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Modeling Hydrogen Fuel Cell of High-Speed Passenger Ship by Using Simulink

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Abstract

The maritime industry is under increasing pressure from environmental regulations, and therefore, it is required to provide energy solutions that comply with sustainable practices immediately. The study conducted by the researchers indicates the creation of a hydrogen fuel cell model that is designed specifically for the MATLAB Simulink high-speed passenger vessels. A detailed analysis sketch is laid out, which shows the design and simulation of the Proton Exchange Membrane Fuel Cell (PEMFC) system, displaying the emission reduction effect of this technology. This model is made up of extra units like a fuel cell stack, a DC/DC converter, and a flow rate regulator these give the operator the capability to change the fuel consumption and the generated power. Several scenarios were tested in simulation and results were compared to study system efficiency and performance, where the findings mostly focused on the role of hydrogen pressures in increasing cell voltage and efficiency. This study proves the potential of hydrogen fuel cells in sustainable maritime propulsion. It discusses the engineering challenges that are met during the experimental deployment and test in naval conditions.

Keywords: *Fuel Cell, Passenger Ship, Modelling Hydrogen Gas, MATLAB Simulink*

1 Introduction

The maritime industry faces increasing pressure to reduce greenhouse gas emissions and transition to more sustainable energy sources. High-speed passenger ships, a significant part of global transportation networks, contribute to environmental pollution by relying on fossil fuels.(Toscano & Murena, 2019). As international regulations become stricter, shipbuilders and operators seek alternative propulsion technologies that meet performance and environmental standards.

Ships that operate on Lake Victoria and Lake Tanganyika and coastal like the Kilimanjaro Fast Ferries are essential means of transportation for both people and cargo in Tanzania. However, most of these ships continue to run on conventional diesel engines, which present environmental problems due to greenhouse gas emissions. Although compressed natural gas (CNG) has been suggested as a substitute because of its ability to lower greenhouse gas emissions and enhance air quality, its uptake is constrained by some issues. Despite its benefits, CNG combustion releases pollutants like nitrogen oxides (NOx) and carbon monoxide (CO), and there are risks of methane (CH4) leakage during extraction, production, and transportation (Khan et al., 2015).

Hydrogen fuel cells have emerged as a potential solution to these challenges, offering a cleaner and more sustainable alternative to conventional marine propulsion systems (Vidović et al., 2023). Despite their promise, hydrogen fuel cell technology adoption in marine applications remains limited, primarily due to technical, economic, and regulatory challenges (Xing et al., 2021). Most hydrogen fuel cell development has focused on automotive and stationary applications, with limited research on their adaptation for marine use (Sürer et al., 2022). The marine environment presents unique challenges, including high power demands, exposure to corrosive saltwater, space constraints, and safety concerns related to hydrogen storage and handling. (Wang et al., 2023; Ajithkumar et al., 2022). Furthermore, there is a lack of standardized design models that address these challenges, hindering the widespread implementation of hydrogen fuel cells in the maritime sector (Igourzal et al., 2024). Without developing a robust and efficient hydrogen fuel cell model specifically designed for marine use, the industry may struggle to meet international environmental regulations and sustainability goals (Yang et al., 2022; Zhang et al., 2020). This could result in continued reliance on polluting fossil fuels, exacerbating ecological degradation and contributing to climate change. This research aims to fill the knowledge gap by developing and analyzing a hydrogen fuel cell model optimized for marine applications.

2 Fuel Cell Modeling

In recent years, the development of models for fuel cells has significantly advanced, with various methodologies employed to enhance accuracy and predictive capabilities. These models are crucial for optimizing fuel cell performance and understanding complex operational behaviors (Mohammed et al., 2029). Recent literature highlights significant advancements in both empirical and computational modeling approaches for different types of fuel cells. One of the most common fuel cell modeling approaches is chemical equations and thermodynamic principles. This method allows researchers to accurately describe the electrochemical reactions occurring within the fuel cell and calculate the resulting energy output.(Vichard et al., 2021). However, while this approach provides valuable insights into the fundamental processes within the fuel cell, it often requires simplifying assumptions that may limit its accuracy in predicting real-world performance (Sahu et al., 2014).

Another prevalent methodology in fuel cell modeling involves the use of computational fluid dynamics (CFD)(Aman et al., 2018). CFD models can simulate the flow of gases within the fuel cell, providing detailed insights into the distribution of reactants and the removal of waste products. These models have proven particularly useful in optimizing the design of fuel cell components, such as the gas diffusion layer and the flow field plates. However, CFD models are computationally intensive and may not be suitable for all applications.

Machine learning techniques have also recently been applied to fuel cell modeling. These methods can identify complex patterns and relationships within data, potentially offering more accurate predictions than traditional modeling approaches.(Shah et al., 2022). However, machine learning models require large amounts of data for training and validation, which may not always be available.

Each methodology has pros and cons, and the choice of method often depends on the study's specific objectives and the resources available. Despite the challenges, the ongoing development and refinement of fuel cell models are crucial for advancing our understanding of fuel cell technology and its potential applications in various sectors, including the maritime industry.

3 Fuel Cell Model Performance Analysis

In performance analysis, the hydrogen fuel cell system is modeled in MATLAB Simulink 2024, and several key components are integrated to simulate the dynamics and performance of the system. The model's core modeling is the Fuel Cell Stack Subsystem, replicating the electrochemical reactions that convert hydrogen and oxygen into electrical energy (MathWorks, n.d). This subsystem uses the Simulink Fuel Cell Stack block, where essential parameters like the number of cells, operating temperature, and pressure are input. The stack generates output voltage and current that depend on the fuel and oxidant flow rates. To regulate the voltage produced by the fuel cell stack, a DC/DC Converter Block Subsystem is incorporated. This subsystem maintains a stable output voltage suitable for powering the connected load. The DC/DC converter ensures that the system operates within a defined voltage range, critical for ensuring consistent power supply to the downstream systems.

The Flow Rate Selector Block Subsystem is included to play a vital role in managing the hydrogen and air supply to the fuel cell. It controls the flow of these gases based on the utilization ratios of hydrogen and oxygen, ensuring optimal fuel efficiency. This subsystem works with the fuel cell’s power demand to dynamically adjust the gas flow rates, optimizing fuel usage and stack performance. A saturation block is included in the model to prevent the fuel cell stack from operating outside its optimal limits. This block restricts the fuel and oxidant flow rates to within practical operational limits, ensuring that the system avoids both fuel starvation and overloading scenarios. This block acts as a protective measure, ensuring the long-term reliability and safety of the fuel cell.

The DC/DC converter manages the DC Bus Voltage and is the stable output voltage provided to the system’s load. The consistency of the bus voltage is crucial for the operation of downstream electronics and power systems, ensuring steady power delivery. A Flow Rate Regulator Block is added to maintain optimal hydrogen and oxygen flow rates. The regulator block dynamically adjusts these rates in response to real-time power demand, ensuring the fuel cell operates efficiently while minimizing unnecessary fuel consumption.

Two Scope Blocks are used to monitor system performance. Scope Block 1 displays key performance indicators such as the utilization of oxygen and hydrogen, with oxygen utilization represented in yellow and hydrogen utilization in magenta. Additionally, this block shows the air consumption in yellow, fuel consumption in magenta, and overall stack efficiency. These real-time graphs provide valuable insights into the operational efficiency of the fuel cell. Scope Block 2 focuses on the fuel cell's electrical output, displaying the stack's voltage and current. These graphs allow for monitoring of the fuel cell’s power output and help assess the stability and performance of the electrical system.

Figure 3.1 below shows a fuel cell model developed and implemented within the MATLAB/Simulink environment. This model serves as a virtual representation of a fuel cell system, enabling detailed analysis of its performance characteristics.

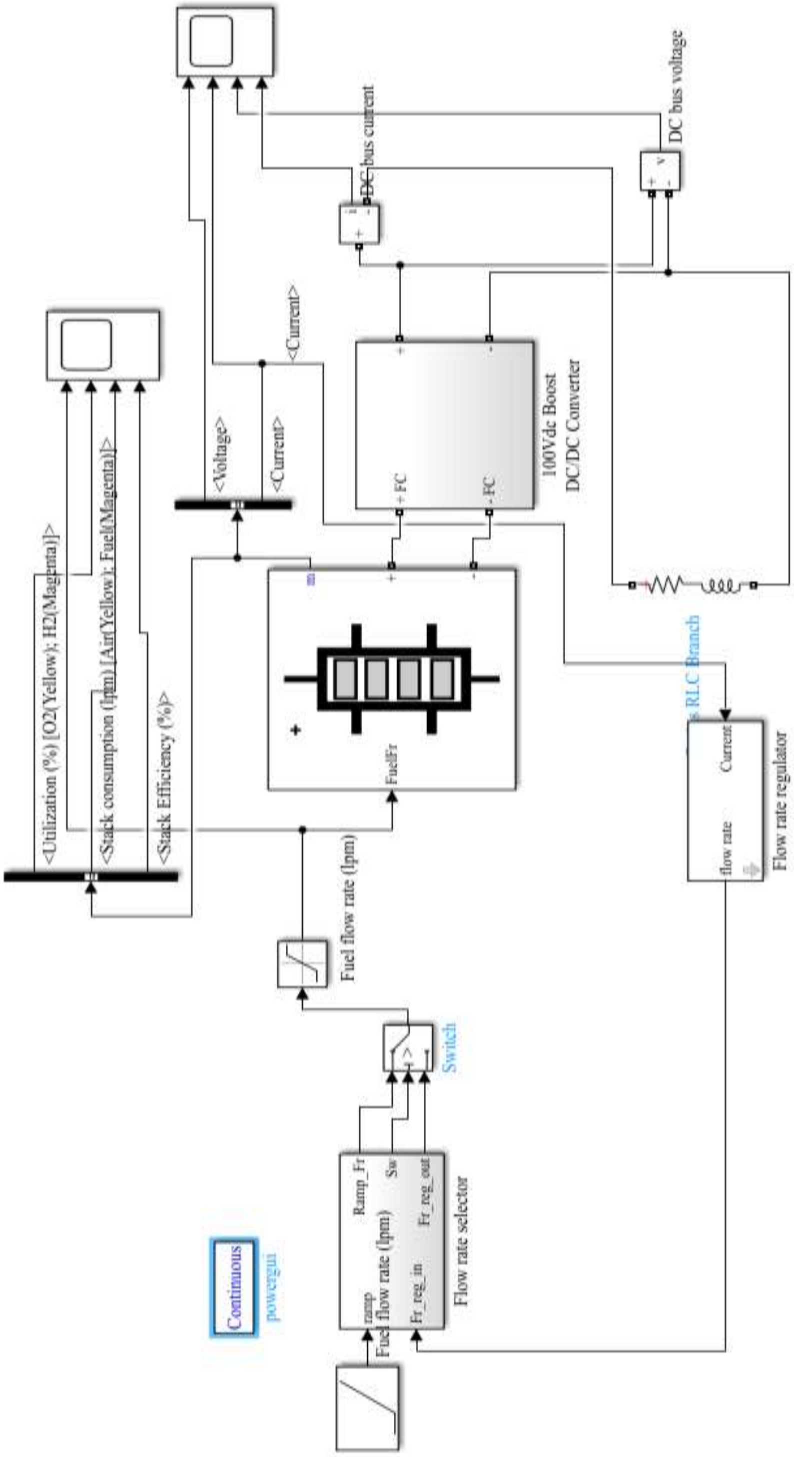

Figure 3.1: Fuel cell model developed and implemented within the MATLAB/Simulink

4 Result and Discussion

The Model PEMFC fuel cell simulation study provides its performance characteristics. The simulation generates detailed performance curves, illustrating the relationship between cell voltage, current density, and power output. These curves identify optimal operating points and evaluate the cell's efficiency and energy conversion capabilities.

The stack configuration, illustrated in Figure 3.5, features a nominal stack voltage (VNFC) of 24 Vdc and a rated power output (PNFC) of approximately 1.26 kW. In this setup, the DC-DC boost converter operates under an R-L load of about 1.26 kW with a time constant of 1 second. A ramp signal is applied to the flow rate selector, which functions based on a clock signal processed through a function block. This signal is compared to a constant threshold more significant than 10, and an edge detector identifies changes by comparing current and previous inputs. The edge detector's output is then routed to a sample-and-hold (S/H) circuit that captures values from both the edge detector and frequency domain inputs from ports 2 and 3, generating a frequency at port 1. The flow rate selector produces three outputs: a ramp frequency, a switching signal, and a frequency domain output. These signals are sent to a switch that compares the ramp frequency against a specified threshold (µ2 > Threshold). The switch output is then processed by a function block that caps the upper saturation limit at 85. This output is directed to the proton exchange membrane fuel cell (PEMFC) system, which operates at 1.26 kW and 24 Vdc.

The fuel cell stack generates both fuel flow rate and DC electrical output. The DC output is fed to a DC/DC boost converter (Boost Chopper) that steps up the voltage from 24 Vdc to 100 Vdc, supplying an RL load with resistance R = 1.67 Ω and inductance L = 1.67 H. Initially, for the first 10 seconds, hydrogen consumption is maintained at 99.56% using a fuel flow rate controller. Operational parameters such as electrolyzer voltage and current, boost converter voltage, and current can be monitored via Scope2.

Figure 4.1 below illustrates the relationship between fuel cell stack voltage and current, showing that the stack voltage fluctuates between 20V and 45V as the current ranges from 0A to 100A. Notably, there is an inverse relationship: as the current increases from 0A to around 100A, the stack voltage decreases from 42V to 20V, confirming that the fuel cell stack voltage is inversely proportional to the current, consistent with typical fuel cell behavior. In addition, Figure 4 presents the correlation between fuel cell stack power and current, with stack power ranging from 0 kW to 2 kW while the current spans from 0A to 100A. The data shows a direct linear relationship, as the power output increases from 0 kW to 2 kW with the rising current from 0A to 100A.

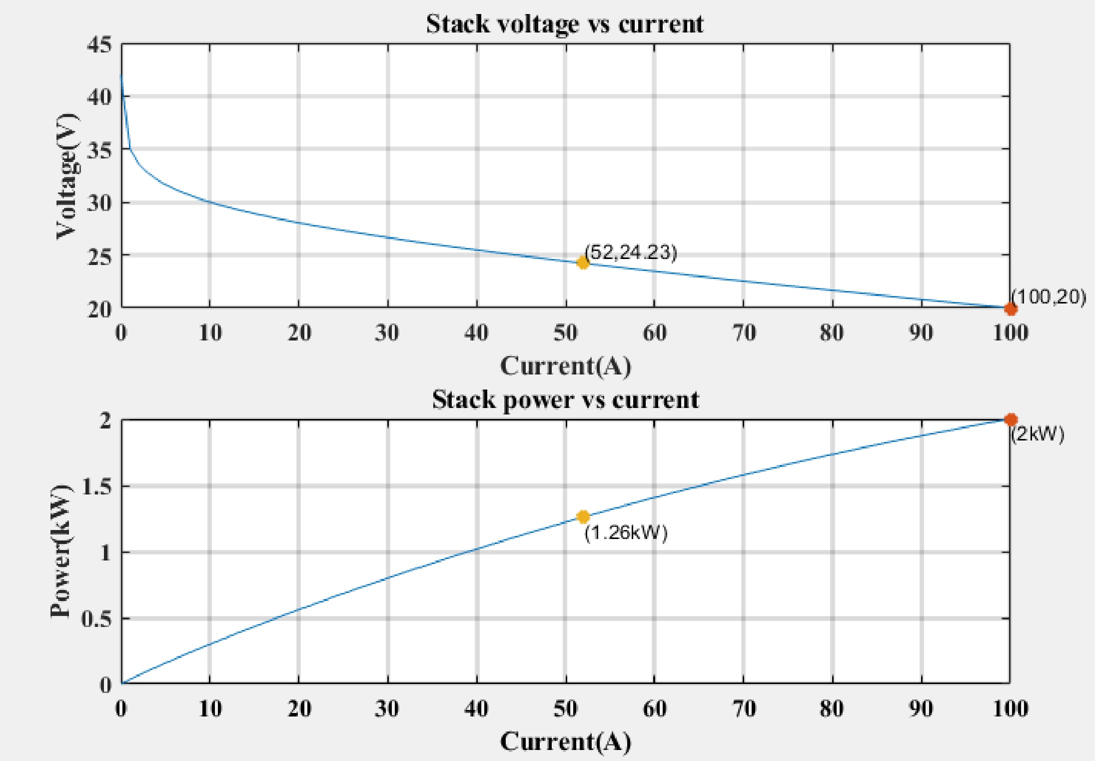

Figure 4.1: **Cell Voltage Current Characteristic**

4.2 Relationship between cell voltage and the partial pressures of hydrogen and oxygen

Upon executing the MATLAB code to simulate the Proton Exchange Membrane Fuel Cell (PEMFC), a 3D surface plot was generated. Figure 4.2 below illustrates the relationship between cell voltage and the partial pressures of hydrogen and oxygen. The results demonstrated that the cell voltage increases with higher hydrogen partial pressures while maintaining constant oxygen pressure, as shown in Figure 4.2 below. Conversely, lower hydrogen pressures resulted in decreased voltage, highlighting the critical role of hydrogen concentration in determining fuel cell efficiency. For instance, as the partial pressure of hydrogen increased from 0.1 atm to 3.0 atm, the cell voltage exhibited a noticeable rise, reaching its peak under optimal hydrogen conditions. This trend is consistent with theoretical predictions based on the Nernst equation.

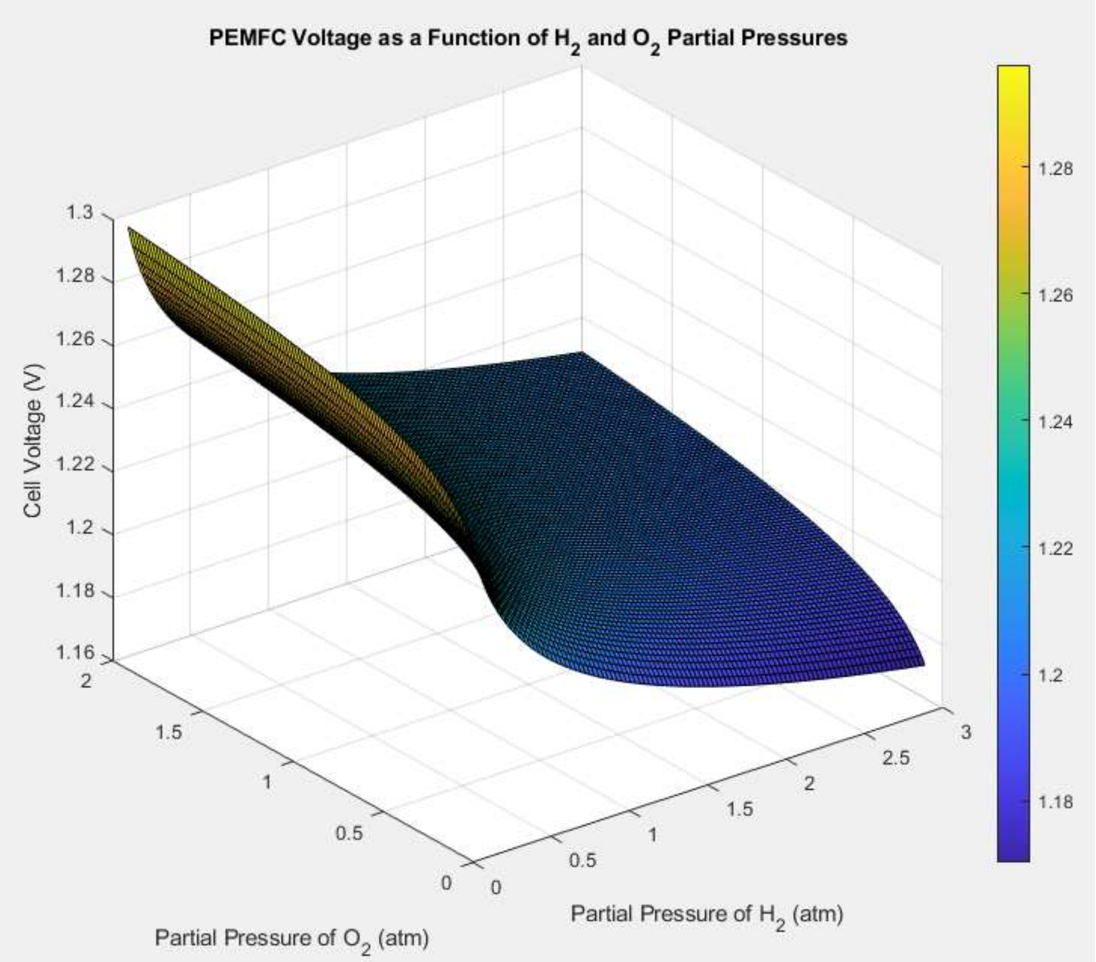

***Figure 4.2*: Cell voltage and the partial pressures of hydrogen and oxygen**

These findings underscore the importance of optimizing reactant concentrations to enhance PEMFC performance. The results confirm the theoretical framework suggesting that the reactant partial pressures significantly influence the Gibbs free energy change and cell voltage. The simulation provides valuable insights for operational adjustments in real-world applications, such as marine propulsion systems. Maintaining optimal hydrogen pressures could significantly improve fuel cell efficiency. Additionally, exploring varying conditions could further refine understanding and inform future designs, ultimately contributing to the development of sustainable fuel cell technologies in maritime applications

4.3 Fuel cell Simulation results MATLAB/Simulink model

The results below show that the fuel cell model simulation yields significant insights. The x-axis uniformly represents time in seconds, with each interval set at 1 second across all observed results.

In Figure 4.3, the fuel flow rate is illustrated on the y-axis in liters per minute (ppm), while the x-axis continues to denote time in seconds. The graph reveals an initial increase in fuel flow rate, rising from 0 to 4.8 lpm within the first five seconds, stabilizing at 4.8 lpm until the 10-second mark.

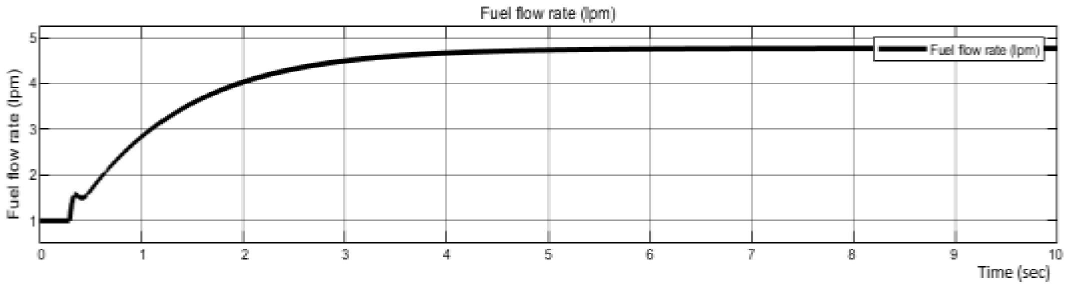

***Figure 4.3*: Fuel Flow Rate vs Time**

Figure 4.4 also displays the utilization rates of hydrogen (H2) and oxygen (O2) as percentages on the y-axis, corresponding to the time in seconds on the x-axis. The black dashed line represents O2 utilization, while the maroon line indicates H2 utilization. H2 utilization is significantly higher, peaking at 99.56% during the first 10 seconds, whereas O2 utilization remains constant at 0.2%. Notably, both H2 and O2 utilization rates converge at 12 seconds.

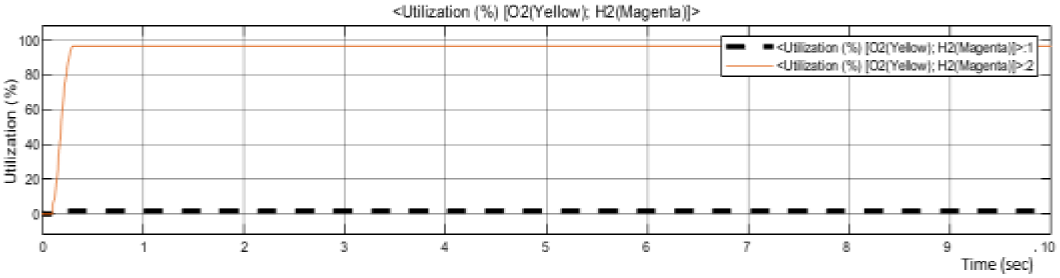

***Figure 4.4*: Utilization of Hydrogen and oxygen**

The consumption metrics for air and fuel within the fuel cell stack are presented in Figure 4.5, where the y-axis reflects their consumption in liters per minute (ppm), and the x-axis shows time in seconds. The black line illustrates airflow, which escalates from 0 to nearly 3 pm until 10 seconds before decreasing slightly and stabilizing at that rate. Concurrently, fuel consumption in the stack rises from 0 to approximately 4.9 lpm, stabilizing at the same rate after 4 seconds.

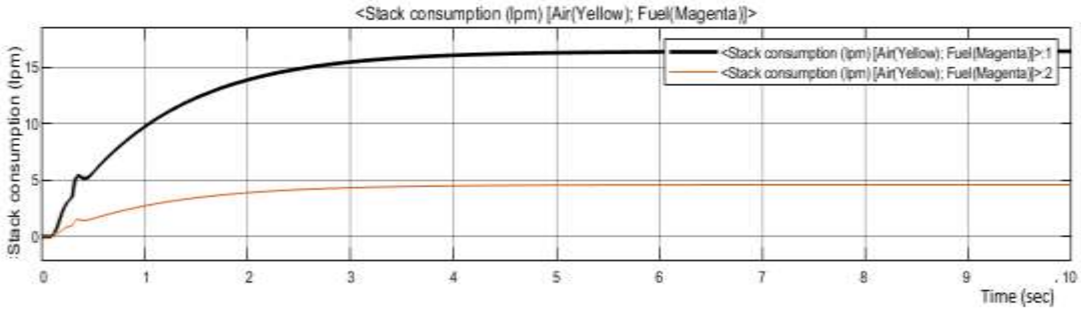

***Figure 4.5*: Stack Consumption**

Lastly, Figure 4.6 depicts stack efficiency, with the y-axis indicating efficiency percentage and the x-axis representing time in seconds. The data shows an initial increase in stack efficiency, peaking at 62% after one second, followed by a decline to 55% within two seconds. After reaching 5 seconds, the efficiency stabilizes at 55%.

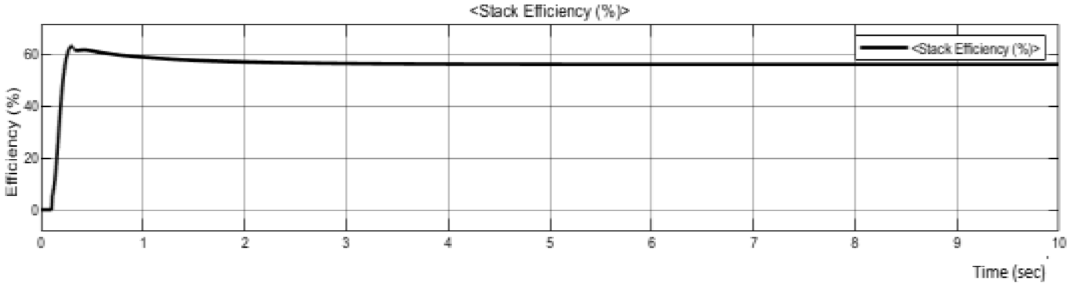

***Figure 4.6*: Stack efficiency**

Figure 4.7 below illustrates the results of a simulated fuel cell model. This model presents the relationship between fuel cell voltage and time, with the y-axis representing voltage (V) and the x-axis denoting time in seconds. Initially, the voltage decreases from approximately 48 V to 31 V over the first four seconds. After reaching this point, the stack voltage stabilizes at around 31 V, indicating a consistent performance of the fuel cell under the given conditions.

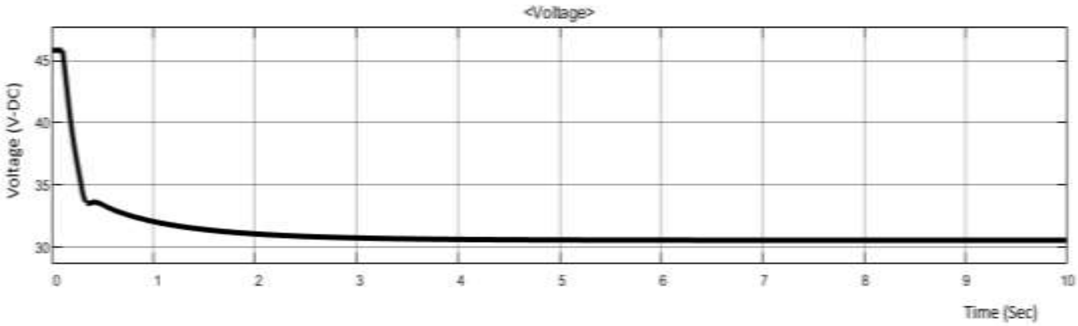

***Figure 4.7*: Cell voltage**

Figure 4.8 further highlights the electrolyzer current, plotted on the y-axis against time in seconds on the x-axis. Within the first five seconds, the current rapidly increases from 0 A to nearly 20 A. Following this initial rise, the current stabilizes at approximately 20 A, demonstrating the system's ability to maintain a steady operational current after the transient period.

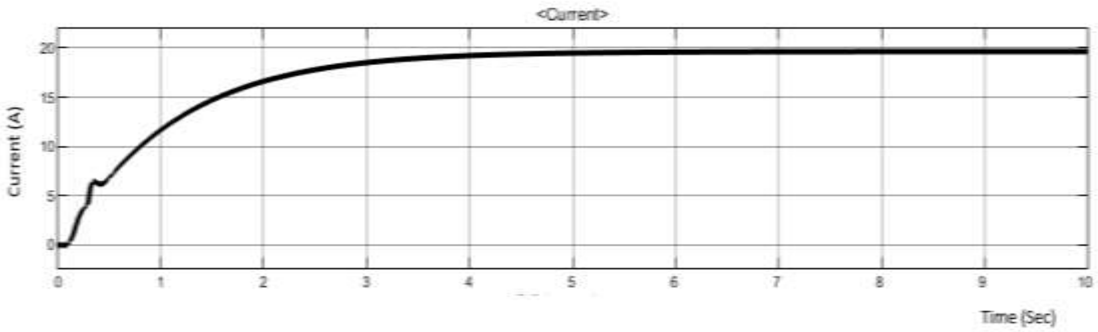

***Figure 4.8*: Cell Current vs Time**

5 Conclusion

This research successfully modeled and simulated a 1.26 kW, 24 Vdc Proton Exchange Membrane Fuel Cell (PEMFC) stack and hydrogen fuel cell propulsion system within the MATLAB/Simulink environment. The simulation results reveal that at time t=0 seconds, the boost converter delivers 100 Vdc to the R-L load, with the initial load current recorded at 0 A. Initial fuel consumption is set at 99.56% of the nominal value, resulting in a current surge of 20 A, with the fuel flow rate dynamically adjusted to optimize consumption. The DC bus voltage, monitored via Scope2, exhibits effective regulation by the converter, showing a transient peak voltage of 100 Vdc at the simulation's commencement. At t =0 to 5 seconds, the fuel flow rate increases from 1 liter per minute (ppm) to 4.6 pm throughout 1 second, leading to increased hydrogen consumption. The findings in Scope 1 evidence these dynamics for fuel cell stack consumption and efficiency characteristics. The simulation results indicate increased Nernst voltage, reducing fuel cell current.

Future research on PEMFC systems for marine applications should prioritize experimental validation to confirm the accuracy of simulation results in real-world conditions. Conducting physical experiments on fuel cell stacks under maritime environmental conditions would help refine model parameters such as temperature, pressure, and fuel impurities. Additionally, since marine vessels operate in dynamic scenarios, future studies should examine PEMFC performance during rapid load changes, varying sea states, and fluctuating power demands to gauge system durability and responsiveness. Long-term degradation studies focusing on corrosion, catalyst deterioration, and membrane fouling would also be essential to improve durability, especially in challenging marine environments.

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