Performance Analysis of a Fuel Cell Connected to a DC-DC Boost Converter

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Abstract- The following paper presents performance analysis of a DC-DC (Direct Current- Direct Current power conversion) boost converter coupled Proton Exchange Membrane Fuel Cell. The fuel cell proves to be a promising source of clean and efficient energy, but it requires a voltage boost to match the demands of many practical applications. DC-DC boost converter is being used for voltage conversion in power electronics. The characteristics of fuel cell coupled to the DC-DC boost converter under various operating conditions, including different loads and input voltages, is investigated. MATLAB is being used to model the fuel cell connected to DC-DC boost converter and to analyse their performance. Use of various controllers like PI, Fuzzy Controller have been simulated and results were compared. Simulation results indicate remarkable improvement when comparing the fuzzy logic controller with traditional PI and PID controllers. Moreover, the system's dynamic response is significantly enhanced, with a rise time of 0.00133 sec and a settling time of 0.00181 sec, showcasing the effectiveness of proposed fuzzy-logic based control strategy. Importantly, the system achieves peak overshoot of nil, indicating superior stability and performance compared to conventional control methods. The results show that DC-DC boost converter can effectively rise voltage output of fuel cell and improve its efficiency.

Keywords DC-DC Boost Converter, Proton Exchange Membrane Fuel Cell, Fuzzy Controller, Hybrid Controller

1. Introduction

Fuel cells (FC) have surfaced as a potential alternative energy solution for an extensive range of uses, encompassing transportation, stationary power production, and mobile gadgets. Unlike traditional combustion-based power sources, fuel cells generate energy using electro-chemical reaction between an oxidizing agent and fuel cell. This process results in low emissions and high efficacy, making fuel cell a viable choice for meeting the growing demand for clean energy. However, fuel cells typically have a low voltage output and require a voltage boost to match the requirements of many practical applications. One common approach for voltage conversion in power electronics is DC-DC boost converter, which can alter level of output voltage for a given power source while maintaining the same power level. Here the DC-DC boost converter is utilized for improving performance of FC systems and enhance their suitability for practical applications [1].

In this work, operation analysis of a FC connected to boost converter is conferred. Investigation of DC-DC boost converter and FC are carried out under various operating conditions, including different loads and input voltages. Simulation tools are used to model the FC and DC-DC boost converter and analyse their results and outputs. Software simulations rely on mathematical models and assumptions to replicate the behaviour of fuel cells. These models may not perfectly capture all the complex physical and chemical processes occurring within the fuel cell system. As a result software simulations may have inherent inaccuracies especially when simulating complex phenomenon or under non-standard operating conditions. The research provides valuable insights into the architecture and optimisation of FC systems for practical utilisations. The primary objective of this research is to comprehensively investigate and analyse the performance of a fuel cell system integrated with a DC-DC boost converter, with a specific focus on its applicability in providing sustainable and reliable energy to rural areas for their daily power needs. This fuel cell technology can be a valuable energy solution for military operations in remote forested locations and rural areas lying across costal region.

1.1 Literature Review

Fuel cells can achieve higher energy conversion efficiencies compared to combustion based power generation systems depending upon type and application fuel cell can have efficiency ranging from 40% to 60%. In[2] A.Sahabani has done three-phase phase boost-inverter topology for power conversion that is employed to enhance FC voltage output. The boosting function is necessary because fuel cells typically generate a low output voltage, which may not be sufficient for certain applications. The boost function increases the voltage to a desired level, allowing for compatibility with the intended load or system requirements. This is achieved by using power electronics components such as inductors, capacitors, and switches to store and manipulate energy. In [2] the converter operates in dual distinct conditions: (a) discharging technique (b) charging technique. In the charging technique, energy is transmitted from the input (fuel cell) to the output. In the discharging mode, energy accumulated in the capacitor and inductor is being transferred to the output.

In [3] M.Jang has utilized boost-inverter to connect fuel cell to a single phase grid. The electrochemical phenomenon involves, the conversion of oxygen and hydrogen into heat and electricity. The FC stack generates low DC voltage output, typically in the range of a few hundred volts. The boost converter operates by controlling the duty cycle of power switches such as Metal Oxide Semiconductor Field Effect Transistor (MOSFETs) or Insulated Gate Bipolar Transistor (IGBTs) to regulate the voltage across an inductor. The boost converter stores energy in the inductor during the "on" state of the switches and releases it to the output during the "off" state, resulting in voltage boosting. The boosted DC voltage is then fed to the grid-connected inverter stage. This configuration offers several advantages, including high energy efficiency, reduced environmental impact, and the ability to participate in grid services such as peak shaving and grid support. It facilitates the integration of fuel cell technology into the electrical grid, enabling the usage of clean sustainable energy sources to produce power.

In [4] FIC (Feedback-Integral Control) of a FC incorporated with boost converter control strategy is employed to monitor the yield of a boost converter that is associated with FC system. Boost converter exhibits a vital function in fuel cell system by raising the low DC voltage generated by FC stack for amplifying voltage suitable for various applications. However, due to uncertainties and disturbances, such as changes in the FC stack operating conditions, load variations, and the yield of the boost converter may deviate from the desired set point. The state feedback component of the control algorithm involves estimating the system's states (such as the converter's output voltage and current) and using this information to design a control law. The control law adjusts the duty cycle of the converter's power switches in accordance to deviation between the estimated states with the desired reference values. By continuously monitoring and adjusting the duty cycle, the control algorithm ensures that the output voltage tracks the desired set point.

In [5] Ramos-Paja has described methods for minimal consumption of fuel for Proton Exchange Membrane (PEM) FC. PEM FC are specialized devices that harness the potential energy accumulated in hydrogen and oxygen, enabling them to generate electrical energy by means of an electrochemical process.. The efficacy of a FC system is highly relying on functioning conditions, particularly amount of fuel consumed. Therefore, optimizing the fuel consumption can lead to improved overall system efficiency and reduced operating costs. The minimum fuel consumption strategy involves adjusting the operating parameters of FC system to find the optimal controlling point that minimizes fuel consumption. These operating parameters may include the air flow rate, hydrogen flow rate, temperature, and other relevant parameters.

1.2. Model of a Fuel Cell

Fuel cell operates on mechanism which transmute the energy amassed in a fuel and an oxidizer into electrical energy through a chemical procedure. The various categories of fuel cell are as follows:

1. Proton Exchange Membrane Fuel Cells (PEMFCs): The crucial component of a PEMFC is polymer electrolyte membrane, which serves as a selective barrier, allowing only protons to pass through while blocking the passage of electrons [1]. Consequently, the electrons are compelled to traverse an external pathway, leading to the generation of an electrical flow that can be utilised for a wide range of objectives. The PEMFC is rated at low temperatures, typically ranging from 60˚C to 80˚C.
2. Solid Oxide Fuel Cells (SOFCs): Anode is composed of a nickel-ceramic compound known as Ni-YSZ, while the cathode, typically made of Lanthanum Strontium Manganite (LSM) or Lanthanum Strontium Cobalt Ferrite

(LSCF). The working functionality of an SOFC revolves around the movement of oxygen ions between cathode and anode. In contrast to numerous other fuel cell variants, a distinct phenomenon occurs in which protons migrate from the anode to the cathode. Once they reach the anode, these oxygen ions undergo a chemical reaction with the fuel, resulting in the production of water or carbon dioxide, heat and notably electrical energy [1].

3. Direct Methanol Fuel Cells (DMFCs): It is a specialized variety of a fuel cell that capitalizes on methanol as its fuel source. Unlike many other types of fuel cells, it doesn't necessitate the prior conversion of the fuel into hydrogen, a feature that brings simplicity and convenience [1]. The anode, typically composed of platinum-ruthenium catalyst, promotes the oxidation of methanol, leading to the production of electrons, protons, and carbon dioxide. Following their generation, the protons subsequently journey through the PEM towards the cathode, whilst electrons simultaneously traverse an external circuit, effectively establishing an electric current [1].
4. Alkaline Fuel Cells (AFCs): It can be classified as a distinct type of fuel cell that leverages the movement of hydroxide ions (OH-) within an alkaline electrolyte to generate electrical energy. The anode, often made of a finely divided nickel or a similar metal, facilitates the oxidation of hydrogen, releasing electrons and forming water by combining with hydroxide ions from the electrolyte. The generated electrons traverse an external circuit, thereby creating an electric current [6].
5. Molten Carbonate Fuel Cells (MCFCs): It represents a particular category of fuel cells characterized by the use of a molten carbonate salt mixture as an electrolyte [6]. The core structure of an MCFC constitute a cathode, an anode, and a molten carbonate electrolyte, typically held within a porous, lithium aluminium oxide (LiAlO2) matrix. Within the anode, typically composed of nickel, a reaction occurs among the hydrogen and carbonate ions derived from the electrolyte. This reaction leads to liberation of water, carbon dioxide, and electrons. Subsequently, these electrons traverse an external pathway towards the cathode consequently generating an electric current.
6. Phosphoric Acid Fuel Cells (PAFCs): This particular fuel cell is characterised by its utilisation of phosphoric acid as the electrolyte and its operation at elevated temperatures, usually between 150°C and 200°C.The anode, often composed of finely dispersed platinum on a carbon substrate, facilitates oxidation of hydrogen, liberating positively charged and negatively charged particles in the process [6] The movement of protons towards the cathode is facilitated by their passage through the electrolyte, whereas the electrons adopt an external trajectory, thus establishing an electric current.

Every individual fuel cell has its own unique features like working temperature, efficiency, and fuel compatibility. The selection of fuel cell technology relies on the unique demands and purposes of the given system.

1.3. Working of Fuel Cell

A FC works by transforming the energy, which is obtained from the chemical reaction of a fuel and an oxidising agent into electrical energy through an electrochemical reaction [7]. In a typical PEMFC operation, the anode receives a supply of hydrogen, while the cathode receives either oxygen or air. The fuel and oxidizing agent must be pure, as impurities can damage the FC. An electrochemical process occurs: At anode, hydrogen molecule separates into protons (H+) and electrons (e-) via oxidation [8]. Protons move across a Polymer Electrolyte Membrane (PEM) towards the cathode, whereas electrons traverses along an external circuit in the same direction. Upon reaching the cathode, protons and electrons fuses with oxygen, leading to the formation of water molecules in a process referred to as reduction. The traversing of electrons across the circuit generates electrical energy, which can be used to power a load or charge a battery. The residues of the electrochemical phenomena are heat and water. The heat can be recovered and used for heating or other applications, while the obtained water is typically removed from the fuel cell as waste [9]. Overall, the FC operates continuously until the fuel and oxidizing agent are given and the electrochemical reaction takes place. The fuel cell is highly efficient, typically around 40% to 60%, depending on the specific fuel cell design and operating conditions.

However, the general principle is that a fuel and an oxidizing agent are brought together in the presence of an electrolyte, and an electrochemical reaction takes place to produce electricity and by-products such as heat and water [7].

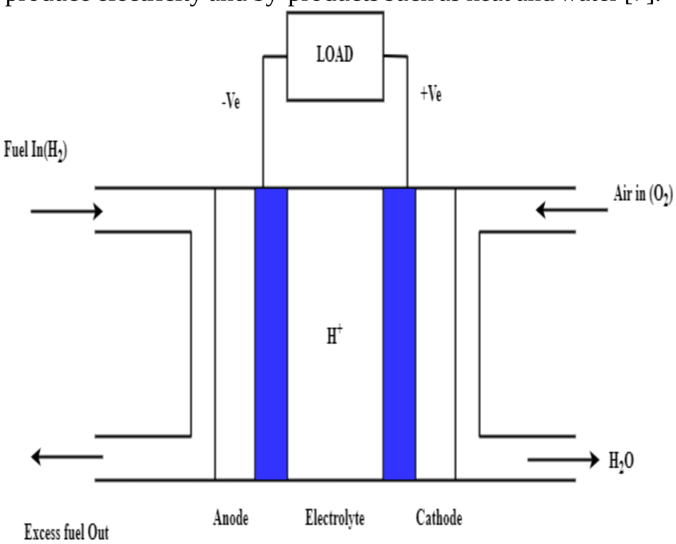

Fig 1. Fuel cell system arrangement

At anode (negative electrode) [18]:

$$2H_2\,(hydrogen) \rightarrow 4H^+\,(protons) + 4e^-\,(electrons) \quad (1)$$

At the cathode (positive electrode):

$$O_2\,(Oxygen) + 4H^+\,(protons) + 4e^-\,(electrons) \rightarrow 2H_2O\,(water) \quad (2)$$

Overall reaction:

$$2H_2 + O_2 \rightarrow 2H_2O + electrical\ energy \quad (3)$$

At the anode, hydrogen gas undergoes a reaction with oxygen ions, resulting in formation of gaseous water and the release of electrons, which serve as an electrical energy generator. Oxygen interacts with the electrons collected from the electrode at the cathode, resulting in oxygen ions [7].

The equation given below describes the output voltage or yield of the FC that uses fuel along with air as its reactant:

$$V_{fc} = E_{nernst} - V_{act} - V_{ohm} - V_{conc} \quad (4)$$

Where,

V_{fc} *is the output of PEM (Volts)*

E_{nernst} *refers to Nernst voltage (Volts)*

V_{act} *refers to voltage drop activation*

V_{ohm} *refers to ohmic voltage drop*

V_{conc} *refers to voltage drop concentration*

As below, known Nernst formula is used to calculate the open-circuit electromotive force of a stack of N_o cells in sequence

$$E_{nernst} = E_0 + \frac{RT}{2F}\ln\left(\frac{P_{H2}P_{O2}^{0.5}}{P_{H2O}}\right) \quad (5)$$

Where,

E_0 refers to reaction free energy's voltage(1.4V)

R refers to universal gas constant

T refers to PEM operating temperature

F refers to Faraday's constant

$P_{H_2}, P_{O_2}, P_{H_2O}$ are hydrogen, oxygen and water partial pressures, respectively. The equations regarding $P_{H_2}, P_{O_2}, P_{H_2O}$ is given as:

$$P_{H2} = \left(\frac{\frac{1}{K_{H2}}}{1+\tau_{H2}}\right)\left(q_{H2} - 2K_r I_{fc}\right) \quad (6)$$

$$P_{O2} = \left(\frac{\frac{1}{K_{O2}}}{1+\tau_{O2}}\right)\left(q_{O2} - 2K_r I_{fc}\right) \quad (7)$$

$$P_{H2O} = \left(\frac{\frac{1}{K_{H2O}}}{1+\tau_{H2O}}\right)\left(2K_r I_{fc}\right) \quad (8)$$

$$q_{H2} = \frac{2K_r}{U_{opt}}\left(\frac{1}{1+\tau_f s}\right) \quad (9)$$

$$q_{O2} = \frac{q_{H2}}{r_{OH}} \quad (10)$$

Where, q_{H_2} flow rate of fuel, q_{O_2} flow rate of oxygen , $K_{H_2}, K_{O_2}, K_{H_2O}$ the hydrogen, oxygen as well as water molar value constants, respectively, $\tau_{H_2}, \tau_{O_2}, \tau_{H_2O}$ are the hydrogen, oxygen and water response time, respectively, τ_f is the response time for fuel in seconds, U_{opt} is the most effective use of fuel, r_{OH} is the hydrogen to oxygen ratio. The energy necessary to achieve the energy constraints in order for the chemical reaction to commence is referred to as activation loss. Anode and cathode side activation losses are provided:

$$I_{fc} = I_O\left(e^{(\alpha_1 F/RT)V_{act}} - e^{(\alpha_2 F/RT)V_{act}}\right) \quad (11)$$

$$V_{act} = \frac{RT}{n\alpha F}\ln\left(I_{fc}/2I_O + \sqrt{\left(I_{fc}/2I_O\right)^2 + 1}\right) \quad (12)$$

Meanwhile, the reduction in performance due to the delayed dispersion of hydrogen along with oxygen gases within the porous components of the cell is referred to as concentration polarization loss and the equation is stated as:

$$V_{conc} = -\frac{RT}{nF}\ln\left(1-\frac{I_{fc}}{I_L}\right) \quad (13)$$

The influx of electrolyte, as well as the flow of electrons across the electrodes, would often encounter resistance. Both of these defeats add up to an ohmic loss. The cell's intrinsic resistance varies with temperature and is calculated using the equation:

$$V_{ohmic} = \left(\gamma \exp\left[\beta\left(\frac{1}{T_O}-\frac{1}{T}\right)\right]\right)I_{fc} = rI_{fc} \quad (14)$$

Where, $T_O = 973K$, T represents the temperature coefficient of the fuel cell, and r is the internal resistance, $\gamma = 0.2\Omega$ and $\beta = -2870K$ are the static coefficients of the fuel cell.

The voltage output for uni stack FC is given as:

$$V_{fc} = E_{fc} - V_{act} - V_{conc} - V_{ohmic} \quad (15)$$

Substituting the values of E_{fc}, V_{act}, V_{conc} and V_{ohmic}

$$V_{fc} = N_0\left\{E^0 + \frac{RT}{2F}\left(\ln\frac{P_{H_2}P_{O_2}^{0.5}}{P_{H_2O}}\right)\right\}$$

$$-A\ln(i) - m(\exp(ni)) - rI_{fc}$$

(16)

The fuel cell performance is commonly represented through a polarisation curve, that illustrates the nonlinear relationship between cell voltage and current (V-I) characteristics. While some research papers only consider the ohmic loss of a fuel cell, this study takes into account all types of losses, including ohmic loss, activation loss, and concentration loss [10], [11]. Fig 2 presents the analysis of the cell voltage versus current density characteristic for general FC system. The graph shows a linear region known as the ohmic polarisation region. In this region, the voltage declines as the current density intensifies due to the internal resistance exhibited by different components. At lower current levels, the impact of ohmic loss is comparatively less pronounced, and the rise in output voltage is predominant attributable to the chemical reactions' activity. This region is referred to as the active polarisation region. However, at very high current densities, voltage drops considerably due to reduced gas exchange efficiency and water flooding in the catalyst. This region is known as the concentration polarisation region. It is important to consider these characteristics when optimizing fuel cell operating parameters, designing power conditioning units, controllers, and fuel cell stack systems.

During the chemical process in a fuel cell, hydrogen undergoes oxidation at the anode, resulting in the generation of protons and electrons. The migration of protons towards the cathode occurs by passing through the proton exchange membrane, while the electrons traverse an external circuit, resulting in the generation of electrical power [12]. On cathode side, oxygen combines with negatively charged electrons and positively charged protons, leading to formation of water molecules.

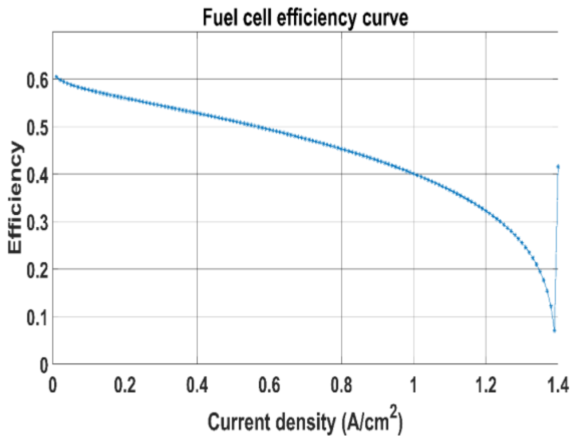

Fig 2: Fuel Cell Polarization Curve (Voltage vs Current Density)

2. Method

2.1Power Conditioning unit

A Power Conditioning Unit (PCU) can be defined as an electronic equipment that is used to regulate, control, and protect the flow of electrical power from a power source to a load. It is typically used in electrical systems where the input power is variable, unstable, or requires conditioning before it can be used by the load. The major role of a PCU is to ensure that power supplied to load is stable and within the required range of voltage and frequency [13]. It achieves this by monitoring the input power and adjusting the power at the output to meet the load's requirements. The PCU works with the objective of converting the feeble dc voltage produced by a fuel cell to a higher voltage level. The PCU comprises of two components: a DC-DC boost converter and a Proportional Integral Controller in its feedback path [14].

2.1.1 Boost Converter

In this chemical transformation, hydrogen experiences oxidation at the anode, producing positively charged protons and negatively charged electrons. The positively charged protons navigate across the PEM in direction of the cathode, while electrons make their way via an external circuit, generating electric energy. Upon reaching the cathode, oxygen combines with electrons and protons, culminating in the creation of water molecules.

In a boost converter, energy that is stored in the magnetic field of inductor as a result of changes in current values. The principle is based on switching mode; there are two types of switching modes available: ON state and OFF state. Upon closing the switch, current flows through the inductor, increasing its energy storage. The diode is reverse-biased during this phase, preventing current from flowing through it [15]. Opening the switch collapses the inductor's magnetic field, thereby inducing a voltage through the inductor that is greater compared to the voltage at the input. This voltage makes the diode forward biased, which lets current from inductor to flow through the diode and into the output capacitor and load.

Following state space equations represent boost converter during ON state and during OFF state respectively [16] :

$$\begin{cases} x = A_1 x + B_1 u & t \in [0, dT_s] \\ x = A_2 x + B_2 u & t \in [dT_s, T_s] \end{cases} \tag{17}$$

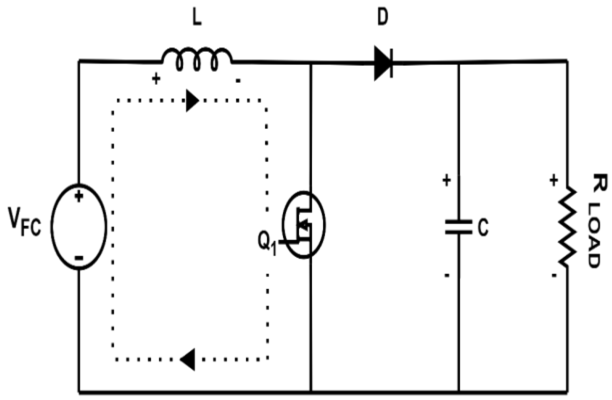

Fig 3. DC-DC Boost Converter during ON State

Boost converter considers the current through the inductor and capacitor voltage as the variables representing its state. When the converter is in the ON state, its state space model is expressed in the form of:

$$\frac{d}{dt}\begin{bmatrix} i_L \\ v_c \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & \frac{-1}{RC} \end{bmatrix}\begin{bmatrix} i_L \\ v_c \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{FC}$$

$$V_o = \begin{bmatrix} 0 & 1 \end{bmatrix}\begin{bmatrix} i_L \\ v_c \end{bmatrix} \tag{18}$$

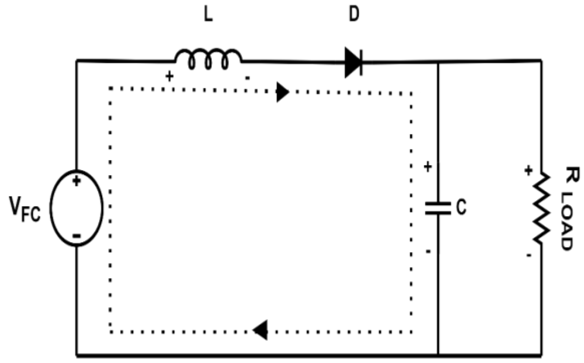

Fig 4. OFF state of DC-DC Boost Converter

$$\frac{d}{dt}\begin{bmatrix} i_L \\ v_c \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{L} \\ \frac{1}{C} & \frac{-1}{RC} \end{bmatrix}\begin{bmatrix} i_L \\ v_c \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{FC} \tag{19}$$

$$V_o = \begin{bmatrix} 0 & 1 \end{bmatrix}\begin{bmatrix} i_L \\ v_c \end{bmatrix}$$

Therefore for formulating state space model it is necessary to amalgate both the converter states. Therefore model of state space can be portrayed as:

$$x = \left(A_1 d + (1-d) A_2\right) x + \left(B_1 d + (1-d) B_2\right) u$$

$$\frac{d}{dt}\begin{bmatrix} i_L \\ v_c \end{bmatrix} = \begin{bmatrix} 0 & \frac{-(1-d)}{L} \\ \frac{(1-d)}{C} & \frac{-1}{RC} \end{bmatrix}\begin{bmatrix} i_L \\ v_c \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{FC} \tag{20}$$

where i_L = Current through Inductor

V_{FC}= Source Voltage

v_c= voltage across capacitor

V_O= Output Voltage

d=Duty Cycle

The following equation depicts ideal boost converter's transfer function in generalized sense

$$\frac{V_o(s)}{d(s)} = G_{d_o}\left(\frac{\left(1-\frac{s}{\omega_{z_1}}\right)\left(1+\frac{s}{\omega_{z_2}}\right)}{\frac{s^2}{\omega_0^2}+1+\frac{s}{Q\omega_0}}\right) \quad (21)$$

$$G_{d_o} = \frac{V_o}{1-d},\ \omega_{z_1} = \frac{R(1-d)^2}{L},\ \omega_{z_2} = \infty,$$

$$\omega_0 = \frac{1-d}{\sqrt{LC}},\ Q = R(1-d)\sqrt{\frac{C}{L}} \quad (22)$$

For switching-mode power supply, MOSFET is commonly used as the switch because it is easy to drive and has fast switching times.

A controller is the brain of a system. To overcome the unregulated supply of voltage and current in converter, controllers are used. A control mechanism is necessary to ensure that the output voltage remains stable and adjusts accordingly as the load fluctuates. This is accomplished by continuously monitoring the output voltage and making significant adjustments in duty cycle of the switch in relation to fluctuations in load. By doing so, control system ensures a consistent output voltage, even as the load conditions vary. This precise regulation not only helps maintain reliable performance but also enhances the overall efficiency and effectiveness of the converter. Basically, it maintains the set point according to demand. The controller usually tries to keep the output parameter closest to the set point or the value of reference point. The DC-DC converter's output voltage regulation is achieved with the help of a controller[17].

An error signal (disparity in between reference and output signal) is being provided to controller, and the controller output is compared with a repeating sequence to generate a gate pulse that is provided to the MOSFET available in the dc-dc converter. The controller usually tries keeping output parameter closest to the set point or to the value of the reference point.

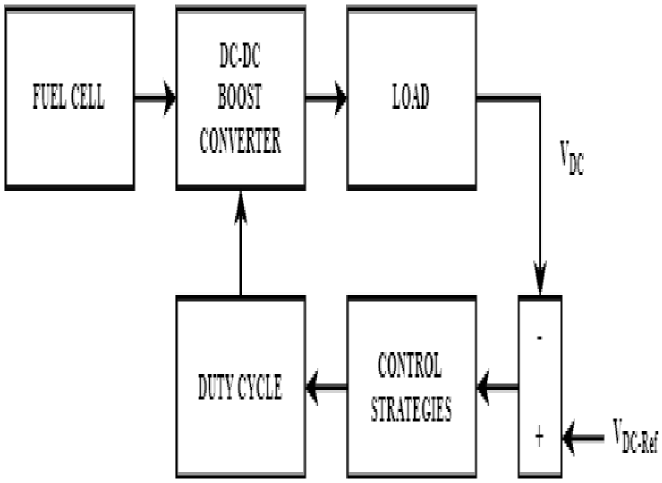

Fig 5: Diagrammatic representation of DC-DC Converter illustrating control strategies

2.2 PI and PID Controller:

The term PI Controller refers to a proportional and integral controller. It is the combination of both controllers. The PI controller is a closed loop where the error signal is calculated by drawing an analogy between output and input of the system to match the set point.

$$u(t) = K_p e(t) + K_i \int e(t)dt \quad (23)$$

PID Controller is the hybrid of derivative, integral and proportional controllers.

$$u(t) = K_P e(t) + K_i \int e(t)\,dt + K_d \frac{de(t)}{dt} \quad (24)$$

It is the feedback loop where the input output gets compared to obtain the error signal.

2.3 Fuzzy Logic Controller (FLC):

During the past few decades, application of fuzzy logic control has become an important aspect of controller design [18]. It has gained popularity for the reasons that it can handle inexact inputs, its working does not need a perfect computational model, and it is best suited for non-linear operations. There are two inputs to a fuzzy logic control: one is error E, and other one is a change in error E. The choice of error is designer dependent, but in most cases it is selected as $\Delta P/\Delta V$.

The FLC (Fuzzy Logic Controller) in this study utilizes seven membership functions for each of its output variable and two input variables. These fuzzy partitions are visually represented in Fig 6, illustrating the linguistic variables assigned to each membership function, like "positive big," "positive medium," "positive small," "zero," "negative big," "negative medium," and "negative small." These semantic designations are utilised to describe and quantify the fuzzy variables within the FLC system [19].

Table 1: Fuzzy Rule Base

		CHANGE OF ERROR						
		NB	***NM***	***NS***	***Z***	***PS***	***PM***	***PB***
ERROR	***NB***	NB	NB	NB	NB	NM	NS	Z
	NM	NB	NB	NB	NM	NS	Z	PS
	NS	NB	NM	NS	NS	Z	PS	PM
	Z	NB	NM	NS	Z	PS	PM	PB
	PS	NM	NS	Z	PS	PS	PM	PB
	PM	NS	Z	PS	PM	PM	PB	PB
	PB	Z	PS	PM	PB	PB	PB	PB

Rule base in the FLC consists of forty-nine rules, which are formulated in the format of "if the error is NM and the rate of change of error is NL, then the output is NL." The inference method employed in this FLC is a basic and straightforward approach using the MIN-MAX method. In this technique, membership function associated with the output for each rule is determined with the application of MIN operator. Final aggregated output is obtained with the application of MAX operator to combine individual rule outputs. The crisp output value is then determined using the centroid defuzzification method, which calculates the centre of gravity of the output membership function to obtain a precise output value.

$$E = \frac{P(K) - P(K-1)}{V(K) - V(K-1)}$$

$$\Delta E = E(K) - E(K-1) \qquad (25)$$

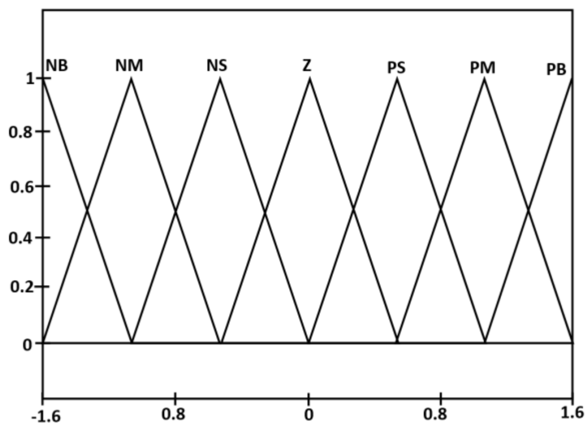

Fig 6: Membership Functions of Fuzzy Controller

FLC comprises of three states: fuzzification, aggregation, and defuzzification. In fuzzification, stage-arithmetical crisp inputs are transformed into semantic variables based on the degree of membership to reliable sets. Membership functions are represented in the above Fig. 6. These membership functions are utilised for assigning grades to linguistic terms.

To evaluate the efficacy of the PEMFC integrated with a DC-DC converter, MATLAB and Simulink were employed for simulation purposes. Several controllers were implemented and compared, and time domain specifications were obtained to facilitate the comparison process. The model was thoroughly analysed under different load conditions to assess its robustness and effectiveness.

3. Results and Discussion

The following section presents the results and discussion of the performance analysis of the fuel cell system integrated with a DC-DC boost converter, utilizing fuzzy logic control. The study encompasses a comprehensive examination of dynamic responses and comparative analysis with traditional control methods such as PI and PID controllers.

Table 2: Simulation Result of Fuel Cell for various loads using PI Controller

SI No.	Reference Voltage (in V)	Load Resistance (in Ω)	Output Voltage (in V)
1	12	50	11.28
2	12	100	24.85
3	12	150	34.68

The above table illustrates the voltage at the output of a boost converter linked with a Proportional-Integral (PI) controller under different load conditions. It should be noted that in a boost converter operating with a small load, the capacitor gradually accumulates charge from the inductor until the voltage reaches a level that may potentially cause a component failure.

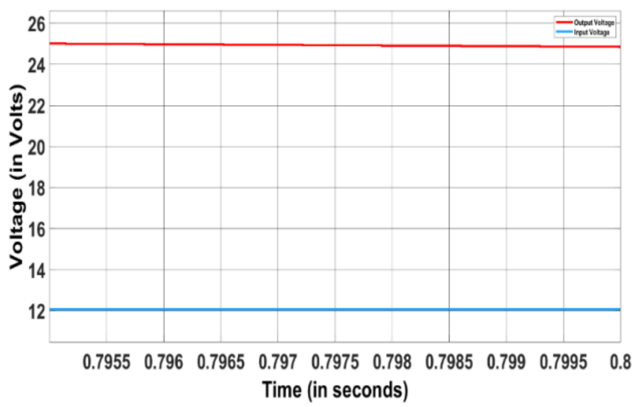

Fig 7: Boost converter output using PI Controller

To improve the research performance, PID controller has been taken into consideration. The below Fig.8 shows the simulation output of a DC/DC energy conversion system using a PID controller. To obtain the output, the entries of

Proportional, Integral, and Derivative controllers are taken as 0.65, 15000, and 0.001, respectively. The below table provides the voltage at the output of a boost converter linked to a Proportional Integral Derivative Controller for different loads of 50 **Ω,** 100 **Ω**, and 150 **Ω.**

Table 3: Simulation Result of Fuel Cell for various loads using PID Controller

SI. No.	**Reference Voltage (in V)**	**Load Resistance (in Ω)**	**Output Voltage (in V)**
1	12	50	11.28
2	12	100	24.85
3	12	150	34.68

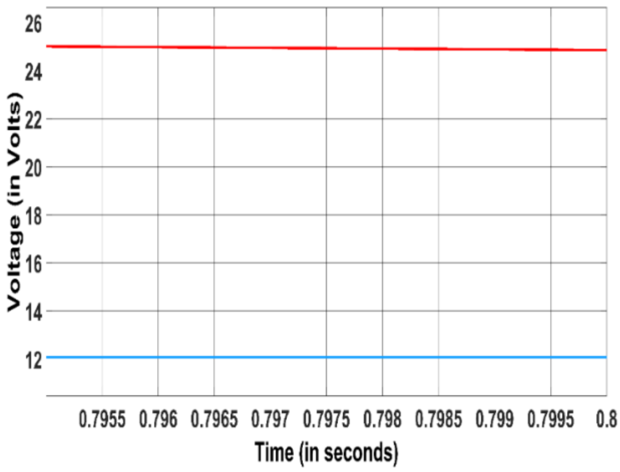

Fig 8: Output waveform of for boost converter using PID Controller

Fuzzy logic focuses on linguistic variables and aims to provide better efficiency. The simulation result of the FLC is shown in Fig. 9. Below table provides the voltage output of a boost converter for various load resistances utilising a fuzzy logic controller. As per the observations, it can be concluded that, without the use of any storage device, a boost converter with a fuzzy controller gives better performance for variations in load.

Table 4: Simulation Result of Fuel Cell for various loads using FL Controller

SI No	**Reference Voltage (in V)**	**Load Resistance (in Ω)**	**Output Voltage (in V)**
1	12	50	13.41
2	12	100	18.7
3	12	150	23.03

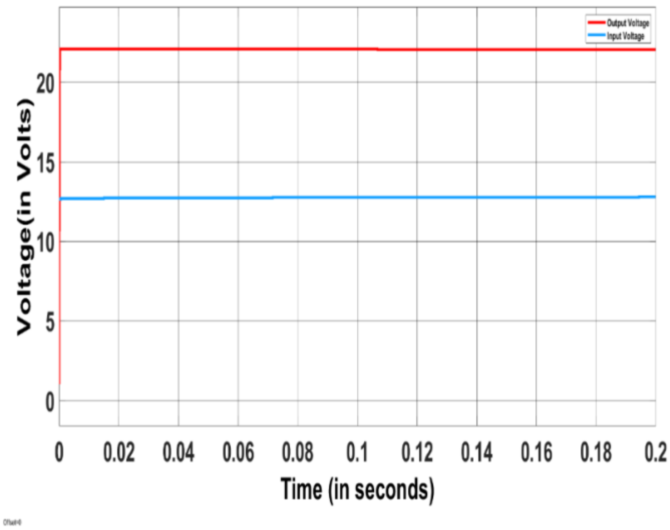

Fig 9: Output waveform of for boost converter using FL Controller

The FC system that is coupled with the boost converter along with different controller strategies are analysed and compared under a variety of parameters. Table V provides an outline of the parameters of system that were utilized for the simulation study. It is possible to draw the following conclusion after examining the table; the FLC offers superior performance, and there is no peak overshoot.

Table 5: Simulation Result of Fuel Cell for various loads using FL Controller

Sl No.	**Controller**	**Rise Time (in sec)**	**Settling Time (in sec)**	**Peak Overshoot (in %)**
1	PI	0.0136	0.0184	1.5
2	PID	0.0129	0.078	5.24
3	FUZZY	0.00133	0.00181	Nil

4. Conclusion

In this study, performance of a fuel cell integrated with a DC-DC boost converter using fuzzy logic control has been explored. To achieve this, successful simulations are conducted using SIMULINK and MATLAB, focusing on control strategies utilizing FC-fed DC-DC BOOST converters. The fuel cell system was modelled in a way that the DC-DC converter enables conversion of DC power to a form that can be connected to an inverter and grid, thus making it usable in rural areas. Various control strategies, including PI, PID, and FUZZY controllers, were investigated in our study. Upon analysis, we found that the FUZZY controller exhibited higher precision, characterized by shorter settling time and rise time, compared to the other controllers. Effective switching of the MOSFET present in the DC-DC boost converter was achieved using pulse width modulation techniques. This model's implementation was made easy through simulation of the DC-DC converter and the selection of an efficient controller.

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