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Design and Analysis of a Fuel Cell and Batteries in Energy Production for Electric Vehicle

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A B S T R A C T

The world's most economically developed countries are facing an energy crisis caused by geopolitical instability, rising energy costs, global stock disruptions, and a shift towards low-carbon energy sources that has yet to be fully realized. Electrification of the transportation industry offers the advantages of increased energy efficiency and reduced local pollutants. Electric Vehicles (EVs) are environmentally friendly because they reduce fossil fuels usage even zero consumption, need fewer maintenance requirements, and lower operating costs than the vehicles powered by gasoline or diesel. However, this study focuses on comparing various energy management strategies (EMS) for a backup energy supply system for EVs. The hybrid power system (HPS) considered in this study includes DC-DC and DC-AC synchronous converters, as well as supercapacitors, batteries, and fuel cells. The EMS analyzed includes state machine control, classical proportional-integral control, equivalent consumption minimization, frequency decoupling, rule-based fuzzy logic, and fuzzy logic control. The HPS's efficiency, hydrogen fuel, supercapacitor or battery state of charge levels, and overall performance are evaluated as primary efficiency criteria. Additionally, the HPS not only increases system energy but also reduces the number of pack batteries required. This study designs and constructs the combined power systems to enhance EV power schemes with rechargeable battery power supplies. The results show that a 6-kW fuel cell hybrid increases the power system capacity to 408 kWh. Moreover, a novel method based on wavelet transforms of the instantaneous power of each energy source is used to quantify the stressors on each energy source that impact its life cycle. To validate all analyses and performance, a simulation model and an experimental test bench are created. Finally, simulation results demonstrate a synchronous converter with a 6-kW output power and 96% efficiency, validating the optimization results.

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INTRODUCTION

Hybrid power systems are becoming a reality as a result of the automobile industry's focus in developing more efficient and environmentally friendly traction schemes during the last 20 years. Automobiles, trains, buses, trams, and aircraft all utilize HPS [1]. Vehicles create electrical power with a very high level of efficiency, less noise, and nearly no pollution as compared to typical diesel, petrol, or gas engines. As the initial step toward producing hybrid power, hybrid power system designers are striving to replace the backup power system, which mostly consists of fuel-cell, supercapacitor, and battery devices [2, 3]. As a result, the emergency power system will perform better, particularly at a cheap cost and in an ecologically responsible friendly.

With the ability to substantially reduce carbon emissions and clear the way for considerable climate change, electric cars have the power to transform the global transportation industry [4]. Transportation is the

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most carbon (CO_2) intensive industry in the nation, accounting for 28% of total emissions in 2022. It is necessary to hybridize fuel cells with modern energy storage technologies, such as supercapacitors or lithium-ion batteries, in order to increase the kinetics and power efficiency of HPS. As some of the load is supplied by the batteries or supercapacitors, this hybridization enables the fuel-cell system to be tuned to achieve improved fuel performance and efficiency [5]. Fuel cells are electrochemical technologies that precisely transfer chemical energy from an electrochemical response to electric power while discarding primarily water and heat. Despite becoming a renewable fuel, they could only produce uncontrolled DC link voltage, necessitating the use of power converters to interrelate the influenced load. A comprehensive fuel cell simulation is required to monitor their kinetic and constant characteristics, which are required for the development, operation, and testing of such converters. In the research, different kinds of fuel cell designs have been published [6]. These concepts are grouped into three types: biochemical, physical, and electromechanical. Biochemical approaches involve highly complicated chemical and kinetics phenomena like mass transfer, thermodynamics, and species diffusion within the cell [2–4]. These designs have a large number of parameters and are difficult to incorporate into electrical simulation models. Physics are used to generate experimental models, which depict the fuel cell using look-up databases or experimental statements [5, 6]. These approaches lack fuel cell kinetics and are unable to account for the effects of operational factors including gas intake pressures, mixtures, flow rates, and temperatures. Electromechanical system components are used to describe the fuel cell in the electrical designs [2, 7]. They do not contain fuel cell thermodynamics but are more suited for fuel cell power system designs. The design parameters are determined alternatively experimentally or by doing experiments on an actual fuel cell throughout all research methodologies. For biochemical and physical designs, polarization curve tests are important, while current interrupted, impedance analysis, and frequency response testing are performed for electrical designs. On the other hand, bioelectricity development is the generation of electricity by microbes of electron transfer during metabolic activities. These created ions could be trapped in order to maintain a constant or consistent fuel source generation. Once given a sufficient basis, microorganisms can break down the molecules, creating electrons that may be collected and used by coupling them via a circuit. These substances can be combined to form a microbial fuel cell (MFC), which can provide power. The fermentation of feedstock by bacteria is required for the creation of electrons as a result of their activity. The aforementioned processes represent the biochemical activities performed out by bacteria in the lack of oxygen [1] and then in aerobic conditions [2].

When a current flows through an electrochemical cell, there are several types of voltage losses that occur. These losses can be classified into three main categories such as Ohmic losses, concentration losses, and activation losses. Moreover, Ohmic losses occur due to the resistance of the electrolyte and the electrode material. When a current flows through the electrolyte, it encounters resistance, and some of the electrical energy is converted into heat. This heat generation causes a loss of energy, which is referred to as the Ohmic loss. Ohmic losses can be minimized by reducing the resistance of the electrode and electrolyte materials. Concentration losses occur due to the depletion of the reactants at the electrode surface. In an electrochemical cell, the reactants are consumed at the electrode surface, which can lead to a depletion of reactants and a decrease in the reaction rate [1]. The concentration loss is the energy required to overcome this decrease in the reaction rate, and it can be minimized by increasing the concentration of reactants at the electrode surface. In addition, activation voltage losses occur due to the energy required to initiate the reaction at the electrode surface. This energy is called the activation energy and must be supplied for the reaction to proceed. The activation voltage loss is the energy required to overcome this activation energy, and it can be minimized by increasing the temperature or pressure of the reactants or by using catalysts. Ohmic losses occur due to the resistance of the electrolyte and electrode material, concentration losses occur due to the depletion of reactants at the electrode surface, and activation voltage losses occur due to the energy required to initiate the reaction at the electrode surface. All three types of losses can have a significant impact on the efficiency and performance of electrochemical systems, and minimizing them is critical for optimizing the performance of these systems [2–6].

An EMS, which balances the load power across renewable resources, enables this minimization. Such an EMS should always be designed to maximize fuel efficiency simultaneously maintaining that each electricity generation performs within its capabilities. Additionally, it is best to minimize the influence of the EMS on the entire HPS life cycle. The most expensive part of an EV is the battery; hence a battery management system is essential to obtain the greatest performance. Lithium batteries have recently become widely utilized for several purposes, and they are the most popular energy storage devices used in place of traditional gasoline [7]. They are widely utilized for many applications, including electric bikes, uninterruptible power supply, electric scooters, and electric vehicles [8]. Because the battery's open-circuit voltage is low, these applications may utilize hundreds of cells in series or parallel to attain high voltage and capacity for the intended applications [9]. They have a low self-discharge rate, are lighter, have a higher density, and have no memory effect [10]. In the last decade, nickel metal hydride (NIMH) technology has advanced. When compared to other batteries, NIMH batteries have better power, reduced self-discharge, higher efficiency, and power density. Besides, manufacturing technology is unable of ensuring equal cell output voltages, resulting in cell imbalances. Unbalanced cells are unavoidable due to electrical and chemical properties, asymmetrical degeneration with age, uneven temperature, interior impedance, and production tolerance [11]. Unbalances limit the battery's lifetime as well as its charge potential, and they are the primary cause of the battery pack's degeneration. Temperature and passivation also limit battery capacity, and this issue worsens with cell age [10]. To correct these imbalances, a battery management system (BMS) is used to guarantee that all cells are completely charged. It monitors battery modules, offers protection, and is essential in electric cars. It contains several characteristics, such as detecting battery charge, voltage, temperature, and discharge current, as well as short circuit protection, under-voltage, and over-voltage. Several cell equalization approaches have been developed in recent decades. These balancing approaches are broadly classified into two types: passive and active balance techniques [11]. Passive balancing techniques link parallel resistors to individual battery packs. Heat dissipates the excess energy. It works by taking energy from the upper packs by bypassing their current until their charge matches that of the lower packs in the pack. There are two modifications of this technique: switching shunt resistors [12] and fixed shunt resistors balancing [13]. The advantages of the resistor balancing approach include low cost and ease of implementation, while the downsides are the demand for a very high-power resistor, low efficiency, and energy dissipation. Instead, a battery management system (BMS) must be used to guarantee that the lithium-ion battery packs are working at the high-temperature range of 10°C to +60°C and state of charge (SOC) points between 35 and 75 % at all the times [11]. Because of its high-power density, silent action, and excessive power efficiency, fuel cells may now be utilized as a convenient power source. Fuel cell ability expanded globally from 65 MW in 2009 to 181 MW in 2014 [11, 14]. However, hydrogen is used as a fuel in several types of fuel cells, including alkaline fuel cells (AFC), phosphoric acid fuel cells (PAFC), and the proton exchange membrane fuel cell (PEMFC) to generate water and power. In comparison to other fuels, hydrogen has high specific energy. There are several uses for fuel cells, including fixed, transit, and portable applications. PEMFCs outperform PAFCs and AFCs in terms of efficiency [11]. Instead of utilizing various battery packs to achieve the same goal, switched boost DC to DC converters provide a way to raise the voltage from a partially decreased voltage level while conserving space. DC to DC boost converters is designed to convert high power qualities and frequency technique that smooth out waveform, and low switching noise into regulated DC voltages using high switching frequency, switching device, and capacitors or inductors. Even when the load currents change, the converter is used a closed feedback loop control system to maintain constant the output voltage. Converters are often substantially more efficient and reduced the linear controller's efficiency by approximately 92%. Noise and intricacy are their drawbacks. Isolated and non-isolated DC converters are presented. The point of isolation converter is measured by whether the input pinpoint ground is linked to the output pinpoint ground. The resonant boost or buck and single-ended primary-inductor (SEPIC) converters are four popular topologies that designers may find useful [15].

To increase the kinetics and energy efficiency of HPS, HPS must be hybridized with novel storage devices for energy including supercapacitors or lithium-ion batteries. Because the supercapacitors/batteries contribute specifically to the load, the fuel-cell system may be adjusted for greater fuel performance and energy efficiency. This is performed with the help of a power system, which balances total the load across the power sources. An EMS must be constructed in such a manner that this really achieves maximum fuel efficiency whereas maintaining each power source performs inside the constraints. Furthermore, the EMS's influence on the overall life cycle of the HPS must be kept to a minimum. In the papers, several energy management solutions for HPS have already been described. State machine management [7, 8] is a well-established principal method in which each EMS guideline or state is created based on logical or experimental past knowledge. As a result, the efficiency of this technique is determined based on how thoroughly the developer understands the working of each of the system's components. Another extensively used solution is a principle of fuzzy logic power generation control, in which power is distributed using algorithms and a set of IF-THEN logic [9, 10]. This method is simple to standardize for optimal development, but also its efficiency is less subject to experimental error and part fluctuations. However, the IF-THEN logic at the foundation of the fuzzy logic microcontroller needs the information and recent knowledge of an authority. Consumption of energy based on traditional proportional-integral (PI) controllers have recently been presented [16]. This technique relies on PI controllers to regulate key performance characteristics including supercapacitor voltage, DC-bus voltage, and battery state of charge (SOC) [1–3]. Technical expertise is not required, and the PI controllers may be easily tuned remotely for the improvement program. The load power is dispersed accordingly so that the fuel-cell system can meet the steady-state load requirement. The frequency buffering method assures that the fuel cell meets low-frequency consumption, while other renewable technologies cope with high-frequency consumption. This is attained by using a low-pass filter, fast Fourier transform methods, or waveform. This method increases the lifetime of the fuel-cell system by avoiding the demonstration of the fuel delivery system. In this case, the fuel-cell system provides practically time series load power, while the other power sources charge or discharge when the load voltage exceeds or falls less than its average value. A value algorithm to solve approach is employed to assure the functioning of the fuel-cell system for optimum fuel efficiency or maximum global performance [13, 14]. The comparable fuel consumption reduction approach is the most frequently used technique for application. The grid voltage is calculated by minimizing an actual set of parameters that includes the fuel efficiency of the HPS as well as the similar fuel efficiency of the other renewable resources. There are also reports of some of the other significant energy management solutions for HPS. Adaptive control [17], heuristic algorithm modeling [18], artificial neural network [19], dynamic optimum control [20] and H-infinity control [21] are among them. These techniques are relatively difficult and need enormous analyses, which may influence the smart energy platform's reaction time. This study focuses especially on more convenient and widely implemented power management techniques utilizing mainstream microcontroller systems.

The main aims of this research work are to propose and analyze several energy conservation methods for an HPS backup electricity system. The main quality assessment factors are hydrogen demand, battery, and energy storage, total system efficiency, and the pressures proficient by each alternative fuel. The following energy conservation methods have been developed for comparing such as the state machine control method [7], guideline fuzzy logic method [9, 10], conventional PI control method [1, 2], frequency dispersion, and fuzzy logic method [11, 12] and equivalent fuel consumption minimization strategy [13, 15]. The energy conservation techniques are evaluated using the modeling and analytically utilizing a 6-kW fuel-cell combined heat and power test scenarios platform and a simulated crisis deployment characteristic of HPS. For improved efficiency, the technique requires normal constraints, which may be exposed on the product's datasheet or by simple tests. The major contribution of this study is a tested efficacy analysis of standard EMS techniques for a fuel cell-based EV system. The study considered how the EMS influences the overall performance and life cycle of the technology. The second is analyzed using a novel method that utilizes the wavelet analysis of the load current of each alternative fuel.

This research paper is prepared as follows. The hybrid power system design is described in section II. Section III is dedicated to component design and justification. The strategies for energy management are presented in section IV. Section V uses simulation and experiments to compare the techniques. Finally, there is a conclusion to this study.

HYBRID POWER SYSTEM DESIGN

The hybrid power system is constructed around the energy and electricity needs of demonstrative EVs. The main supply system of a fuel cell is intended to meet load requirements of 6 kW, while the supercapacitors and batteries are intended to assist both of these throughout sustained and transient generation capacity. As shown in Figure 1, the fuel-cell power, supercapacitor power, and battery power are regulated through their connected DC/DC converters using a current source controller.

This paper does not contain a comprehensive study of the structure and configuration selection for the purposes of simplification. For regard, the hybrid scheme is constructed using the methods developed by Sin and Najmi [1], and the topology used is addressed by Rahman et al. [2], Nesaraj [7], and Rahman et al. [8]. Figure 1 depicts the process schematic diagrams, which include electronegativity battery configurations such as 12 V, and 48 Ah, and supercapacitor configurations like 48 V, and 90°F. The fuel cell scheme is included Hydrogenics of 6-kW, a proton exchange membrane (PEM), and a fuel-cell power subsystem. In addition, the DC-to-DC converters involve an output voltage and an optimum output or input current reference signal, both of which are calculated by the BMS. Due to time constraints, two converters are utilized with the rechargeable battery in this paper because a bidirectional DC-to-DC converter was not widely available. On the other hand, a BMS safeguards energy storage against overcharging, overheating, and over-discharge. However, a protecting resistor is also utilized to avoid supercapacitor or power converter input voltage fluctuation. An AC to DC synchronous inverter customizable load is used to generate the crisis peak load. Because the primary purpose of this research is to evaluate the outcomes of several power generation management techniques, off-the-shelf parts were chosen. In other words, the power density factor, which is serious for mixing the scheme on EVs, is not taken into account at this time [22]. Fuel cells and batteries are both important technologies for energy production in electric

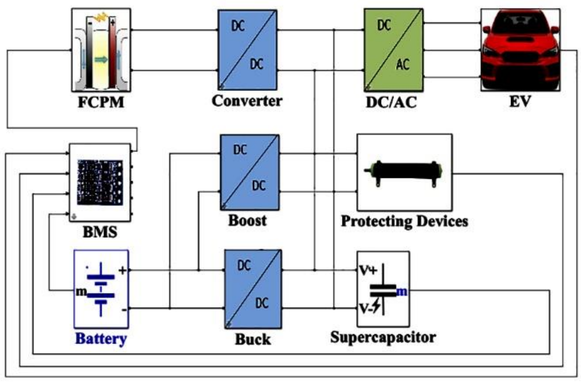


Figure 1. MATLAB circuit for hybrid power system schematic

vehicles, and their significance lies in their ability to provide a more sustainable and environmentally friendly alternative to traditional internal combustion engines [23].

Fuel cells are electrochemical devices that convert chemical energy from a fuel into electrical energy, without combustion or emissions. The fuel cell technology has several advantages over traditional engines, including high efficiency, low emissions, and quiet operation. Fuel cells are particularly well-suited for use in electric vehicles due to their ability to provide a long driving range and quick refueling times. Batteries, on the other hand, store electrical energy in a chemical form, and release it when needed to power an electric motor. Batteries have become increasingly popular in electric vehicles due to their high energy density, long life, and relatively low cost [24]. With the development of advanced lithium-ion batteries, electric vehicles can now travel hundreds of miles on a single charge, making them a viable alternative to traditional gasoline-powered vehicles. The novelty of fuel cells and batteries in energy production for electric vehicles lies in their ability to provide a cleaner, more sustainable alternative to traditional internal combustion engines. They offer lower emissions, higher efficiency, and better performance, making them an attractive option for consumers and manufacturers alike [25]. Moreover, the development of fuel cells and batteries is driving innovation and research in the field of energy storage and conversion. As these technologies continue to evolve and improve, they are likely to play an increasingly important role in the transition to a more sustainable energy future. Therefore, fuel cells and batteries represent a significant step forward in the development of environmentally-friendly and sustainable energy solutions for the transportation industry [26].

CHARACTERISTICS OF FUEL CELL-BASED EV SYSTEMS

The fuel-cell system consists of 6-kW liquid-cooled PEM, a fuel-cell power subsystem with designed auxiliaries that operates at 48 to 55 VDC such as filter, air blower, H_2 pressure controller and valves, H_2 recirculation pump, fans, and coolant pump, etc. Fuel cells are electrochemical devices that convert the chemical energy of a fuel directly into electricity, without combustion, by means of a redox reaction. There are several types of fuel cells, each with unique characteristics that make them suitable for different applications. Here are some of the most common types and their characteristics such as polymer electrolyte membrane fuel cells (PEMFCs), solid oxide fuel cells (SOFCs), Alkaline Fuel Cells (AFCs) Direct Methanol Fuel Cells (DMFCs) Phosphoric Acid Fuel Cells (PAFCs) and molten carbonate fuel cell (MCFC). PEMFCs operate at relatively low temperatures, making them suitable for transportation applications such as cars and buses. They use hydrogen gas as a fuel, which is converted to electricity by the reaction of hydrogen with oxygen from the air. PEMFCs are efficient and have a low environmental impact, but they are expensive. SOFCs operate at high temperatures, making them suitable for stationary applications such as power generation. They can use a variety of fuels, including hydrogen, natural gas, and biogas, and they have high electrical efficiency. However, their high operating temperatures make them expensive and less durable. AFCs use an alkaline electrolyte, which allows them to operate at relatively high efficiencies. However, they require pure hydrogen as a fuel, which limits their practical applications. DMFCs use methanol as a fuel, which makes them convenient for portable applications such as laptops and cell phones. They are relatively simple and compact, but their efficiency is relatively low, and they produce carbon dioxide emissions. PAFCs use phosphoric acid as an electrolyte, which makes them suitable for stationary applications such as power generation. However, each type has its own unique characteristics that make it suitable for different applications as summarized in Table 1.

Table 1. characteristics of different tpes fuel cell-based EV systems

Fuel Cell	Electrolyte/ Construction	Advantage	Disadvantage	Ref.
PEMFC	Plastic, metal, and carbon. H^+ ions.	Power density high. Temperature range 40-110°C.	Biased to CO impure H_2 was high cost. Use in EV.	[1] [4] [23]
AFC	Plastic, metal. OH^- ions (KOH solution)	Efficiency 60 to 85%. Temperature range 45-58°C.	Intolerant to CO and air, oxidization, costly. Use in EV.	[1, 7] [21]
DMFC	Plastic, metal.	High power density. Temperature around 55-120°C. Use in small EV.	Efficiency around 20-40%. Methanol crossover & poisonous byproduct	[7] [17] [12]
MCFC	Metals, porous ceramics. CO_3^{2-} ions	Efficiency 50–60. Temperature around 600–650°C.	Electrolyte instability, corrosion & sulfur poisoning.	[1, 4] [17]
SOFC	Ceramics, high temperature metals. O^{2-} ions.	Efficiency approxmatly 40-60%. Direct fossil fuel. Use in central, heat& power.	Temperature range 600-1000°C. Thermal stress failure and poisoning.	[1, 4] [7]

A molten carbonate fuel cell (MCFC) is a type of fuel cell that uses a molten carbonate salt as an electrolyte. The molten carbonate electrolyte is typically composed of lithium or sodium carbonate, which is mixed with a ceramic material to form a paste-like substance that is heated to a high temperature (around 650-750°C) before being used in the fuel cell. MCFCs are known for their high efficiency and low emissions, and are often used in large-scale power generation applications. One of the key advantages of MCFCs is their ability to capture and utilize waste heat generated during the power generation process, which can be used for other applications such as heating buildings or producing steam. However, MCFCs also have some limitations, including their high operating temperature, which can lead to material degradation over time, as well as their relatively high cost compared to other types of fuel cells. Nevertheless, ongoing research and development efforts are focused on improving the efficiency and durability of MCFCs to make them a more viable option for large-scale power generation. However, they are relatively expensive and require pure hydrogen as fuel. Generally, fuel cells offer a clean and efficient alternative to traditional combustion-based technologies.

The fuel-cell power subsystem also includes an integrated control system for communication with the central controller and safeguards which are H_2 low pressure, over current, under voltage, and stack over temperature. The scheme dynamic air flow rate selector and fuel flow rate controllers are depicted in Figure 2. The H_2 and O_2 tanks are represented respectively. They both pass in the leading system of the fuel cell stack such as the anode and cathode terminal to obtain electricity [23].

The fuel cell is related to the boost DC to DC average mode converter to raise the output voltage from 48 V DC, which is essential for the energy storage system and the load. Fuel cells function similarly to batteries, except they do not essential to be recharged. They generate power and heat as long as fuel is available. A fuel cell is made up of two electrodes, one negative (or anode) and one positive (or cathode), sandwiched by an electrolyte.

Battery model

An active model for a battery is already integrated into MATLAB2022a / Simulink/Simscape and is constructed on an improved Shepherd curve-fitting circuit model. The polarization voltage element was included in the discharge battery voltage equation to guarantee that the influence of battery the state of charge (SOC) on battery presentation was accurately represented. For the polarization resistance, the strained battery current is used in place of the real battery current for simulation stability. For discharging and charging, the model employs the following two second-order linear differential Equation (1) [17]:

When $i_1 < 0$, the discharge model is activated.

$$V_{Battry} = V_0 - \left(K \times \frac{Q}{Q-i_t} \times i_1\right) - \left(K \times \frac{Q}{Q-i_t} \times i_t\right) + \text{A} \times \text{EXP}\ (\text{-B} \times i_1) - R_{battry} \times I \quad (1)$$

where i_t, Q, R_{battry}, i_1, A, V_0, B, and K are the battery pack charge (A-h), the storage capacity (A-h), the battery parasitic resistance (Ω), the censored rechargeable battery current (A), the incremental zone peak value (V), the consistent potential difference of the battery (V), the exponential zone time constant opposite (Ah^{-1}), and the magnetization constant (V/Ah^{-1}), respectively.

Polarization voltage is denoted by the expression $K(\frac{Q}{Q-i_t}) \times i_t$ from Equation (1), whereas polarization resistance Polres is denoted by the term $K(\frac{Q}{i_t+0.1Q}) \times i_t$. The battery voltage quickly rises after being completely charged during charging; this characteristic is illustrated by changing the ionic conductivity as follows [10, 11]:

When $i_1 > 0$, the charge model is activated.

$$V_{Battry} = V_0 - \left(K \times \frac{Q}{i_t+(0.1 \times Q)} \times i_1\right) - \left(K \times \frac{Q}{Q-i_t} \times i_t\right) + \text{A} \times \text{EXP}\ (\text{-B} \times i_1) \quad (2)$$

$$Pol_{res} = \left(K \times \frac{Q}{Q-i_t} \times i_t\right) \quad (3)$$

Figure 3 shows the active mathematical flow model for a battery in MATLAB2022a/Simulink circuit. The charge and discharge currents are regulated through DC-to-DC converters.

This system detects the transient and steady performance of battery modules in response to load demand throughout modes of discharging and charging techniques. Table 2 depicts the model of battery input parameters for the battery system.

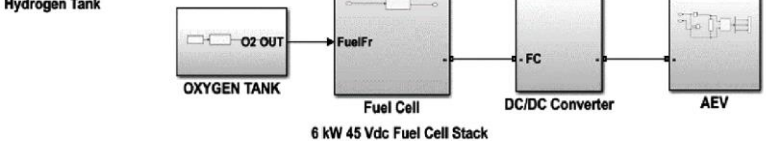


Figure 2. MATLAB circuit of dynamic model fuel cell-based EV system

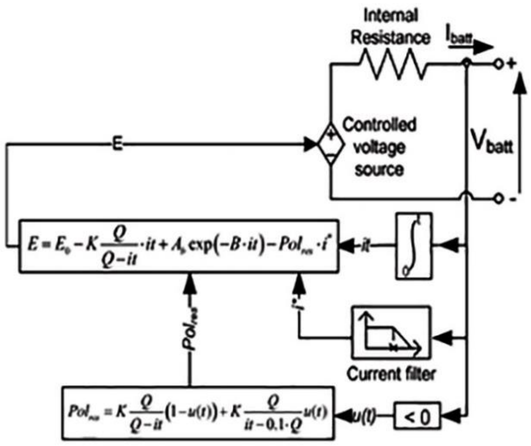


Figure 3. Active flow model for battery [20]

Table 2. Input parameters of active battery model

Name of the Parameters	Units	Values
Battery Minimal Voltage	V	48
Completely Charged Voltage	V	55.87
Rated Volume of Battery	Ah	24
Capacity at Minimal Voltage	Ah	30.74
Concentrated Capacity	Ah	24
Discharge Minimal Current	A	24.78
Parasitic Resistance	Ω	0.05

Fuel cell based on converter model

DC to DC converters connects the fuel-cell and storage subsystems to the DC to AC inverter as shown in Figure 4. This enables energy conversion between low and high energy and vice versa, in addition, to complete control over the fuel cell to input DC-bus potential difference and battery nominal current. The converter in the fuel-cell system is of the boost type, although the energy storage converters comprise one converter of the boost model like discharge DC to DC converter and one converter of the buck model like charge DC to DC converter.

DC to DC converter is signified by two different models: average-value models and switching models. The switching simulations circuit is mostly utilized for design and to explore different categories of PWM schemes in terms of switching losses and harmonics. Because these models need a short sample period to see all switching activities, the simulation takes a long time. On the other hand, the average-value models require less time since the modifications are switched with regulated energy sources. The frequency switching harmonics noise is not characterized, but all of the dynamic converters are preserved, making these simulations model appealing since time-consuming sampling times may be utilized. Some formulae have been constructed to compute the values for the capacitance is represented by

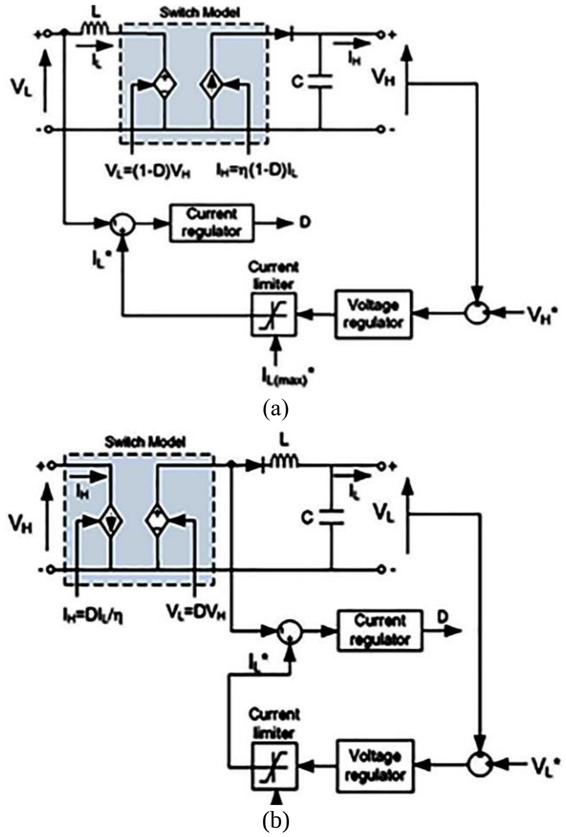


Figure 4. MATLAB Switch model for (a) Boost & (b)Buck DC/DC converter

C (F), the duty cycle is exposed to D, and the inductance is represented by L (H) for DC-to-DC converter parameters [21]:

$$D = 1 - \frac{V_{in}\times\eta}{V_{out}} \quad (4)$$

$$L = \frac{V_{in}\times(V_{out}-V_{in}}{i_{in}\times f_s\times V_{out}} \quad (5)$$

$$C = \frac{I\times D}{f_s\times v_R} \quad (6)$$

where V_{in} is the usual input voltage (V), the duty cycle is D, which equivalents the proportion of the time. According to switching logic, the switch is in position turned “ON”. Therefore, the switching condition is $0 \leq D \leq 1$, whereas η is the efficiency and up to a set of 98%. The adjustable f_s is represented by the switching frequency, v_R represents the output ripple voltage (v), i_{in} represent the current input (A), and V_{out} represents the voltage output (v) [22].

SIMULATION RESULTS AND DISCUSSION

The performances of the simulations on the 6-kW fuel-cell system as shown in Figure 1.

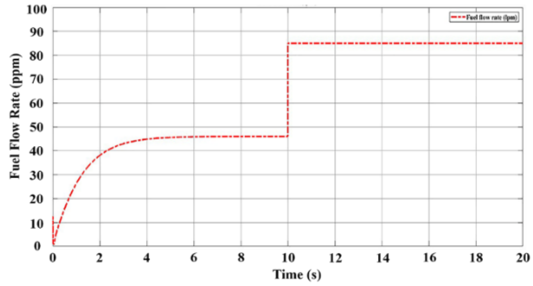
MATLAB2022a/Simulink was used to implement each scheme. However, the fuel cell model makes the following assumptions: all gases or fuels or air are faultless, compression dips diagonally flow stations are minimal, and fuel cell each cell voltage reductions are caused by feedback kinetics energy and charge transfer [23]. A proportional integral is utilized to adjust the switching frequency of the DC-to-DC converter stable the output voltage in order to keep the battery and AEV at 48 V to 55V. In this case, the PI controller coefficients have been assumed K_p of 0.00015, K_i of 0.15 and sample time of $1e^{-3}$s.

At t is 0s, this is DC-to-DC boost converter supplies $100V_{DC}$ to the output circuit like the R_L load or DC-to-AC inverter circuit, whereas the initial load current of 0A because no load condition current is always zero. In addition, the nominal fuel consumption is set to 99.56 percent. As a result output current may reach a maximum of 133A as shown in Figure 5. The gas or air flow rate is automatically regulated to sustain the insignificant fuel usage. Examine the converter output are connected DC bus circuit arrangements. The DC bus voltages are converted and controlled exceptionally well. The $122V_{DC}$ peak voltage found at the start of the simulation is produced by the voltage regulator's transient state error.

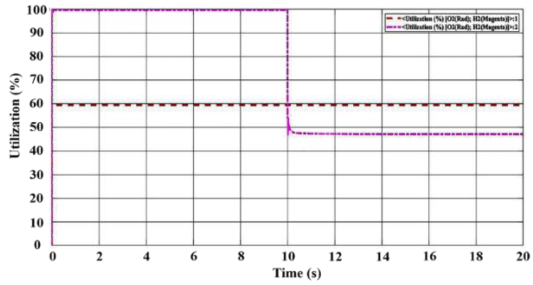
At t = 10 s, the fuel flow rate increases in 3.5 seconds from around 50 to 85 liters per minute (lpm), reducing hydrogen consumption as shown in Figures 5(b). As a result, the Nernst voltage rises and the fuel cell current lowers. Stack consumption and efficiency was drop illustrated in Figures 5(c) and 7(d) suffer as a result.

Cell activation losses are another type of loss that can affect the performance of a fuel cell, particularly in the stack of multiple cells as depicted in Figure 6. Activation losses are related to the energy required to initiate the electrochemical reaction at the electrode surfaces, which is known as the activation energy. Activation losses occur because the activation energy must be overcome before the electrochemical reaction can occur, which results in a delay in the generation of electrical energy. In a fuel cell stack, activation losses can lead to a reduction in the overall efficiency of the stack because the delay in the generation of electrical energy reduces the amount of electrical energy that can be generated for a given amount of fuel input. The effect of activation losses on stack efficiency can be quantified using the Tafel equation, which relates the rate of the electrochemical reaction at the electrode surface to the over-potential, which is the difference between the actual voltage of the fuel cell of 2.5V and the thermodynamic voltage 3.5V.

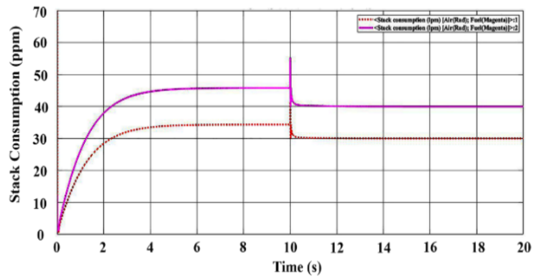
The Tafel equation shows that the activation energy required for the electrochemical reaction increases as the rate of the reaction increases, which means that the activation losses become more significant at higher current densities of almost 0.48A/cm^2. This is particularly important in a fuel cell stack because the current density is typically higher than in a single cell,



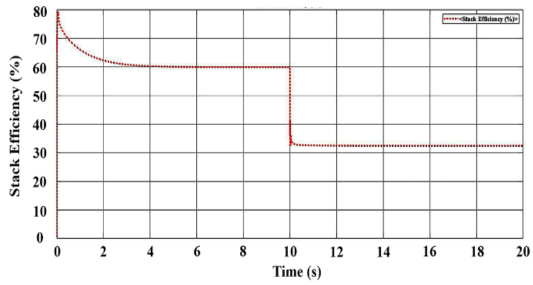
(a)



(b)



(c)



(d)

Figure 5. Fuel cell of (a) fuel flow rate, (b) utilization of hydrogen and oxygen, (c) stack consumption and (d) efficiency and (c, d) converter

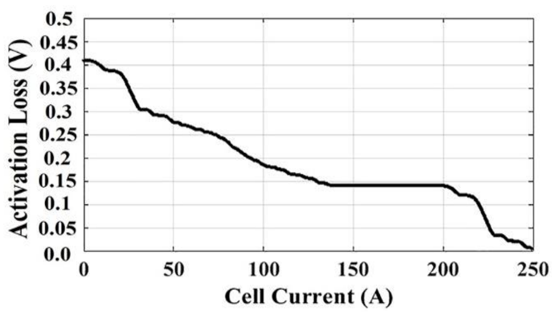


Figure 6. Fuel cell activation voltage losses

which means that activation losses can have a more significant impact on stack efficiency almost 85%. To reduce the impact of activation losses on stack efficiency of average 60%, several strategies can be employed, including optimizing the design of the fuel cell electrodes to reduce the activation energy required for the electrochemical reaction, increasing the operating temperature of the fuel cell to enhance the rate of the reaction, and improving the catalyst materials to increase the reaction rate. Activation losses in a fuel cell stack arise from the activation energy required to initiate the electrochemical reaction at the electrode surfaces, and can lead to a reduction in the overall efficiency of the stack. To minimize the impact of activation losses, it is necessary to optimize the design of the fuel cell electrodes, increase the operating temperature, and improve the catalyst materials.

According to Figure 7, the fuel cell began to function after t = 20 seconds to power the EV. The fuel cell manufacturer recommends this starting time, which is regulated by the proton exchange biofilm-based fuel cell controller. To prevent storage system damage, the battery SOC is set of 50 percent and cannot be charged to 100 percent. 24.5 A is the nominal discharge current. From Figure 7(a) it is clearly observed that the output voltage of fuel cell around 56V after 10s. At time 10s to 20s the fuel output is stable when compare to the initially condition al 0s to 10s. The fuel cell output voltage is gradually fall down which is around 50V.

While the output current of the fuel cell is opposite trained because the voltage is decreased in the same time current is increased. Figure 7(b) depicted that the fuel cell output current all most 110A after 10s. In addition, Figures 7(c) and 7(d) illustrated that the fuel cell supply to the DC bus voltage and current are 100VDC and 120A, respectively. The mechanisms in the fuel cell are the inverse of those utilized in battery and supper capacitor system. Battery requires at least 48V before the water starts to split; often, the voltage is greater. The voltage throughout the fuel cell is around 55V when the current flow is extremely minimal or nil. This is known as open voltage waveform. The size and integrity of the input molecules are important in the context of the fuel cell. The voltages decrease as more current is taken from the fuel cell. As a result, the current increases exponentially as the voltage decreases.

Cell concentration losses are another type of loss that can affect the performance of a fuel cell. These losses are related to the transport of reactants, such as hydrogen flow rate 2g/s and oxygen flow rate 0.75 g/s, to the electrodes of the fuel cell, and the rate at which they can be consumed in the electrochemical reactions that generate electricity output power of around 100 kW. In a fuel cell, the transport of reactants to the electrode surfaces is critical for the generation of electricity. However, the rate of transport is often limited by diffusion, which means that the concentration of reactants at the electrode surfaces can be significantly lower than the bulk concentration of the fuel and oxidant. This concentration gradient leads to a reduction in the rate of the electrochemical reactions at the electrode surface, resulting in a reduction in the output voltage and current of the fuel cell as presented in Figure 8.

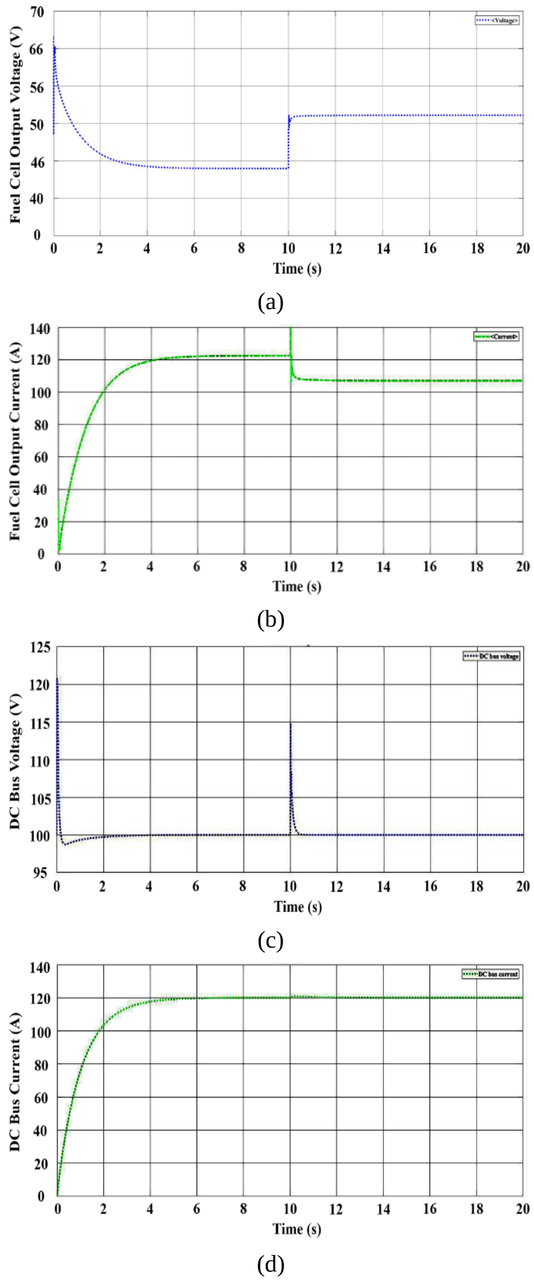


Figure 7. The fuel cell (a) voltage & (b) current and converter output (c) voltage & (d) current waveforms

The effect of concentration losses on the output voltage around 0.23V and when the output current of around 250A a fuel cell can be quantified using the Butler-Volmer equation, which relates the rate of the electrochemical reaction at the electrode surface to the

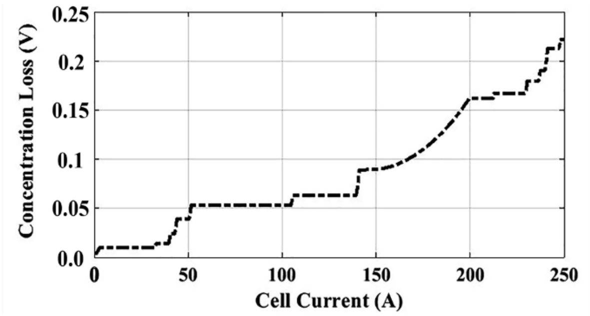


Figure 8. Fuel cell concentration losses

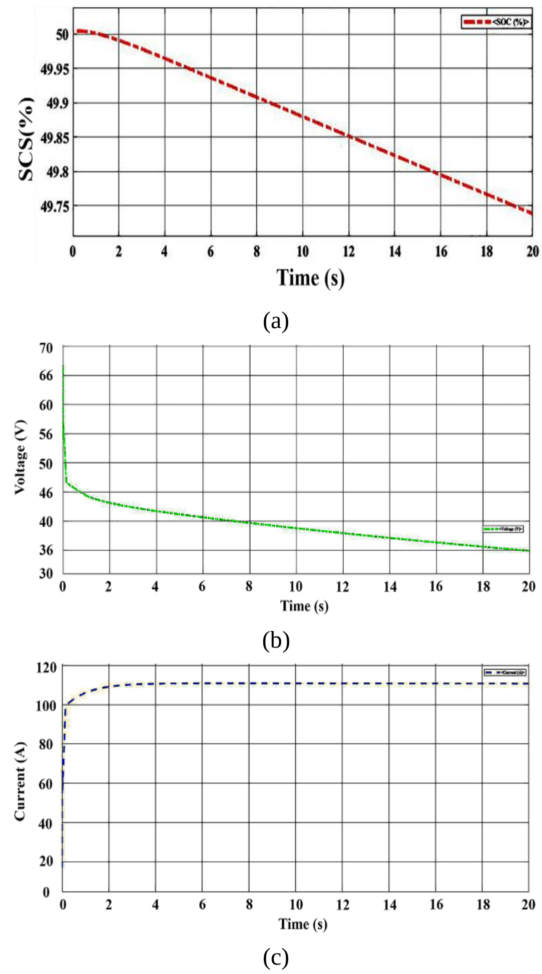


Figure 9. The battery characteristic for (a) SCS, (b) voltage and (c) current

concentration of reactants and the over-potential, which is the difference between the actual voltage of the fuel cell and the thermodynamic voltage. The equation shows that the rate of the electrochemical reaction decreases as the concentration of reactants decreases, leading to a reduction in the output voltage and current of the fuel cell. To reduce the impact of concentration losses on the output voltage and current of a fuel cell, several strategies can be employed, including optimizing the design of the fuel cell electrodes to maximize reactant transport, increasing the operating temperature of the fuel cell to enhance reactant diffusion, and improving the reactant supply system to ensure a steady and adequate supply of fuel and oxidant. Concentration losses in a fuel cell arise from the concentration gradient of reactants at the electrode surfaces, and can lead to a reduction in the output voltage and current of the fuel cell. To minimize the impact of concentration losses, it is necessary to optimize the design of the fuel cell electrodes, increase the operating temperature, and improve the reactant supply system.

In order to compare the conventional PI control system fairly to other schemes, the SOC value is assigned at a SOCmin of 50%. The condition shown in Figure 9(a) is performed for 20 min in order to attain the load profile utilized for performance evaluation. Battery charge and discharge based on fuel cell using DC to DC converter has become the simplest common technique for charging a battery.

It shortens charging time while increasing capacity by up to 20%. However, this strategy lowers efficiency by around 10%. The recharging voltage is retained consistent in this approach across the charging procedure as shown in Figure 9(b). Because when battery is in a discharge state, the current flowing is significant at first. As the battery charges, the current steadily decreases, leading to a rise in converter as demonstrated in Figure 9(c). The charging current is effectively zero towards the end of the charge because the battery voltage is approximately equal to the voltage of the power circuit. On the other hand, as the battery voltage is increased, the charging current is maintained constant by lowering the resistance in the circuit. To minimize significant overloading, the charging could be done in two parts. A greater charging speed at the start and a lower charging speed at the end. However, concentration losses can be minimized by increasing the concentration of reactants at the electrode surface. This can be achieved by increasing the flow rate of reactants, increasing the pressure of the reactants, or by optimizing the electrode design to increase the surface area and improve the mass transport of reactants to the electrode surface.

The hybrid energy is utilized to power an electrolyzer and recharge the batteries while also producing oxygen and hydrogen gas. The fuel cell power generation is modest in comparison to PV and wind power because the fuel cell is integrated into the rechargeable battery, resulting in a huge quantity of energy to power the DC converter. The findings for power density and specific power for the backups and existing performance with the fuel cell are shown by Rahman et al. [2]. The assumptions are based on the whole overall mass and weight, which may be represented as the combination of the capacity and fuel power systems. Because of the major proportion of system components that were incorporated into industrial fuel cells, the projected outcomes are displayed in Figure 10. At low current densities (per cell of 0.43 A/cm^2), the greatest fuel cell efficiency was less 80%, power output almost 6kW and stable current was 110A, meanwhile the input power for optimum power production was 1.2 A/cm^2 per cell of fuel cell. Because the anode composition was 1.43, 39% of the hydrogen was vented, and so efficiency could have been greatly enhanced by running the cell in anode dead-end condition. It is well known that when current decreases, efficiencies rise [14].

In Figure 10, efficiency decreased for very low currents, owing mostly to the test bench's hydrogen flow rate regulators operating at a basic flow rate of 1.25 NL/min, giving a larger flow rate of hydrogen than necessary for extremely low currents. According to Albarghot et al. [11], batteries cell has specific energies ranging from 0.165 kWh/kg to 0.207 kWh/kg and energy densities ranging from 0.329 kWh/L to 0.490 kWh/L. When compared to batteries cell to cell, the most significant gains are in the specific energy of the fuel cell complete devices. By incorporating the fuel cell into the device, the energy storage is raised while the number of batteries is decreased.

Fuel Cell Ohmic losses refer to the loss of electrical energy in a fuel cell due to the resistance of the various components of the fuel cell, including the electrodes, the electrolyte, and the interconnects as described in Figure 11. These losses can have a significant impact on the overall efficiency of the fuel cell, reducing the amount of electrical energy that can be generated for a given amount of fuel input. Ohmic losses are caused by the resistance of the various components of the fuel cell to the flow of electrical current which is around 110A. As the current flows through these components, it encounters resistance, which results in a voltage drop 0.10V. This voltage drop represents a loss of electrical energy, which reduces the overall efficiency of the fuel cell around 35%.

The effect of Ohmic losses on fuel cell efficiency can be quantified using the voltage loss equation, which relates the voltage loss to the current density and the resistance of the various components of the fuel cell. The equation shows that the voltage loss increases as the current density increases or as the resistance of the components increases, leading to a reduction in the overall efficiency of the fuel cell. From the result of fuel cell, the resistance of the various components of the fuel cell to the flow of electrical current, and can have a significant impact on the overall efficiency of the fuel cell. To improve fuel cell efficiency, it is necessary to minimize these losses by optimizing the design of the fuel cell components and improving the operating conditions of the fuel cell.

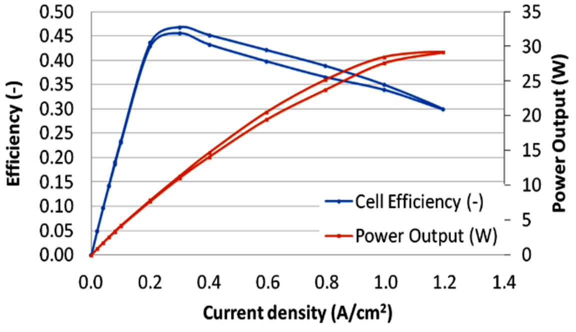


Figure 10. Fuel cell efficiency curve and power curve for hybrid mode

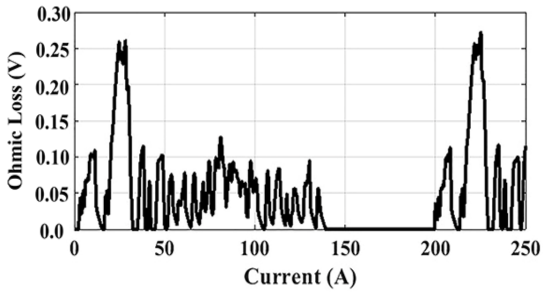


Figure 11. Fuel cell ohmic losses

CONCLUSION

Fuel cells are increasingly being utilized in various technologies such as vehicles, transportable devices, and residential power production. To design and simulate these technologies, a simple and effective fuel cell model is needed to specify conventional fossil fuel generation and related conversion. This study proposes a general fuel cell design that can reflect the performance of most fuel cells that are supplied with hydrogen and air, using only a few parameters provided in the manufacturer documentation. The calculations can be run without the use of an actual fuel cell, and the suggested concept has been verified using a standard specification graph and simulation results from an actual setup. The difference between the actual stack power and the calculated power is less than 1% if the condition within the stack is regulated. The influence of moisture leads to a 1% error for every 9% increase in air flow and a 3% error for every 15% reduction in temperature. This fuel cell design is included in SimPowerSystems and is used to simulate a fuel cell-based electric vehicle system. The vehicle's performance has been determined to be quite similar to its true values in terms of fuel consumption, optimum vehicle efficiency, and power output. The fuel cell-based electric vehicle model demonstrates how the fuel cell stack model is utilized in conjunction with other electrical system concepts and can serve as an excellent reference point for the development and modeling of fuel cell power mechanisms. The future work on fuel cells involves improving the efficiency, durability, and cost-effectiveness of fuel cells to make them a more viable alternative to traditional fossil fuel-based technologies. Overall, future work on fuel cells is aimed at making them a more practical and economical solution for a wide range of applications, from transportation to stationary power generation.

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Persian Abstract

چکیده

توسعه‌یافته‌ترین کشورهای جهان از نظر اقتصادی با بحران انرژی ناشی از بی‌ثباتی ژئوپلیتیکی، افزایش هزینه‌های انرژی، اختلال در ذخایر جهانی و تغییر جهت به سمت منابع انرژی کم کربن مواجه هستند که هنوز به طور کامل محقق نشده است. برقی شدن صنعت حمل و نقل مزایای افزایش بهره‌وری انرژی و کاهش آلاینده‌های محلی را ارائه می‌دهد. وسایل نقلیه الکتریکی (EVs) سازگار با محیط زیست هستند زیرا مصرف سوخت‌های فسیلی را حتی مصرف صفر را کاهش می‌دهند، به نیازهای تعمیر و نگهداری کمتری نیاز دارند و هزینه‌های عملیاتی کمتری نسبت به خودروهایی که با بنزین یا گازوئیل کار می‌کنند، دارند. با این حال، این مطالعه بر مقایسه استراتژی‌های مختلف مدیریت انرژی (EMS) برای یک سیستم تامین انرژی پشتیبان برای خودروهای الکتریکی متمرکز است. سیستم قدرت هیبریدی (HPS) در نظر گرفته شده در این مطالعه شامل مبدل‌های سنکرون DC-DC و DC-AC و همچنین ابرخازن‌ها، باتری‌ها و پیل‌های سوختی است. EMS تجزیه و تحلیل شده شامل کنترل ماشین حالت، کنترل انتگرال-نسبی کلاسیک، کمینه‌سازی مصرف معادل، جداسازی فرکانس، منطق فازی مبتنی بر قانون، و کنترل منطق فازی است. بازده HPS، سوخت هیدروژن، سطح شارژ ابرخازن یا باتری و عملکرد کلی به عنوان معیارهای بازده اولیه ارزیابی می‌شوند. علاوه بر این، HPS نه تنها انرژی سیستم را افزایش می‌دهد، بلکه تعداد باتری‌های بسته مورد نیاز را نیز کاهش می‌دهد. این مطالعه سیستم‌های قدرت ترکیبی را برای بهبود طرح‌های برق EV با منابع تغذیه باتری قابل شارژ طراحی و ساخته می‌شود. نتایج نشان می‌دهد که یک هیبرید پیل سوختی ۶ کیلوواتی ظرفیت سیستم قدرت را به ۴۰۸ کیلووات ساعت افزایش می‌دهد. علاوه بر این، یک روش جدید مبتنی بر تبدیل موجک قدرت لحظه‌ای هر منبع انرژی برای تعیین کمیت عوامل استرس زا در هر منبع انرژی که بر چرخه زندگی آن تأثیر می‌گذارد، استفاده می‌شود. برای اعتبارسنجی تمام تحلیل‌ها و عملکرد، یک مدل شبیه‌سازی و یک میز آزمایش تجربی ایجاد می‌شود. در نهایت، نتایج شبیه‌سازی یک مبدل سنکرون با توان خروجی ۶ کیلووات و راندمان ۹۶ درصد را نشان می‌دهد که نتایج بهینه‌سازی را تایید می‌کند.