Faculty of Electronic and Computer Engineering and Technology

SIMULATION MODEL DEVELOPMENT OF HYDROGEN FUEL CELL FOR ELECTRIC VEHICLE USING MATLAB SIMULINK

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Bachelor of Electronics Engineering Technology (Industrial Electronics) with Honours

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DEDICATION

To my beloved mother, Engku Saleha binti Tuan Nor, and father, Mohd Yusoff bin Mat who have given courage to me to pursue bachelor degree and always support also do not lose hope in me.

ABSTRACT

This project investigates the use of hydrogen fuel cells as a sustainable energy source for electric vehicles (EVs), with a focus on the creation of a MATLAB Simulink simulation model. By turning hydrogen and oxygen into energy and emitting only water, hydrogen fuel cells provide an environmentally benign alternative to typical combustion engines. Despite past obstacles such as infrastructure and expense, the growing emphasis on lowering greenhouse gas emissions has made hydrogen fuel cells a more significant choice for car power. The project's goal is to meet the global need for cleaner transportation energy by utilizing the benefits of hydrogen fuel cells to provide a viable alternative to fossil fuels and battery-powered EVs. The study explores the dynamic behavior of the fuel cell system in response to various inputs using a simulation model written in MATLAB Simulink, assessing power consumption and efficiency during acceleration. This model attempts to improve knowledge of the performance of the fuel cell in EVs, which is critical for developing energy management methods and advancing sustainable transportation solutions. The simulation results show a clear relationship between accelerator input and vehicle acceleration, with higher inputs resulting in faster acceleration. An unexpected non-linear connection in power consumption was observed, with total consumption significantly decreasing at maximum accelerator input, implying that optimal efficiency does not always correspond with maximum power output. The vehicle's efficiency rose with higher accelerator inputs, peaking at full power. These findings highlight the significance of optimizing EV performance in order to balance energy efficiency with acceleration demands.

ABSTRAK

Projek ini menyiasat penggunaan sel bahan api hidrogen sebagai sumber tenaga lestari untuk kenderaan elektrik (EV), dengan memberi tumpuan kepada pembangunan model simulasi MATLAB Simulink. Dengan mengubah hidrogen dan oksigen menjadi tenaga dan hanya mengeluarkan air, sel bahan api hidrogen menyediakan alternatif yang mesra alam berbanding dengan enjin pembakaran biasa. Walaupun terdapat halangan sebelum ini seperti infrastruktur dan kos, penekanan yang semakin meningkat terhadap pengurangan emisi gas rumah hijau telah menjadikan sel bahan api hidrogen pilihan yang lebih penting untuk kuasa kenderaan. Matlamat projek ini adalah untuk memenuhi keperluan global akan tenaga pengangkutan yang lebih bersih dengan menggunakan kelebihan sel bahan api hidrogen untuk menyediakan alternatif yang boleh dijalankan berbanding dengan bahan api fosil dan EV yang dikuasai bateri. Kajian ini meneroka tingkah laku dinamik sistem sel bahan api sebagai respons kepada pelbagai input menggunakan model simulasi yang dibangunkan dalam MATLAB Simulink, menilai penggunaan kuasa dan kecekapan semasa pecutan. Model ini cuba untuk meningkatkan pemahaman mengenai prestasi sel bahan api dalam EV, yang kritikal untuk mengembangkan kaedah pengurusan tenaga dan memajukan penyelesaian pengangkutan yang lestari. Hasil simulasi menunjukkan hubungan yang jelas antara input pemecut dan pecutan kenderaan, dengan input yang lebih tinggi menghasilkan pecutan yang lebih cepat. Satu hubungan tidak linear yang tidak dijangka dalam penggunaan kuasa diperhatikan, dengan jumlah penggunaan yang menurun dengan ketara pada input pemecut maksimum, menunjukkan bahawa kecekapan optimum tidak selalu sepadan dengan output kuasa maksimum. Kecekapan kenderaan meningkat dengan input pemecut yang lebih tinggi, mencapai puncak pada kuasa penuh. Penemuan ini menekankan kepentingan pengoptimuman prestasi EV dalam menyeimbangkan kecekapan tenaga dengan keperluan pecutan.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Background

Hydrogen fuel cell technology is a clean and efficient alternative to traditional combustion engines. It is an electrochemical device that converts the chemical energy of hydrogen and oxygen into electricity, with water being the only by-product. This makes it an ideal solution for reducing greenhouse gas emissions and achieving a more sustainable energy future.

The history of hydrogen fuel cells can be traced back to the early 19th century, when Sir William Grove discovered the principle of the fuel cell. However, it was not until the 1960s that fuel cells gained attention as a potential source of energy for space missions. The first commercial application of hydrogen fuel cells was in the 1970s, where they were used in remote locations and for backup power.

Today, the use of hydrogen fuel cells is gaining popularity as a means of powering transportation, particularly in the form of hydrogen cars. These vehicles use fuel cells to power electric motors, providing a quiet and efficient mode of transportation. The benefits of hydrogen cars include reduced emissions, longer range, and faster refueling times compared to traditional electric vehicles.

Currently, the adoption of hydrogen cars is still in its early stages, with limited infrastructure and high costs being major barriers to widespread use. Additionally, research is ongoing to improve the efficiency and durability of fuel cells, as well as to reduce the cost of production.

1.2 Addressing Better Global Environment Through Application of Hydrogen as Energy Source for vehicle.

The global demand for power sources for vehicles continues to grow as concerns over climate change and the need for sustainable energy sources become increasingly urgent. The widespread adoption of hydrogen fuel cell systems represents a significant opportunity to address these challenges and provide a clean, efficient, and sustainable energy source for transportation. The system offers several advantages over traditional combustion engines and battery-powered electric vehicles, including longer range and faster refueling times. In addition to their benefits for transportation, hydrogen fuel cells also offer significant benefits for the global society. Hydrogen is an abundant element and can be produced from a variety of sources, including renewable energy sources such as wind and solar. This makes hydrogen fuel cells a key part of a sustainable energy system, providing a reliable and efficient energy source without relying on fossil fuels. Hydrogen fuel cells also offer significant benefits for air quality and public health. Unlike traditional combustion engines, which produce harmful emissions that contribute to air pollution and climate change, hydrogen fuel cells produce only water vapor and heat. This can help to reduce air pollution and improve public health, particularly in urban areas where air quality is a major concern. As infrastructure and production costs continue to improve, hydrogen fuel cell systems have the potential to play an important role in meeting the world's growing demand for clean and efficient transportation.

1.3 Problem Statement

The current power sources for vehicles, such as gasoline and diesel engines, are major contributors to environmental pollution and climate change. The combustion of these fossil fuels releases greenhouse gases, particulate matter, and other harmful pollutants into the air, causing adverse health effects and environmental damage. Moreover, the limited availability of fossil fuels and their rising costs make them an unsustainable and unreliable source of energy for vehicles in the long term. Additionally, the current energy system of EV that use battery require long time of charging which is not efficient for emergency situation. Therefore, there is an urgent need to transition towards cleaner and more sustainable power sources for vehicles that can reduce their environmental impact and ensure energy security.

1.4 Project Objective

The main aim of this project is to develop a model of hydrogen fuel cell to recharge battery for EV. Specifically, the objectives are as follows:

a) To develop simulation model for hydrogen fuel cell for EV using MATLAB.

b) To investigate hydrogen fuel cell dynamic behavior for different input value.

c) To analyze model power consumption efficiency while accelerating.

1.5 Scope of Project

This project aims to develop a dynamic simulation model specifically focused on the hydrogen fuel cell system for light electric vehicles (EVs) using MATLAB. The scope encompasses the creation of a closed-loop system, concentrating on the dynamic behavior of the hydrogen fuel cell during various operational scenarios. The primary objectives include investigating the output behavior of the fuel cell in response to different input values and conducting sensitivity tests to analyze the system's response to small changes. This project has certain limitations inherent to its small-scale focus and exclusive concentration on the hydrogen fuel cell in light electric vehicles. The simulation will not encompass broader vehicle dynamics or the integration of other critical components like air conditioning, electronic sensors, and lighting systems. Therefore, the outcomes of the simulation may not fully reflect the holistic behavior of a complete electric vehicle. Additionally, the closed-loop system is designed to specifically target the hydrogen fuel cell, excluding the modeling and analysis of other power sources or energy storage systems. While the simulation model aims to provide insights into the fuel cell's dynamic behavior, the project's scope may not capture the intricacies of the entire electric vehicle system.

1.6 Expected Outcome

The expected outcomes of this project are:

a) Succeed to do simulation using MATLAB to simulate the system.

b) Successfully determine dynamic behavior of hydrogen fuel cell during various operational scenarios.

c) Able to analyze model power consumption efficiency while accelerating and discuss the finding.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter focuses on conducting a comprehensive review of previous research and analysis pertaining to hydrogen fuel cells for electric vehicle machines. The aim is to compile relevant information for the literature review section of this project. The sources utilized for this review include papers, previous journals, and websites, all of which have been appropriately cited. References are provided to ensure the credibility and traceability of the information presented.

2.2 Hydrogen Fuel Cell

A fuel cell is an energy conversion device that continuously converts chemical energy in a fuel into electrical energy, as long as both the fuel and oxidant are available [1]. It offers several advantages over conventional combustion-based technologies and finds applications in critical fields such as electronics, power generation for residential areas, power plants, passenger vehicles, and military operations [2] .

Fuel cells exhibit higher efficiency compared to combustion engines, with electrical energy conversion efficiency exceeding 60% [3] .This higher efficiency translates into lower emissions. In hydrogen fuel cells, the only byproduct of the power generation process is water, leading to no carbon dioxide emissions or air pollutants that contribute to smog formation and health issues [1]. Additionally, fuel cells operate quietly due to their minimal number of moving parts, resulting in reduced noise emissions [4].

Fuel cells are available in various types, but they function based on a similar principle. Generally, a fuel cell consists of three main components: the anode, electrolyte, and cathode [5]. At the anode, hydrogen undergoes an oxidation reaction, generating cations (H^+) and electrons (e^-) ($H_2 \rightarrow 2H^+ + 2e^-$). The cations migrate through the electrolyte to the cathode, while the electrons flow through the external circuit. Meanwhile, at the cathode, a reduction reaction occurs where oxygen combines with the cations and electrons to form water ($4H^+ + O_2 + 4e^- \rightarrow 4H_2O$) [6].

The theoretical voltage generated by the reaction between oxygen and hydrogen is 1.23 Volts, but in practice, the actual voltage is lower. Typically, for practical purposes, a fuel cell system produces a voltage of approximately 0.6-0.7 V at a specified current. This decrease in voltage and increase in current during the chemical reaction are influenced by various factors, including ohmic losses, activation loss, and mass transfer losses [7].

2.2.1 Fuel Cells Classification

Fuel cells can be classified into different types based on the electrolyte used, including alkaline fuel cells (AFCs), proton exchange membrane fuel cells (PEMFCs), phosphoric acid fuel cells (PAFCs), molten carbonate fuel cells (MCFCs), and solid oxide fuel cells (SOFCs) [8]. Each type of fuel cell has its unique characteristics and operating conditions.

2.2.2 Proton Exchange Membrane Fuel Cells (PEMFCs)

Proton exchange membrane fuel cells (PEMFCs) utilize a proton-conducting membrane as the electrolyte. The mobile ions in PEMFCs are H+ protons, and the operating temperature ranges from -40 °C to 90 °C. The cathode can use air or oxygen as oxidants. PEMFCs are known for their rapid start-up time, wide range of operating temperatures, and high specific energy. These characteristics have made PEMFCs suitable for fuel cell vehicles and stationary applications [9].

Among these fuel cell types, PEMFCs have gained significant attention and are widely used in fuel cell vehicles and stationary applications due to their advantages of rapid start-up time, wide operating temperature range (-40 °C to 90 °C), and high specific energy. The structure of a typical PEMFC consists of various components, which are illustrated in Figure 2.1 [10].

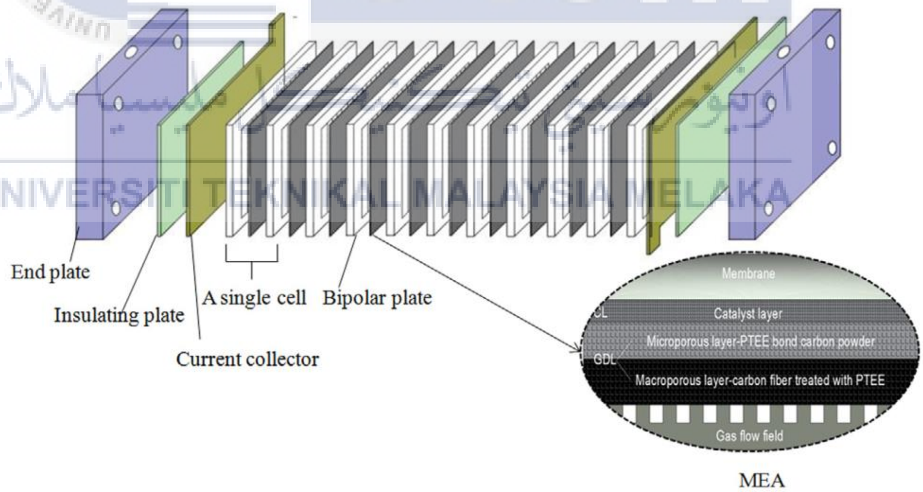

Figure 2.1 Basic structure of typical integrating PEMFC [1]

Water management and thermal management are crucial issues in PEMFCs. Effective water management ensures optimal membrane hydration, preventing membrane drying or flooding. Thermal management addresses heat dissipation to maintain appropriate operating temperatures and prevent degradation of the fuel cell components.

2.3 Hydrogen fuel cell in vehicles

The adoption of Fuel Cell Vehicles (FCVs) is of significant importance in many countries due to their potential to reduce environmental stress and decrease fossil fuel consumption [11]. FCVs can be classified into two categories: pure FCVs (PFCVs) and fuel cell hybrid electric vehicles (FCHEVs). FCHEVs combine fuel cells with other energy storage systems, such as flywheels (FC+FW), batteries (FC+B), ultracapacitors (FC+UC), or a combination of batteries and ultracapacitors (FC+B+UC) [12]. Typically, fuel cells, particularly PEMFCs, serve as the primary power source in FCHEVs, while lithium batteries and ultracapacitors are installed as backup systems to handle peak power demands and fast transient conditions [13].

The information on the range and fuel economy of some commercial FCVs since 2014, utilizing hydrogen as a fuel are shown in Table 2.1. The maximum range achieved in a single refueling is up to 435 miles, with the Toyota Mirai exhibiting the best fuel economy of 66 MPGe in both city and highway driving conditions. The Mirai and Honda FCVs operate in PFCV mode due to the superior dynamic characteristics of their PEMFCs, while the Audi A7h and Honda Clarity adopt PCHEV mode for better acceleration to compensate for operational instability. To address the drawbacks of FCHEVs, various control strategies have been introduced, including peaking power source strategy, operating mode control strategy, fuzzy logic control strategy, and equivalent consumption minimization strategy [14]. In a study [15], a detailed model of FCHEVs developed in MATLAB/Simulink revealed that both FC+B and FC+B+UC vehicles were equally suitable for practical applications. FC+B vehicles are generally less expensive, while FC+B+UC vehicles offer lower operating costs due to higher fuel efficiency and extended fuel cell lifetime. Wang et al. (2019) [16] proposed a semi-theoretical and semi-empirical model to optimize FCHEV systems, considering cell degradation and fuel cell deterioration to extend their lifespan.

Table 2.1 Summary of commercial FCVs [1].

Vehicle prototype	Year	Running range (mile)	Fuel economy MPGe at city	Fuel economy MPGe at highway	Type
Honda FCX clarity	2014	231	58	60	PFCV
Honda FCV Concept	2014	435	/	/	PFCV
Audi Sportback A7h-tron Quattro	2014	500	62	62	FCHEV
Roewe 950 Fuel cell	2014	350	/	/	PRFV
Volkswagen Golf Hymotion	2014	426	/	/	PFCV
Toyota Mirai	2020	750	66	66	PFCV
Hyundai Tucson Fuel Cell	2016	265	49	51	PFCV
Honda Clarity Fuel Cell	2017	434	/	/	FCHEV

2.4 Energy storage

In FCVs, the electrical energy generated by the fuel cell stack needs to be efficiently stored and transmitted to the electric motor. In a typical FCV, the auxiliary battery plays a secondary role, primarily involving starting the vehicle and temporarily storing electric power. Compared to battery electric vehicles (BEVs), the importance of the auxiliary battery in FCVs is relatively insignificant. Consequently, a low-capacity battery is commonly employed due to its limited role in the overall power supply system.

Heavy-duty commercial vehicles, such as trucks and buses, have unique energy requirements due to frequent long-distance driving and high-power consumption. To meet these demands, a substantial amount of electricity needs to be stored. However, the installation of numerous high-capacity batteries to address this requirement can lead to a significant increase in logistics costs and overall vehicle price.

One advantage of using a hydrogen fuel cell system is that the battery can be charged while the vehicle is in motion, mitigating the need for a significantly larger battery capacity. The hydrogen fuel cell system enables the battery to be replenished during driving, thereby compensating for the limitations of a low-capacity battery. In the context of large hydrogen vehicles, such as sizeable electric trucks, a specific example highlights the use of a relatively small battery with a capacity of 73.2 kWh. This capacity is substantially smaller compared to the typical 500 kWh battery employed in large electric trucks. However, the smaller battery capacity is suitable for the operational requirements of these hydrogen vehicles due to the ability of the fuel cell system to charge the battery while driving [17].

The battery module serves the purpose of supplying the dynamic portion of the required power, while the PEMFC is responsible for supplying the static or average portion of the required power. This division of responsibilities ensures that when the demanded power exceeds the optimum power output of the PEMFC, the battery module will discharge and provide the remaining required power. Conversely, when the demanded power is lower than the PEMFC's optimum power output, the excess power from the PEMFC will charge the battery module. Consequently, through a well-designed and controlled strategy, the battery will never require external charging sources for operation within the vehicle [18].

2.5 Energy conversions and controls

Power converters play a crucial role in ensuring a consistent voltage supply to the load. These devices convert energy and can either step up or step down the voltage. One commonly used power converter is the DC/DC converter, which adjusts the voltage from multiple power sources to match the rated voltage of the DC machine. By working in conjunction with motor drive techniques like inverters, the DC/DC converter facilitates controlled power flow in and out of the system based on the power conditions. Popular power converter topologies include the buck, boost, and Cuk converters. The buck converter, for instance, is employed to decrease the voltage level [19]

E-BOP, or Electrical Balance of Plant, is a system in electric vehicles that includes converters and inverters to regulate the power supplied by fuel cells and batteries [17]. The battery voltage remains stable within a specific range, while the fuel cell voltage decreases as power generation increases. To maintain stability, the fuel cell voltage needs to be boosted to match the inverter input voltage. This is achieved using a DC-DC boost converter. The converter adjusts current and increases voltage by controlling the transistor's on/off duty ratio. The inverter converts DC voltage to AC voltage and supplies power to the motor. A simplified model is used to simulate the system, and specific equations are employed for the converter and inverter [17].

$$V_{conv} = \frac{V_{FC}}{1-D} \tag{1}$$

$$I_{conv} = \frac{V_{FC} I_{FC}}{V_{conv}} \tag{2}$$

$$V_{inv,3p} = \begin{cases} \sqrt{2} V_{dc} \cos\left(\theta^*\right) \\ \sqrt{2} V_{dc} \cos\left(\theta^* - \frac{2}{3}\pi\right) \\ \sqrt{2} V_{dc} \cos\left(\theta^* + \frac{2}{3}\pi\right) \end{cases} \tag{3}$$

$$\theta^* = \int w_e^* dt \tag{4}$$

The control strategy ensures the converter output voltage matches the battery voltage for stable power distribution. When the battery discharge current increases, the converter adjusts its voltage to match the battery, while reducing the input voltage. This control mechanism increases the fuel cell current, which decreases the battery discharge rate.

If the battery reaches a steady state or switches to charging mode, the fuel cell current decreases to increase the fuel cell voltage. This reduces the converter's downstream current and the battery charging current. The system's control logic proves effective in stabilizing the overall operation, and the duty ratio serves as a control variable to optimize system parameters without risking instability.

In a specific study [20], interleaved converters were proposed for powering brushless DC motors. These converters offer advantages such as high voltage gain, wide output range, and long lifespan. However, they also add complexity and cost to the system.

To address these challenges, a new high-voltage gain DC-DC converter topology was introduced. This converter, placed between the fuel cell and the load, uses MOSFETs and diodes as power semiconductor devices. MOSFETs were chosen for their features like high input impedance, low energy consumption, and fast switching speed, which are ideal for automotive applications. The proposed converter provides benefits such as robustness, low power loss, fewer components, and efficient voltage conversion [21].

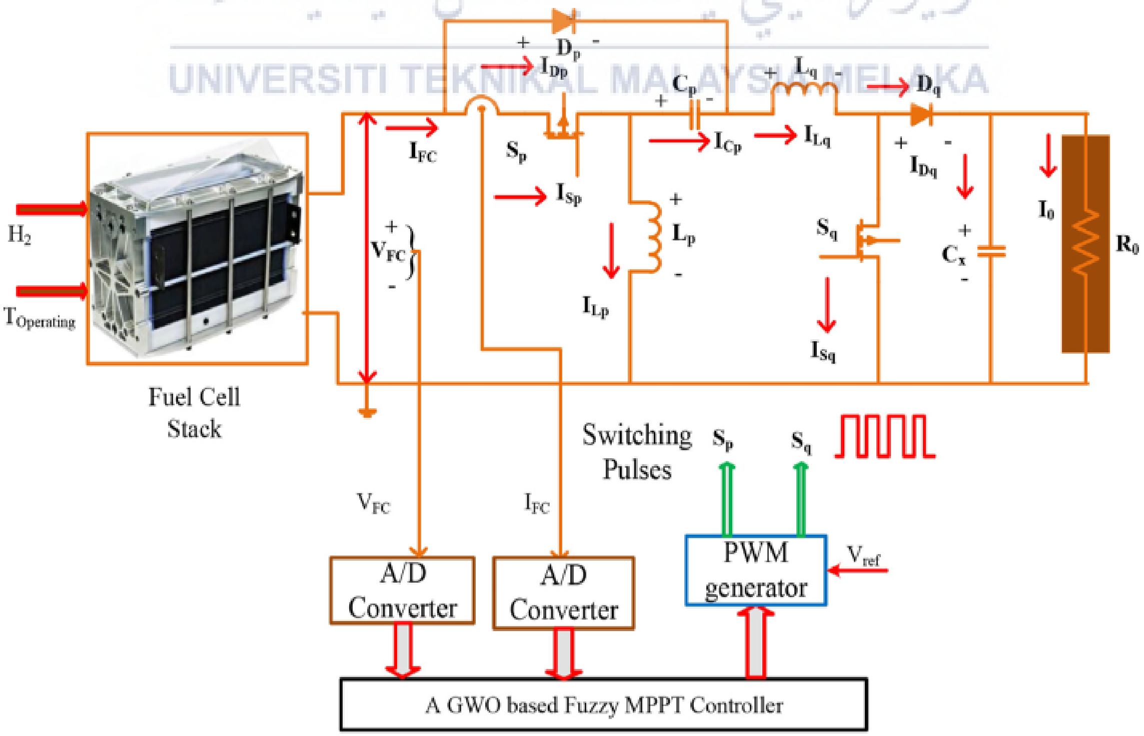

Figure 2.2 Detailed working operation of PEM fuel cell [21]

The converter operates by applying pulse width modulation (PWM) dependent pulses to the power switches at zero displacement angle. When the MOSFETs are activated, the diodes go into a reverse biased condition, allowing the energy storage elements (Lp and Lq) to accumulate energy while the static devices (Cp and Cq) absorb power. The power switches then enter a reverse biased condition, turning on the diodes. The converter's voltage gain can be determined based on the provided figures.

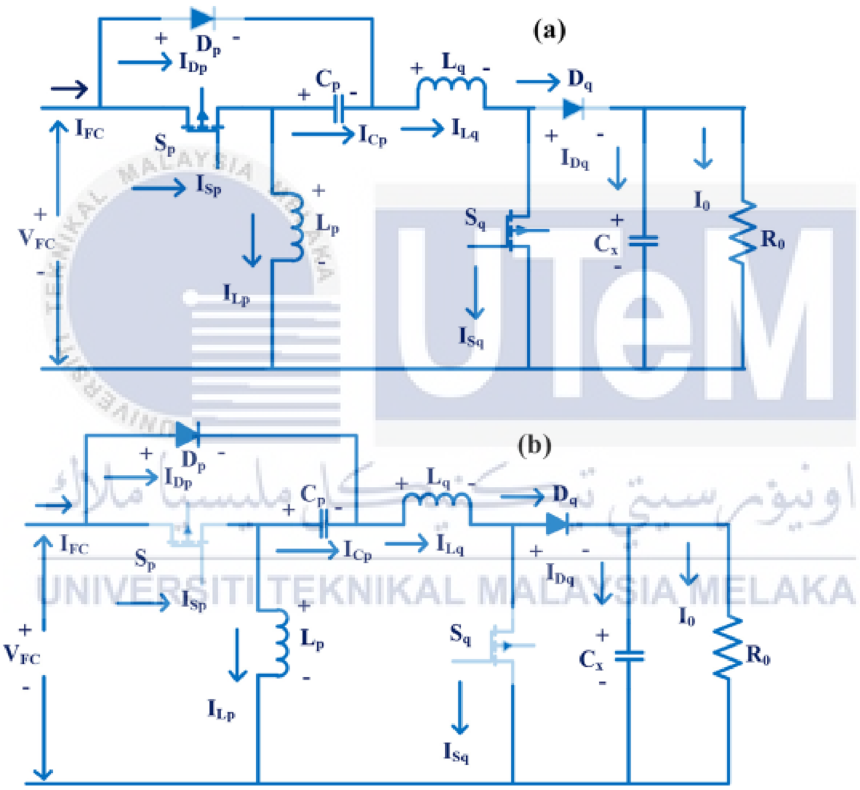

Figure 2.3 Power converter working stages under, (a). ON condition, plus (b). OFF condition. [21]

In article [22] focuses on utilizing two boost converters connected in an interleaved manner. This configuration provides several advantages, including a high voltage conversion ratio, wide output range, low power losses, and continuous power supply to the induction motors. The circuit diagram for the proposed interleaved converter is shown in Figure 2.3.

Two Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) are used as switches to control the fuel cell's supply voltage. MOSFETs are selected for their benefits such as high temperature tolerance, compact size, low conduction resistance, moderate power absorption, and long lifespan. The circuit includes three inductors (Lx, Ly, and Lz) connected between the fuel cell and the load. During the switch ON state, these inductors charge for a specific time period (DTs) and have corresponding charging potentials (VLx, VLy, and VLz). At this stage, the three diodes (Dx, Dy, and Dz) are in an ideal switch-off state. In the second state, when the switches are completely off, the inductors start discharging for a specific time period ((1-D)Ts), and the diodes begin operating.

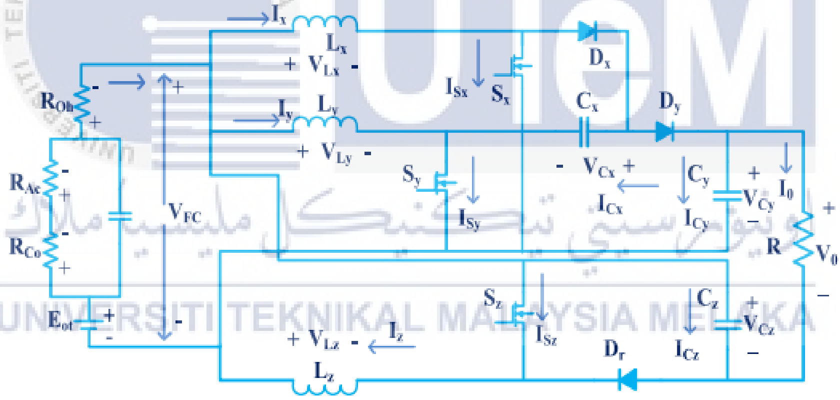

Figure 2.4 Circuit diagram of the interleaved DC-DC converter [22]

2.6 Current issues and challenges

PEMFCs, offer several advantages for fuel cell vehicle development and have the potential to replace traditional internal combustion engines. These fuel cells operate using hydrogen, which has a high specific energy value three times that of gasoline. They only produce water as waste, resulting in zero air pollution. Additionally, PEMFCs exhibit greater efficiency compared to conventional vehicles and have compact size, quick response, and a wide range of power capabilities.

Although PEMFCs have several advantages for fuel cell vehicle development, but as the system becomes more efficient, it also becomes more costly. There are challenges in terms of efficiency, cost, and design considerations that need to be addressed. Despite their benefits, PEMFCs are still relatively expensive due to the use of platinum catalysts and low manufacturing quantities. Efforts are being made to reduce costs by exploring alternative catalyst materials [23].

Renewable energy sources have limitations in terms of energy and power density, preventing them from meeting the performance standards of vehicles powered by internal combustion engines (ICEs). One major drawback is the high cost of these vehicles, making them unaffordable for many consumers. Moreover, substantial investments are required to establish the necessary refueling infrastructure, which poses a significant financial challenge. Additionally, there is a need for an extensive study on hydrogen production for fuel cells, including delivery and storage systems, as well as the development of refueling infrastructure [24].

2.7 Existing Technologies

Table 2.2 compiles and summarizes the key criteria, technology, renewable energy source, and electrical characteristics from various research studies. This table provides a comprehensive comparison of the research methodologies employed, highlighting the advantages and disadvantages associated with each approach.

Table 2.2 Outline methodology, advantages and disadvantages from selected review papers

No.	methodology	fuel cell type	operating voltage	power load	advantages	disadvantages	reference
1	proposes a methodology for optimizing power output in an Electric Vehicle (EV) system using a fuel cell as the power source. It suggests the integration of a Maximum Power Point Tracking (MPPT) controller with a Grey Wolf Controller (GWC) based fuzzy technique to extract peak power from the fuel cell stack. Additionally, a high voltage gain DC-DC converter is employed to overcome the low supply voltage of the fuel cell.	PEMFCS	45.1 V	5.98kW	*excellent dynamic response, quick starting time, optimal size, high temperature withstand ability *high voltage conversion ratio, moderate power losses during conduction, low voltage stress on switches, high steady-state stability, and wide input operation. *reduces oscillations around the Maximum Power Point (MPP), achieves high tracking speed, and requires fewer sensors for current and voltage sensing.	does not discuss the cost, complexity, or scalability considerations of implementing the proposed methodology, which could be important factors to consider in real-world applications.	Design of GWO based fuzzy MPPT controller for fuel cell fed EV application with high voltage gain DC-DC converter(CH Hussaian et. al. 2023)

2	implementing a Maximum Power Point Tracking (MPPT) technique using an Artificial Neuro Fuzzy Inference System (ANFIS) controller optimized with Genetic Algorithm (GA), aiming to achieve high power extraction with minimal voltage distortions. The performance of the fuel cell-based system is analyzed using MATLAB/Simulink software.	PEMFCS	28 V	910 W	*high flexibility, fast startup, compact size, lightweight, and cost-effectiveness. *reduced oscillations, faster convergence, higher efficiency, good dynamic response, fast tracking speed, and high accuracy. *high input voltage sharing capability, reduced conduction losses, low voltage stress on switches, and high efficiency.	does not discuss other important factors such as system complexity, scalability, or potential limitations of using the MATLAB/Simulink software for testing and analysis.	Design of high voltage gain converter for fuel cell based EV application with hybrid optimization MPPT controller(Shaik Rafikiran et. al. 2023)

3	a fuel-cell (FC)/battery hybrid backup power system using a newly developed three-port converter for high step-up applications. The converter achieves a high voltage gain through a quasi Z-source network and energy transfer capacitor. Controllers based on the converter's small-signal model are designed to regulate power levels and smooth the FC power profile according to the proposed energy management strategy (EMS).	PEMFCS	69.67 V	1.2 kW	*high step-up ratios by utilizing a qZc network and energy-transfer capacitor. * (EMS) effectively smooths the FC load profile, and the designed PI compensators based on the small-signal model of the converter contribute to the performance of the strategy.		A fuel-cell/battery hybrid DC backup power system via a new high step-up three port converter (F. Akar 2021)
4	involves using multi-criteria decision-making methods to determine the most suitable fuel cell type for integration into a normal class small aircraft hybrid powertrain	PEMFCS	-	-	*high energy conversion efficiency, making them a promising alternative for clean and efficient power generation. *have rapid startup times, allowing for quick power generation when needed, making them suitable for applications that require instant power availability.	*relatively expensive to manufacture due to the use of costly materials *sensitive to impurities present in the fuel and oxidant streams. Even small amounts of impurities can cause performance degradation	Decision mechanism between fuel cell types: A case study for small aircraft (Murat Ayar et. al. 2023)

2.8 Summary

This literature review focuses on hydrogen fuel cells for electric vehicle applications. It provides an overview of fuel cell technology, its advantages over traditional combustion engines, and the various types of fuel cells available. The review highlights proton exchange membrane fuel cells (PEMFCs) as the most widely used type in fuel cell vehicles and stationary applications due to their rapid start-up time, wide operating temperature range, and high specific energy. The review also discusses the classification of fuel cells based on electrolyte type and explores the range and fuel economy of commercial fuel cell vehicles. It further delves into energy storage considerations in fuel cell vehicles, emphasizing the role of hydrogen fuel cells in charging the auxiliary battery while driving. The literature review concludes by examining power converters and control strategies, including the use of DC/DC converters and interleaved converters, to regulate power distribution in fuel cell systems. The challenges and current issues associated with PEMFCs, such as cost and efficiency, are also addressed.

CHAPTER 3

METHODOLOGY

3.1 Introduction

The methodology section of this project is pivotal in delineating the systematic and structured approach employed to simulate a hydrogen fuel cell system for electric vehicles (EVs) using MATLAB Simulink. This section encompasses various facets, including components selection, parameterization, analysis methods, project flowchart, block diagram, and an acknowledgment of method limitations.

Following the literature review, the focus shifts towards understanding the intricacies of MATLAB Simulink, the chosen software for simulation. Additionally, the selection and parameterization of components crucially contribute to the overall system's efficiency and performance. The project methodology also includes defining analysis methods, outlining the steps and tools used to evaluate the simulated system's behavior and performance. Furthermore, a detailed project flowchart and block diagram will be presented to illustrate the sequential and hierarchical arrangement of tasks within the project. Despite the meticulous planning and execution, it is crucial to acknowledge the limitations inherent in the chosen methodology. These limitations will be addressed transparently, providing insights into the potential constraints and challenges that might impact the project's outcomes.

In essence, the methodology section serves as a compass, guiding the reader through the intricacies of the project's implementation, ensuring a robust and comprehensive understanding of the approach taken to simulate a hydrogen fuel cell system for electric vehicles.

3.2 Project Overview

This project utilizes both fuel cells and batteries as power sources have gained significant attention in recent years due to their potential for improved energy efficiency and reduced emissions. In this system, the fuel cell serves as the primary power source, while the battery provides additional power and assists during peak demand periods. The power converter and power distribution controller play crucial roles in managing the power flow between these components and the electric motor.

3.3 Project Flowchart and Block Diagram

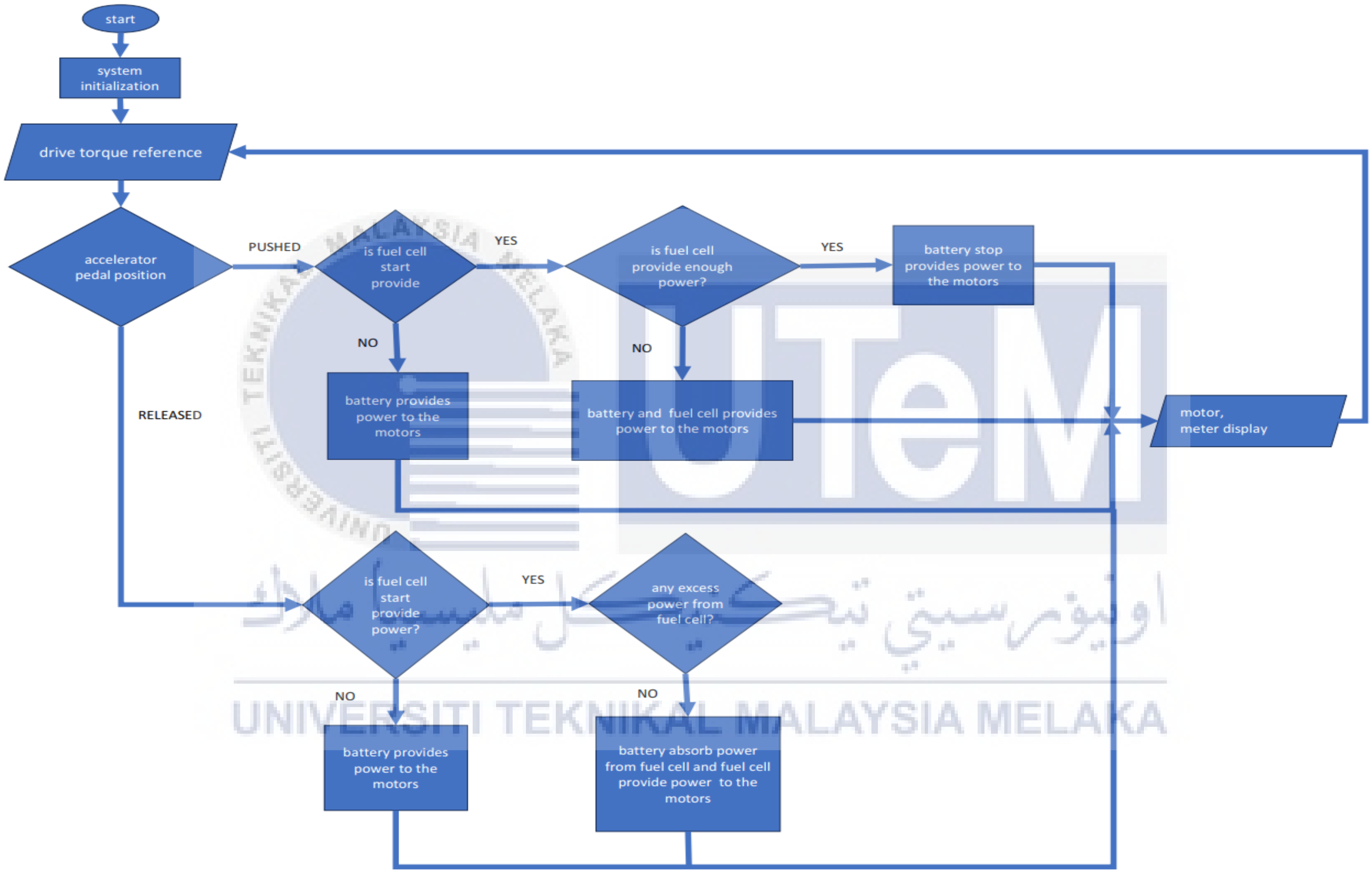

Figure 3.1 System Flowchart

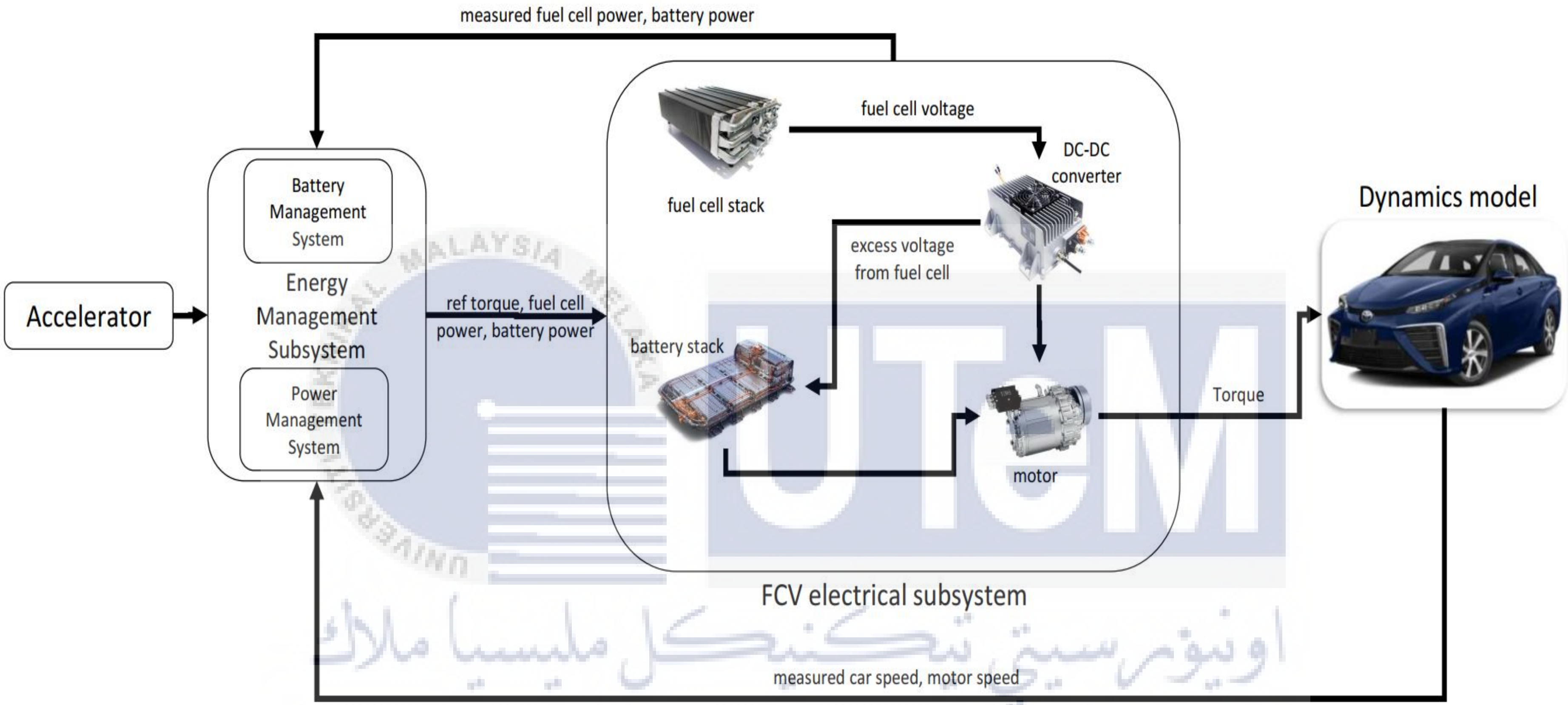

Figure 3.2 System Block diagram [25]

3.4 Methodology

The Energy Management Subsystem (EMS) is pivotal in coordinating power distribution within the FCV powertrain. It computes reference signals for the electric motor drives, fuel cell system, and DC/DC converter, factoring in accelerator position (ranging from -100% to 100%) and the measured FCV speed, where negative accelerator positions signify braking. The EMS ensures precise power allocation between the two electrical sources, considering the dynamic interplay of the accelerator and FCV speed.

Simultaneously, the Battery Management System (BMS) upholds the battery's State-Of-Charge (SOC) within the targeted range (40% to 80%) and guards against voltage collapse by regulating the power drawn from the battery. Concurrently, the Power Management System (PMS) governs the electric motor's reference power by distributing the power demand based on the available power from the battery and the fuel cell. The DC/DC converter current is employed for controlling this power distribution. Collectively, these systems collaborate to optimize the utilization of both the battery and fuel cell, ensuring the efficient and stable functioning of the FCV powertrain.

In simulation highlights diverse operational modes of the FCV, showcasing the system's adaptability to variations in the accelerator pedal position. Throughout the simulation cycle, the FCV experiences acceleration, cruising, battery recharging during acceleration, and regenerative braking. The integration of the EMS, BMS, and PMS facilitates smooth transitions between these modes. The scenario delineates specific time instances where the battery and fuel cell work in tandem to supply power and meet the required torque, underscoring the intricate coordination necessary for effective energy management across different driving scenarios.

3.4.1 Parameters

3.4.1.1 MATLAB

Figure 3.3 MATLAB logo [26]

Matlab and Simulink serve as a dynamic duo for conducting comprehensive simulations and analyses of hydrogen fuel cell systems. Matlab's computational prowess and extensive mathematical libraries empower users to build precise mathematical models of fuel cells, incorporating vital parameters like reactant flows, temperature, pressure, and electrochemical reactions. Complementing this, Simulink offers an intuitive graphical interface to construct interconnected block diagrams, representing various system components. This seamless integration of Matlab and Simulink enables engineers and researchers to holistically explore fuel cell behavior, optimize performance, and evaluate different operational scenarios.

Furthermore, Simulink provides diverse simulation capabilities, including time-domain and frequency-domain analyses, allowing users to assess transient responses, frequency characteristics, and system stability. It also supports sensitivity analysis, Monte Carlo simulations, and parameter sweeps, facilitating the examination of uncertainties and design variations. In essence, this combination of Matlab and Simulink offers a robust framework for the design, testing, and refinement of hydrogen fuel cell systems, making it an indispensable tool for professionals in the field of sustainable energy.

3.4.1.2 Hydrogen Fuel Cell

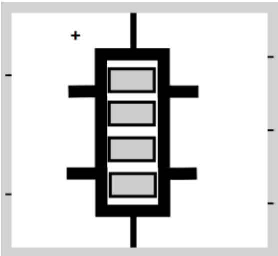

Figure 3.4 Fuel cell stack symbol [27]

Cell no. : 400 cells

Rated Voltage : 288 Vdc

Rated Power : 100 kW

Type : Proton Exchange Membrane Fuel Cell (PEMFC)

A Proton Exchange Membrane Fuel Cell (PEMFC) is a key part of hydrogen fuel cell systems used in things like vehicles and stationary power sources. In a PEMFC, hydrogen goes to the positive side (anode), and oxygen or air goes to the negative side (cathode). Inside the cell, there's a special membrane (the proton exchange membrane) that separates the anode and cathode. When hydrogen meets the anode, it reacts and turns into protons (H+) and electrons (e-). The protons move through the membrane to the cathode, and the electrons travel outside the cell through a circuit, creating an electric current that can be used for different purposes.

In the simulation of a PEMFC system with 400 cells rated at 288 Vdc and 100 kW, it's important to note that the flowrate of hydrogen and oxygen supply to the PEMFC is always maximized to ensure optimal power generation. This means that a continuous and efficient supply of hydrogen and oxygen is maintained to meet the fuel cell's power demands.

3.4.1.3 Battery

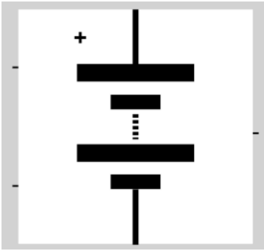

Figure 3.5 Battery symbol [28]

Capacity	: 13.9 Ah
Rated Voltage	: 288 Vdc
Rated Power	: 25 kW
Type	: Lithium-Ion battery

Lithium-Ion battery with a capacity of 13.9 Ah and rated at 288 Vdc and 25 kW plays a pivotal role as a backup energy source for the Proton Exchange Membrane Fuel Cell (PEMFC). The battery serves as a reliable backup during periods of high energy demand when the fuel cell alone cannot meet the required power output. Whenever the load exceeds the fuel cell's capacity, the battery seamlessly steps in to provide the extra energy needed, ensuring a stable and uninterrupted power supply. Additionally, during the system initialization phase or when the fuel cell generates excess power, it efficiently charges the lithium-ion battery, allowing for energy storage and subsequent utilization during peak demand or as a contingency measure, thereby optimizing the overall energy management and reliability of the system. This dynamic interplay between the PEMFC and the lithium-ion battery ensures a robust and versatile energy solution capable of meeting a wide range of power demands and operational scenarios.

3.4.1.4 DC-DC Converter

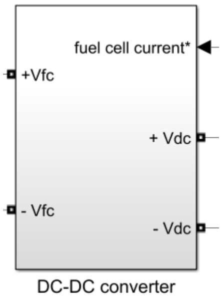

Figure 3.6 DC-DC Converter Symbol [29]

The DC/DC converter, specifically of the buck type, operates as a current-regulated device in this system. Its primary function is to efficiently convert energy from the fuel cell source to both the battery and the motor. This converter ensures a controlled flow of electrical current, facilitating the seamless transfer of power between these essential components, ultimately optimizing energy utilization and performance in the integrated system.

3.4.1.5 Electrical Motor

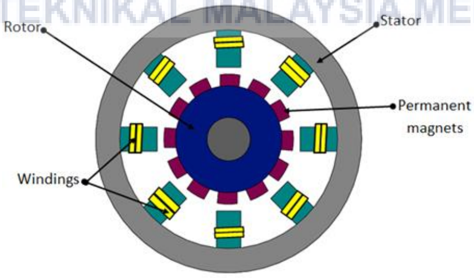

Figure 3.7 Electrical motor symbol [30]

Rated voltage : 288 Vdc,

Rated Power : 100 kW

Type : Permanent Magnet Synchronous Machine (PMSM)

The Permanent Magnet Synchronous Machine (PMSM) in this system is a formidable power source with a rated voltage of 288 Vdc and a robust rated power of 100 kW. Its primary role is to generate torque within the dynamic model, serving as a crucial component for propulsion or mechanical work. As a high-performance electric machine, the PMSM efficiently converts electrical energy into mechanical motion, providing the necessary torque to drive the dynamic model's mechanical components. Its synchronous operation, facilitated by permanent magnets, ensures precise control and synchronization of the torque output, making it an ideal choice for applications demanding both power and accuracy within the dynamic model.

3.5 Simulation

The simulation method employed in this project involves the manipulation of the accelerator pedal to simulate various driving scenarios, and the subsequent observation of output parameters using dynamic meter scope within the MATLAB environment. The accelerator pedal serves as the control input, allowing us to mimic real-world driving conditions such as accelerating, slowing down, and braking. By adjusting the accelerator pedal's position, able to effectively simulate changes in the driver's behavior and intentions.

The dynamic meter scope plays a critical role in this simulation setup as it allows us to monitor and record key parameters in real-time. These parameters include the accelerator pedal position, the car's speed in kilometers per hour (km/h), the torque reference versus the measured torque in Newton-meters (Nm), and the measured power in Watts (W) from the motor, fuel cell, and battery. This comprehensive data collection provides valuable insights into the dynamic behavior of the vehicle and its energy management system under different driving scenarios.

3.6 Data collection

During the data gathering phase, the simulation simulates scenario where vehicle acceleration by varying the accelerator pedal position from 80% to 90% to 100%. The time taken for the vehicle to accelerate from 0 to 100 km/h was recorded during these simulations. Furthermore, extensive power consumption measurements were carried out, using data from both the fuel cell and the battery, adding to the quantification of total energy consumption during the acceleration phase. The collected data was then analyzed to evaluate the efficiency of power usage during acceleration from 0 to 100 km/h.

3.7 Limitation of proposed methodology

While robust, the technique used in this project has several limits, particularly in terms of software capabilities and the simulation's capacity to recreate dynamic real-world settings. To begin, despite its great features, the use of MATLAB Simulink has inherent limits. Its simulation environment may not completely capture all real-world details, such as changing ambient variables or unexpected hardware behaviors. This disparity may result in inconsistencies between simulated and actual real-world performance. Furthermore, the simulation may fail to account for dynamic and unexpected real-world variables. Factors like as changing road conditions, the impact of various weather scenarios, and differences in driver behavior are complicated and fluid, making accurate representation in a simulated environment difficult. This constraint emphasizes the importance of interpreting simulation results with caution, understanding that they may not perfectly reflect the intricacies and volatility inherent in real-world circumstances.

3.8 Summary

In this chapter, the methodology for simulating a hydrogen fuel cell system in electric vehicles using MATLAB Simulink is outlined. The process is detailed, beginning with a structured approach that involves component selection, parameterization, and analysis methods, with the role of MATLAB Simulink in ensuring system efficiency and performance being highlighted. The incorporation of fuel cells and batteries as power sources is also discussed, focusing on their contribution to energy efficiency and emission reduction. Key systems such as the Energy Management Subsystem (EMS), Battery Management System (BMS), and Power Management System (PMS), essential for effective power distribution in the fuel cell vehicle powertrain, are introduced.

Further elaboration is provided on the simulation parameters, with emphasis on the use of MATLAB and Simulink for the development of mathematical models and graphical interfaces for various system components. The specifics of the Proton Exchange Membrane Fuel Cell (PEMFC), lithium-ion battery, DC/DC converter, and Permanent Magnet Synchronous Machine (PMSM), and their roles in the system are explained. The simulation process, which includes mimicking real-world driving scenarios. Lastly, the limitations of using MATLAB Simulink for such simulations are acknowledged, including potential gaps in replicating real-world complexities, underscoring the challenges faced in accurately simulating complex systems like hydrogen fuel cells in EVs.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

The results of a MATLAB Simulink simulation of a hydrogen fuel cell system for electric vehicles are presented and analyzed in this chapter. It is an important portion since it displays the practical application of the previously described ideas and approaches. Under several simulated scenarios, the performance of the fuel cell system, including its efficiency and dependability, is investigated. The data analysis phase entails a comprehensive evaluation of the results to ensure that the interpretation is correct.

4.2 Result and Analysis

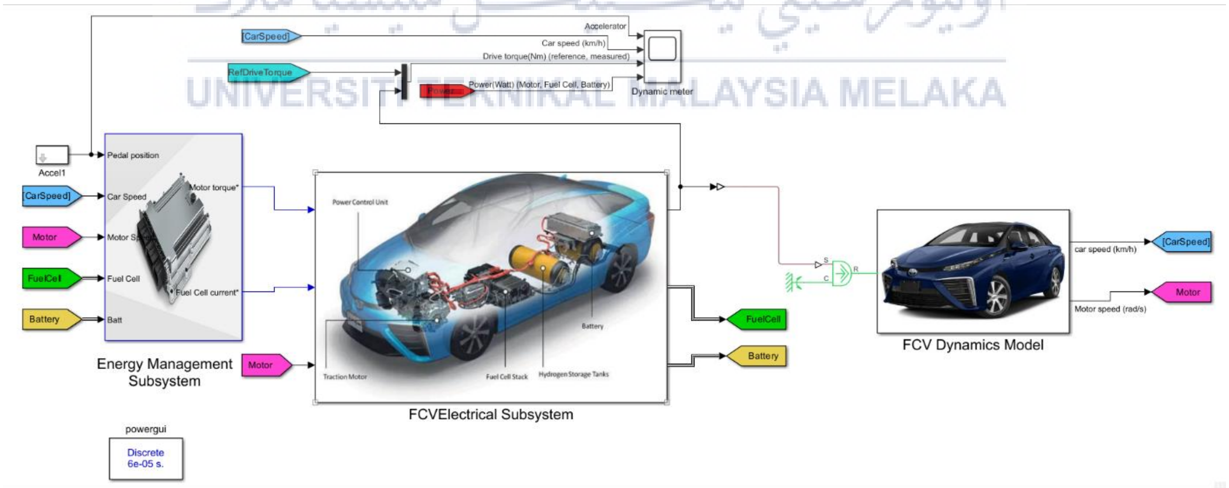

Figure 4.1 Simulation layout [31]

Figure 4.1 depicts a simulation layout for a Fuel Cell Vehicle (FCV) Electrical System. On the left, there's an Energy Management Subsystem which processes inputs such as pedal position and outputs data like motor torque and fuel cell current. At the center, the major components like the battery, motor, and hydrogen fuel cell stack, is placed within the FCV Electrical Subsystem. On the right, the FCV Dynamics Model translates the subsystem's outputs into tangible vehicle dynamics, displaying car speed and motor speed as measurable outputs. This layout serves as a roadmap for understanding the energy flow and dynamic response of the FCV during operation.

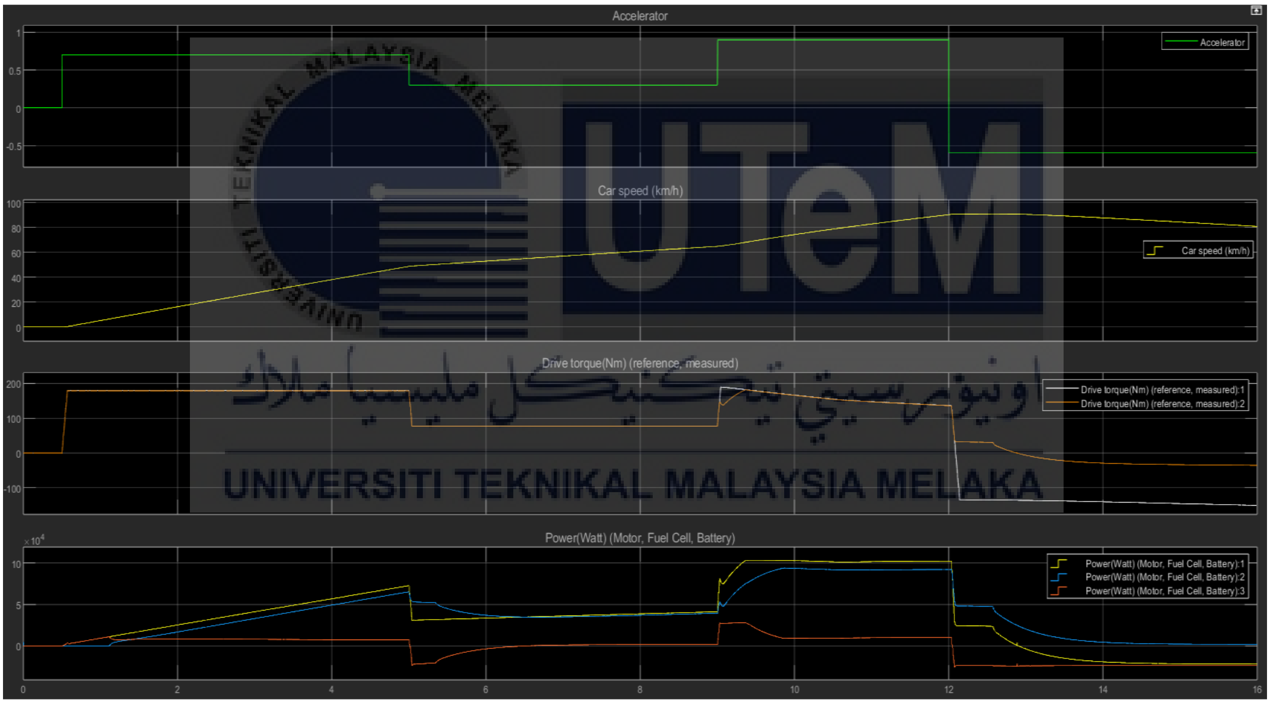

Figure 4.2 Simulation result on various scenerio

The simulation depicts numerous aspects of the FCV's operation over the course of a full cycle, including acceleration, steady driving, battery charge while accelerating, and energy recovery when braking. When started, the simulation runs in accelerator mode for around a minute. The vehicle's speed is recorded to increase from a standstill to around 90 km/h in 12 seconds before decreasing to 81 km/h at the 16-second mark. This is accomplished by putting the accelerator pedal to 70% between 0.5 and 5 seconds, dropping it to 30% upon release, then boosting it to 90% for another 4 seconds before engaging regenerative braking at -60% for the remaining period.

The FCV is initially immobile. The driver accelerates in half a second by pressing the pedal to 70%, with the battery first powering the motor until the fuel cell kicks in. The fuel cell begins to contribute power after 1 second, but because to its intrinsic delay, it cannot match the demand immediately, forcing the battery to compensate. When the pedal is lowered to 30% after 5 seconds, the fuel cell does not immediately drop its output, so the battery absorbs the excess power to help maintain the required torque. The fuel cell delivers enough power in 6 seconds, eliminating the need for the battery.

When the pedal is pressed to 85% in 9 seconds, the motor requires 75 kW, but the fuel cell can only give 48 kW instantly. The battery compensates for the loss with an additional 27 kW, but the overall power still falls short of the demand, resulting in a torque imbalance. As the fuel cell ramps up power, the torque output equals the target at 9.35 seconds, and the battery's contribution is reduced to 9 kW. Activating regenerative braking by putting the pedal to -60% for 12 seconds converts the motor into a generator, harnessing the FCV's kinetic energy and turning it into electrical energy stored in the battery. Because of the battery's absorption limit of 25 kW, the intended -147 Nm torque is not possible. Finally, the fuel cell's output declines to roughly 2 kW after 15 seconds, which is its minimal power level.

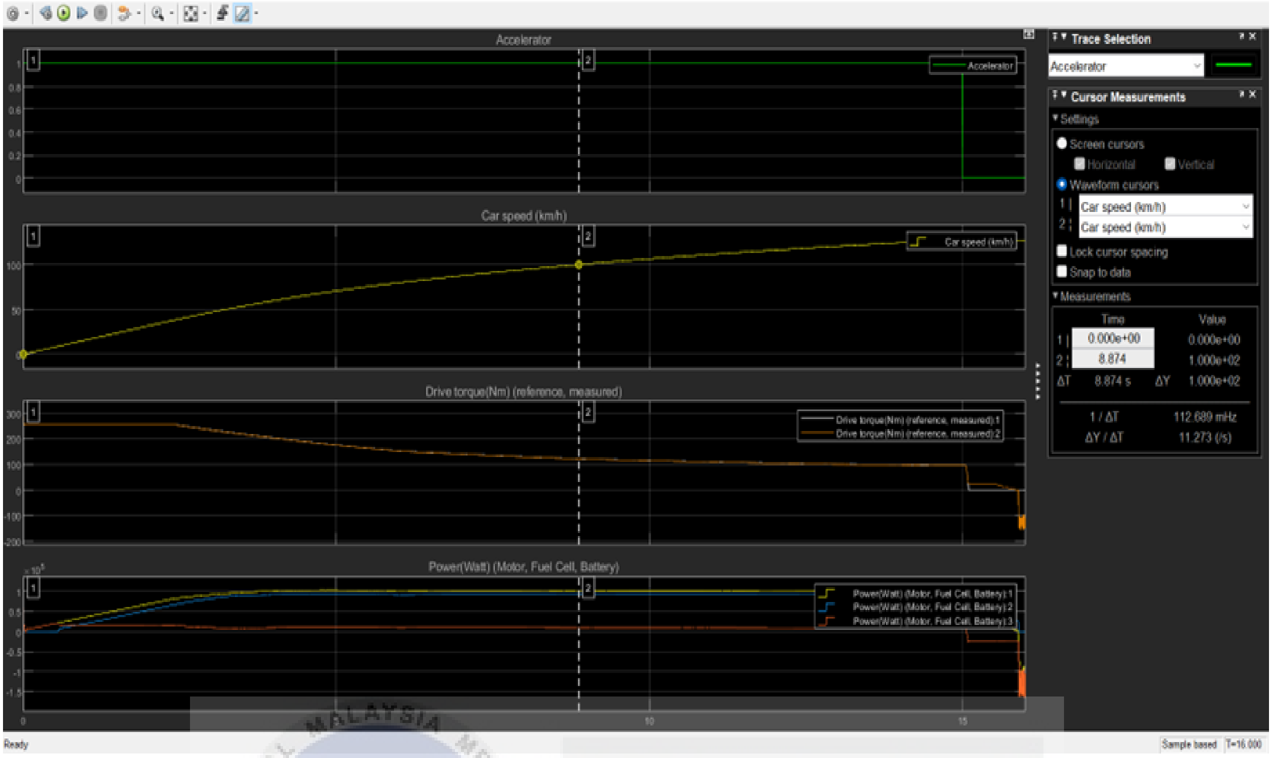

Figure 4.3 Simulation for Acceleration 0-100km/h at 100% Accelerator Input

Figure 4.3 shows the simulation for acceleration from 0 to 100 km/h with 100% accelerator input reveals important insights into power consumption. The data on power consumption is methodically gathered by calculating the area under the graph of fuel cell power(blue) and battery power(red), which highlights the dynamic energy demands by motor(yellow) throughout the acceleration process in the graph of the fourth row. The simulation was repeated for accelerator input at 90% and 80%.

Table 4.1 Time Taken and Power Consumtion for Acceleration 0-100km/h

accelerator	time 0-100kmh,s	total power consumption, kWh	Efficiency, kWh/s
80%	9.675	0.1982	0.02049
90%	9.180	0.1992	0.02170
100%	8.874	0.1981	0.02232

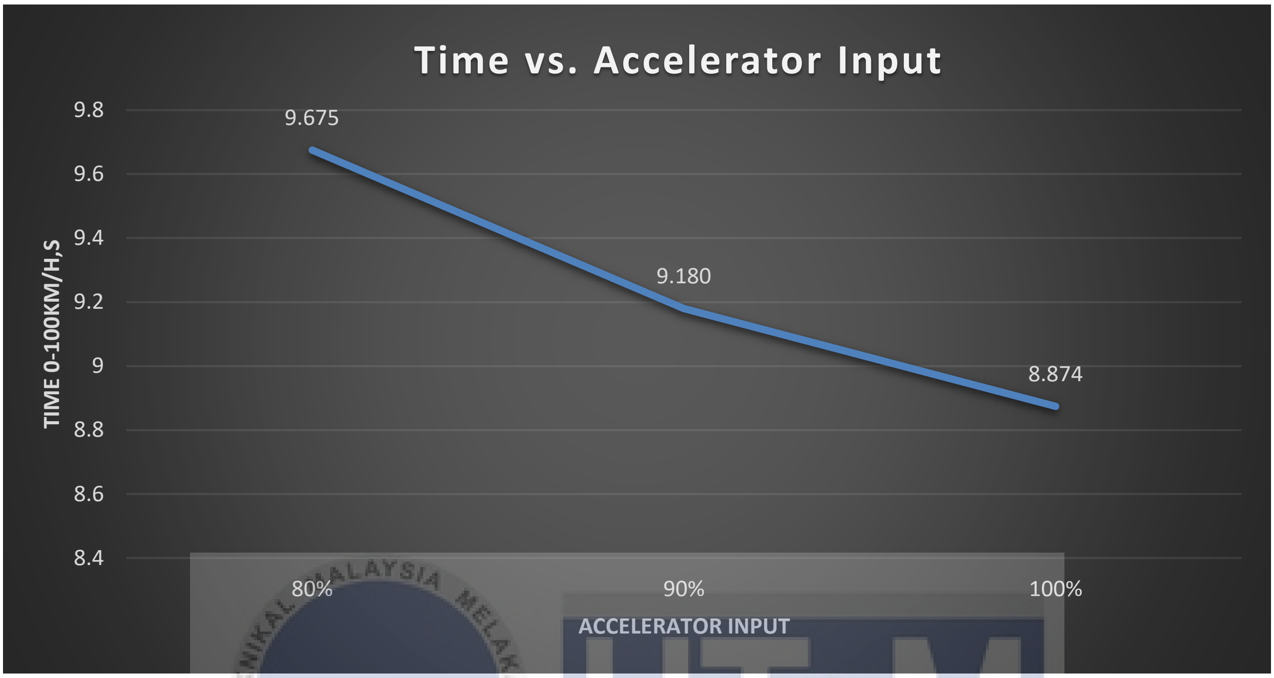

Figure 4.4 Time vs. Accelerator Input Graph

The figure 4.3 and Table 4.1 show the link between accelerator input and the time it takes a vehicle to accelerate from 0 to 100 km/h. The time required for the car to reach 100 km/h reduces as the accelerator input goes from 80% to 100%. Specifically, the car takes 9.675 seconds at 80% throttle, 9.180 seconds at 90% throttle, and 8.874 seconds at 100% throttle. This chart demonstrates a definite positive association between throttle input and vehicle acceleration performance.

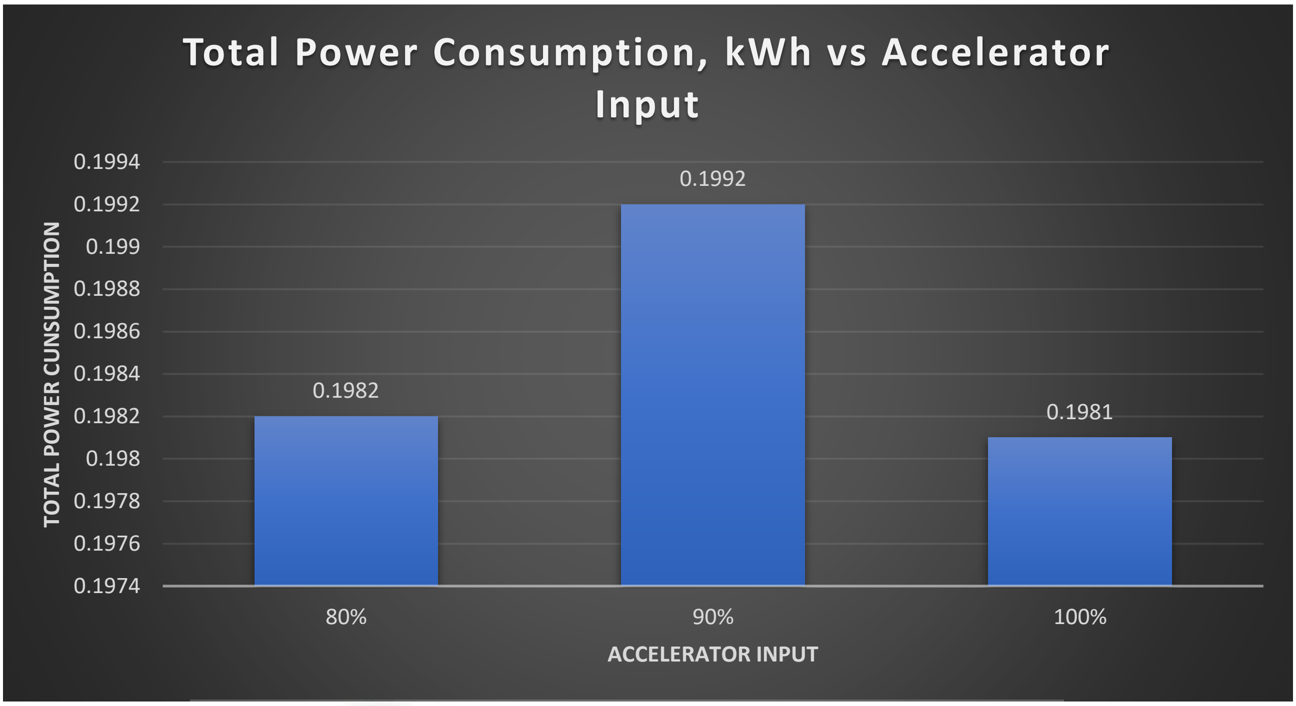

Figure 4.5 Total Power Consumption, kWh vs Accelerator Input

The figure 4.4 represent a vehicle's overall power usage at various accelerator inputs, measured in kilowatt-hours (kWh). The vehicle consumes 0.1982 kWh at 80% accelerator input, increasing slightly to 0.1992 kWh at 90% accelerator input. Surprisingly, with full power and 100% accelerator input, consumption drops to 0.1981 kWh. Despite the increased power consumption caused by the increased accelerator input, the overall power utilized at 100% accelerator input is somewhat less than at 90%. This could indicate that the vehicle is more efficient at full throttle in terms of energy consumption per distance or output, or it could indicate a nonlinear relationship between power consumption and accelerator input.

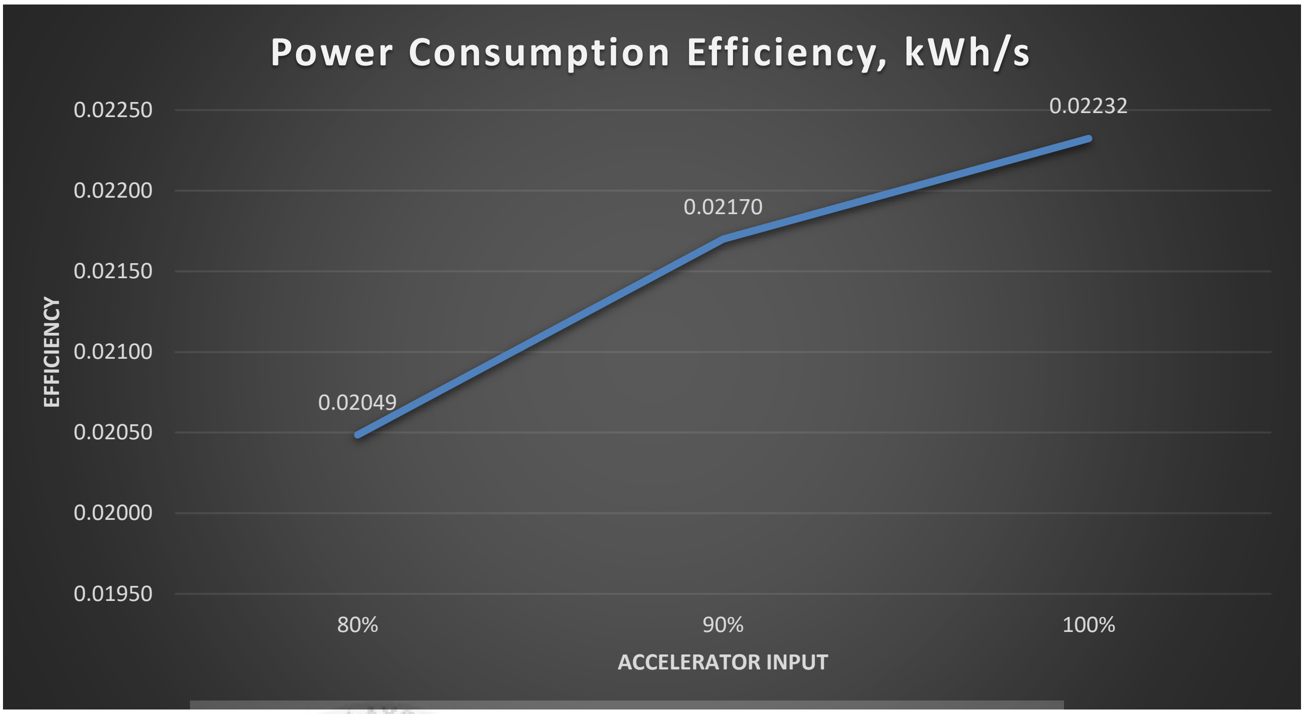

Figure 4.6 Power Consumption Efficiency, kWh/s

The graph depicts a vehicle's efficiency in relation to accelerator input. As the accelerator input increases from 80% to 100%, efficiency (measured in kWh/s) increases. At 80% input, efficiency is 0.02049 kWh/s, at 90% input, it is 0.02170 kWh/s, and at 100% input, it peaks at 0.02232 kWh/s. This means that at larger accelerator inputs, the vehicle functions more effectively, transforming more of the power into motion rather than wasted energy. Despite having a slightly lower total power consumption at full throttle compared to 90% input, the vehicle's efficiency is highest at 100% accelerator input.

4.3 Summary

In this chapter, a noticeable relationship was discovered between accelerator input and vehicle acceleration performance. It was discovered that increasing the accelerator input from 80% to 100% reduced the time required for the vehicle to accelerate from 0 to 100 km/h. This inverse relationship demonstrated that larger accelerator inputs are associated with faster acceleration times. This part of the FCV's operation was crucial in evaluating the vehicle's responsiveness to driver inputs and subsequent driving performance.

A closer look at the simulation data revealed an unexpected trend in total power consumption. Total power usage was not immediately proportional to the increase in accelerator input, contrary to predictions. It peaked at 90% accelerator input and then dropped somewhat when the input was at full power (100%). This non-linear pattern indicates that the FCV's powertrain is subject to a complicated set of dynamics that effect power usage differently at different throttle input levels. The electric motor and power control systems are both involved in the formation of this pattern, which could be indicative of an optimal operating position for efficiency that does not correspond to maximum power output.

These findings are significant because of their implications for performance optimization, energy management, and sustainability goals. Strategies for optimizing vehicle performance while retaining energy efficiency can be developed by defining how the FCV responds to different degrees of accelerator input. These findings are especially useful in the context of FCV energy management, since they propose approaches to balance acceleration needs with energy usage. Furthermore, in the search of greener transportation solutions, such extensive studies aid in the development of cars that are both efficient and sustainable, adding to the larger goals of decreasing environmental impact and supporting sustainable mobility behaviors.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The project has demonstrated, through MATLAB Simulink simulation, the promise of hydrogen fuel cells as a sustainable power source for electric vehicles (EVs). The simulation provided a detailed analysis of the system's response to varying levels of accelerator input, revealing a directly proportional relationship between accelerator input and the vehicle's acceleration capability. The simulation results clearly exposed the dynamic behavior of hydrogen fuel cells in electric vehicles, demonstrating how fuel cells respond to varying accelerator inputs, with consequences for vehicle performance. The results show that when the fuel cell system is powered up, it can efficiently supply the power demands of the motor. Initially, the battery compensates for the longer response time of the fuel cell to power demands by delivering instant energy while the fuel cell ramps up its production. As the accelerator input grows, so does the fuel cell's contribution, eventually meeting the bulk of the power required.

One of the most compelling outcomes of the simulation was the discovery of a non-linear pattern in the vehicle's total power consumption. Contrary to expectations, the total power consumption didn't rise in tandem with the increased accelerator input. Instead, it reached a peak at an intermediate input level before experiencing a slight decline as the input reached its maximum. This unexpected result suggests the existence of an optimal efficiency operating point where the fuel cell system delivers the required power output without proportionately increasing energy consumption, a point that notably does not coincide with the maximum power output. This nuanced understanding of the fuel cell's performance under different demand conditions provides a substantial foundation for optimizing energy usage in real-world EV applications.

5.2 Project Potential

The potential of hydrogen fuel cell EV simulation holds significant importance in the industry. As the automotive sector increasingly shifts towards sustainable solutions, understanding the dynamic behavior of hydrogen fuel cells through simulations becomes crucial for manufacturers. Accurate simulations, as demonstrated through MATLAB Simulink, provide valuable insights into the performance of fuel cells under varying conditions, aiding in the optimization of electric vehicle designs. This technology allows manufacturers to assess the efficiency and responsiveness of hydrogen fuel cell systems, fine-tune power distribution, and enhance overall vehicle performance. Furthermore, it enables the identification of optimal operating points, contributing to the development of energy-efficient EVs. Commercializing such simulations can streamline the design and testing phases, reducing development costs and accelerating the adoption of hydrogen fuel cell technology in the automotive industry. This supports the broader transition towards sustainable and environmentally friendly transportation solutions.

5.3 Future Works

i) Advanced Control Systems: Future initiatives should focus on the development of advanced control systems that can predictively manage the power distribution between the fuel cell and the battery. This includes the implementation of machine learning algorithms that can learn from driving habits and conditions to optimize the power flow and enhance overall vehicle efficiency.

ii) Integration with Renewable Energy Sources: Research should be directed towards integrating hydrogen fuel cell technology with renewable energy sources for hydrogen production. Investigating the use of solar, wind, and hydroelectric power to generate hydrogen would position fuel cells as a central component of a fully renewable energy ecosystem.

iii) Broader System Integration: Integrating the hydrogen fuel cell system more comprehensively with other vehicle systems such as HVAC, electronic sensor arrays, and adaptive lighting is essential. This holistic approach would help in understanding the interdependencies and in designing more energy-efficient vehicles.

iv) Long-term Durability Studies: Long-term durability studies are crucial for assessing the lifespan and performance consistency of fuel cells under varied operational stresses. Such studies would provide valuable data for manufacturers o improve the robustness and reliability of fuel cells, ensuring their longevity in consumer vehicles.

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APPENDICES

PSM 2 PLANNING GANTT CHART 2023														
MONTH	OCTOBER		NOVEMBER				DECEMBER				JANUARY			
ACTIVITIES	1	2	3	4	5	6	7	8	9	10	11	12	13	14
PSM 2 Briefing														
Study and setup fuel cell configuration														
Study and setup dc-dc converter														
Study and setup motor speed controller														
Study and developing power management system														
Initial simulation testing and troubleshooting														
Adding dynamic model to simulation														
Finalizing simulation														
Updating report, data collection and analysis														
Final verification and supervisor final update														
Final report submission														
Presentation PSM 2														