$$

Here, the utilization factor, denoted by U with a value of 0.8, is employed. The stack voltage is calculated by multiplying the number of cells by the output voltage per cell, as indicated in (13):

$$V_{stack} = V_{cell}N_{cell} \quad (13)$$

Dynamic models assume a pivotal role in analyzing the overall performance and response time of fuel cell systems. Additional information about the parameters utilized in the dynamic model of the OC-PEM fuel cell is provided in Table 3. Dynamic models depict the rate at which a fuel cell system adjusts to alterations in input conditions. Figure 2 illustrates the dynamic model depicting the flow of hydrogen and oxygen.

Table 3. Parameters for the dynamic model of OC-PEM fuel cell

Parameter	Value
Hydrogen time constants (τ_{H_2})	3.37 s
Oxygen time constants (τ_{O_2})	6.74 s
Hydrogen valves constants (K_{H_2})	0.843 mol/s.atm
modeling constant (K_r)	1.4251×10^{-6} kmol s ⁻¹ atm
Oxygen valves constants (K_{O_2})	2.52 mol/s.atm

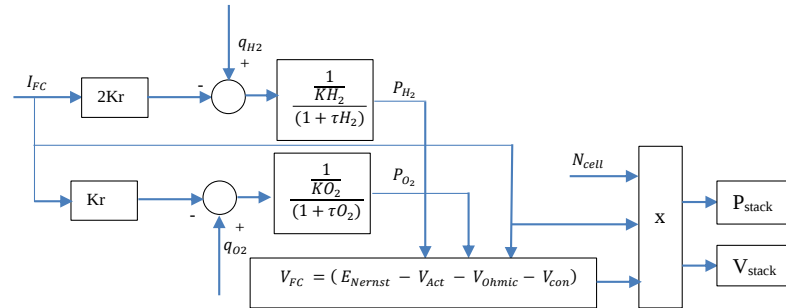


Figure 2. Dynamic model of OC-PEM fuel cell

2.3. Wavelet-fuzzy controller

This study integrates wavelet transform into a hybrid control system alongside a fuzzy controller. Within this framework, wavelets serve as a filtering technique for input signals directed to the fuzzy controller. The established OC-PEM fuel cell model is employed to realize a wavelet-fuzzy control system, and Figure 3 illustrates the block diagram of this integrated system.

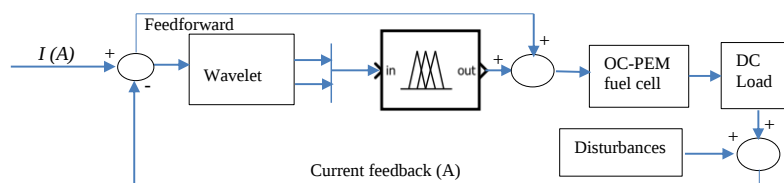


Figure 3. Structure of wavelet-fuzzy controller

2.3.1. Wavelet transforms

In this study, we employ the biorthogonal cohen-daubechies-feauveau (CDF) 5/3 wavelet transformation due to its benefits, including a lack of overshoot and fast response [28]. The CDF 5/3 wavelet utilizes two sets of filter coefficients, distinguishing between those used in the analysis (decomposition) stage and those employed in the synthesis (reconstruction) stage. Specifically, for the analysis stage of the CDF 5/3 wavelet, the filter coefficients are as (14) and (15):

$$h(z) = -\frac{1}{8}z^{-2} + \frac{1}{4}z^{-1} + \frac{3}{4} + \frac{1}{4}z^1 - \frac{1}{8}z^2 \quad (14)$$

$$g(z) = -\frac{1}{2}z^{-1} + 1 - \frac{1}{2}z^1 \quad (15)$$

Additionally, the synthesis (reconstruction) filter coefficients are intricately linked to the analysis filter coefficients, guided by specific properties to guarantee a flawless reconstruction process [29]. Specifically, the synthesis filter coefficient for CDF 5/3 is (16) and (17):

$$\bar{h}(z) = \frac{1}{2}z^{-1} + 1 + \frac{1}{2}z^1 \quad (16)$$

$$\bar{g}(z) = -\frac{1}{8}z^{-2} - \frac{1}{4}z^{-1} + \frac{3}{4} - \frac{1}{4}z^1 - \frac{1}{8}z^2 \quad (17)$$

In Figure 4, the CDF 5/3 wavelet structure is depicted, wherein the production coefficient, denoted by α , is represented as $-1/2$, and the update coefficient, symbolized by β , possesses a value of $\beta=-1/4$. According to the information in Figure 4, there are two inputs for the wavelet: the error ($e(k)$) and the rate of change of the error, denoted as $ec(k)$.

$$e(k) = I_{fc}^* - I_{fc} \quad (18)$$

$$ec(k) = e(k) - e(k-1) \quad (19)$$

Where I_{fc}^* is the fuel cell set point current.

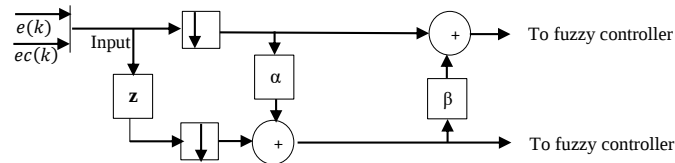


Figure 4. Structure of CDF 5/3 wavelet

2.3.2. Fuzzy controller

The suggested fuzzy logic controller manages the hydrogen flow by adjusting the current by (12). In Figure 5, a fuzzy control structure is illustrated, featuring two inputs derived from the CDF 5/3 wavelet output, specifically the approximation and details.

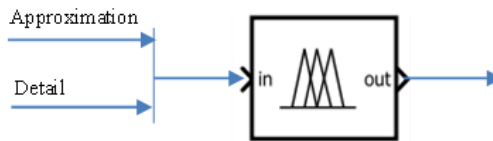


Figure 5. Structure of fuzzy controller

Gaussian-type membership functions are employed for the error (e), error change (ec), and control output (u_{H_2}). The fuzzy domains for e and ec are defined within the range of $[-0.5, 0.5]$, whereas for u_{H_2} , the range is $[-0.2, 0.2]$. The fuzzy set for e , ec , and u_{H_2} comprises Ng_Bg representing negative big, Ng_Sm for negative small, Zo for zero, Po_Sm for positive small, and Po_Bg indicating positive big. The fuzzy control rule base is detailed in Table 4. Here are some examples of fuzzy rule bases:

If e is Ng_Bg and ec is Ng_Bg then u_{H_2} is Ze

If e is Ze and ec is Ng_Bg then u_{H_2} is Ng_Bg

If e is Ze and ec is Ng_Sm then u_{H_2} is Ng_Sm

Table 4. Rule base of fuzzy control

e	Ec				
	Ng_Bg	Ng_Sm	Ze	Po_Sm	Po_Bg
Ng_Bg	Ze	Ze	Ng_Bg	Ze	Ze
Ng_Sm	Ze	Ze	Ng_Sm	Ze	Ze
Ze	Ng_Bg	Ng_Sm	Ze	Po_Sm	Po_Bg
Po_Sm	Ze	Ze	Po_Sm	Ze	Ze
Po_Bg	Ze	Ze	Po_Bg	Ze	Ze

The centroid defuzzification method calculates the output value based on the center of gravity of the output membership function, as expressed by (20):

$$u_{H_2} = \frac{\sum_{i=0}^n \mu_{Ci}(u_{H_{2i}})u_{H_{2i}}}{\sum_{i=0}^n \mu_{Ci}(u_{H_{2i}})} \quad (20)$$

The fuzzy logic controller employs gaussian membership functions to represent the degree of membership for both input and output variables. Figure 6 illustrates the input variables for error (e) and error change (ec). Meanwhile, for the control output variable, it is indicated in Figure 7.

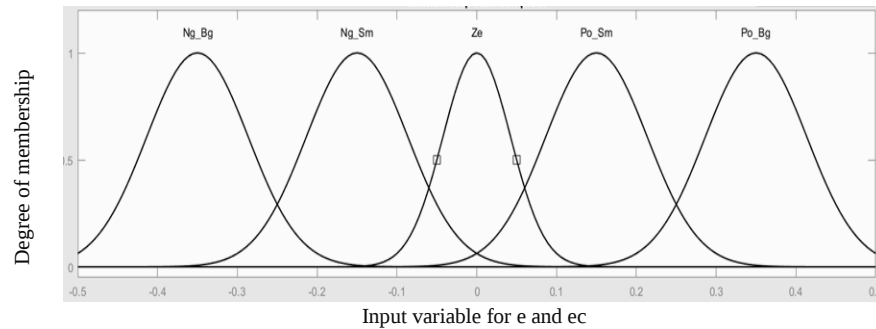


Figure 6. Gaussian membership function of the error (e) and error change (ec)

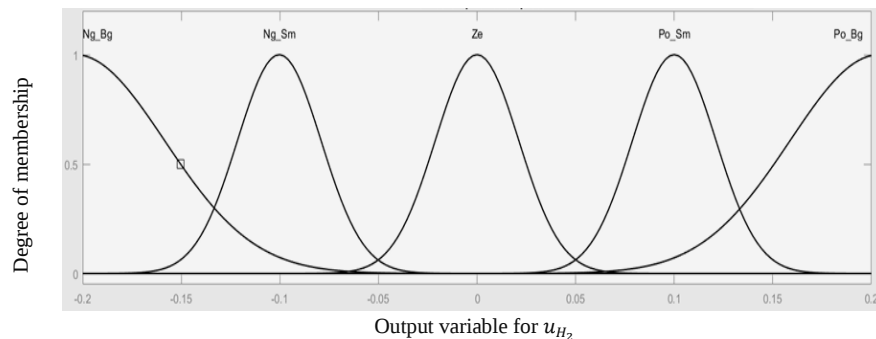


Figure 7. Gaussian membership function of control output (u_{H_2})

3. RESULTS AND DISCUSSION

3.1. Discoveries from simulation and experimental results

The model validation involved a comparison between experimental and simulation results, as depicted in Figure 8. Figure 8 illustrates the relationship between current and power obtained with a constant hydrogen flow input of 8 L/min. During this investigation, the current load was incrementally raised from 1 A until it reached a maximum of 7.87 A, and the power began to decline after reaching 252.4 W. The experimental results indicated that at low loads, ranging from 1 to 6 A, there were no significant output voltage fluctuations. However, as depicted in Figure 9, fluctuations become noticeable with an increase in the load. This image also highlights the presence of undershoot voltage, signifying that the output does not reach the maximum voltage.

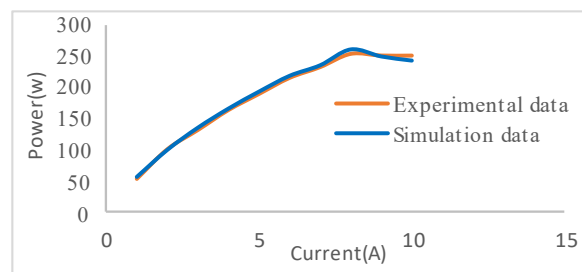


Figure 8. Maximum load for hydrogen input 8 L/min

Instabilities in the output voltage lead to variations in the current and power supplied to the load, as evident in Figure 10. Additionally, Figure 10 reveals fluctuations in the load current at 7.5 A, yet the current does not reach the targeted set point value.

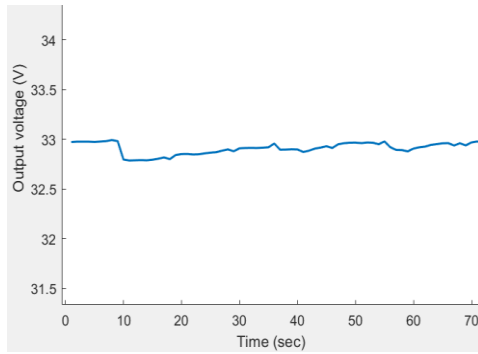


Figure 9. Output voltage under a 7.5 A load

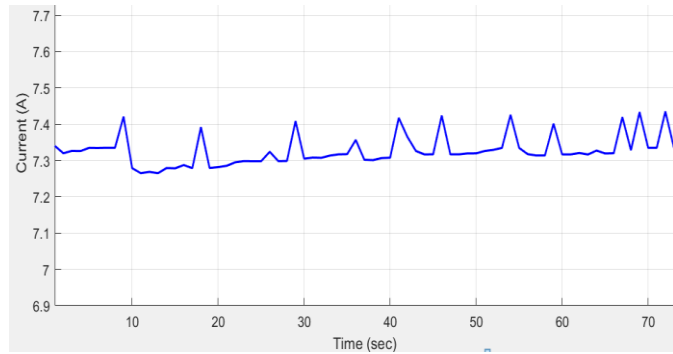


Figure 10. Output current fluctuation

3.2. Wavelet-fuzzy controller performance

Evaluating the performance of the wavelet-fuzzy controller involves utilizing an 8 L/min hydrogen flow input. Figure 11 exhibits a well-regulated and stable flow of hydrogen gas. In testing the control system, a set point value of 7.5 A is applied, considering fluctuating current disturbances, as illustrated in Figure 10. The outcomes of voltage response testing with wavelet-fuzzy control are depicted in Figure 12.

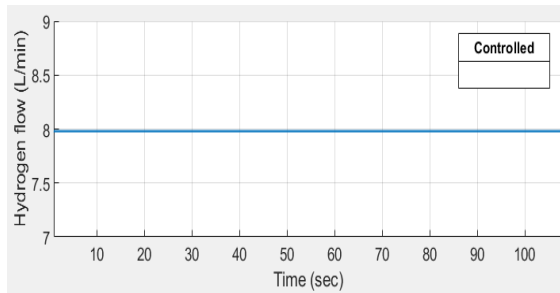


Figure 11. Hydrogen flow output of the wavelet-fuzzy control system

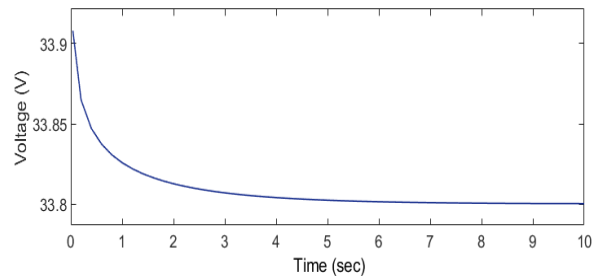


Figure 12. Output voltage response of the wavelet-fuzzy control system

Figure 12 demonstrates the exceptional stability of the output voltage, maintaining a constant value of 33.8 V. This indicates the effective suppression of fluctuations through the proposed system control strategy. Comparing the accuracy of the output voltage with the optimal value of 34 V yields a high accuracy of approximately 99.412%.

4. CONCLUSION

This paper introduces a hydrogen flow control system aimed at ensuring voltage stability using wavelet-fuzzy. The application of this control system is demonstrated under fixed loads. Experimental findings reveal fluctuations in the output voltage when a load of 7.5 A is applied, characterized by undershoot within a range of 0.1 V to 0.3 V below the set point value. Upon implementing the proposed control system, a hydrogen flow stability of 8 L/min is achieved, contributing to the stability of the output voltage at 33.8 V, closely approaching the target value of 34 V. The performance analysis of the control system indicates high accuracy, reaching 99.4%.

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