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Modeling and Analysis of Fuel Cell Power Generation System Using Proportional Integral Speed Controller

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ABSTRACT

This paper proposes the modeling and economic analysis of proton exchange membrane type fuel cells. Fuel cells (FC) are electrochemical devices that convert chemical energy into electrical energy. FC offers clean and effective energy production and it undergoes rigorous growth by numerous manufacturers with different applications. FC is a promising new technology for the generation of electrical energy. This technology contains hydrogen and oxygen to produce electrical energy through the electrochemical process. A mathematical model of an FC is developed which shows the cathode and anode, output voltage, and economic analysis of the fuel cells. The simulation results of the fuel cell for a suitable converter controller are proposed in Matlab 2021b software.

Keywords: proton-exchange membrane, fuel cell, photo-voltaic, proportional integral speed.

INTRODUCTION

The traditional use of fossil fuels such as coal, gas, and petroleum, which currently meet more than 90 percent of the world's energy needs, is rapidly running out of fuel [1]. Additionally, the byproducts of their combustion are contributing to global issues like the greenhouse effect and pollution, which constitute an enormous risk to our ecosystem and ultimately to all life on our planet. Solar, wind, tidal, geothermal, and various other renewable energy sources are becoming more popular as alternative energy sources. Photovoltaic (PV) and fuel cell energy from renewable sources have both been extensively used in low-power applications. As clean and effective sources Molten carbonate fuel cell enormous amount of interest. A fuel cell is an electrochemical energy translation device that creates electricity through the conversion of the molecules hydrogen and oxygen into water. Large quantities of current may be generated by fuel cells [3]. The five major types of fuel cell technologies utilized to create electricity with minimal gas pollution are phosphoric acid fuel cells (PAFC), alkaline fuel cells (AFM), solid oxide fuel cells (SOFC), fuel cells with proton exchange membranes (PEMFC), and fuel cells made from molten carbonate (MFFC). The proton-exchange membranes (PEM) plays a vital role in facilitating the electrochemical reactions within the fuel cell [15, 17-20], converting chemical energy, typically from H_2 and O_2 , into electrical energy and H_2O [7]. The PEM consists of a thin, solid polymer electrolyte that is typically made of a perfluorosulfonic acid-based material, such as Nafion. This polymer structure provides excellent proton conductivity while maintaining impermeability to gases and liquids [9]. PEMFCs have gained significant attention as clean and efficient energy conversion devices and automotive vehicles to stationary power generation [10]. The design and properties of the PEM directly impact the overall performance and efficiency of the fuel cell. Researchers continue to explore ways to enhance PEMs, focusing on factors such as proton conductivity, chemical stability, mechanical strength, and cost-effectiveness [8]. In addition to fuel cells, PEM technology finds application in other electrochemical devices, such as electrolyzes for hydrogen production and various types of sensors [21]. As renewable energy sources and clean technologies become increasingly important in addressing environmental and energy challenges, the development and optimization of proton exchange membranes continue to be a crucial area of research and innovation. The future of FC's holds significant promise and potential, as these clean energy technologies continue to advance and find broader applications.

Overall, the forthcoming FCs are likely to be characterized by improved efficiency, reduced costs, increased durability, and expanded applications in various sectors, contributing to a more sustainable and cleaner energy landscape [17]. However, challenges such as materials development, infrastructure deployment, and market adoption will need to be addressed for these technologies to reach their full potential [11].

Modern fuel cells encompass a range of advanced technologies that change chemical energy to electricity through electrochemical reactions. These technologies are being developed and applied in various sectors to provide clean and efficient power generation. Modern fuel cell technologies are part of the growing movement towards cleaner and more sustainable energy sources [12]. As research and development continue, advancements in materials, efficiency, and cost reduction are expected to drive their widespread adoption across various industries and applications. The history of fuel cells, its various varieties, and their uses in distributed power generation, home electricity, and portable power are covered in the literature review [1]. The basic concepts and specifications of the fuel cell were examined, demonstrating its sensitivity [2]. Reviewing the benefits and drawbacks, advancements, and many uses of FC, as well as some of the most recent studies on the application of FC to actual systems, were the main objectives of the review [1–14].Advances have been made by researchers in comprehending and alleviating catalyst and other component degradation problems.

Fuel cells have well-documented environmental benefits, including reduced greenhouse gas emissions. The scientific and engineering communities are aware of known obstacles, such as the high cost of materials like platinum, scaling problems, and the requirement for infrastructure development. It is still difficult to comprehend and enhance fuel cells' long-term durability. To improve the lifespan of fuel cell systems and address degradation causes, research is required. Although there has been progress, more study is required to resolve intermittency and grid integration issues and enhance the hybrid system's combination of fuel cells and renewable energy sources. Fuel cell knowledge is constantly evolving as new research tackles long-standing problems and pushes the envelope of what is already known Addala [1], the article gives clarity of fuel cell integrated system and a detail modelling is proposed Kalaiarasi [2], in order to generate electricity, PEMFC uses air as a catalyst for oxidation and hydrogen gas as fuel. Rather than utilizing a separate battery, the fuel cell-powered car in the illustration gets its power from hydrogen Zhai [3], in order to take make use of of the supporting features offered by SOFC and PEMFC, this paper suggests integrating an IES development for hydrogen energy storage with both fuel cells Cheng [4], This article's main focus is on a backup battery system that consists of lithium-ion and two fuel cells. Model predictive control is the basis for the energy management plan that is suggested Agila [5], this work covers the development and execution of a series of specialized procedures for the dynamic regulation of the polymeric membrane's humidification, which are based on approximate reason approaches Correa [6], for the sensitivity research on PEMFC electrochemical models is presented in this paper in order to figure out the relative impact of every parameter on the model outputs Correa [7], In a bid to depict, simulate, and assess the performance of tiny generating systems – with a focus on PEMFC stack Naderi [8], A optimization strategy based on application is introduced to obtain the optimum operational state of a fuel cell with a proton-exchange membrane Sohani [9], a polymer fuel cell electrolyte membrane approach is proposed and put into practice as a case study.

El-Shafie [10], this document discusses the hydrogen method of production from both fossil and non-fossil fuels Rau [11], the long-term behavior of the innovative nickel-based catalyst is the investigation's main focus in this work. This includes testing how the start-up process affects reforming efficiency following the catalyst's required activation Rashid [12], the current breakthroughs in the PEM electrolysis of water including powerful yet low cost HER and OER electro catalysis and their problems new and old linked to electro catalysts and PEM cell components also discussed. Senath [13], this research examines how electrolysis process could be improved by altering the electrodes' Dufour.C. [14], the simulation results of a FC hybrid electric vehicle based on PEM are presented in this study in real time and at a high speed Mann [15], This article describes a generic model of FC parameters Baschuck [16], a mathematical framework has been developed for this study Chu [17], Instead of focusing just on the performance of a single cell, the fuel PEMFC stack's performance was assessed in a variety of environmental settings Correa [18], the dynamic electrochemical model presented in this study can be used to simulate, depict, and assess the performance of small-scale generation systems that use PEM fuel cells. The fuel cell's output voltage, efficiency, and power are predicted using the model's results Wang [20], Dynamic models of PEM fuel cells built in MATLAB/SIMULINK. Experimental data is used to validate the model responses that are collected under both steady-state and transient situations.

The state of knowledge in the field of fuel cells is dynamic, with ongoing research addressing existing challenges and pushing the boundaries of current understanding. While there is progress, further research is needed to optimize the combination of FC with renewable energy sources in hybrid-systems, addressing intermittency and grid integration challenges. A new controller designed is too implemented to increase the voltage from output of the fuel cell for integration tenacity. So that the efficiency, durability, and cost-effectiveness of fuel cells will be improved which is the most significant changes of fuel cell technology.

MODELLING OF PEMFC SYSTEM

A PEMFC's basic parts are two electrodes, or the anode and cathode that are divided by a thin layer of membrane. The anode port receives the hydrogen fuel, whereas the cathode port gets the oxygen. The electrode membrane assembly, which includes an anode, an electrolyte membrane (PEM), and a cathode, is the main component of a fuel cell [4–9]. These parts are enclosed between two bipolar current collection plates and two gas diffusion backings [16]. A mutual interface between the fuel and electrolyte must be supplied by the anode (fuel electrode), which must also catalyze the oxidation reaction and electrons conduct from this reaction site to other. In order to catalyze the oxygen reduction process, carry e^- from the external means to the oxygen electrode, and deliver a common boundary for oxygen and electrolyte, a cathode (oxygen electrode) is required [1–6].

The diffusion gas supports FC's to offer reactants to electrodes and start an electrical interaction between electrodes and plates. They also allow the reaction's product water to exit the electrode surface and water to pass between the electrode surfaces and the flow channels. Bipolar plates, also known as separator plates, in a fuel cell stack serve as a structural support the electrically link the cells. Materials for bipolar plates need to be very conductive and gas-impermeable [10–13].

In order to compensate for the effect of these voltage drops, a capacitor is placed in parallel with the V_{ACT} and V_{CON} voltages on the corresponding circuit of Figure 1. Similarly, Figure 2 represents electrochemical processes in PEM fuel cells [14]. The voltage across the fuel cell V_{FC} is,

$$V_{FC} = E_{Nernst} - V_{Con} - V_{Act} - V_{Ohmic} \quad (1)$$

If n cells coupled the voltage is

$$V_S = n \cdot V_{FC} \quad (2)$$

where: E_{Nernst} – represents thermodynamic potential, V_{Act}, V_{Ohmic} V_{Con} – represents actual, Ohmic voltage drop and reduction in voltage.

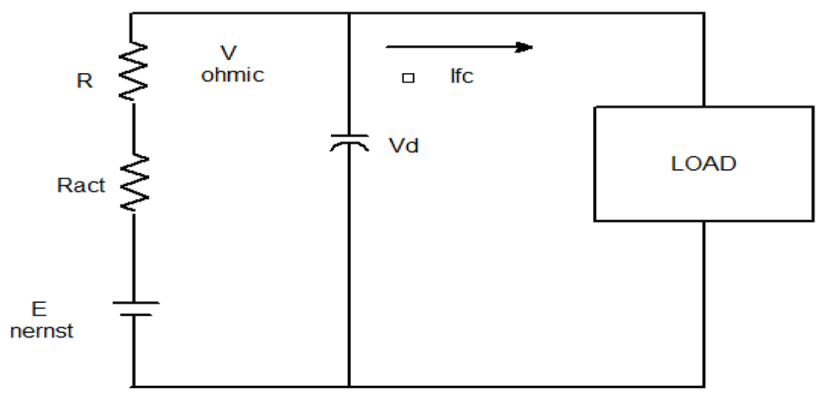

Figure 1. Equivalent diagram of PEMFC

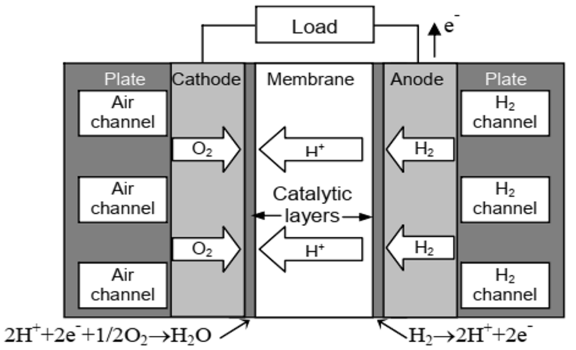

Figure 2. Flow diagram of electro-chemical processes

$$ENernst = [1.229 + 0.85 \times 10^{-3} (T - 298.15) + 4.3085 \times 10^{-5}\ T\,[ln\,(P_{H2}) + 0.5\ ln\,(P_{O2})]] \quad (3)$$

where: T – temperature in Kelvin.

The activation loss [2] can be written mathematical as

$$V_{ACT} = [\zeta_1 + \zeta_2 \cdot T + \zeta_3 \cdot T \cdot ln\,(C_{O2}) + \zeta_4 \cdot T \cdot ln\,(I_{FC})] \quad (4)$$

where: ξ_1, ξ_2, ξ_3 and ξ_4 – parametric constants.

The voltage drop at concentration is provided by

$$V_{con} = B\ ln\,((J/J_{max}) - 1) \quad (5)$$

where: B – parametric coefficient, J – denotes current density.

The Ohmic loss is given by

$$V_{Ohmic} = I_{FC}\,(R_M + R_C) \quad (6)$$

Similarly, the mathematical formula for voltage efficiency is

$$Voltage\ efficiency = (Actual\ voltage / Theoretical\ voltage) \quad (7)$$

In the Figure 3 shows the FC's used to inserts energy into the grid [8]. The power from the FC's is given by:

$$P_{FC} = V_{FC} \cdot I_{FC} \quad (8)$$

The FC efficiency

$$\eta = (\mu f \cdot VFC)/1.48 \quad (9)$$

where: µf – the utilization coefficient.

The economics of fuel cell is given by

$$Cost\ of\ electricity\ (\$/kWh) = \frac{\left(Annualized\ capital\ cost\ \left(\frac{\$}{yr}\right) + Annual\ fuel\ cost\ (\$/yr)\right)}{(Annual\ electricity\ production\ (kWh/yr)} \quad (10)$$

$$Fuel\ cost\ per\ annum\ is\ cost\ of\ hydrogen\ cost \cdot \frac{(Annual\ electricity\ production\ (kWh/yr)}{(Annual\ fuel\ cell\ efficiency)} \quad (11)$$

The FC in the proposed system's block layout, as seen in Figure 3, acts as a source that continuously provides electricity to the load. The FC controller senses the voltage at the bus bar and draws power from the FC to make up for the drop in available power when the load demands it. Energy conservation means that the power delivers to the load should match the fuel cell's power. Not all of the power generated is given to the load because of nonlinear components and power loss in converters switches, chokes resistances at transmission line etc. For the sake of simplicity, these losses can be neglected because the suggested model has a basically pure resistive demand and has very low power device losses [4–6].

SIMULATION DIAGRAM

The Simulink model is shown in Figure 4. A single-phase load is fed by FC in this scenario. An inverter (DC-AC) is used to convert DC to AC voltage, while a DC boost converter is used to send the maximum amount of power to the load. A PIS controller-based boost converter is necessary in a fuel cell system to control the fuel cell's power output to the bus bar and improve the fuel cell's voltage to the correspondingly higher voltage at the DC bus-bar. Figure 5 shows the proportional integral speed (PIS) controller based fuel cell

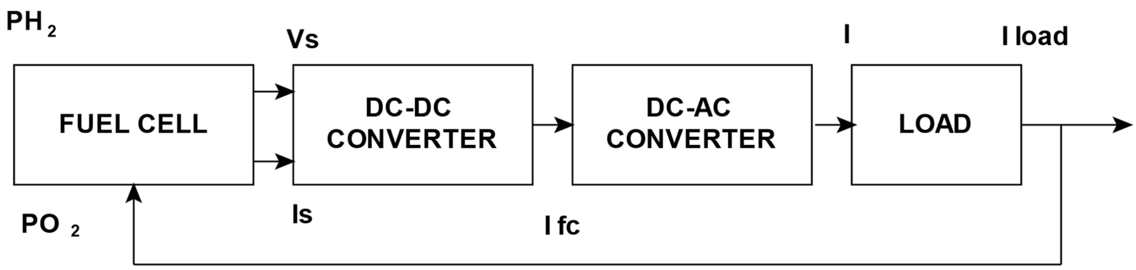

Figure 3. Block diagram of FC connected to grid

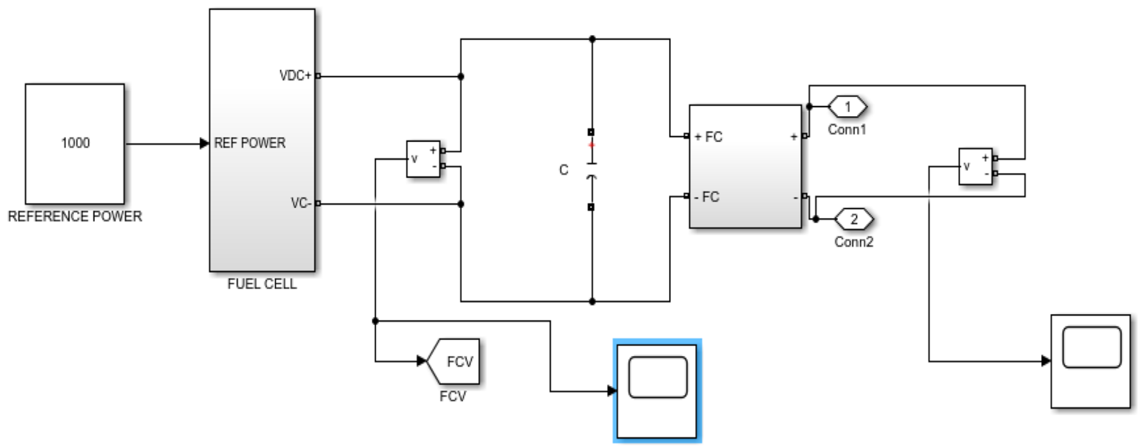

Figure 4. Fuel cell model simulink diagram with DC-DC converter

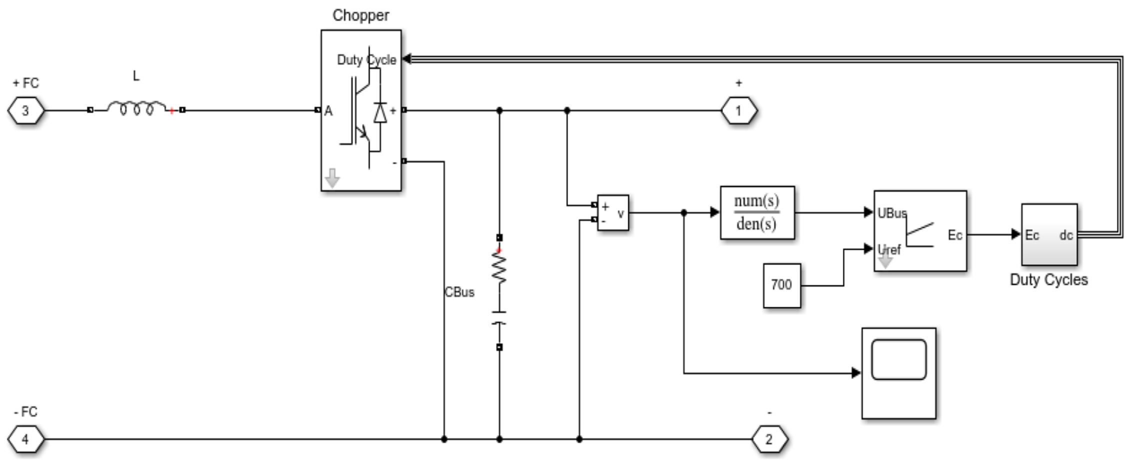

Figure 5. Simulink diagram of PISC based DC-DC converter

controller model. Where, the voltage at DC bus bar is measured and compares with the reference DC voltage; if the two values vary, the fuel cell boost converter's duty cycle is adjusted step-by-step to lessen the discrepancy between the voltage at the bus bar and the voltage at the fuel cell boost converter's output. By changing the reference voltage, the power offered to the load may be changed. This lessens load-related power fluctuations. It is evident that power profile and voltage variation across load are both enhanced by keeping bus bar voltage constant. Fuel cell efficiency varies according on the amount of electricity needed.

RESULTS AND ANALYSIS

The voltage, currents, power at load, and fuel cell have been taken into consideration while simulating the proposed model for a non-linear load. Fuel cell duty cycle is controlled by measuring bus-bar voltage source and compare with reference value, in order to guarantee that the load receives power consistently. The working voltage of the PEMFC has an intimate connection to its efficiency. The cell efficiency and hydrogen's efficiency in converting energy are both at their lowest at the point of maximum electricity production.

The Figure 6a shows that the modelling of fuel cell by taking all the parameters assigned in Table 1, the output voltage of fuel cell is about 400V; which is quite enough to supply power to low grid application. But when we connect to Grid application the voltage is not enough to satisfy the power application. Therefore, A PIS controller tuned DC-DC Converter is used which is used to boost the incoming voltage to high and desired voltage which is shown in Figure 6b. An voltage of around 700v is produced from the DC-DC converter.

Table 1. Parameters of fuel cell model

No	Parameters	Specification
1	Standard potential [V]	E0 = 1.23
2	Constant gas [(J/(mol*K))]	R = 8.3
3	Faradays constant [(C/mol)]	F = 96485
4	Temperature [K]	T = 298
5	Nernst voltage correction factor	lambda = 1.5
6	Electrode area [cm^2]	A = 50
7	Exchange current density [A/cm^2]	i0 = 0.01
8	Number of electrons transferred	n = 2
9	Time step [s]	t = 0.001
10	Simulation time [s]	tf = 1
11	Initial voltage [V]	Vcell = 0
12	Hydrogen flow rate [mol/s]	m_dot_H2 = 0.1
13	Oxygen flow rate [mol/s]	m_dot_O2 = 0.2

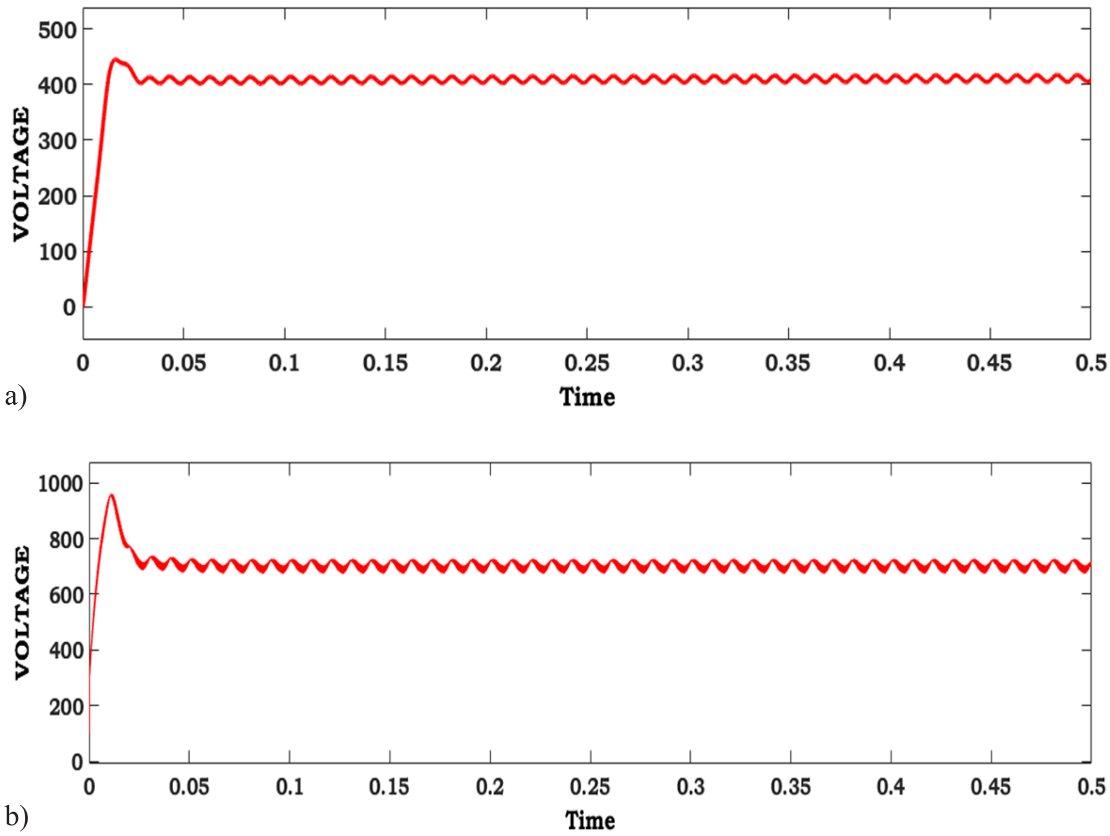

Figure 6. The result of the simulation voltage of the FC (a) before the time and DC-DC conversion, (b) after DC-DC conversion and time

The simulation results shown in Figure 7a, 7b and 8 describes about the current, voltage and power response across the nonlinear load. Similarly, when we use the LPF-PWM controller-based DC-DC converter, the responses the responses of the voltage, current and power are shown in the below Figures 9, 10 and 11.

Therefore, by comparing the responses of voltage, current and power for PIS controller and LPF-PWM controller based DC-DC converter which is shown from the Figures 6a, 6b, 7a, 7b and 8 and Figures 9, 10 and 11. It is to be observed that the output of the PIS controller tuned DC-DC converter is giving the better response for

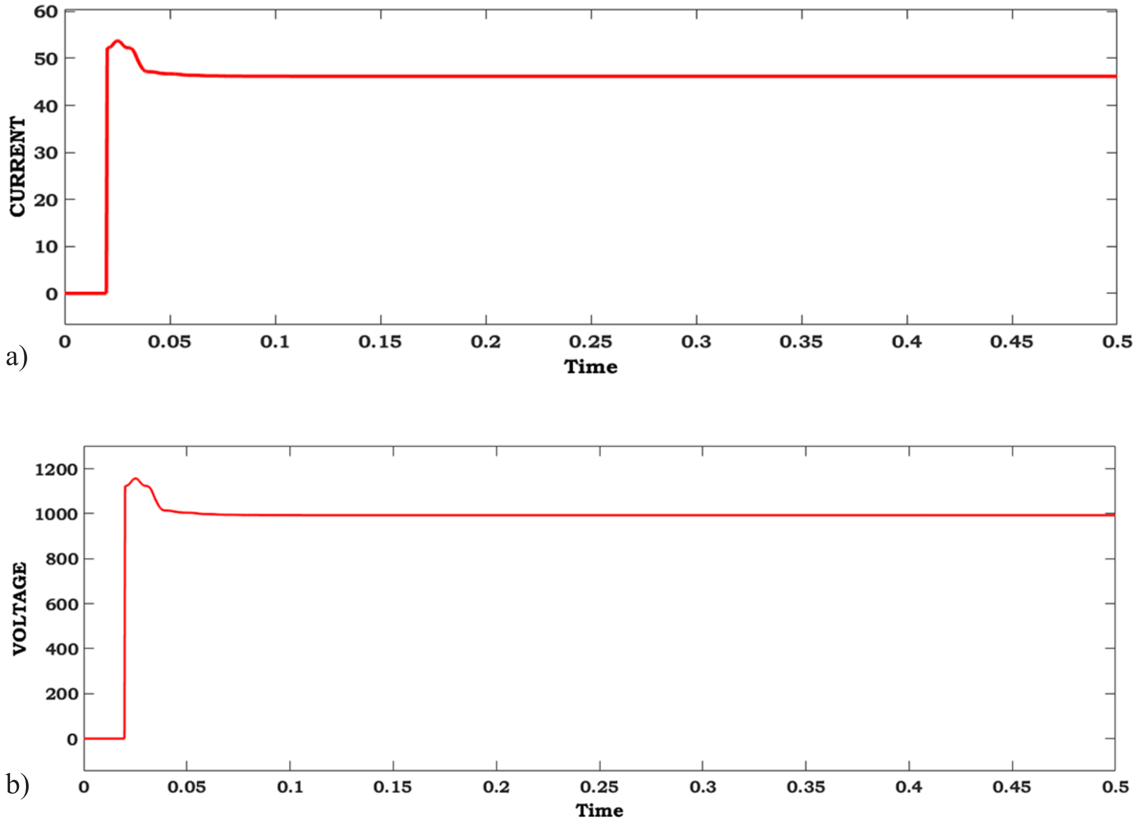

Figure 7. Simulation output (a) current across the load and time, (b) voltage across the load and time

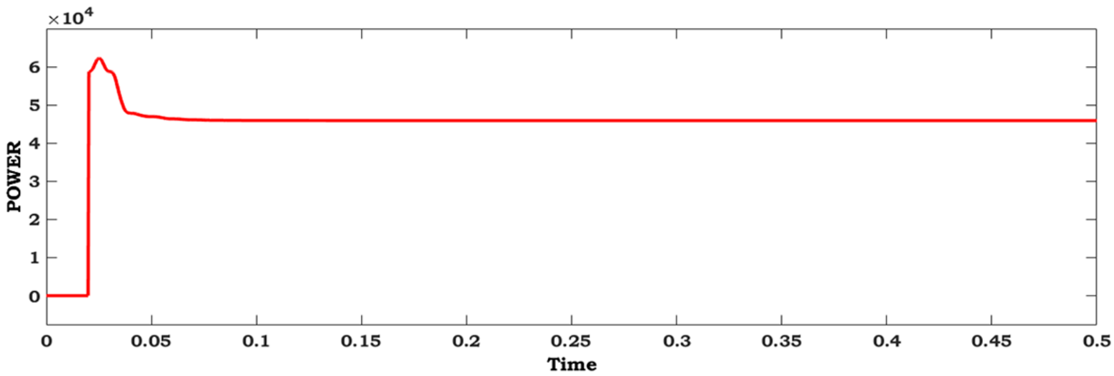

Figure 8. Simulation output power across the load and time

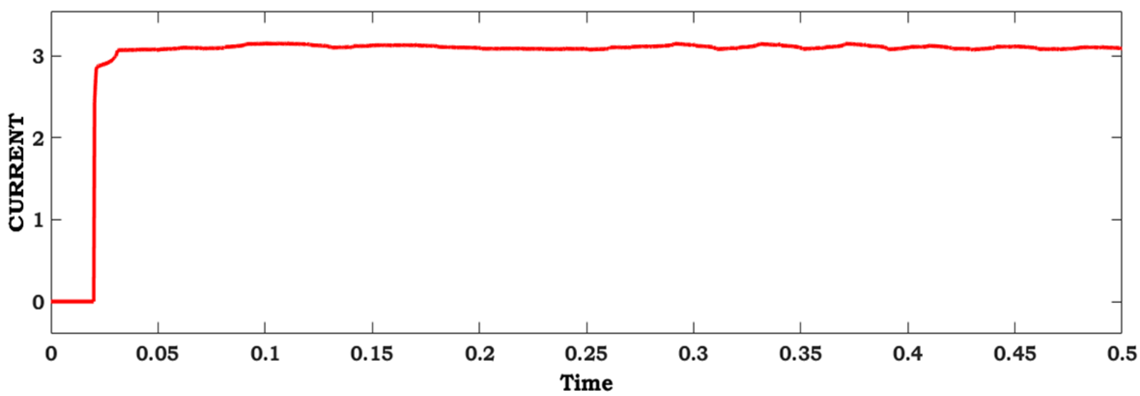

Figure 9. Simulation output current across the load and time

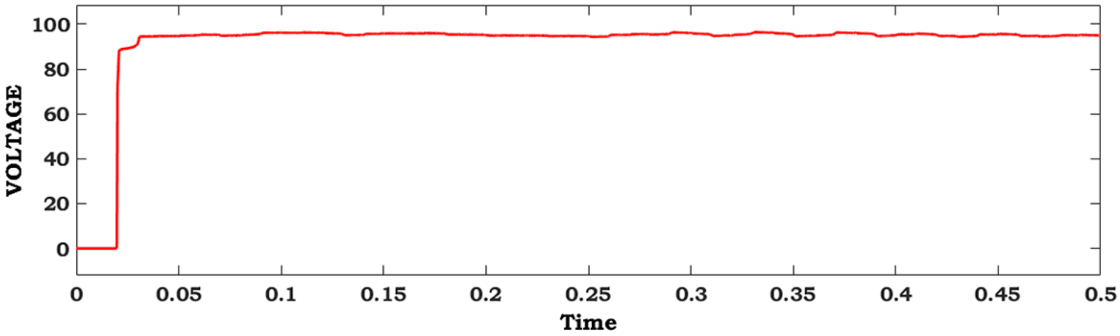

Figure 10. Simulation output voltage across the load and time

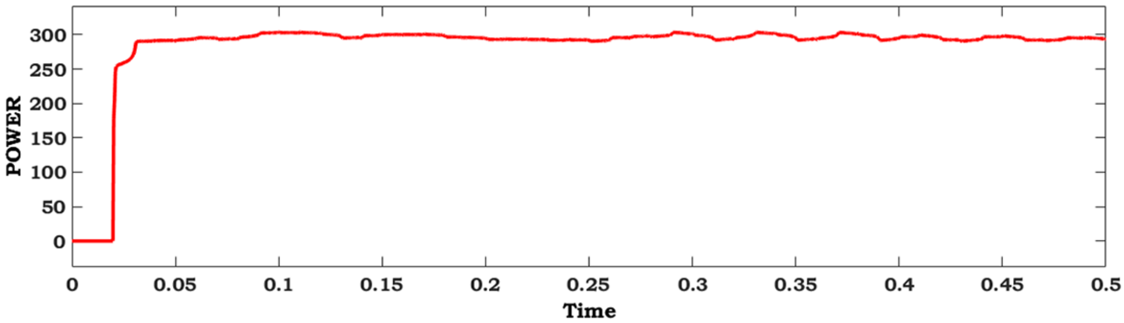

Figure 11. Simulation output power across the load and time

the fuel cell when it compared with LPF-PWM controller-based DC-DC converter.

CONCLUSIONS

In this work, the modelling and analysis as well as the economic analysis of PEMFC system are presented. A modified PIS controller based DC-DC converter is used, which is the best solution for obtaining the V-I characteristics of the fuel cell. The proposed strategy PIS controller provides an effective performance across the single phase load when it is compared with LPF–PWM controller based DC-DC converter. On comparing the two control strategy the LPF-PWM controller attains the voltage across the load 92 V and current as 3.2 A, whereas the PIS controller attains the voltage value as 1000 V and 42 A .The simulation results of fuel cell have been conducted, to test the output voltage on a nonlinear load, which helps in obtaining the effectiveness of the FC. The proposed strategy ensures continuous power supply to load and demonstrates that fuel cells are a good substitute for other energy sources that require a consistent voltage and power profile, even in the event of load change. In the modern power generation, the development of fuel cell technology has enormous potential for the production of clean and sustainable energy.

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