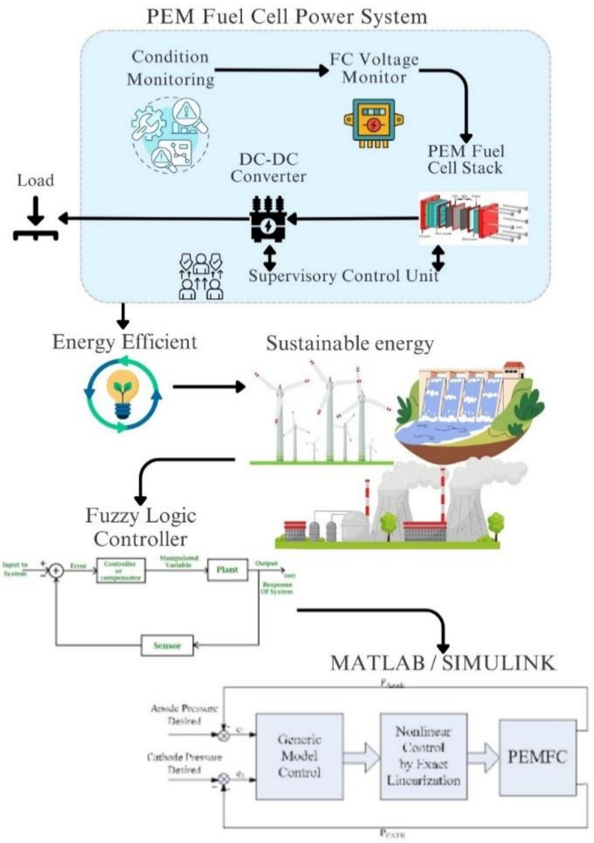
Global NEST Journal, Vol 26, No X, pp 1-8

Sustainable energy optimization in pem fuel cells through fuzzy logic control experiments

Arulvedi H.[1] **and Suresh Kumar P.**[2]
[1]Assistant Professor, Department of Electrical and Electronics Engineering Mahendra Engineering College, Namakkal, Tamil Nadu, India
[2]Professor, Department of Electronics and Communication Engineering, Chennai Institute of Technology, Kundrathur, Chennai
Received: 23/03/2024, Accepted: 08/10/2024, Available online: 28/11/2024
*to whom all correspondence should be addressed: e-mail: arulvedih@gmail.com
https://doi.org/10.30955/gnj.005954

Graphical abstract



Abstract

The primary source of energy in the globe has been shown to be the reliance on hydrocarbon fuel for the production of electricity. The past century has seen an explosion in the use of energy due to population and activity growth. Developing a flow field for reaction gas distributions on a PEM fuel cell to lead sustainable energy was the aim of this study. In the flow field design, the effect of flow field plate channel designs on a PEMFC's efficiency was examined. In order to optimise channel characteristics, the impacts of channel widths, lengths, and curves on a flow field plate were examined. It is anticipated that the development of these design techniques using the Fuzzy Logic Controller (FLC) will be necessary. Using an FLC model, the impact of sinuous flow channel designs on PEMFC efficiency was investigated. Experiments validated the accuracy of this model. The impact of fuel cell efficiency on flow field design was determined using the numerical data. The PEM fuel cell model in this study was created using the MATLAB SIMULINK model, and the flow rate of the input gases was regulated using a comprehensive mathematical modelling system that included the FLC controller. The simulation's findings demonstrate the viability of the fuzzy logic controller (FLC) and its three primary parts, which also regulate the input gas flow rate: fuzzyzification, fuzzy rule basis, and defuzzification. This allowed us to modify the gas flow field's structure, which enhanced water management and gas dispersion. This study will assess the relationship between pressure loss and velocity dispersion and channel width, channel geometry, and flow field features using a numerical model. The purpose of the testing is to validate the power curve and polarisation computational predictions. The results of this investigation will give us the fundamental understanding needed to build and operate fuel cells.

Keywords: Fuzzy logic controller (FLC), fuel cell, flow channel, optimization, proton exchange membrane, matlab simulink model, sustainable energy

1. Introduction

PEMFC has resurrected a significant state in the power and other industries. Enhancing fuel cell architecture will address a slew of energy-related difficulties. Some issues, however, remain unresolved. Solving fuel cell problems will lead to the advancement of other innovative technologies. As a result, improving alternative technologies can help alleviate human misery. As a consequence, from the 1970s, fuel cells and varieties have been found, and organizations, scientists, and enterprises have made several improvements. PEM as well as other fuel cells are used in these improvements. Because of some recognised problems, some advancement have yet to be completed. Fuel cells are supported by NASA and related agencies, as well as a number of European and international organisations. In addition to focused efforts aimed at addressing fuel cell longevity, power, and wastewater issues.

(Mammar *et al.*, 2019) However there is no uncertainty that the advent of fuel cell automobiles aids in enhancing thermal performance in transportation sectors and lowering pollution issues in metropolitan areas, there are a number of issues, including cost, efficiency, and fuelling infrastructure. (Kart *et al.*, 2024) Aside from car uses, various manufacturers are working on small scale PEMFCs for household usage, with the goal of creating a new idea of "personal energy production." (Boyacioğlu *et al.*, 2023) PEMFCs have the potential to be employed as a realistic source of power for transportation due to their low temperatures operating and increased membrane efficiency (Aly *et al.*, 2022)

Because the vehicle market will permit significant commercial production of fuel cells in the future, there is a strong anticipation of lower costs. (Harrag *et al.*, 2018) Furthermore, its environmental flexibility inspired major automobile producers to build fuel cell-powered vehicles. (Daud *et al.*, 2017) suggested an isothermal, two-dimensional model. (Benchouia *et al.*, 2015) The electroosmosis drag force was used to convey water across the membrane, and also heat exchange from the solid matrix to the gaseous state along the flow stream. (Escobet *et al.*, 2014) In the simulation, the gas diffusion levels were ignored. (Hai *et al.*, 2023) created a non-isothermal 3-dimensional model for PEMFCs (Figure 1).The temperature distribution was also considered in the simulation. (Schumacher *et al.*, 2004) Inside flow pathways and gas dispersion layers, the simulation formulas were calculated. The model's flaw was that the flow was solely determined by oxygen content. (Rakhtala *et al.*, 2016) A fuzzy logic controller (FLC) simulation has recently been found to be a useful tool in modelling processes. FLC has the potential to provide a wealth of useful data for the design of PEM fuel cell technologies. (Rezk *et al.*, 2021) The use of computational fluid dynamics (FLC) can help researchers investigate both transport and electrochemical processes in fuel cells. However, modelling fuel cells in three dimensions is complex and requires some hypotheses (Tanveer *et al.*, 2020)

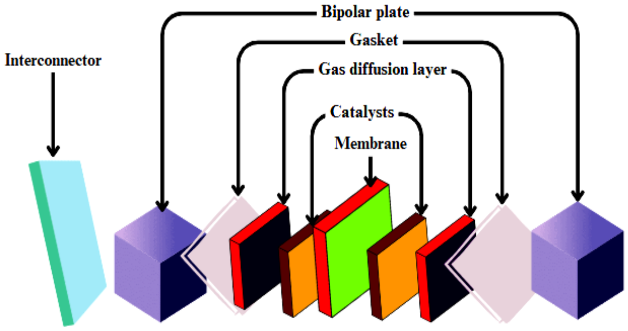


Figure 1. Anatomy of a single PEMFC

It addresses the difficulties that fuel cell systems face in achieving uniform flow distribution. They describe a new approach for regular flow field channel distribution that takes into account numerous stages of flow channel bifurcations and distributes flow evenly from n to 2n levels of bifurcation flow field networks. (Thanapalan *et al.*, 2009) Using FLC fluent software, the effects of flow channel divergence geometry and design on the homogeneity of airflow pattern in the fuel cell were explored. On a PEMFC, a adaptive FLC analysis was conducted to observe the efficiency of three different typical flow channels that had been converted to tubular plates. (Khanafari *et al.*, 2024) The FLC simulation formula was solved, as well as the FLC electrochemical framework and numerous distribution contour parameters. The distribution contours enable a local investigation of transport frequency, indicating that the tubular construction has more consistent oxygen levels, H levels, present frequency, and pressure ranges than a standard flow channel design. The tubular design with straight channels was found to have the least pressure loss among the channels.

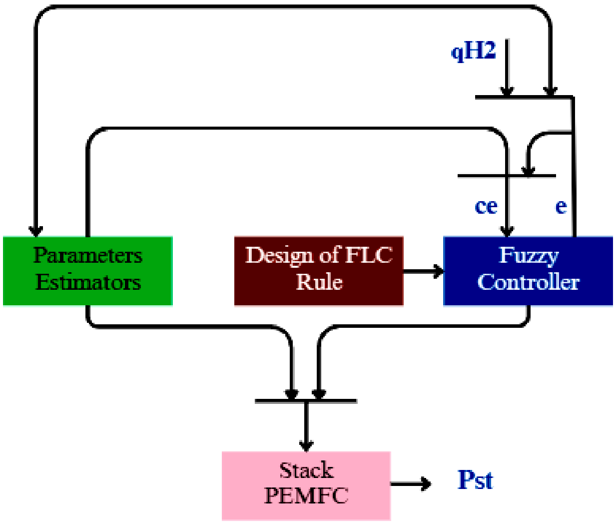


Figure 2. The fuzzy controller block of the PEMFC

2. Proposed Methodology

2.1. Design of PEMFC fuzzy logic controller (FLC)

The fuzzy logic controller makes decisions and regulates the controller's output using fuzzy logics. The defining of the controller's variables of output and input, designing fuzzy control rules, fuzzification, defuzzification and inference are the five processes and components that make up the fuzzy controller. By regulating the hydrogen flow, the power transmission from the PEMFC to the load is managed. Through the manipulation of the hydrogen flow, the suggested FLC regulates the active power. The architecture of the closed-loop fuzzy control system is depicted in Figure. 3. The fuel cell's output power is managed by a fuzzy control system with two inputs; in this instance, the controller is an FLC with inputs for error e (k) and error change. Fuzzy control is a very appropriate solution to address the fuel cell's control problem, despite the fact that PEM fuel cells are nonlinear processes. The fuel cell system's power and temperature control works with fuzzy inference techniques (Figure 2). The real-time control and the fine control, however, frequently clash. Well control must include more control rules, which will result in a heavier computation load.

The experimental configuration for the fuzzy controller module of a Proton Exchange Membrane Fuel Cell (PEMFC) involves integrating multiple components to monitor and regulate the fuel cell's operating parameters. The PEM fuel cell stack is the central component, linked to sensors that measure temperature, pressure, humidity, and hydrogen and oxygen gas flow rates. These sensors deliver real-time data to a data gathering system that connects to the fuzzy logic controller. A microcontroller or digital signal processor (DSP) is required to handle fuzzy logic algorithms. The fuzzy controller is built using rules and membership functions based on expert knowledge and empirical data. During the experiment, real-time data is inputted into the controller, which processes it based on predetermined rules. The controller then modifies control actions, such as reactant gas flow rates, system temperature, and fuel cell pressure. Actuators like valves and pumps receive signals from the fuzzy controller to execute these changes. A monitoring system, often a computer with specialized software, is used to visually display the system's functioning and refine fuzzy control rules. This configuration ensures the Proton Exchange Membrane Fuel Cell functions within its optimal range, improving power density and efficiency while delivering consistent power output.

Table 1. Pem fuel cell - Data collections and Measurement

Data	Measurement Value	Unit
Catalyst layer thickness (cathode side)	0.1	Mm
Active area	30	cm2
Thickness of the catalyst layer	0.1	Mm
Length of the cell electrode	70	Mm
width of collector (anode)	50	Mm
width of collector (cathode)	50	Mm
The thickness of the gas diffusion layer (anode)	0.4	Mm
The thickness of the gas diffusion layer (cathode)	0.4	Mm
Channel depth in a gas flow field	3	Mm
Channel width in a gas flow field	50	Mm
Membrane thickness	0.8	Mm

2.2. Data collection and measurement

The geometric model was created using MATLAB SIMULINK model software. The design was then built in this programme, along with relevant areas for the modelling areas such active material, velocity field pathways, gas diffusion layers, catalyst layers, and substrate for both, as exposed in Figure. 3. The grid was then imported into the licenced version of ANSYS FLUENT 18.0, which was utilised to solve the meshing and the whole set of the unit. Various needs and model parameters for each location were defined after reading the simulations into the FLUENT app.

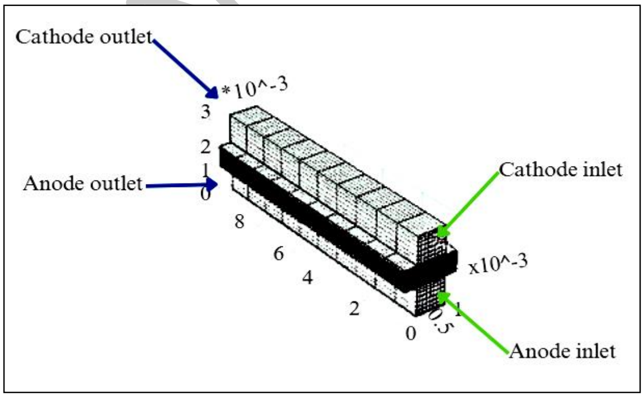


Figure 3. The single PEM fuel cell and its components in four dimensions

The domain of this numerical method is a single cell shape. The reactant gases in this system are humidified H and air. The mass flow input was regulated using stoichiometry values of 0.8 on the anode side and 0.6 on the cathode side. Temperatures of 389, 367, and 375 K were used. The operating pressures were respectively 345, 199, and 134 kPa. The model's active area is 55 cm2, and the channels are 3 mm wide and 2 mm deep. The ribs are 2 mm wide. The geometrical attributes and simulation settings are shown in Table 1.

2.3. Boundary conditions

After it was determined that the mesh was adequate, it was transferred to the FLUENT setup function to begin iterations. The boundary restrictions are constant cathode and anode mass flow rates at both incoming gas pathways, as well as a constant pressure condition at the channel's output. To improve parallel computational power, the F-cycle was used. Bi-conjugate gradient stability was employed for species content, water saturation, electronic and protonic potential because it offers superior convergence results than any other stabilisation method. The mass flow intake category was chosen for the cathode and anode regions of the reactant inlet temperature, and the pressure outlet was chosen for the gases output.

2.4. Computational domain

This research uses a three-dimensional framework of a PEMFC. The geometric model of a solitary fuel cell was combined and intertwined using the MATLAB SIMULINK mesh interfaces procedure, which included features such as cathode and anode gas flow routes, membrane, FLC, current collectors and CLs. It was completed using the spontaneous meshing approach, with the model's size parameter set to homogeneity. The element order was straight, and the relevance axis was fine. The changeover was meant to be very quick. There are 59,160 nodes and 85,173 components in these settings. There are 41,999 grid cells in the whole computational area.

2.5. Numerical simulation

The underlying system of formulas used to solve the mathematical model in this work was presented. These formulas include species, energy, weight conservation, charge, and momentum charge transfer equations. The bulk flux propagation Ji, of I species is provided along direction by:

$$\mathrm{J}_{i,\epsilon} = -\rho \mathrm{D}_i \frac{\partial Y_i}{\partial \epsilon} \tag{1}$$

the diffusion coefficient Di as:

$$\frac{\mathrm{D}_i \varepsilon^{1.5} \mathbf{D}_i^{O} \left(\frac{P_o}{P}\right)\left(\frac{T}{T_o}\right) 3}{2} \tag{2}$$

where DOi stands for the permeability of I species at 1 atm and 300K, and so on. The membrane electrolyte's conductivity is influenced by its moisture and temperature.Water produced by the electrochemical reaction disperses to the anode area, with reverse diffusion and electro-osmotic force influencing water transport in the membrane. A PEMFC's ionic permeability is calculated as follows:

$$\sigma_{\mathrm{mem}} = \epsilon\left(0.514\lambda - 0.326\right)\exp\left[1268\left(\frac{1}{303} - \frac{1}{T}\right)\right] \tag{4}$$

The porosity of the membrane is #, and the amount of water in the membrane is _, which is described as:

$$\lambda = \begin{cases} 0.043 + 17.18a_k - 39.85a + 36a_k^3 & a_k < 1 \\ 14 + 1.4\left(a_k - 1\right) & a_k < 1 \end{cases} \tag{5}$$

The activity of fluid is a_k, and it can be calculated using the formulas below:

$$a_k = \frac{P_{\mathrm{vap}}}{P_{\mathrm{sat}}} \tag{6}$$

The only nonzero origin values or transfer currents within the catalytic layer are Rsol = -Ra on the anode surface and Rsol = Rc on the cathode surface. In the membrane stage, Rmem = +Ra on the anode surface and Rmem = Rc on the cathode surface. The following is how the Butler–Volmer formula is used to calculate the exchange rate densities, Ra and Rc:

$$\mathrm{R_a} = i_a^{ref}\left(\frac{H_2}{H_{2ref}}\right) r_a \left[\exp\left(\frac{\alpha_a F_{n_a}}{RT}\right) - \exp\left(-\frac{\alpha_a \Gamma_a}{RT}\right)\right] \tag{7}$$

$$\mathrm{R}_c = i_c^{ref}\left(\frac{O_2}{O_2\ \mathrm{ref}}\right) r_c \left[\exp\left(\frac{\alpha_c\ \mathrm{F}_c}{RT}\right) - \exp\left(-\frac{\alpha_c \mathrm{In}_c}{RT}\right)\right] \tag{8}$$

The open-circuit value of a fuel cell represents the cell's reversible working condition. Owing to the PEM fuel cell's low operating temperatures, this parameter is a function of temperature and concentration. A fuel cell's irreversible operational voltage, on the other hand, is described as:

$$V_{oc} = V_{oc} - n_{\mathrm{lact}} - n_{\mathrm{ohm}} - n_{\mathrm{conc}} \tag{9}$$

where n_{act} stands for activation over-potential, that is the immutability in the cell induced by energy drops during contaminant activation responses; ohm stands for ohmicoverpotential, that is the immutability induced by the movement of ions throughout the electrons and electrolyte across the active material and diodes; and conc stands for mass transfer or intensity over-potential, that is induced by the fuel cell's large voltage density procedure.When there is a strong demand for energy, electrochemical reactions use energy more quickly. Integrating a fuzzy logic controller (FLC) into a Proton Exchange Membrane Fuel Cell (PEMFC) system leads to notable enhancements and optimisations that greatly improve the performance and efficiency of the fuel cell. One of the main optimisations involves dynamically adjusting the flow rates of hydrogen and oxygen. Conventional control methods frequently establish flow rates using predetermined parameters, which can result in inefficiencies when operational conditions change. The FLC continuously monitors the load demand and ambient conditions, and adjusts the flow rates in real-time to maintain the ideal stoichiometry of the reactants, thus maximising the efficiency of the electrochemical reaction.

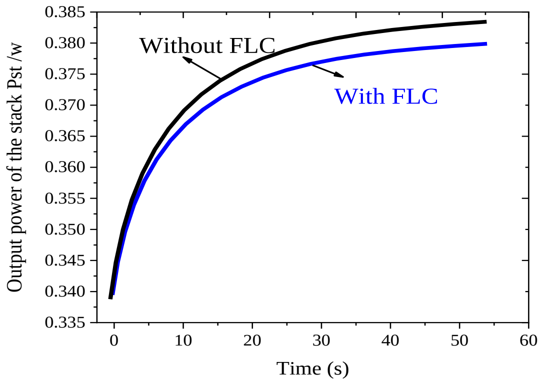


Figure 4 Changes in output power with FLC and without FLC

Another crucial enhancement is the meticulous regulation of the working temperature. Ensuring the fuel cell remains at its proper temperature is essential for achieving peak performance, since any variations might result in higher losses and decreased efficiency. The FLC utilises real-time temperature data to make precise modifications, effectively managing the heat produced by the electrochemical reactions and meeting the cooling needs, so ensuring a consistent and ideal temperature range. The FLC also improves humidity management. Ensuring the appropriate level of moisture in the proton exchange membrane is crucial for maintaining optimal ionic conductivity and preventing both membrane dehydration and flooding. The fuzzy controller regulates the humidity levels by utilising real-time feedback, guaranteeing that the membrane remains within its optimal hydration range. Furthermore, the FLC enhances the system's speed of response and stability. The FLC effectively minimises transient inefficiencies and maintains a constant power output by swiftly adjusting to changes in load demands and external variables. The capacity to adapt minimises the likelihood of performance decline and extends the durability of the fuel cell components.

3. Results

3.1. PEM fuel cell output power variation with and without FLC

The PEM fuel cell's output power is shown in Figure. 5(a) beside the FLC reference power. It's evident that the controller was successful in causing the reference power to vary in its electrical flow. The PEMFC system's stack power and voltage output responses without control are depicted in Figure. 4(b). Additionally, it has been noted that as power demands fluctuate, PEMFC's stack power and voltage adjust correspondingly.

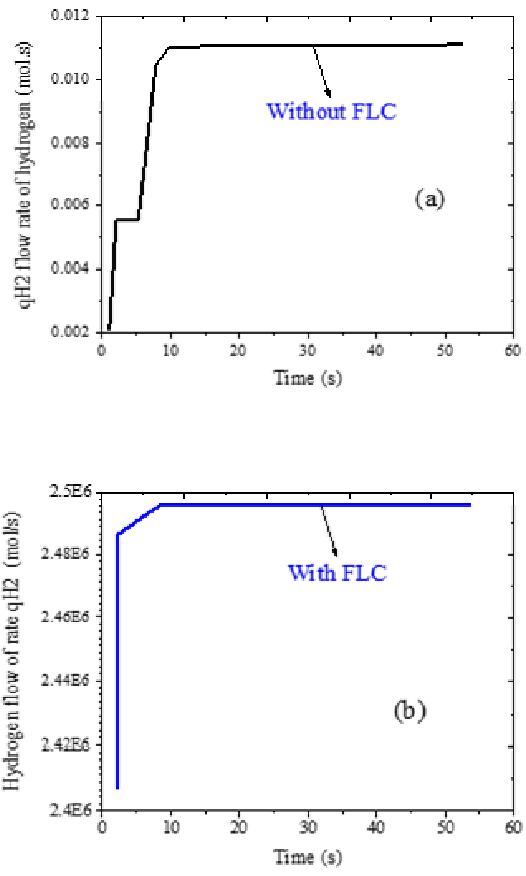


Figure 5. The hydrogen flow rate in two ways: (a) without FLC and (b) with FLC

3.2. The flow rate of hydrogen changes with FLC

It is evident from Figure. 5(a) that there must be a little response delay during the gas reaction process. In general, the PEM fuel cell's output voltage is not able to remain constant. The hydrogen flow rate variation with FLC is depicted in Figure. 5(b). It is clear that when more and more hydrogen is taken from the PEMFC stack, the hydrogen flow rate gradually lowers over time.

3.3. Power density

In this study, the input factors were fuzzified, nine fuzzy sets containing linguistic parameters were created, a rule base was formed, output values were calculated using a rule-based fuzzy model method, and the experimental outcomes were compared to these results. Multiple coefficient of measurement techniques were used to compare these data, and the FL model was used to estimate the results that were not part of this experimental investigation. Similarly, Figure. 6 displays the fuzzy triangle membership functions network for the output variable.

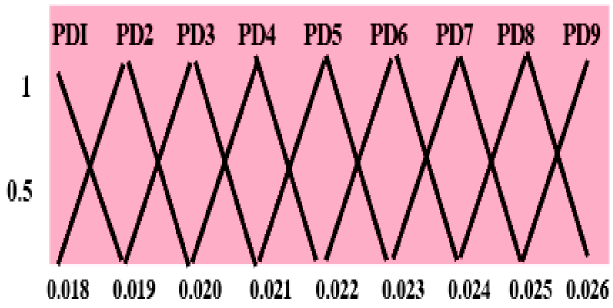


Figure 6. power density using FLC

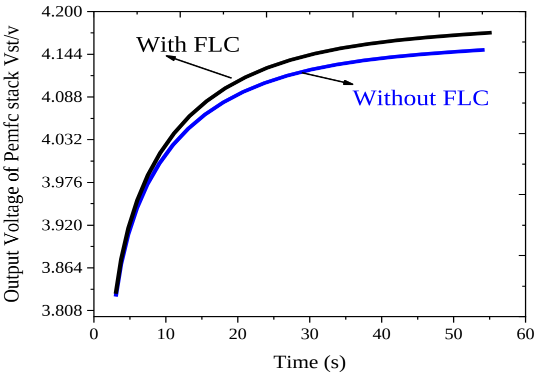


Figure 7. shift in output voltage with FLC and without FLC

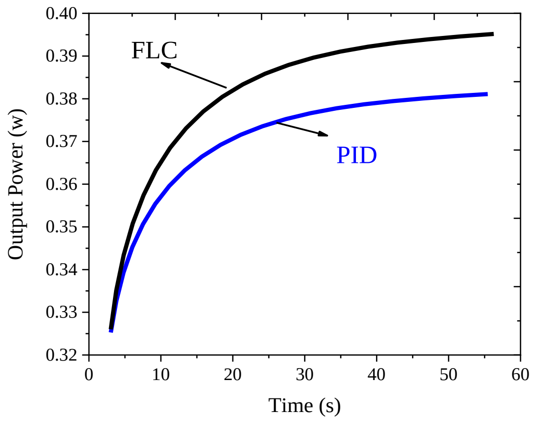


Figure 8 Fuzzy logic control and PID output power curves

3.4. Output voltage change of PEM fuel cell with and without FLC

When the output power of a PEMFC system rises, so does the output voltage. The relationship between the FC system's voltage and power validates the PEMFC model's dependability. As seen in Figure. 7, the transient result of the PEM fuelcell voltage system to load variations varies depending on the system's power supply. Generally speaking, the PEM fuel cell's voltage output cannot be kept constant, as shown in Figure. 7.

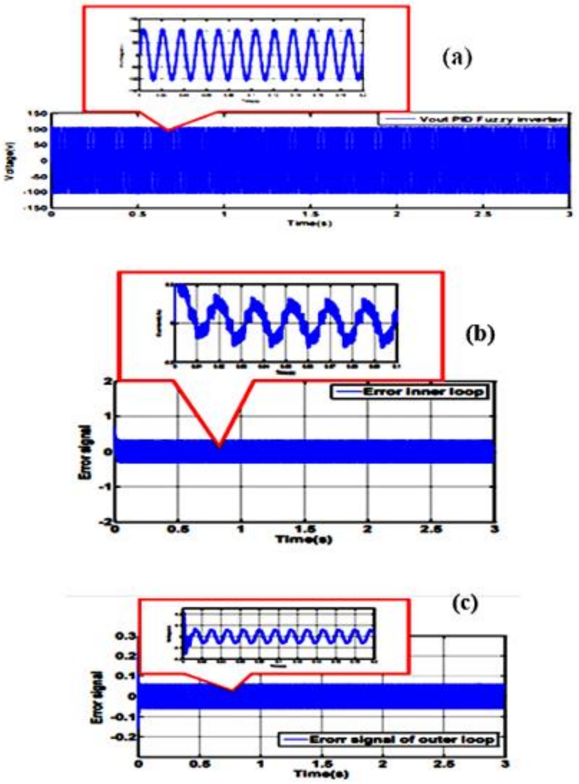


Figure 9 (a) The inverter's signal for output with fuzzy PID (b) Fuzzy PID error signal for the inner loop of the inverter; (c) Fuzzy PID error signalling for the outer loop of the inverter

Fuzzy logic controllers (FLC) have significantly enhanced the power density of Proton Exchange Membrane (PEM) fuel cells by addressing inherent uncertainties and non-linearities. PEM fuel cells generate electrical energy through electrochemical reactions, which are influenced by operational factors like temperature, pressure, humidity, and gas flow rates. Conventional control approaches often struggle to handle these dynamic and unexpected characteristics, leading to suboptimal performance. FLCs, designed to replicate human decision-making, can handle complex and ambiguous data by employing predefined rules and membership functions to assess and modify control actions in real-time. Incorporating a fuzzy logic controller in a PEM fuel cell system requires the development of a knowledge base with IF-THEN rules, which are used to determine the most favorable operating conditions by consistently monitoring performance and making instantaneous changes to input variables. FLCs can regulate hydrogen and oxygen flow rates, temperature, and pressure within the fuel cell to maintain optimal reaction conditions, resulting in enhanced energy conversion efficiency and minimizing losses related to transient states and changing loads. Furthermore, FLCs improve the system's response time and stability, reducing downtime and inefficiencies by promptly responding to changes in operating conditions. Fuzzy logic's flexibility and adaptability make it ideal for real-time control of PEM fuel cells, resulting in consistent high performance and enhanced power output.

3.5. Fuzzy PID Control modelling for pem fuel cell

The system output curves for the fuzzy and PID controllers on the same time scale are shown in Figure. 8. In order to assess performance, both controllers were tested for a particular input signal for a 60-second period. The output is smooth and free of overshoot for both controllers. However, fuzzy controller outperforms PID controller for both rise and settling times. Compared to traditional PID controllers, fuzzy controllers have shorter rise and settling times and help the system reach a steady state much faster.

Figure 9 (a) displays the sine wave, which is the fuzzy PID inverter's output figure, in the time frame [-100,100]. Figures 9(b) and 9(c) display the faults in the both outer and inner loops.

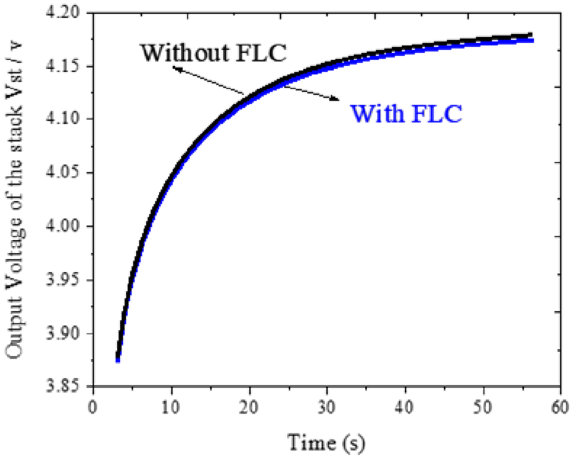


Figure 10. Comparison between output voltage change without FLC and change with FLC

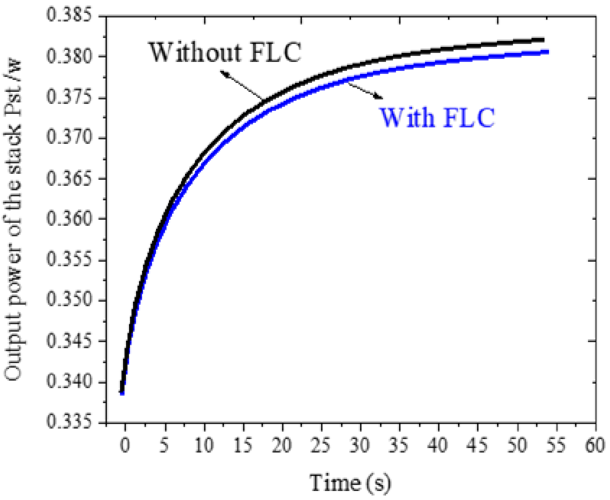


Figure 11. A comparison of the output power changes with and without FLC

Lastly, the suggested controller's robustness is demonstrated through modelling of the controller in noisy conditions, and its performance is contrasted with that of the conventional PID. With the advancement of technology, fuzzy control systems have surpassed traditional PID control systems in popularity and dependability. Every process's uncertainty can be handled using a fuzzy logic control system. PID controllers are widely utilised for process control in any industry. However, occasionally displays subpar performance. It is evident to us from a comparison of these numbers that the FLC suggested in this work has the advantage of a quicker time response and greater precision. The simulation findings, which are displayed in Figure. 10, 11, have remarkably similar features. In 40 seconds, the output power stabilised at 0.382 W, and the PEMFC voltage returned to a stable state at 4.14 V. The MATLAB SIMULINK modelling software was used to run simulations in order to confirm the viability of the suggested fuzzy controller. PEM fuel cells primarily consist of 2 electrodes, known as the anodes and cathodes.

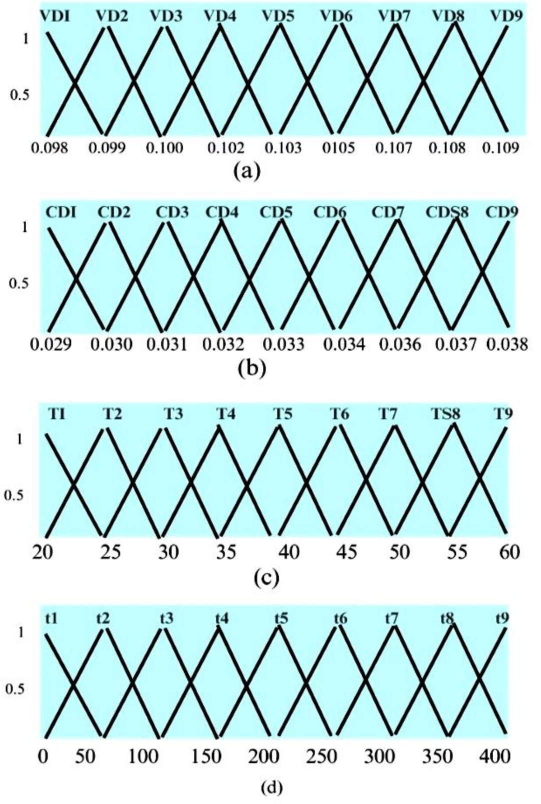


Figure 12. Four input variables with fuzzy membership functions. The following fuzzy set graphics are (a) VD; (b) CD (c)T (d); t;

The PEM fuel cell serves as a barrier between them. A small layer of platinum catalyst is applied to one edge of both electrodes. Fuel cell anode edges are used to supply hydrogen for fuel. In platinum catalyst existence at the anode, it splits into free ions and electrons. An electrical current is formed by the free electrons being utilised in the outer loop. Protons travel to the cathode after passing through the PEM, where they combine with surrounding oxygen to produce heat and clean water. Proton conduction-capable membranes made of polymers are the key component of PEM fuel cells. The fuel cell membrane's job is to move protons as quickly as possible from the anode to the cathode region. To prevent short circuits, the polymer electrolyte that is to be employed in the fuel cell membrane must permit proton transfer and be devoid of electrical conductivity. Furthermore, the fuel must be able to travel through the membrane. Figure. 12 displays the fuzzy triangle membership functions for each of the input variables.

4. Conclusion

This study develops a control system, comprising the FLC controller, for regulating the flow rate of input gases, as well as a comprehensive mathematical modelling and MATLAB SIMULINK model for the PEM fuel cell. The simulation's findings demonstrate the viability of the FLC with its three primary components—fuzzification, fuzzy rule base, and defuzzification—which are also utilised to regulate the flow rate of input gases. The two loops that make up the single phase inverter's control structure are placed in a cascaded pattern. Two loops form the control framework: an exterior feedback loop called the cascade controller and an inside loop called the inductor current. Designing a current mode fuzzy and PID controller forms the basis of control law. This work presents a control approach for a DC/DC boost converter that uses a fuzzy PID controller. The standalone system, which uses a fuel cell as its main source of energy and a voltage-generating inverter, is designed to generate a high-quality sinusoidal output voltage. Particularly for standalone uses, the suggested single-phase inverter is appropriate for producing power for homes. Along with strong robustness, the control approach has outstanding both static and dynamic characteristics. By comparing the system's performance using FLC, its efficacy is assessed. With FLC, the output power response is more precise and superior than it would be without FLC. Therefore, fuzzy controllers perform better than PID controllers. This indicates that the fuzzy controller tracks the output voltage at the required value with extremely good efficiency and resilience characteristics. More research, though, should validate whether the findings can be applied to a hardware control's actual implementation. This study showcases the exceptional efficacy of Fuzzy Logic Controllers (FLC) in enhancing the efficiency of PEM fuel cells by dynamically controlling gas flow rates. FLC surpasses conventional PID controllers, guaranteeing accurate and robust power generation in diverse circumstances, which is essential for improving sustainable energy solutions. The study's findings emphasise the capacity of FLC to enhance dependable and effective PEM fuel cell technologies, therefore facilitating wider use in renewable energy systems.

Abbreviation

FLC	fuzzy logic controller.

Competing interests

The authors declare that they have no competing interests.

Funding

This research study is sponsored by the **institution name**. Thank you to this college for supporting this article!

Availability of data and materials

Not applicable

Authors' contribution

Author A supports to find materials and results part in this manuscript. Author B helps to develop literature part.

Acknowledgement

I offer up our fervent prayers to the omnipotent God. I want to express my sincere gratitude to my co-workers for supporting me through all of our challenges and victories to get this task done. I want to express my gratitude for our family's love and support, as well as for their encouragement. Finally, I would like to extend our sincere gratitude to everyone who has assisted us in writing this article.

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