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Modelling and Control of a PEM Fuel Cell Hybrid Energy System Used in a Vehicle with Fuzzy Logic Method

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Abstract

PEM (Proton Exchange Membrane) fuel cells, which are commonly used in vehicles, are critical for sustainable transportation in the future. In this study, it is aimed to enhance the system efficiency of the PEM fuel cell and provide fuel economy. To achieve this goal, the hybrid energy system with a PEM fuel cell and battery pack is controlled with two different strategies. The first control strategy is designed using Fuzzy Logic (FL), while the other control strategy is designed with the classical on-off method with the 'Relay' block. Power output of the fuel cell is determined depending on the change in the charging state of the battery pack and the power consumed by the electric vehicle in this study. The aim is to provide that the fuel cell operates in a high-efficiency range and can generate enough power when needed. Vehicle and fuel cell modeling were per-formed in Matlab/Simulink environment. NEDC (New European Driving Cycle) and WLTP (Worldwide Harmonized Light Vehicles Test Procedure) driving cycles were considered and fuel cell efficiency and hydrogen consumption were compared at different state of charge values of the battery. The analyses were carried out over long distances by repeating the driving cycles. It was observed that fuzzy logic control provided 11.6% less fuel consumption than classic on-off control in NEDC and WLTP driving cycles repeated five times. The values obtained as a result of the study showed that fuzzy logic control is more advantageous to increase the energy efficiency of fuel cells.

Keywords: PEM fuel cell; Fuzzy logic control; modeling; fuel efficiency

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1. Introduction

Due to the increasing world population and energy needs, the use of traditional fossil fuels is increasing [1,2]. The increase of internal combustion engine vehicles worldwide further increases this usage and demand. Although the emission values of newly produced internal combustion engines are lower than in previous years, they still cause air pollution because they cannot be reduced to zero. Today, climate change and increasing air pollution are significant problems that significantly affect the health of people and other living things on Earth. Therefore, obtaining the energy needed in the world from renewable clean energy has become important [3].

Based on the World Energy Outlook 2021 report published by the International Energy Agency (IEA), electricity production from renewable energy sources increased by 7.5% in 2020, accounting for 29% of global electricity production. According to the IEA, hydrogen energy is also experiencing significant growth. Hydrogen energy production increased by 4 million tons in 2020 compared to 2019, an increase of 20%, and by 50% compared to 2015 [4]. This shows that hydrogen, which has a critical role in the energy sector in the 21st century, may be widely used for electricity in the future [5]. The transportation industry is calling for a decarbonization program as it is currently almost entirely dependent on fossil fuels [6]. This program has focused primarily on electric vehicles (EVs) in the automotive industry [7]. In recent years, the development of electric vehicles, the increase in production and usage rates, and the increase in hydrogen fuel production have shown that PEM fuel cells that use hydrogen as fuel can be widely used in electric vehicles in the future. The use of PEM fuel cell electric vehicles (PEMFCEVs) contributes greatly to reducing greenhouse gases in the transportation sector [8]. Because instead of the dirty emissions released by internal combustion engines, only pure water is released as a byproduct of the electrochemical reaction between hydrogen and oxygen. This makes it even cleaner, especially when hydrogen is generated from renewable energy sources [9].

Fuel cells are not limited by the Carnot cycle because they have three times the efficiency of internal combustion engines (ICE) [10]. In addition, fuel cell electric vehicles (FCEVs) lag behind electric vehicles (EVs) in view of driving range and charging time [11]. But, fuel cells also have some disadvantages. These disadvantages can be listed as low power density, load mutation response, and hysteresis. Low power density can lead to limited energy production. In the case of load mutation, fuel cells cannot respond quickly and hysteresis can affect efficiency and performance [12,13]. Competitiveness is low today due to the initial purchase cost of the fuel cell stack used in the FCEVs energy system and the expense of hydrogen fuel [14]. To make the electric motor run more stably and smoothly due to the sensitivity of fuel cells to high load changes that cause performance degradation and the loss of operating efficiency in a shorter time than expected, extra energy storage systems are integrated into FCEVs. This energy storage system also enables energy to be recovered during braking. A battery or ultracapacitor is typically an energy storage system. However, there are configurations where power sources are used together and separately.

There are different configuration situations where electric energy obtained from fuel cells is transferred to the electric motor without being stored, the fuel cell is connected in series to energy storage systems such as ultra capacitors, and the fuel cell is connected in parallel with the battery through a DC/DC converter interface [15,16]. However, in systems where the fuel cell is the only energy source, a more powerful fuel cell stack, and excessive hydrogen consumption are required to meet power require-ments due to high power demand. Since efficiency degradation and power delay can also occur, this situation can be compensated with an auxiliary energy storage system. This energy storage system also enables energy to be recovered during regenerative braking through a bidirectional converter interface. Ultra capacitors, which have a higher power density than batteries, provide better energy recovery with regenerative braking [17]. However, the most popular transmission configuration among electric vehicle manufacturers is a battery system connected in parallel to the fuel cell through a bidirectional DC/DC converter [18]. The energy storage unit provides temporary power by being connected in parallel to the fuel cell. This energy supply system makes it possible to recover regenerative energy by shortening the start-up time [19]. This hybrid energy system is used in vehicles. For example, Toyota Mirai is one of these vehicles [20]. In spite of the advantages of FCEVs, investigations are needed to manage the flow and exchange of energy between energy storage systems. Power and energy variables must be properly controlled to provide the equivalent hydrogen consumption and efficiency of the vehicle during the journey. In addition, additional energy storage systems must be kept within the optimum operating range. Therefore, they should be designed to minimize fuel consumption. ‘Rule-Based’ and ‘Model-Based’ are the main energy management systems [21].

Rule-based fuzzy logic theory determines the power re-quested from the fuel cell by If-Then rules based on membership functions such as power consumed by the electric motor and battery charging status to adjust the power distribution between the fuel cell and battery in the best possible way. This method can cope with sudden load changes of the electric motor while adjusting the management of hybrid energy systems. It shows that it can im-prove the efficiency and fuel consumption by making the energy system more sustainable [22].

Since the efficiency of the fuel cell is highly dependent on the state of charge (SOC) value, our energy needs must be met according to the battery’s state of charge. Therefore, in the second energy management system, a model design that varies only depending on the SOC. A second energy management system with a classic on-off control of fuel cell electric power generation controlled at two points de-pending on the battery state of charge value was designed and compared.

There are some studies conducted by researchers in the literature on this subject. Yang et al. [22] proposed a fuzzy logic-based energy management strategy for fuel cells and energy storage systems. Experimental results showed that this fuzzy logic-based control strategy can extend the life of the battery by preventing overcharging or over-discharging of the battery and can ensure efficient operation of the fuel cell. Luciani et al. [23] examined the benefits of fuel-cell hybrid vehicles in the transportation sector and different control strategies to improve system efficiency. It has been shown that different control strategies are effective in improving fuel cell system efficiency. System efficiency was increased by 30% in low-load cycles and 33% in high-load cycles using control techniques. This shows that fuel consumption is significantly reduced. Trinh et al. [24] aimed to coordinate the energy from energy sources such as batteries, fuel cells and super capacitors that arise from load power demand. The method-ology depends on high and low-level control systems. It has been observed that this energy management system effectively provides power distribution even in sudden changes in power distribution and increases fuel cell efficiency. In addition, it exhibited an efficiency of up to 53% by reducing hydrogen consumption by 21.4%. Truong et al. [25] aims to manage the energy flow between power sources using a hybrid energy storage system consisting of batteries, fuel cells and super capacitors. A rule-based and fuzzy logic-based energy management strategy has been developed. Simulation results showed that this strategy improved fuel economy by 10.919% and improved fuel cell system efficiency. Dao et al. [26] include PEM fuel cell design and energy systems for hydraulic excavators. This design also includes batteries and ultra capacitors. The energy management strategy was considered using a new mapping fuzzy logic control and analyzed with simulation with different load demands. As a result of the simulation, it was observed that energy management strategy with fuzzy logic-based increased fuel cell efficiency by up to 47%. Weyers et al. [27] investigate the energy management of hybrid energy storage systems consisting of fuel cells and batteries in mobile applications. Three different energy management concepts were simulated and compared in view of performance criteria. It was seen that the hardness coefficient model and fuzzy logic controller were better than the hysteresis controller and that limiting fuel cell power could be beneficial. Peng et al. [28]

designed a power system without a grid connection for a hybrid tram. A design consisting of PEM fuel cells, batteries, and super capacitors is presented. In this design, differential power processing compensation and fuzzy logic hysteresis state machine were used as energy management strategies. The suggested energy management strategy ensures the stability of the hybrid power system and improves fuel economy. In addition, it was observed that efficient power management was provided between PEM fuel cell, battery, and supercapacitor subsystems, and an approximately 7% fuel efficiency was achieved. Regad et al. [29] implemented the renewable hybrid power system with PID control. Bingül et al. [30] achieved successful results by controlling the active suspension system with fuzzy logic and PID controller in a 4x4 in-wheel engine driven electric vehicle environment. Yıldız and Özel [31] examined the energy consumption and recovery of autonomous hydrogen fuel cell electric vehicles with different power transmission components. They stated that the two stage gearbox provides the lowest energy consumption, the REG system increases energy recovery, and the size of the electric motor can be reduced by using a continuously variable transmission. Hemi et al. [32] designed a power management strategy using a realtime fuzzy logic controller approach for hybrid electric vehicles. The study evaluates the performance of different configurations consisting of fuel cells, batteries, and super capacitors. The proposed fuzzy logic control strategy demonstrates the ability to provide an appropriate power supply and efficient power distribution in unknown driving cycles. The results confirm that the fuel cell/battery/super capacitor structure reduces hydrogen consumption, and increases battery life by providing fast charging and discharging. According to a literature review on the subject, it has been determined that energy management systems implemented using the fuzzy logic method are more efficient. However, it has been observed that the energy management system controlled by the fuzzy logic method has not been tested over long distances. At the same time, it has been determined that no comparison has been made between the energy management system that opens and closes within a certain range. Due to the absence of such a comparison in the literature, these two energy management systems have been selected. It is thought that making this comparison in this study will contribute to the literature in terms of determining which one is more efficient for fuel cells. The originality of this study is to test energy management in long-range tests by repeating driving cycles and comparing them in different driving cycles. The aim is to reduce fuel consumption and increase efficiency. For this purpose, it is to compare the simulation results obtained by modeling energy management strategies in Matlab/Simulink environment in detail. It contributes to the literature in determining the correct energy management.

2. Material and Method

The study consists of four basic parts: modeling of the hybrid vehicle, modeling of energy system and fuel cell, modeling of fuzzy logic control strategy, and modeling of on-off control strategy.

2.1. Hybrid Vehicle Model

DC and AC motors can be used in electric vehicles. DC motors are widely preferred in trains, vehicles, and industrial applications due to their high starting torque. DC motors are generally more compatible in this area than AC motors with a fixed rotating field because they have variable speed control [33]. In this study, the torque/speed map and efficiency map of the DC electric motor was used. Maximum torque of electric motor 400 Nm and maximum speed is 8000 rpm. In addition it gives 145 kW power output belonging to the UQM brand and named 'PowerPhase 145' were used. Technical data for the UQM PowerPhase 145 motor is given in Table 1 [34].

Table 1. "UQM PowerPhase 145" electric motor specifications

Maximum Power	145 kW
Maximum Torque/ Speed	400 Nm
Maximum Efficiency	94%/8000 RPM
Power Density	2.9 kW/kg
Diameter/Length	280 mm/279 mm
Weight	50 kg

Due to the unknown values of the electrical circuit elements of the motor, the torque/speed graph in the product catalog was used to find the maximum torque value at all different speeds of the motor in electric motor modeling. The efficiency map that varies depending on torque and speed was also used to determine the motor efficiency. Fig. 1 shows the motor efficiency map and also the torque/speed graph.

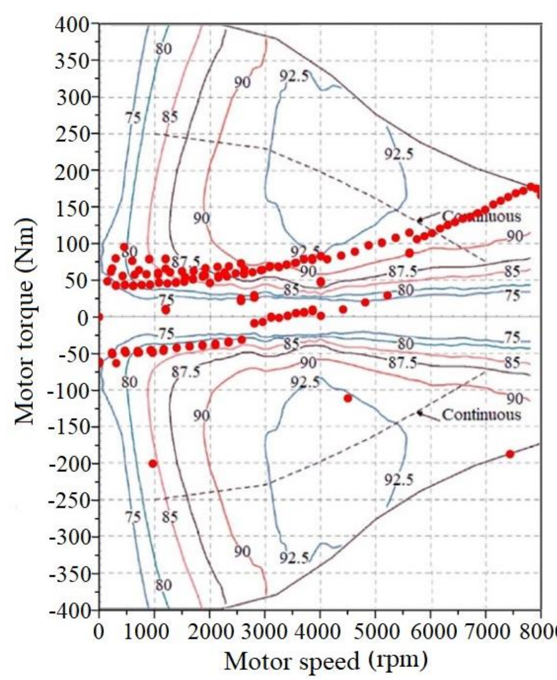

Fig. 1 UQM PowerPhase 145 electric motor efficiency map, electric motor operating points and torque/speed graph [34]

In order to obtain the maximum torque value that the motor can operate at that speed in electric motor modeling, a '1-D Lookup Table' block was modeled in the Matlab/Simulink environment by taking the instantaneous speed of the electric motor as the input value.

The efficiency expression for electric motors is obtained by dividing the power taken from the shaft by the power drawn from the grid. Electric motor efficiency is directly related to energy consumption, and the more efficient the electric motor is, the lower the energy consumption. The electric motor was modeled by processing its values in the torque/speed/efficiency map with a '2-D Lookup Table' block. The current speed and torque information of the electric motor was provided as input to this block, and its output was used to determine the efficiency of the electric motor at its current torque and speed points. The modeling of the electric motor is given in Fig. 2.

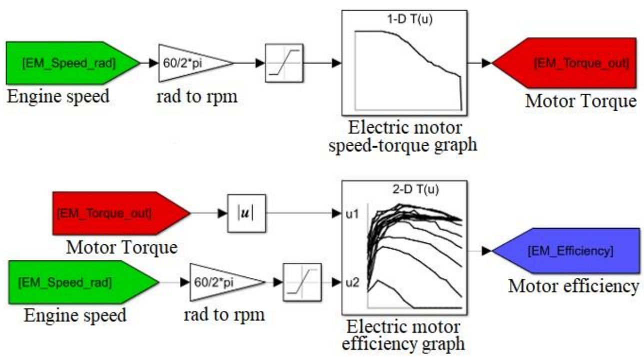

Fig. 2 Modeling of the electric motor

2.1.1. Vehicle Resistance and Modeling

The vehicle is subject to different resistances while in motion. These resistances create a force that opposes the motion of the vehicle. In the vehicle, electric motor provides acceleration by generating torque above the resistance forces applying on the vehicle. As the resistance forces acting on the vehicle increase, the force required to move the vehicle also increases along with a significant increase in energy consumption. Vehicles are affected by aerodynamic resistance, rolling resistance, acceleration, and slope resistance during cruising. These resistances affecting the vehicle are included in the model. Fig. 3 depicts a schematic representation of these resistances on a vehicle.

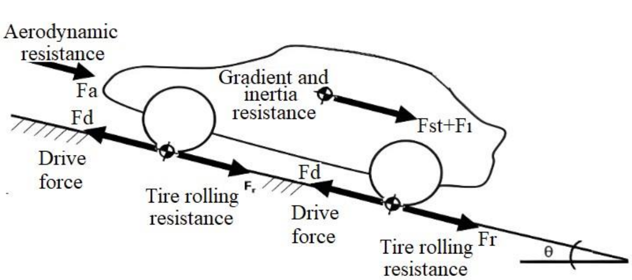

Fig. 3 Resistance forces affect the vehicle

Aerodynamic resistance is a force that occurs because of the interaction of a moving object with air. This resistance is due to the high air pressure on the front surface of the vehicle during forward movement. As the vehicle speed increases, this resistance increases. The aerodynamic resistance coefficient (C_d) varies depending on the design of the vehicle. The calculation of the aerodynamic resistance affecting the vehicle is provided by mathematical equations obtained by experimental and theoretical methods. Aerodynamic resistance was calculated using Equation 1 [35].

$$F_a = 0.5\rho C_d A_f (V + V_0)^2 \quad (1)$$

According to Newton's second law of motion, a resistance force occurs in the opposite direction during the acceleration or deceleration of an object. It encountered by the vehicle during positive and negative acceleration is called acceleration resistance. Vehicle acceleration resistance is directly related to the mass and acceleration of the vehicle. Acceleration resistance is calculated using Equation 2.

$$F_{ac} = m.a \quad (2)$$

The elastic structure of the wheels creates a resistance force in front of the wheel contact point against the wheel rotation movement. As the mass of the vehicle increases, the wheel applies more force on the ground, which causes to an increase in rolling resistance force. In addition, the ground reaction force in a moving vehicle acts towards the front of the wheel and creates a pressure difference, which creates a resistance force against the rotation of the wheel. The equation for rolling resistance force is given in Equation 3 [36].

$$F_r = mgC_r\cos\propto \quad (3)$$

Slope resistance arises from the parallel component of the vehicle's weight on the inclined road during the movement of the vehicle. If the movement is uphill, this component resists the movement of the vehicle. This resistance is called slope resistance. The equation for slope resistance is given in Equation 4.

$$F_{gr} = mg\sin\propto \quad (4)$$

The total resistance force is calculated by adding the aerodynamic, acceleration, rolling, and slope resistance forces affecting the vehicle. The Simulink model of the total resistance forces affecting the vehicle is shown in Fig. 4.

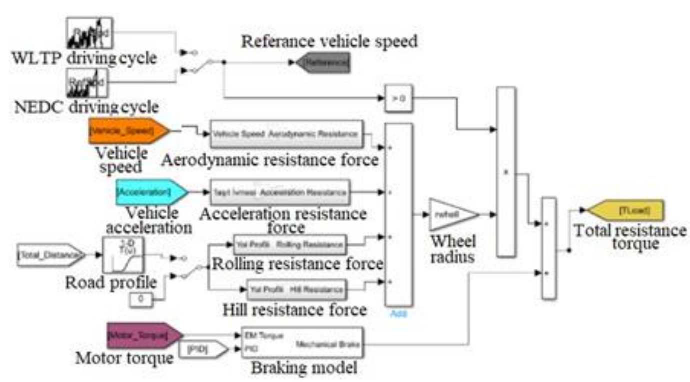

Fig. 4 Simulink model of the total resistance forces acting on the vehicle

2.1.2. Vehicle Dynamic Model

Dividing the motor torque obtained from the electric motor model by the instantaneous motor efficiency and then dividing it by the total load force affecting the vehicle after finding the mass moment of inertia value gives the angular acceleration of the propeller shaft. The angular velocity of the propeller shaft is found by taking the integral of the angular acceleration over time. The angular velocity of the axles is found by dividing the differential reduction ratio of differential efficiency and multiplying it by the angular velocity of the propeller shaft. Since the axles are directly connected to the wheels, their angular velocities are equal. The linear velocity of the vehicle is found by multiplying the radius of the wheels by the angular velocity of the wheels. The derivative of vehicle linear velocity concerning time gives acceleration and integrating it with respect to time gives distance traveled. The vehicle dynamic model in the Simulink environment is shown in Fig. 5. The mathematical equation of the vehicle dynamics model that includes these processes is given in Equation 5.

$$\frac{d\omega_m}{dt} = \frac{\left[T_m - \frac{T_{load}}{i_d \ .\eta \ _d}\right]}{[(4J_t + 2J_a)/(i_d^2.\eta \ _d) + J_m]} \quad (5)$$

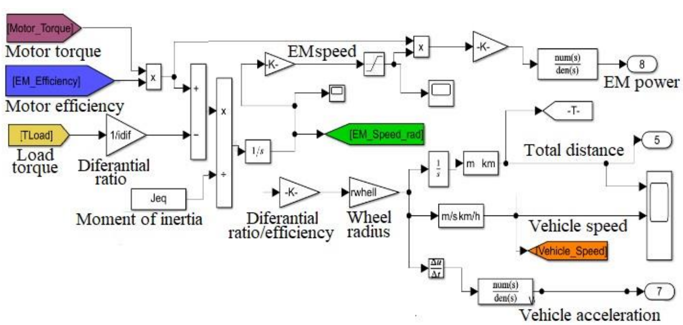

Fig. 5 Vehicle dynamic model

A PID controller is utilized to regulate acceleration by trolling the value between -1 and 1 in the gas pedal model made to ensure that the reference speed taken from the driving cycle is the same as the vehicle speed. The model is given in Fig. 6.

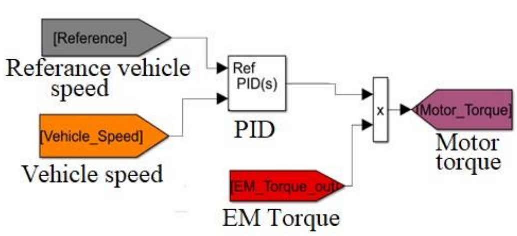

Fig. 6 Gas pedal model

Vehicle parameters and other data input into the simulation were taken from sources found in the literature [34, 37-41].Table 2 shows the vehicle dynamic simulation parameters and vehicle characteristics.

Table 2. Vehicle Dynamic Simulation Parameters and Vehicle Characteristics [29, 37-41]

Vehicle Mass	1500 kg
Wheel Radius	0.32 m
Differential Reduction Ratio	10
Differential Efficiency	%95
Vehicle Cross-Sectional Area (A_f)	2.27 m^2
Aerodynamic Resistance Coefficient (C_d)	0.28
Air Density (ρ)	1.12 kg/m^3
Gravity (g)	9.81 m/s^2
Rolling Resistance (C_r)	0.01

2.2. Fuel Cell and Modeling

2.2.1 Fuel Cell Model

Fuel cell performance can be resumed with a graph that shows current density-voltage values. This graph, called the current density (i)-voltage (V) curve, shows the voltage output of a fuel cell depending on a certain current density. Current density is found by dividing the instantaneous current value by the active area of the cell. A fuel cell with a large active area can produce more electricity than a fuel cell with a smaller active area. In this case, using the current density on the curve is more suitable for comparing different fuel cells.

Polarization curves shown in Fig. 7 are a common method that shows the performance of different fuel cell stacks. Although these curves do not show certain problems exactly, they allow the calculation of general performance [42,43].

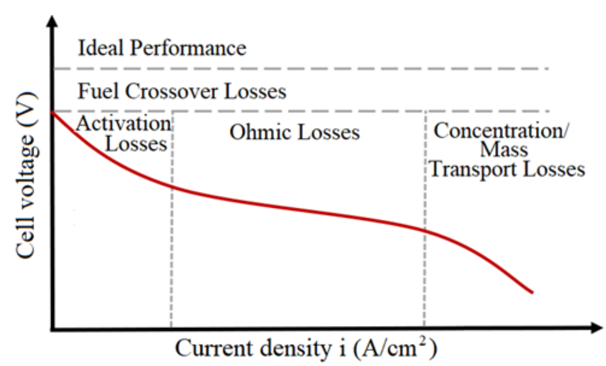

Fig. 7 Polarization curve

An ideal fuel cell maintains a constant voltage determined by thermodynamics while providing any amount of current as long as sufficient fuel is supplied. However, the actual voltage output of a real fuel cell is lower than the ideal voltage predicted by thermodynamics. Furthermore, if the current drawn from a real fuel cell exceeds a certain level, it reduces the cell's voltage output and limits the total power that can be obtained. The power provided by a fuel cell (P) is found by multiplying current (i) and voltage (V). The power calculation equation is given in Equation 6 [44].

$$P = i.V \quad (6)$$

A fuel cell's power density curve can be created, which shows the power density that varies with the current density of the fuel cell. The power density curve is obtained by multiplying the voltage at each point on the i-V curve by the current density. It is given in Fig. 8. While the fuel cell voltage is shown on the y-axis on the left side, the power density is shown on the y-axis on the right side [44,45].

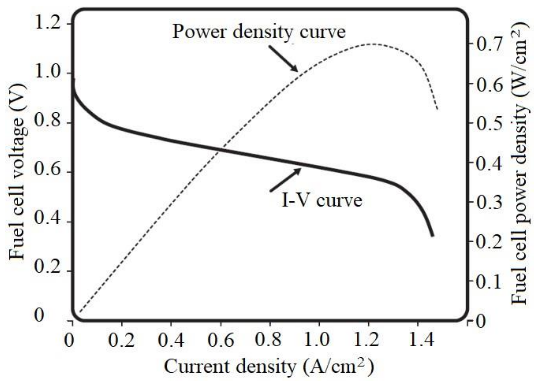

Fig. 8 I-V curve and I-Wcm^2 curve

Table 3 shows the fuel cell characteristics features.

Table 3. Fuel cell characteristic features [37,39]

Fuel Cell Parameters and Features	Values and Units
Fuel Cell Active Area	225 cm^2
Number of Cells	200
Stoichiometric Ratio	1
Temperature	25 °C
Electrolyte Thickness	125 μm
Anode Thickness	350 μm
Cathode Thickness	350 μm

These curves are processed into the '1-D Lookup Table' block in the Matlab/Simulink environment. With these curves, the input value is set as current density, and the output data is obtained as cell voltage and power density. The voltage and current density curves shown in Fig. 7 and Fig. 8 are applied to the '1-D Lookup Table' block in Simulink. As seen in Fig. 9, Fig. 10, the curves have been incorporated into the program.

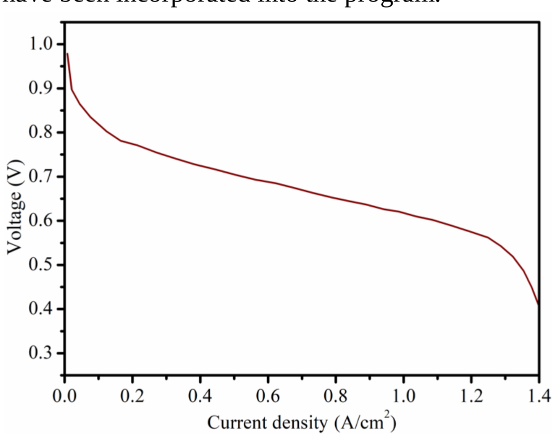

Fig. 9 Simulink current density- voltage curve

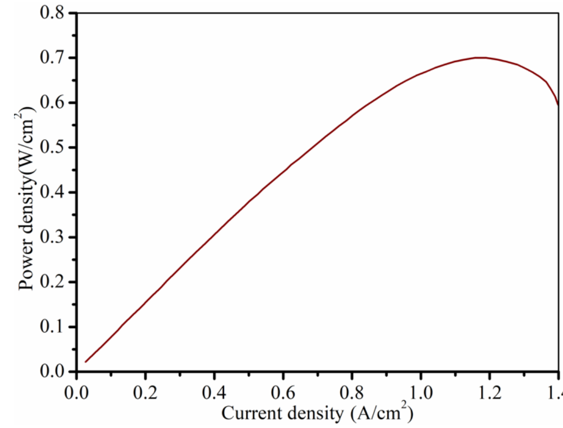

Fig. 10 Simulink current density-power density curve

Since the output value is obtained by dividing the power density by the active area of the fuel cell, it gives the power value produced by a single cell by multiplying the active area of the fuel cell with the block whose output value is power density. Multiplying the found value with the number of cells gives the total power produced instantly by the fuel cell. When the integral of the instantaneous power produced is taken concerning time and converted from seconds to hours, the kWh value produced by the fuel cell in a certain time interval is reached. The operations described in equation 7 are given as equations and the simulink modeling is shown in Fig. 11, the kWh value produced within 15 minutes is calculated in a constant state where the current density is 1.

$$\int[(P_{\text{density}} * A * n)/1000])/1000 \quad (7)$$

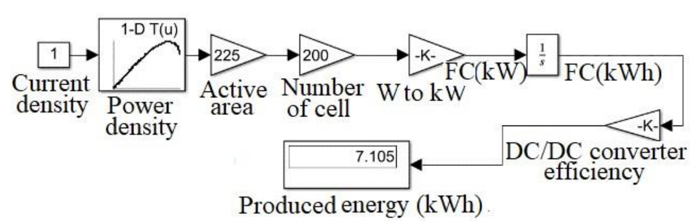

Fig. 11 Fuel cell power generation model

The active area of the PEM fuel cell is determined as 225 cm^2 and the number of cells is determined as 200. It is known that the active area in Honda Clarity FCEV is approximately 300 cm^2 [40]. It is known that the active area of the Toyota Mirai FCEV model is 237 cm^2 and the number of cells is 370. Toyota Mirai weighs approximately 1850 kg [41]. According to this information, the active area of the PEM fuel cell in this vehicle designed as 1500 kg is determined as 225 cm^2 and the number of cells is determined as 200.

2.2.2. Calculation and Modeling of Fuel Cell Efficiency

The PEM fuel cell has a total efficiency of about 80% and an electrical efficiency between 40-60% [42,43]. The efficiency of any energy conversion device is stated as the ratio between energy output and energy input. In a fuel cell, the energy output is the generated electrical energy and the energy input is the enthalpy of hydrogen, which is the high calorific value of hydrogen. When it is considered that all Gibbs free energy can be converted into electrical energy, the maximum efficiency that a fuel cell can achieve, i.e., theoretical efficiency, is calculated as follows [44]. The theoretical efficiency calculation under conditions where the stoichiometric ratio is 1 and at 25 °C temperature is given in Equation 8 [44].

$$\eta_{\text{theoretical}} = \frac{\Delta G}{\Delta H} = \frac{237.34}{286.02} = 0.83 \quad (8)$$

The theoretical efficiency of the fuel cell is found to be 83%. However, the electrical efficiency is lower than this theoretical value owing several losses in fuel cell performance. So, the actual electrical energy efficiency is as stated in Equation 9 [45].

$$\eta_{FC} = \frac{n.F.V_{cell}}{\Delta H} \text{ x } 100\% \quad (9)$$

As shown in Fig. 12, the electrical efficiency of the fuel cell stack differs from the overall net electrical efficiency of all fuel cells. Additionally, it demonstrates that for a fuel cell stack, when all other variables are kept constant, the maximum electrical efficiency is achieved during minimum electrical power draw.

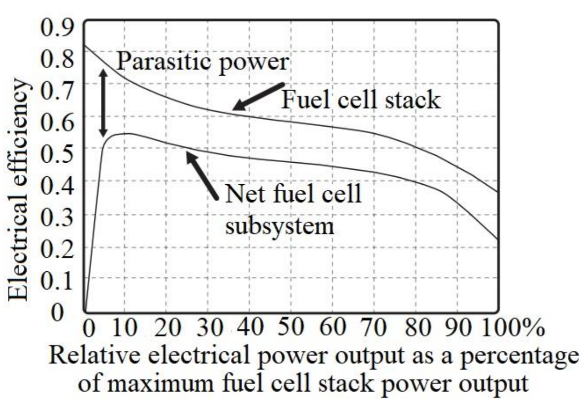

Fig. 12 Electrical efficiency curve [38]

In the modeling shown in Fig. 13, at a constant current density of 0.5, the V_cell value can be taken as the output of the '1-D Lookup Table' block. When the mathematical expression stated in Equation 8 is modeled, the instantaneous electrical efficiency of the fuel cell is achieved.

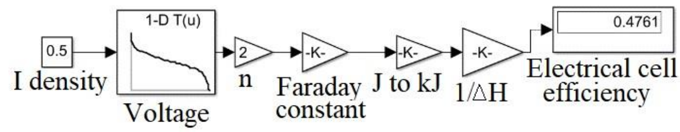

Fig. 13 Fuel cell electrical efficiency modeling

2.3. Control of the Energy System Using Fuzzy Logic Method

Determining a hybrid energy management strategy is the most significant goal for the efficient and stable operation. An appropriate energy management strategy can provide optimum energy distribution. This can be controlled by the fuzzy logic method [46]. The fuzzy logic method is widely used in energy management systems. The fuzzy logic method is based on transferring expert human views to If-Then rules and membership functions, along with many advantages. It has mathematical and natural robustness without requiring a full system model [47].

The goal of energy management is to provide that the fuel cell operates in a high-efficiency range while producing power. Thus, improving efficiency is aimed to improve fuel consumption. However, in some cases, it is desired that the fuel cell produces extra power when the electric vehicle consumes too much power. It is aimed to control this power demand through the energy management system.

Models have been prepared for controlling the power-sharing between fuel cell system using the fuzzy logic method and vehicle battery. The general control modeling of the energy management system is given in Fig. 14.

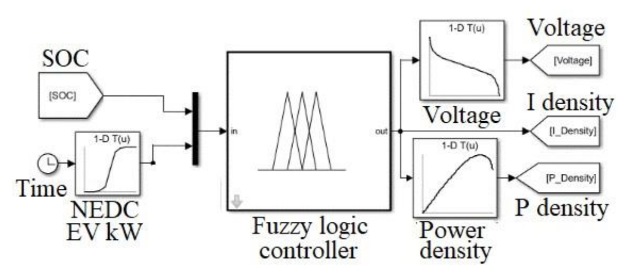

Fig. 14 Simulink model of the energy management system with fuzzy logic

Fuzzy logic data ranges, input and output values have been determined by looking at other studies in the literature. The difference from these studies is that the number of fuzzy inputs and fuzzy outputs has been increased.

There are two input variables and one output variable in the fuzzy logic controller. The input variables are the power demand of the electric motor (EVKW) and battery charge status (SOC). The output variable is the current density. Through this output, the requested power amount from the fuel cell is also determined. As seen in Fig. 15, input variables, rules, and output variables are added to the system control design called ‘Fuzzy Logic Designer’, which is available in Matlab applications.

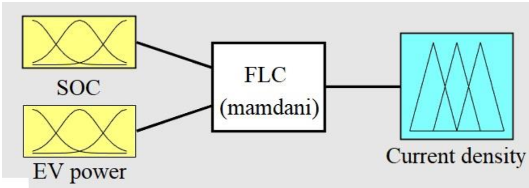

Fig. 15 Fuzzy logic design

The fuzzy controller requests power from the fuel cell according to the EVKW and SOC input membership functions and If-Then rule. At the same time, it controls the fuel cell system against load variations. Determining of the membership function takes into account the operating efficiency and service life of the fuel cell. It also tries to keep the SOC value of the battery within a certain range.

As seen in Fig. 16, the fuzzy logic membership functions for the SOC (State of Charge) value are set as {Very_Low, Low, Medium, High}.

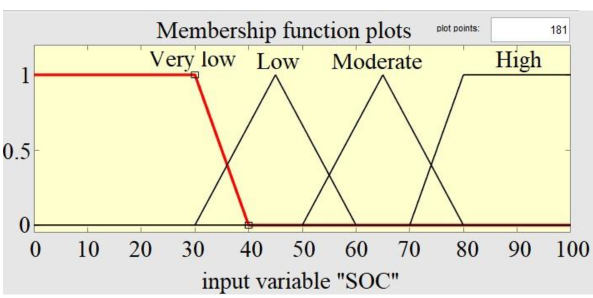

Fig. 16 SOC fuzzy logic membership functions

As shown in Fig. 17, the EVKW (Electric Vehicle Power) fuzzy logic membership functions are defined as {Very_Low (VL), Low (L), Moderate_Low (ML), Moderate (M), Moderate_High (MH), High (H), Very_High (VH), Maximum (M)}.

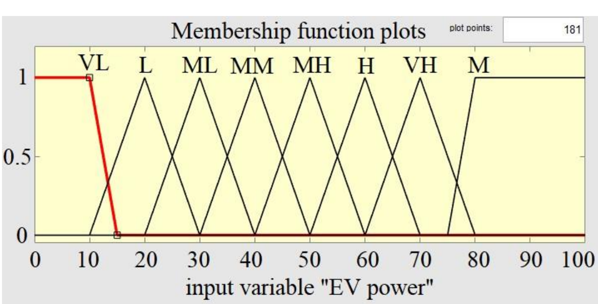

Fig. 17 EVKW fuzzy logic membership functions

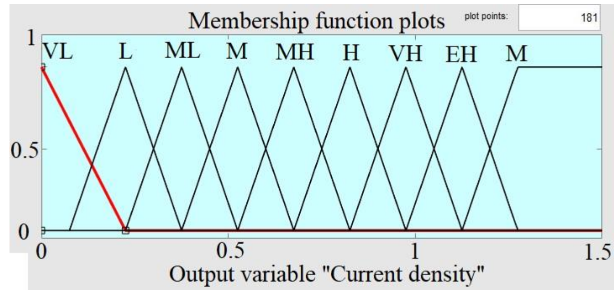

Fig. 18 Fuzzy logic membership functions of current density

As seen in Fig. 18, the fuzzy logic membership functions for Current Density are set as {Very_Low (VL), Low (L), Moderate_Low (ML), Moderate (M), Moderate_High (MH), High (H), Very_High (VH), Extra_High (EH), Maximum (M)}.

Depending on the control strategy, 32 fuzzy logic rules have been formulated. The fuzzy logic rule table is shown in Table 4.

Table 4. Fuzzy Logic Rule Table

Current Density		SOC			
		V_L	L	M	H
EVKW	V_L	M	M_L	L	V_L
	L	M_H	M	M_L	L
	M_L	H	M_H	M	M_L
	M	V_H	H	M_H	M
	M_H	V_H	V_H	H	M_H
	H	E_H	V_H	V_H	H
	V_H	E_H	E_H	V_H	V_H
	MM	MM	E_H	E_H	V_H

V_L: Very Low, L: Low, M_L: Moderate Low, M: Moderate, M_H: Moderate High, H: High, V_H: Very High, E_H: Extra High, MM: Maximum

For example, if the EVKW power request is high and the battery SOC is low, it is aimed that the fuel cell raises the battery SOC level to a certain level and provides high power production. If EVKW power demand is low and battery SOC level is high, the battery supports most of the power and the fuel cell provides less power. By providing energy management for various situations, overcharging and over-discharging of the battery are prevented.

Fuzzy inputs such as High, Low, and Maximum are determined by rules to create fuzzy outputs. These fuzzy outputs provide exact outputs and numerical values of current density by being defuzzified. Thus, with the use of fuel cell power obtained and values such as converter efficiency, feeding the battery, and SOC modeling are completed by extracting the energy used from the battery. The battery SOC modeling is given in Fig. 19.

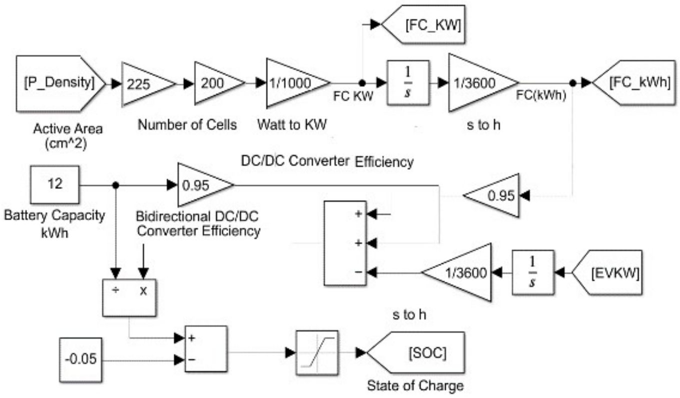

Fig. 19 Power sources, power consumption, and SOC model

2.4. Control of the Energy System Using Classic On-Off Control Strategy

The aim of this energy management, which ensures that fuel cell energy production changes only depending on SOC value, is to increase electricity production of the fuel cell when the SOC value falls below a certain point. The determination of this point is changed depending on which value SOC ends according to the simulation made with the fuzzy logic method for comparison. This control design provided by the 'Relay' Block ensures that the simulation ends at the same SOC value as the system controlled by the fuzzy logic method, allowing designs to be compared. Running the fuel cell at a minimum current density of 0.1 instead of completely shutting it down ensures more accurate system efficiency calculation. The modeling of a classical on-off control strategy is given in Fig. 20.

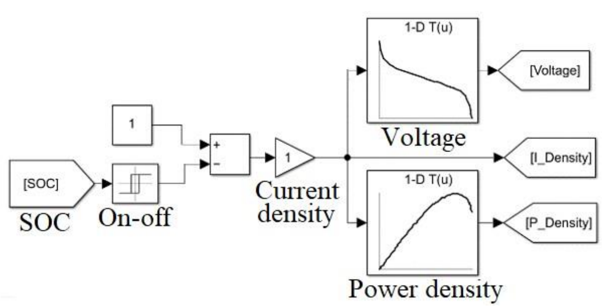

Fig. 20 Classic On-Off control model

In this model, for example, the fuel cell operates at a current density of 0.1 until the SOC value drops from above 90% to below 20%. When the SOC value drops below 20%, the current density value is adjusted according to the determined operating point until it reaches 90%. The operating point of the fuel cell has been manually determined to be equal to the power consumed by the electric vehicle's driving cycle and the energy produced during fuzzy logic control.

2.5.Calculation of Average Fuel Cell Efficiency

The efficiency of the fuel cell varies versus current density at which the cell is operated. As the current density increases, there is a decrease in voltage and efficiency values. The average fuel cell efficiency indicates the percentage efficiency value per unit of energy produced by the fuel cell for the vehicle. The model for calculating the average fuel cell efficiency is given in Fig. 21.

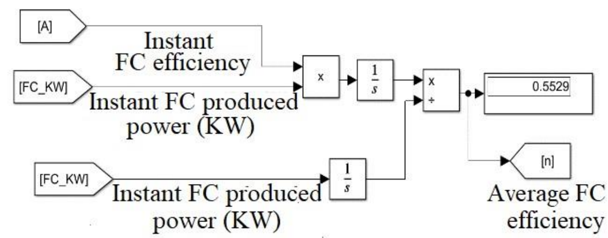

Fig. 21 Model for calculating average fuel cell efficiency

2.6.Calculation of Consumed Hydrogen

The reactants' flow rate at the inlet of a fuel cell must be equal to or higher than the rate at which those reactants are being consumed in the cell. According to the Faraday's law, the rates at which hydrogen and oxygen are consumed and water is produced are determined. The study only considers hydrogen consumption. The consumption value obtained in mol/s is converted to gram/s by the conversion of hydrogen molar mas. The equations by which hydrogen consumption is calculated are given as equations 10 and 11 [38].

$$\dot{N}_{H2} = (I/2F) \tag{10}$$

$$\dot{m}_{H2} = (I/2F).M_{H2} \tag{11}$$

The transformation of these equations 10 and 11 into mathematical modeling is shown in Fig. 22.

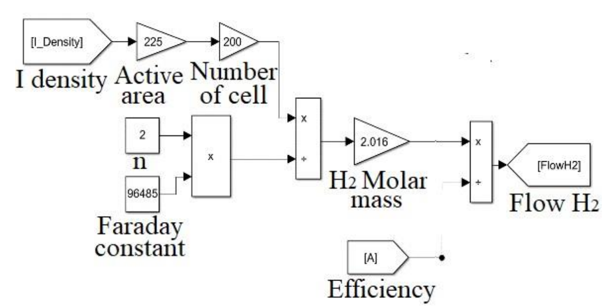

Fig. 22 Hydrogen consumption model

3. Results and Discussion

In the energy management system design made with the fuzzy logic method, data obtained by completing the reference cycle of the vehicle in 55 km as a result of repeating the NEDC driving cycle 5 times in 5900 seconds were evaluated. Thus, simulating consecutive driving cycles shows that the energy management system works correctly. The simulation results for this cycle are given in Fig. 23.

The energy management system design, developed using a fuzzy logic approach, has been rigorously evaluated by collecting data after completing the vehicle's reference cycle of 116.25 km. The data was obtained by repeating the WLTP driving cycle five times within an impressively short span of 9000 seconds. In this simulation, it has been observed that the SOC value does not fall below zero and sufficient level. This also demonstrates that the energy management system is not incorrect. Fig. 24 presents the simulation results for this cycle.

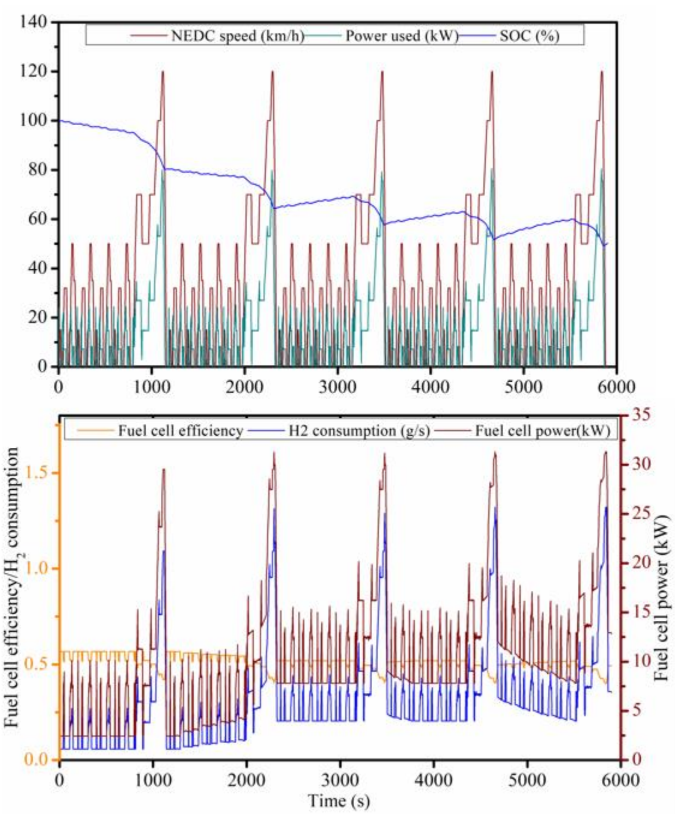

Fig. 23 Graphs obtained from simulation results (Fuzzy Logic-5xNEDC)

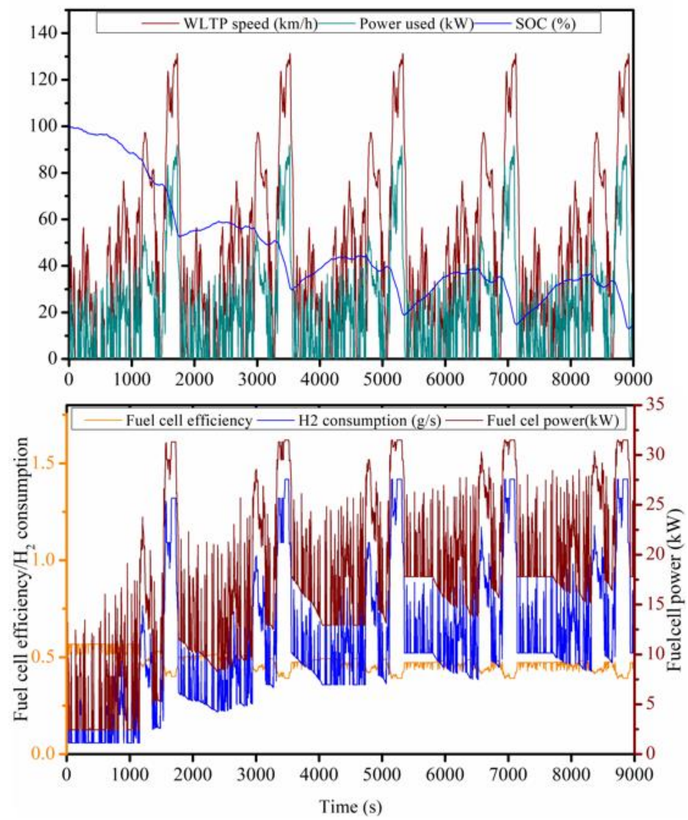

Fig. 24 Graphs obtained from simulation results (Fuzzy Logic-5xWLTP)

The energy management system's effectiveness can be seen by analyzing the data obtained by running the vehicle through its reference cycle in 55 km after performing the NEDC driving cycle five times in 5900 seconds. This evaluation was done using the traditional on-off control strategy. Fig. 25 shows the simulation results for this cycle.

Evaluating the data obtained by completing the vehicle's reference cycle in 116.25 km as a result of repeating the WLTP driving cycle 5 times in 9000 seconds in the energy management system design made with the traditional on-off control strategy demonstrates that the energy management system works properly because SOC is never below the zero. Fig. 26 depicts the simulation findings for this cycle.

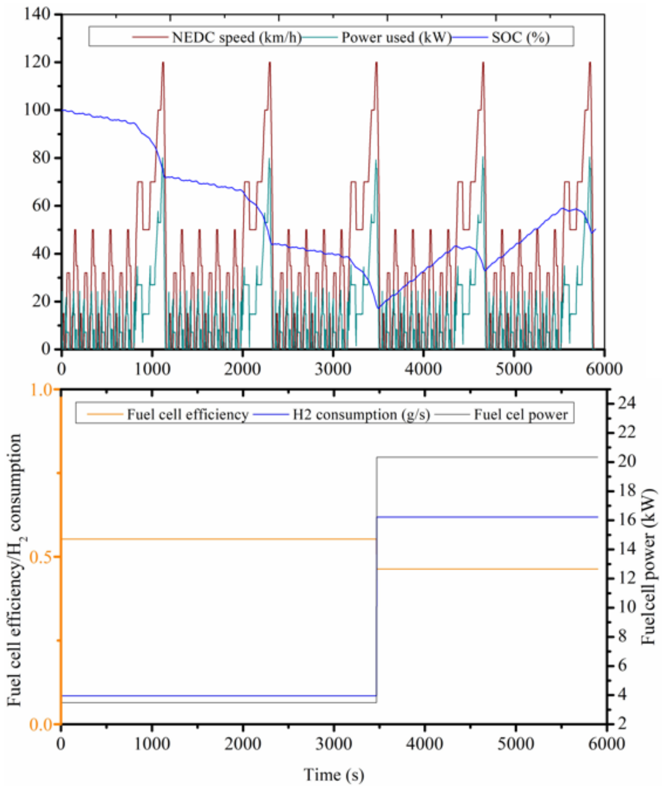

Fig. 25 Graphs obtained from simulation results (Conventional On-Off-5xNEDC)

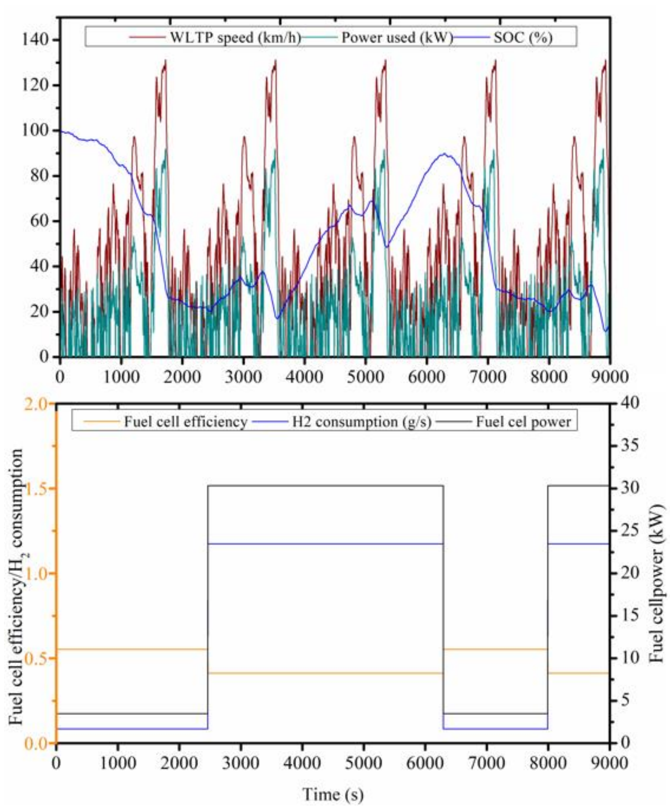

Fig. 26 Graphs obtained from simulation results (Conventional On-Off-5xWLTP)

When the battery SOC value is 100% and its capacity is 12 kWh, average fuel cell efficiencies and energy values produced by the fuel cell are determined. In NEDC driving cycle conditions, 48.81% efficiency was obtained with the fuzzy logic method and 48.12% efficiency was obtained with the on-off control strategy. The average fuel cell efficiency under different driving cycle conditions is shown in Fig. 27.

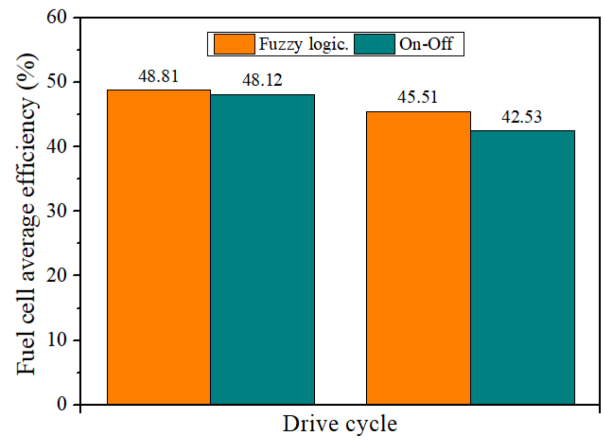

Fig. 27 Fuel cell efficiency values under different driving cycle conditions, using fuzzy logic and On-Off control strategy

4. Conclusions

In this study, two different energy management control strategies of a hybrid energy system of a vehicle with a fuel cell and battery were compared. The aim of the strategies is to operate the fuel cell in the high-efficiency range as much as possible according to the battery SOC status and the power consumed by the vehicle. In addition, it was aimed to meet this need when the power demand increased. Testing this targeted energy management, in the long run, has shown the accuracy of energy management by adding originality to the study. As a result of repeating the NEDC driving cycle 5 times with fuzzy logic control, average fuel cell efficiency was observed as 48.81%, and fuel cell efficiency was observed as 45.51% as a result of repeating the WLTP driving cycle 5 times. As a result of repeating the NEDC driving cycle 5 times with classical on-off control, fuel cell efficiency was observed as 48.12% and fuel cell efficiency was observed as 44.82% as a result of repeating the WLTP driving cycle 5 times. It has been observed that fuzzy logic control is 11.6% better than classical on-off control in total hydrogen consumption in two-cycle processes.

Nomenclature

A	Fuel cell active area (cm^2)
A_f	Vehicle Cross-Sectional Area (m^2)
c_d	Aerodynamic Resistance Coefficient
$EVKW$	Power demand of the electric motor
F_a	Aerodynamic resistance
F_{ac}	Acceleration resistance

FCEV	Fuel cell electric vehicle
F_{gr}	Slope resistance
F_r	Rolling resistance force
FL	Fuzzy Logic
I	Current (A)
ICE	Internal combustion engines
IEA	International Energy Agency
i	Current Density (A/cm^2)
i_d	Differential reduction ratio
J_a	Axle moment of inertia
J_m	Motor moment of inertia
J_t	Total moment of inertia
$\dot{m}_{H2}$	Hydrogen flow (gram/s)
$\dot{M}_{H2}$	Hydrogen molar mass
n	Number of cells
η_d	Differential efficiency
$\eta_{theoretical}$	Fuel cell theoric efficiency
η_{FC}	Fuel cell efficiency
NEDC	New European Driving Cycle
$\dot{N}_{H2}$	Hydrogen flow (mol/s)
P	Power (kW)
$P_{density}$	Power Density (W/cm^2)
PEM	Proton Exchange Membran
PEMFCEV	PEM fuel cell electric vehicle
SOC	State of charge
T_m	Motor Torque
V	Voltage (V)
V_{cell}	Instantaneous cell voltage
ω_m	Angular speed of motor output shaft
WLTP	Worldwide Harmonized Light Vehicles Test Procedure
T_{load}	Sum of resistance torques
ρ	Air Density (kg/m^3)
ΔG	The change in energy available for doing work
ΔH	Enthalpy of reaction

Conflict of Interest Statement

The author must declare that there is no conflict of interest in the study.

CRediT Author Statement

Nurettin Mert Boyacıoğlu: Conceptualization, Investigation, Writing-original draft, Writing-original draft.
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Mustafa Batar: Methodology.
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Hamit Solmaz: Supervision, Writing-review & editing.

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