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Simulating energy management in a lightweight hybrid vehicle with fuel cells and nickel metal hydride (NiMH) batteries

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Abstract:

A compact electric vehicle was simulated utilizing the Advanced Vehicle Simulator (ADVISOR), a MATLAB/Simulink-based program. The primary power source for the vehicle was a 200W small Proton Exchange Membrane (PEM) fuel cell, complemented by AA-type Nickel Metal Hydride (NiMH) batteries serving as backup energy sources. Each NiMH battery had a voltage of 1.2V and a capacity of 1.9Ah. The performance of both the PEM fuel cell and the NiMH batteries was evaluated using an electronic load to meet the power requirements of the hybrid vehicle. The hybrid vehicle operated in three distinct modes: Starting Mode, Accelerating Mode, and Steady Mode, each with its specific configurations. Simulation results revealed that the batteries successfully initiated the drivetrain in the Starting Mode, while the fuel cell provided support during the Accelerating Mode. In Steady Mode, as the battery state of charge decreased, the PEM fuel cell seamlessly supported the battery and powered the load simultaneously. Various matching schemes were analyzed to meet the dynamic performance requirements of the vehicle and achieve the optimal synergy between the fuel cell and NiMH battery. The study aimed to identify the most effective configuration to ensure efficient energy management and dynamic performance in different operational modes of the hybrid vehicle.

Keywords: hybrid vehicle, PEM fuel cell, NiMH battery, energy management strategy

1. Introduction

In the realm of transportation, the escalating global demand for petroleum has driven the automotive industry to enhance power generation systems for more efficient transportation. Fuel cells have become a focal point for researchers, industries, and governments due to their capacity to generate power without emitting greenhouse gases. Widely recognized as a highly favorable and clean alternative for power generation in both mobile and stationary applications [1], fuel cells harness energy through the chemical reaction of hydrogen and oxygen from the air, tapping into an abundant resource. Among various types of fuel cells, PEM fuel cells stand out for small electronic devices, attributed to their lower operating temperatures and quicker startup times.

PEM fuel cells hold appeal for the automotive sector due to their superior energy conversion efficiencies compared to internal combustion engines (ICE), coupled with their compatibility with hydrogen. By utilizing hydrogen as fuel, fuel cells produce power and water exclusively, without emitting harmful gases into the environment. On a parallel note, batteries present an alternative energy source, offering advantages over conventional ICE vehicles, including high energy efficiency and zero pollution [2]. The optimal strategy for mitigating greenhouse gas emissions in the transportation sector involves combining fuel cells and batteries, leveraging their high energy efficiencies and minimal emissions.

Fuel cell hybridization enables the reduction of fuel cell size by incorporating a battery or an alternative power source. During periods of high-power demand, such as operating under heavy loads or during acceleration, the battery provides additional power, enhancing the overall efficiency of the fuel cell system. The utilization of the battery facilitates swift start-ups and the storage of regenerative energy. However, hybridization introduces challenges, including increased vehicle system complexity, added weight, and additional costs associated with the battery [3].

Various hybrid powertrain structures are currently available, encompassing load-following and load-leveling structures, as well as energy and power hybrid structures [4, 5]. In this study, a battery bank system was chosen to initiate energy production, followed by the utilization of hydrogen by the fuel cell to generate energy. The hybrid small vehicle under investigation incorporated a 200 W PEM fuel cell stack and a pack of 40 AA nickel-metal hydride batteries. This study involved the construction of vehicle models, fuel cells, batteries, and motors, with energy vehicle control strategies established using ADVISOR software [6]. Simulation tools prove valuable for designing and optimizing vehicle performance, aiding in the refinement of innovative models that incorporate multiple power sources and drive systems.

2. Materials and Methods

This research delves into the performance assessment of a compact electric vehicle propelled by a proton exchange membrane fuel cell (PEMFC) and nickel metal hydride (NiMH) battery, aiming to explore the practical applications of automobile technology. The work focuses on a fuel cell/battery hybrid car, specifically featuring a 200W PEM fuel cell stack and 40 AA type NiMH batteries. Each battery in the configuration possesses 1.2 volts and 1900 mAh.

The main goal of this research is to formulate an energy management strategy that optimally balances environmental impact, fuel efficiency, and dynamic vehicle performance. Leveraging ADVISOR as a fundamental tool for the initial design of fuel cell-battery hybrid vehicles, the study seeks to identify a strategy that minimizes environmental impact, lowers fuel consumption, and fulfills the dynamic performance criteria of the vehicle. The research expands upon the groundwork established in the master's study conducted by Harahap [7].

2.1. Drive train configuration

The drive train of a vehicle comprises components responsible for transmitting power to the driving wheels, excluding the engine or motor that generates this power. While the engine or motor and the drive train collectively form the powertrain, their distinct roles are noteworthy. The powertrain's

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primary function is to establish a connection between the power-producing motor and the driving wheels, converting generated power into mechanical force.

Given that the operating speeds of the engine and the wheels differ, maintaining optimal performance necessitates precise synchronization achieved through the application of the correct gear ratio. It is imperative to ensure that the engine operates at an approximately constant speed, irrespective of fluctuations in vehicle speed, to facilitate efficient performance. This synchronization may be achieved through automatic adjustments or manual interventions as required.

Several drivetrain configurations and energy storage technologies are employed by fuel cell vehicle developers in their cars (Fig. 1). In practice, there are four power source arrangements, each with its own set of advantages and disadvantages, depending on factors such as vehicle performance, operating conditions, control complexity, development cost, and fuel economy potential. Fig. 2 illustrates the fuel cell drivetrain arrangements and the control strategy schematically considered in this paper.

A power control strategy has been suggested to uphold overall system efficiency and monitor the state of charge (SOC) of the battery, providing insight into energy flow. The performance of the fuel cell, including power, voltage, and current over time, as well as hydrogen consumption (fuel economy), is intricately linked to the strategy employed for distributing power between the fuel cell and the battery during vehicle operation across diverse driving cycles [8].

In (a) Starting/Normal Mode, the car utilizes energy from the batteries to provide full power to the motor, as the power demand falls within the operating range, and the battery SOC remains high. In the low-speed mode (b), the fuel cell charges the battery if its SOC is below a specified threshold, simultaneously serving as the main power source for the motor. Once the power demand reaches maximum output, the battery kicks in to supply energy to the motor, supporting the fuel cell. In this mode (c), the fuel cell and the battery operate efficiently, collaborating to deliver ample power to the motor. The Steady/Charging Mode (d) involves the fuel cell exclusively charging the battery when the vehicle is stationary, requiring no power for motor generation, and when the battery SOC is low.

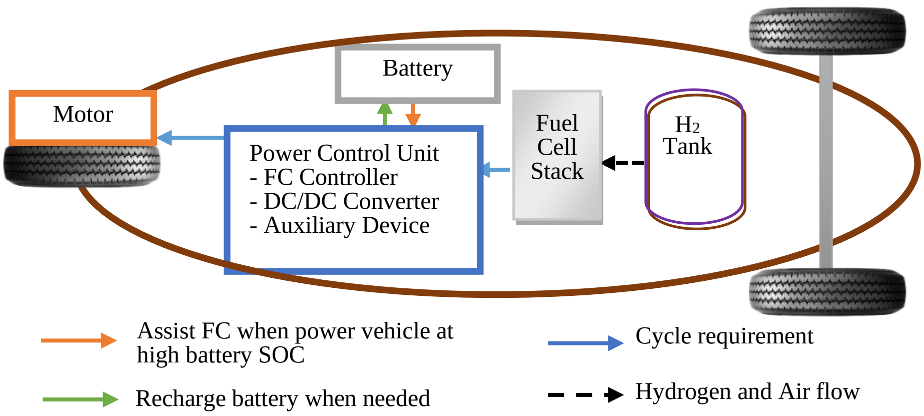

Fig. 1. Configuration of a Fuel cell hybrid vehicle

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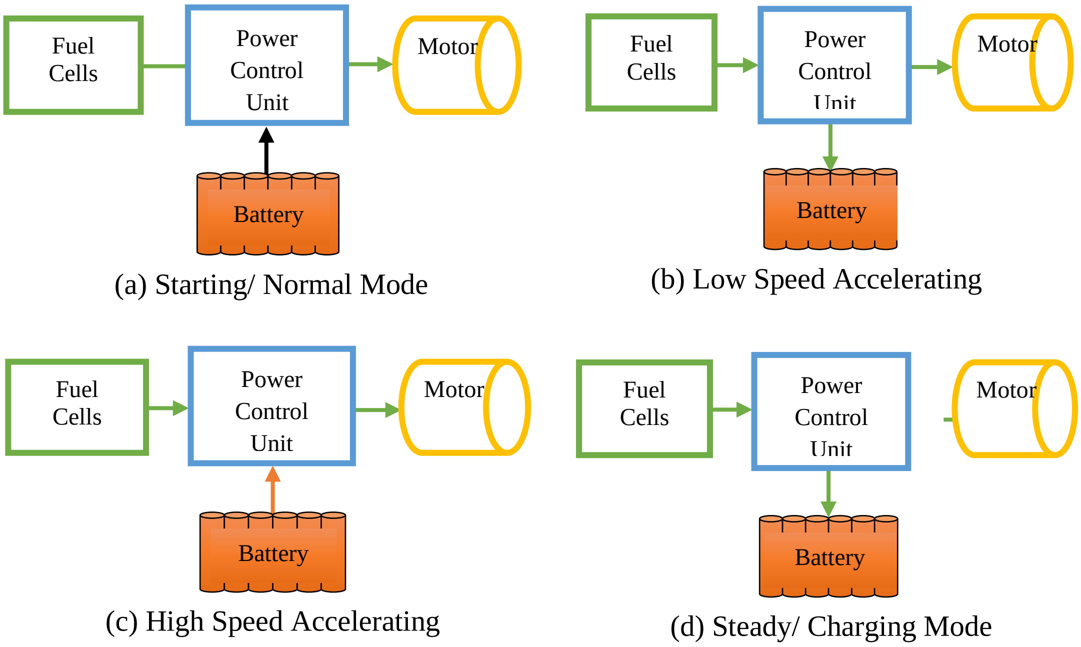

Fig. 2. FCHV drivetrain configuration control strategy

2.2. Energy Management Strategy

The control strategy, essentially an algorithm, dictates the power generation distribution between the fuel cell systems and the energy storage system during each sampling interval. Its primary goal is to maintain a power balance between the load power and the various power sources [9, 10]. Themanner in which this power split is executed can influence the minimization of hydrogen consumption. Various control techniques, addressing minimization problems, have been explored to achieve an optimal global solution.

Vehicle energy consumption occurs across three distinct modes: starting/normal mode, accelerating mode, and steady mode. The fuel cell's operating range for maximum power was constrained to 40-60%, allowing power withdrawal from the NiMH battery to maintain the fuel cell within its high-efficiency domain. Despite the low fuel efficiency, operating the fuel cell at high current density and power was necessary to propel the vehicle. Parameters such as the maximum rate of increasing fuel cell converter power (180 W/s) and the maximum rate of decreasing power (-280 W/s) were defined.

Under specific conditions, when the required vehicle power is below 20% of the fuel cell's maximum power, the battery supplies all necessary power, and the fuel cell shuts off. Conversely, if the required power exceeds the fuel cell's maximum capacity, the battery steps in to balance the power. The fuel cell activates when the battery State of Charge (SOC) reaches its low limit at 40%, and the highest desired battery SOC is set at 80%.

2.3. Determining vehicle components

The simulation employed the open-source software ADVISOR, which also supports offline usage. Widely adopted by automotive manufacturers, university researchers, and the industry, this program utilizes a MATLAB/Simulink module for modeling, simulating, and conducting dynamic system analysis. It accommodates instant, linear, non-linear systems in time domain systems, or hybrid systems through its backward and forward-facing simulation attributes [11]. The simulation process begins by configuring the vehicle model, defining driving cycle conditions, and specifying power schemes, followed by the computation of parameters within the software. Fig. 3 illustrates the ADVISOR-vehicle data settings, and additional vehicle dynamic performance parameters, including the fuel converter, energy storage, motor, transmission, wheel/axle, accessories, and powertrain, are

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configured on this page. These components and associated files can be saved individually, allowing for future analysis.

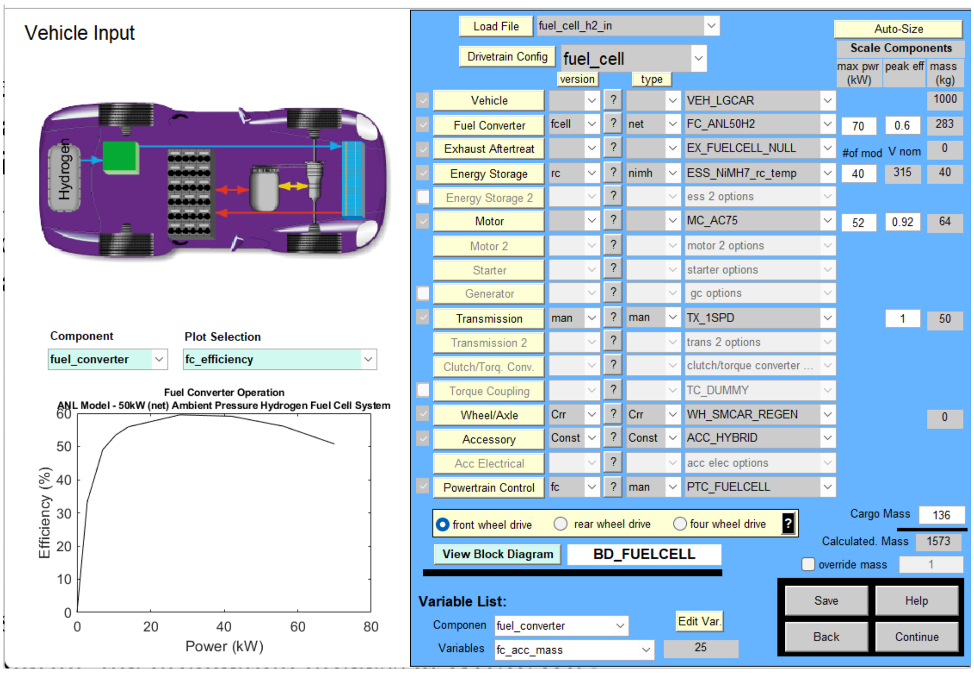

Fig. 3. ADVISOR vehicle input page

2.3.1. Fuel cells

A 200W PEM fuel cell stack was utilized to generate electricity for the motor. After testing, the stack exhibited an open-circuit voltage of 30 V, with a maximum current output of 10.49 A, resulting in a peak power of 176 W at 16.8 V (Fig. 4). The system was configured with an open-cathode design, comprising a stack of 40 cells, each featuring an active area of 19 cm^2. The pertinent parameters are detailed in Table 1 for configuration within the Advisor software.

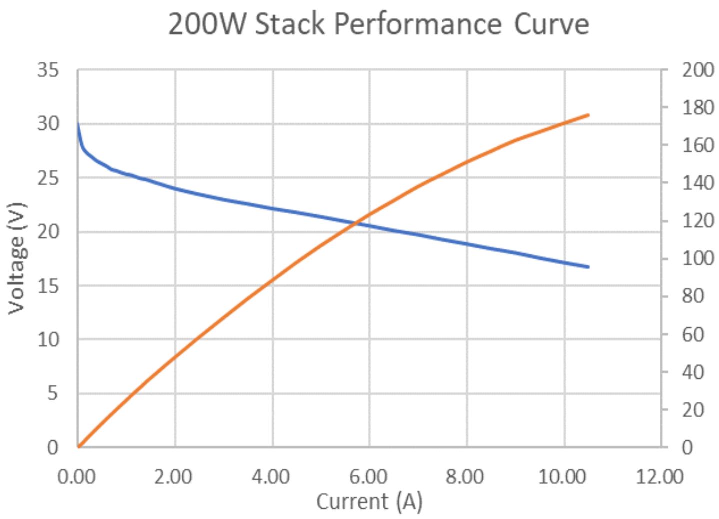

Fig. 4. Fuel cells polarization curve

Table 1. PEMFC main parameters

Parameter	Index	Unit
Number of cells	40	cell
Hydrogen pressure	0.45	bar
Flow rate at max output	2.6	L/min
Rate performance	24	V
Fuel cell power	200	Watt
Fuel cell efficiency at peak (24V)	40	%
System weight	2.63	kg

2.3.2. Energy storage systems

The energy storage system employed in this vehicle comprises a series of NiMH batteries capable of storing electrical energy generated by the fuel cell during low system load conditions and assisting the fuel cell during high system load conditions. ADVISOR provides four distinct battery models: resistive-capacity model, internal resistance model, basic lead-acid model, and neural network model [12]. The battery specifications are detailed in Table 2 and were further defined by specifying parameters like open-circuit voltage (OCV), internal resistance over temperature, and state of charge (SOC). Data for the modeling process were obtained from an analysis of an existing Panasonic Eneloop NiMH battery type AA, conducted using a Maynuo Electronic Load. Fig. 5 shows the experimental results from the electronic load use to measure the battery performances from 0.1A to 10A. From the experiment, battery performance at 5A was chosen which shows the battery voltage at 1.18V (~1.2V) with the battery capacity is 1.72 mAH and can be used for 157 s.

Table 2. Specifications of NiMH Batteries

Parameter	Index	Unit
Average voltage module	48	V
Module capacity	1900	mAh
Module mass	0.54	kg
Number of battery in series	40	pcs

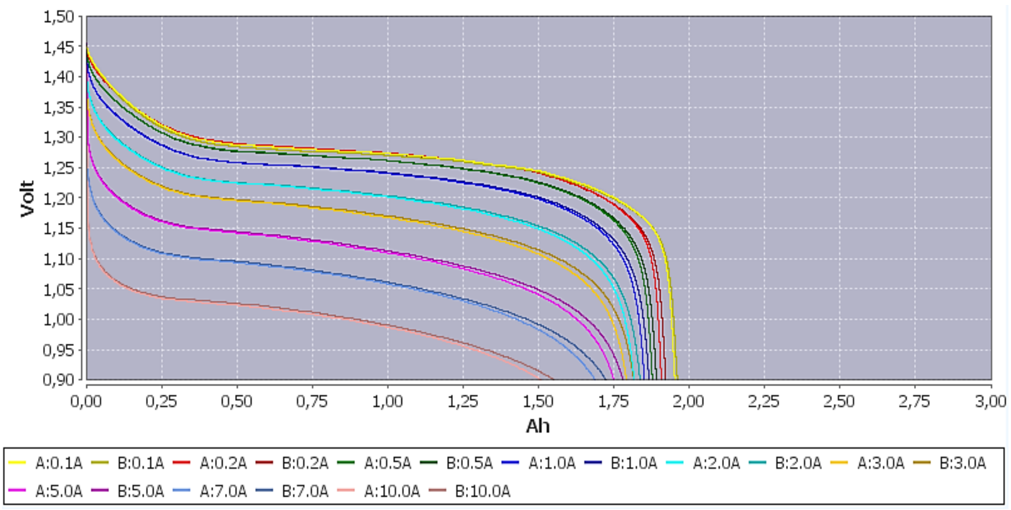

Fig. 5. Discharge curve of Eneloop BK-3MCC

2.3.3. Vehicle body specification

The vehicle was conceived based on a compact fuel cell hybrid electric vehicle (FCHEV), derived from the prototype of a pure electric vehicle. The external dimensions of the prototype remain unaltered, while the powertrain undergoes a transformation, integrating a hybrid electric powertrain consisting of a fuel cell and batteries. The vehicle's configuration aligns with the ENE1-GP requirements for racing competitions in Japan [13]. This configuration ensures precise positioning of the center of mass halfway between the two axles, with traction force applied exclusively to the rear wheels. The visual representation of this vehicle is depicted in Fig. 6. Key parameters of the vehicle are succinctly summarized in Table 3.

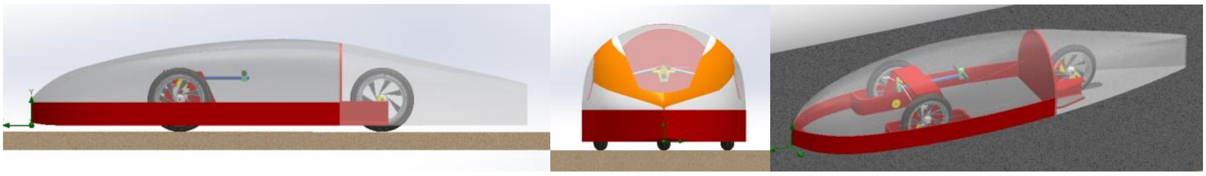

Fig. 6. Appearance of the hybrid vehicle

Table 3. The main parameters of the vehicle

Parameter	Index	Unit
Vehicle glider mass	26	kg
Vehicle full load total mass	90	kg
Cross-sectional area of the frontal vehicle	0.53	m^2
Drag Coefficient	0.19	-
Coefficient of rolling resistance	0.004	-
The tire radius	0.7	m
Maximum speed	72	km/h
Air density	1.2	kg/m^3
Drag Force	649.5	N
Drivetrain	Rear-wheel	-

2.3.4. Electric motor

The vehicle is outfitted with an in-wheel motor, specifically the Mitsuba model M0124D-V, commonly employed in lightweight electric vehicle competitions. These motors enable the direct application of torque to the wheels, precisely where it is needed, while occupying minimal space within the vehicle. The motor's performance was assessed using 48V to measure maximum torque, speed, RPM, and efficiency, with the results depicted in Fig. 7.

Table 4 shows the parameters of the motor. The motor/controller model was modified from an existing permanent magnet motor model with the average controller efficiency was set up to 90%.

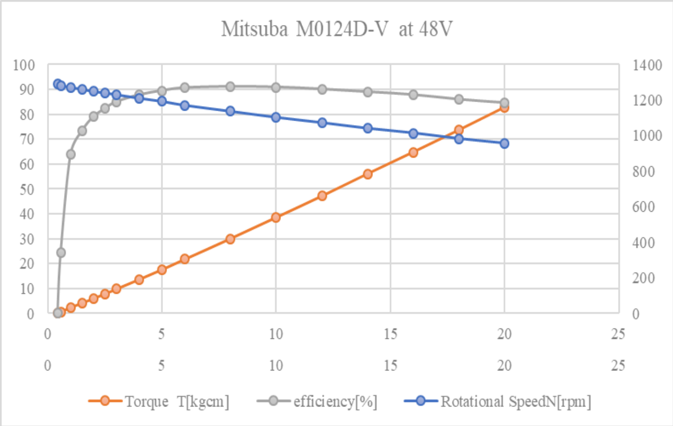

Fig. 7. Mitsuba motor performance at 48V

Table 4. Mitsuba in-wheel motor main parameters

Motor Parameter	Index	Unit
Nominal voltage	48	V
Rotational speed	1288	rpm
Nominal power	960	W
Maximum torque	8.11	Nm
Efficiency	84.5	%
Mass of motor	3.4	kg
Controller Parameter		
Nominal voltage	24	V
Voltage range	6-32	V

2.4. Model Parameters

The driving range stands out as a pivotal metric for electric cars, as a longer range enhances the car's overall utility. In this work, among the 59 driving conditions in ADVISOR, the Extra-Urban Driving Cycle (EUDC) was specifically chosen for analysis. The pertinent data regarding driving conditions is outlined in Table 5. In addition to these conditions, a customized driving profile can be incorporated, allowing for analysis of unconventional driving scenarios. The selection of the EUDC is grounded in its ability to provide a more accurate representation of real-world driving behavior, a crucial factor for competitive evaluation. The distance to be covered and the average speed serve as essential parameters to achieve optimal performance.

Fig. 8 illustrates that the test procedures necessitate a continuously variable speed. Notably, the EUDC incorporates a substantial segment characterized by extreme accelerations, reaching speeds of up to 80 km/h. It's important to note that the EUDC cycle has a maximum speed of 120 km/h, with a restriction for low-powered vehicles set at 90 km/h [14]. Information from Table 5 provides a succinct overview of driving cycle parameters, detailing test duration, distance, and target speeds. The cycle configuration was accomplished through the ADVISOR software, allowing users to either select a predefined driving cycle from the list or create a new one using MATLAB. The Simulink diagram depicted below illustrates the step-by-step process of conducting the simulation. Fig. 9 showcases the model for the fuel cell/battery hybrid vehicle within Simulink.

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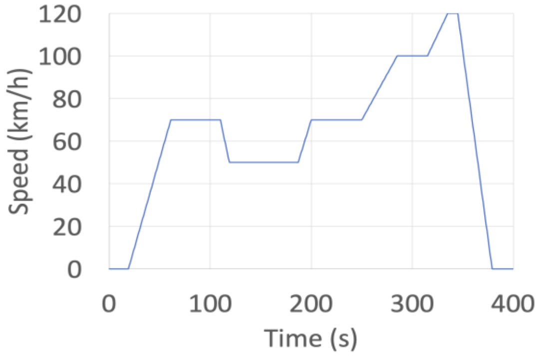

Fig. 8. EUDC cycle for light-duty vehicles

Table 5. EUDC driving condition parameters

Parameter	Index	unit
Duration	400	s
Idle time	39	s
Simulated distance	6.955	km
Maximum speed	120	km/h
Average speed	62.6	km/h
Maximum acceleration	0.83	m/s^2
Average acceleration	0.354	m/s^2

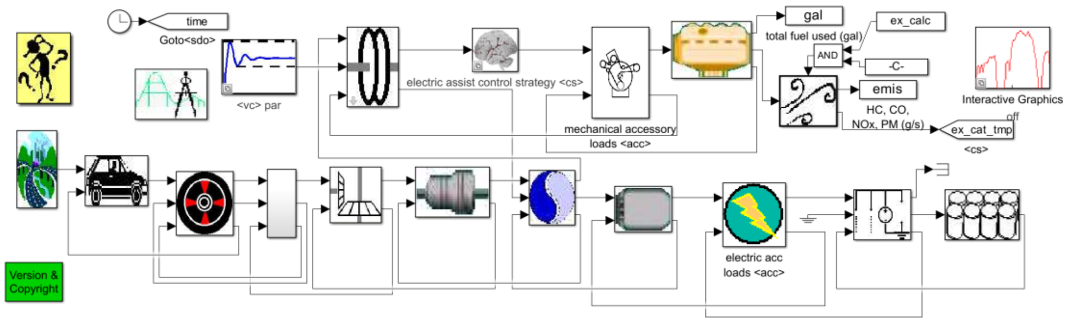

Fig. 9. The Simulink block diagram of a Fuel cell/ battery hybrid vehicle

2.5. Presenting the Analysis Findings

The ADVISOR reveals the outcomes of the analysis through graphical representations (Fig. 10), offering a comprehensive overview of vehicle performance both throughout a cycle and instantaneously at any cycle point. Summary results, including fuel economy and emissions, are presented on the right side of the window, while the left side displays detailed time-dependent results. The information displayed on the left can be dynamically adjusted to reveal various details (e.g., engine speed, engine torque, battery voltage, etc.) using pull-down menus in the upper right section of the window [15].

ADVISOR generates 150 distinct graphs post-analysis to observe the impact of the fuel cell on vehicle performance. Following the simulation, one can analyze the results as a whole or obtain subsystem-specific results separately. During the simulation, both individual data points and comprehensive data sets can be accumulated and compared. Crucial graph results from ADVISOR include fuel consumption, fuel emissions, average acceleration and speed, and maximum distance to travel. These results, aligned with dynamic vehicle performance, contribute to the fundamental design of fuel cell-battery hybrid vehicles.

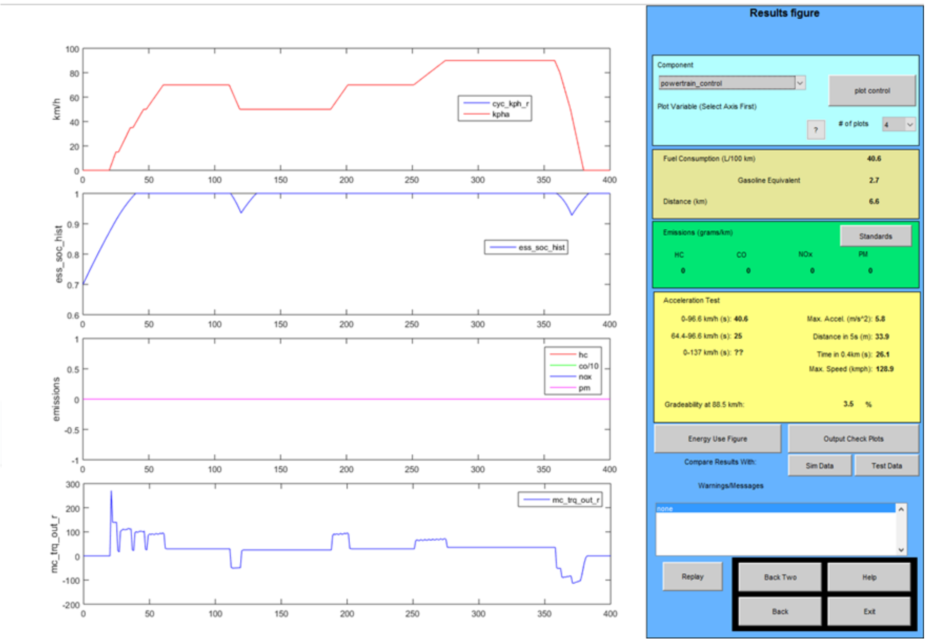

Fig. 10. Advisor results page

3. Results and Discussions

Key results were derived from ADVISOR simulations, featuring plots illustrating the velocity profile and state-of-charge (SOC) variation throughout a lap in the EUDC driving cycle. If the battery SOC falls below the desired level, the battery storage necessitates charging, and the charging power is provided by the fuel cells. Fig. 11 illustrates the SOC graph of the drive-train in this operational mode, while the vehicle's hydrogen consumption will be showcased in Fig. 12.

In Fig. 13, the average motor controller efficiency surpasses 80% during driving performance, suggesting highly favorable simulation outcomes. Beyond the ADVISOR results, the subsequent figures depict acceleration and gradeability tests aligned with EUDC driving requirements. In Fig. 14, the vehicle attains a peak acceleration of 5.8 m/s², traversing 33.9 meters in 5 seconds. Additionally, the simulation indicates that the vehicle covers a distance of 0.4 km within 26.1 seconds during the acceleration test. The vehicle's gradeability is determined to be 3.5%, affirming its ability to ascend sloping roads.

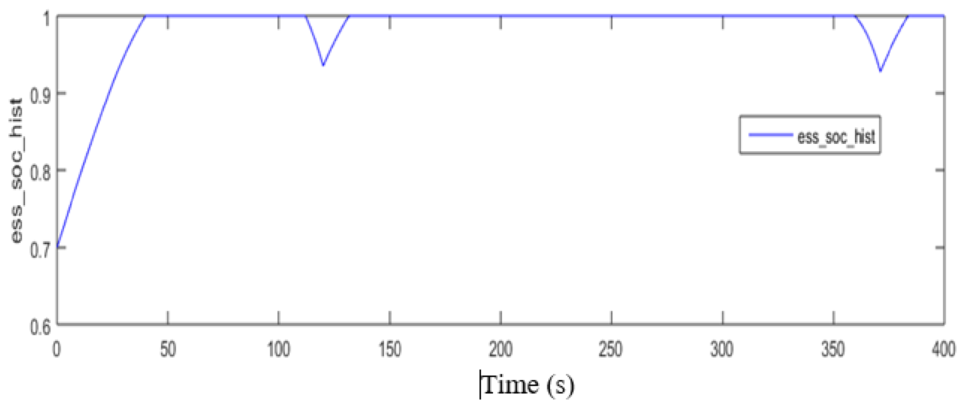

Fig. 11. Vehicle energy storage system (ESS) SOC [7]

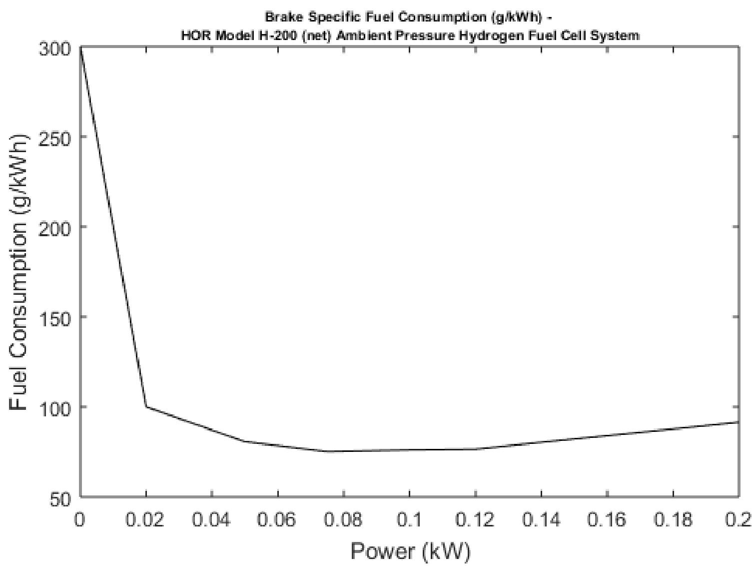

Fig. 12. Vehicle fuel consumption

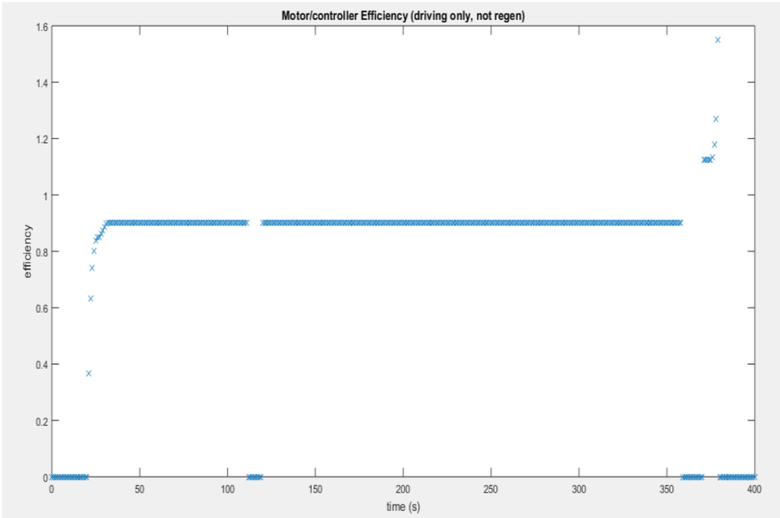

Fig. 13. Motor controller efficiency [7]

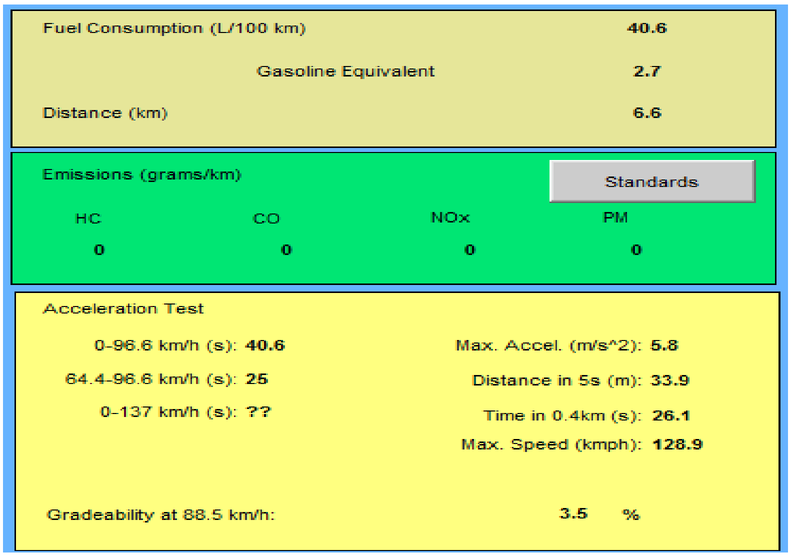

Fig. 14. Simulation results of acceleration and gradeability test

4. Conclusions

In this study, an analysis of a 200W PEM fuel cell was conducted using ADVISOR. The remaining vehicle components, including the drivetrain and the Panasonic Eneloop NiMH AA-type battery selected for vehicle energy storage, were also stabilized for the analysis. The Extra-Urban Driving Cycle (EUDC) was chosen for simulation due to its suitability in replicating electric vehicle driving performance. This driving cycle closely aligns with key parameters such as distance, maximum speed, and average speed, making it comparable to other available cycles in the software.

The EUDC was utilized not only for analyzing the performance of the fuel cell hybrid car but also for internal combustion and electrically powered vehicles. The vehicle demonstrated the ability to navigate sloping roads with a 3.5% gradeability, achieving a fuel consumption of approximately 40.6 L/100 km over a distance of 100 km. Accelerating to 33.9 m took 5 seconds, while covering 0.4 km required 26.1 seconds. The simulation effectively illustrates the dynamic system and control strategy embedded in the software, providing a comprehensive evaluation of the power and fuel economy performance of the fuel cell-battery electric hybrid vehicle. The results from the vehicle prototype simulation further confirm its adherence to design requirements.

Acknowledgements

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