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Fuel Consumption Reduction of a Fuel-Cell Hybrid vehicle Using Look-Ahead Fuzzy Control Approach

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ABSTRACT

Environmental pollution and reduction of fossil fuel resources can be considered as the most important challenges for human society in the recent years. The results of previous studies show that the main consumer of fossil fuels and, consequently, most of the air pollutants, is related to the transportation industry and especially cars. The increasing growth of vehicles, the increase in traffic and the decrease in the average speed of inner-city vehicles have led to a sharp increase in fuel consumption. To address this problem, automakers have proposed the development and commercialization of hybrid vehicles as an alternative to internal combustion vehicles. In this paper, the design of an energy management system in a fuel-cell hybrid vehicle based on the look-ahead fuzzy control is considered. The preparation of fuzzy rules and the design of membership functions is based on the fuel efficiency curve of the fuel-cell. In look-ahead fuzzy control, the ahead conditions of the vehicle are the basis for decision in terms of slope and speed limit due to path curves as well as battery charge level. The fuzzy controller will determine the on or off status of the fuel-cell, as well as the power required. The motion of the fuel-cell hybrid vehicle on a real road is simulated and the performance of the proposed look-ahead controller is compared with the base controller (thermostatic method). The simulation results show that using the proposed approach can reduce the fuel consumption of the fuel-cell hybrid vehicle as well as travel time.

1. Introduction

Greenhouse gas sources are classified into three main groups: Power plants (the most important centralized source of greenhouse gas emissions), Transportation industry (the use of cars, trucks and buses for passenger and freight transportation) and oil production complexes. The rank of China is first and Iran is tenth in greenhouse gas emissions [1].

A fuel-cell or hybrid electric vehicle (FCEV) is a type of hydrogen vehicle which uses a fuel-cell to generate electricity and run an electric motor. Basically, a hydrogen fuel-cell acts like a battery and generates electricity, but instead of being recharged like a battery, its tank must be filled with hydrogen. According to Figure 1, all fuel-cells consist of three parts: electrolyte, the anode and the cathode. In Figure 1, the type of electrolyte is written in the middle row, which is

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specified according to the type of electrolyte, the operating temperature of the fuel-cell and the type of reaction according to this figure. For instance, in a solid oxide fuel-cell, the operating temperature is between 900 and 1000 ° C and the reaction is $H_2 + CO + O_2 \rightarrow CO_2 + H_2O$.

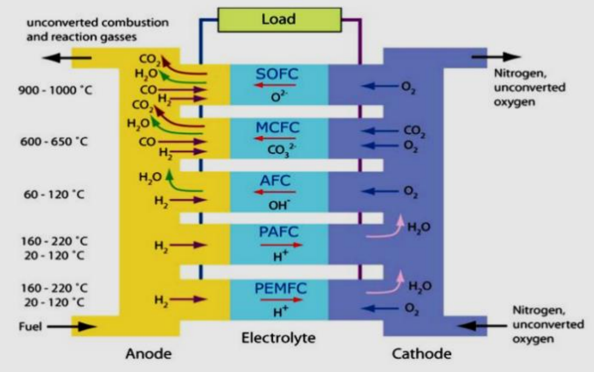
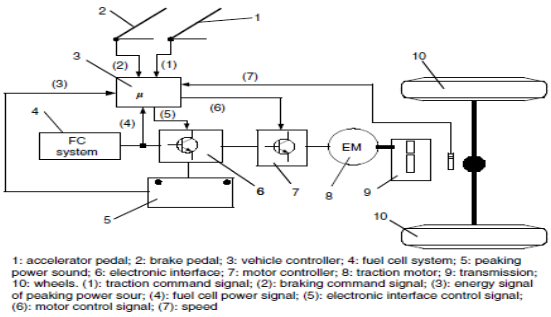


Figure 1. General structure and reactions performed in different types of fuel-cell [2].

The main components of the propulsion system of a fuel-cell hybrid vehicle are shown in Figure 2 [3, 4]. This system basically includes the fuel-cell as the primary power source, maximum power source (electric battery), electric motor assembly (motor and its controller), vehicle controller and the electronic interface between the fuel-cell system and the maximum power source [3]. The vehicle controller controls the power (or torque) of the electric motor, as well as the share of the fuel-cell and battery assembly in supplying the power required by the electric motor, according to the power (or torque) command received from the accelerator or brake pedal, as well as other operating signals. When power is in high demand, for example in fast acceleration, both the fuel-cell system and the battery pack provide the power required by the electric motor.

When braking, the electric motor acts as a generator, converting some of the braking energy into electrical energy and storing it in the battery pack for the essential time. Also, the battery pack is able to recover and charge the energy of the fuel-cell system when the power required by the electric motor is less than nominal power of the fuel-cell system. The general purpose of this paper is to design a suitable controller for a polymer electrolyte fuel-cell hybrid vehicle with the aim of reducing fuel consumption.



1: accelerator pedal; 2: brake pedal; 3: vehicle controller; 4: fuel cell system; 5: peaking power sound; 6: electronic interface; 7: motor controller; 8: traction motor; 9: transmission; 10: wheels. (1): traction command signal; (2): braking command signal; (3): energy signal of peaking power sour; (4): fuel cell power signal; (5): electronic interface control signal; (6): motor control signal; (7): speed

Figure 2. General structure of the propulsion system of a fuel-cell hybrid vehicle [3].

Although fuel-cell has recently emerged as one of the ways to generate electricity, its history dates back to the nineteenth century and research of sir William Grove who is an English scientist researcher. He built the first fuel-cell in 1839, following the example of the water electrolysis reaction, in reverse action and in the presence of a platinum catalyst. The term fuel-cell was coined in 1889 by Ludvik Mend and Charles Linger. They built a fuel-cell that consumed air and coal fuel. Numerous attempts were made in the early twentieth century to develop a fuel-cell, none of which were successful due to a lack of scientific understanding of the problem. The interest in using fuel-cells waned with the discovery of cheap fossil fuels and the prevalence of steam engines [5]. New research in this field began in the early 1960s with the culmination of activities related to human conquest of space. The NASA Research Center sought to power manned spaceflight. After rejecting the available options such as battery (due to heaviness), solar energy (due to high cost) and nuclear energy (due to high risk), NASA chose fuel-cell system. Research in this field led to the manufacture of polymer fuel-cell by General Electric Company. The United States used fuel-cell technology in the Gemini space program, which was the first commercial application of this system.

Since 1970, fuel-cell technology has been developed for ground systems. The oil embargo from 1973 to 1979 intensified efforts by US officials and researchers to develop this technology to cut dependence on oil imports. During the 1980s, researchers focused on providing the materials needed, choosing the right fuel, and reducing costs. Also, the first commercial product for car power was introduced in 1993 by Blard Company [6]. Looking-ahead (prospective) control is one of the newest approaches in reducing fuel consumption, which in this section will review related articles. Although access to complete driving information for the future is unrealistic, it is possible to access detailed information about distance beyond the driver's sight (using new technologies such as Global Positioning System (GPS) and traffic flow information systems) [7]. GPS can be used in conjunction with geographic information systems (GIS) to access fixed information such as road slopes [8]. Simple telematics devices that are able to communicate with other vehicles or road infrastructure can provide dynamic information such as leading traffic speeds [9]. The integration of this device with the power management controller enables the vehicle to achieve more fuel savings by previewing the driving pattern and path information. The amount of fuel savings used by such information depends entirely on the performance of the predictive power management controller. This section is devoted to reviewing existing predictive controllers.

Johnson et al. [10] have presented the ability to save fuel according to different levels of access to driving information. At the lowest level, information about the driving pattern, means highway driving, is modeled with a homogeneous Markov driver model that demands power and speed as state variables. The SDP-based Infinity Horizon control approach is used for this action. At the highest level, information on road slope and vehicle speed is modeled with the Markov heterogeneous driver, which is transferred from one mode with speed and acceleration modes to another. In this case, a finite horizon SDP-based control approach is used. The main drawback is that the controllers studied are far from the actual implementation.

Beck et al. [11] have demonstrated the use of DP in predictive power management for automobiles. Their main focus is on demonstrating how to overcome the challenges of adopting DP as a power management algorithm. Therefore, a simple movement is considered in which the vehicle travels on a known route (due to the use of GPS) and at a constant speed. To solve the optimization problem at each time step, DP is applied by following the forward horizon method. In general, using DP to solve the power management issue consumes a lot of computational time due to the discretization of the state space. This research explains computational time reduction tools using methods such as constraining the SOC search space and resizing the SOC network. However, the time taken for a full trip is still very long. Fuzzy logic-based predictive controllers are notable for their fast computation and resilience to changing driving circumstances. Adaptive fuzzy controller developed by Rajagopalan et al. [12] using GPS data on traffic information in the form of speed information as well as altitude information along a looking-ahead window, the electrical system is prepared for future conditions such as heavy traffic, etc. This controller not only increases fuel efficiency, but also reduces greenhouse gas emissions, and the simulation results show a good compromise between them.

Among all the methods, ECMS is a concept that is widely used to develop predictive controllers, because when this method is well designed, it has fast computations as well as near-optimal performance. The overall equivalent parameters that ensure minimum fuel consumption and final charge maintenance cannot be defined for a trip with complex driving conditions (such as the sequence of highway cycles). So, equivalent parameters must be set in motion. In the predictive controller, Mossardo et al. [13] set the equivalent coefficients for the current driving style. However, the performance of the algorithm is indirectly influenced by external factors such as nonlinear optimizer performance. Embol and Gozella [14] obtained the equivalent coefficient as a function of the deviation of SOC from a reference surface. Ergo, this method is mainly based on defining the SOC reference path for each trip. An approximate driving cycle with GPS tracking and vehicle information is built into each section of the road. Using this driving cycle, positive and negative power changes during the trip are calculated. Using this information, the SOC reference path is constructed using a quadratic optimization strategy to maximize recovery energy uptake and maintain minimal SOC changes. For driving cycles in which driver demand dominates road changes through driving style, the SOC reference path must be upgraded on the move to achieve proper final charge retention. In a similar work, Zhang et al. [15] developed a ground-based ECMS that uses the driver's future demand (as predicted by GPS-derived road data). The main contribution of this study is the development of a power management strategy that can manage driving situations (which largely fluctuate the SOC).

According to the reviewed sources, it can be said that the fuzzy looking-ahead control approach has played an important role in reducing the fuel consumption of conventional and electric hybrid vehicles, but so far it has not been used in the control of fuel-cell hybrid vehicles.

2. Control strategies

The control strategy is a steering role that is already embedded in the vehicle's central controller and manages the performance of the elements. The vehicle controller receives two operating signals, including the driver's command and feedback from the propulsion elements, based on which it decides how to use the appropriate operating modes. Obviously, the performance of the driving forces depends mainly on how it is controlled and the quality of the control strategy plays a decisive role. Existing control strategies can be used to drive vehicles with different requirements.

2.1. Thermostatic control

In the thermostatic control according to Figure 3, two important levels are considered for the state of charge (SOC). The lower limit of the SOC is the minimum charge and the upper limit of the charge state is the maximum charge. When the SOC reaches a low level of charge, the use of the battery stops and the fuel-cell will be the main source for energy consumption. This process continues until the SOC reaches the top of the charge status, after which the use of the battery will start and this cycle will be repeated throughout the route.

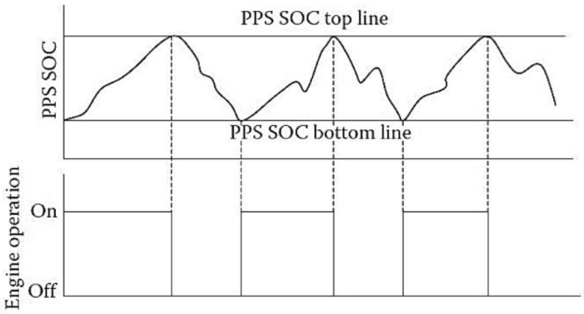


Figure 3. How the fuel-cell thermostatic control strategy works [3].

During periods when the fuel-cell is on, the controller aims to bring the SOC to the maximum level defined for it. When the battery charge is at its maximum, the fuel-cell is switched off and the electric motor will run only on the power received from the battery. When the battery charge reaches its minimum defined level, the fuel-cell is switched on again to maximize the battery charge. This control method uses the battery power as the main power supply, and the fuel-cell will either operate at its optimum operating position to charge the battery or turn it off. It should be noted that in this control method, the battery must have enough power to meet the required power of the car in all conditions. In this way, considering the maximum and minimum amount for charging the battery, the controller decides when to turn on the fuel-cell and when to turn it off.

2.2. Design of Fuzzy look-ahead controller

The main idea proposed in this paper is to use a look-ahead control approach in the energy management of a fuel-cell hybrid vehicle. In this approach, the slope information of the ahead path is used in the controller decision. In fact, the look-ahead controller, before reaching the next section of the route, takes compensatory measures so that the car travels to the next section of the path with less energy consumption. The prerequisite for correct decision-making of look-ahead control is access to forward path information, which is assumed to be available to the controller through geographical maps in the form of a database in this paper. To implement the look-ahead approach in this paper, a fuzzy controller as shown in Figure 8 is used. This controller has three inputs and two outputs. Inputs include: slope changes, SOC, and total requested power. The controller outputs are: the power requested from the fuel-cell and the desired speed changes.

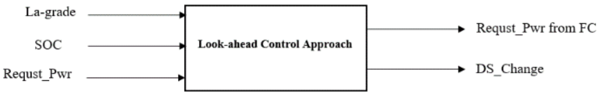


Figure 4. Schematic of a look-ahead controller.

The designed membership functions of the look-ahead fuzzy system include: L in the low sense, M in the medium sense, H in the high sense, VH in the very high sense, and VL in the very low sense. The membership functions used for the input and output variables of the look-ahead fuzzy controller are shown in Figures 5 to 9.

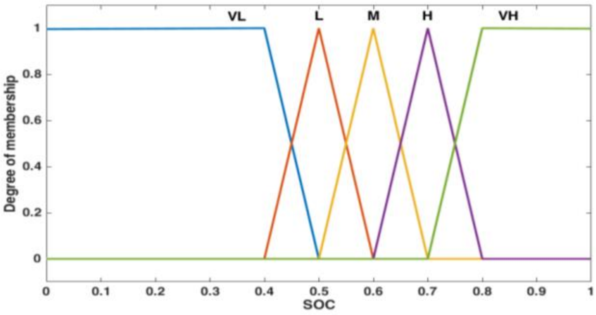


Figure 5. Membership functions for the battery SOC.

In the definition of membership functions in Figures 6 to 9, each is indicated by a letter, which are: NH in the high negative sense, NL in the low negative sense, Z in the zero sense, PL in the low positive, and PH in the high positive sense.

The proposed fuzzy system type is Mamdani and the three-dimensional surfaces of the fuzzy rules are shown in Figures 11 to 13.

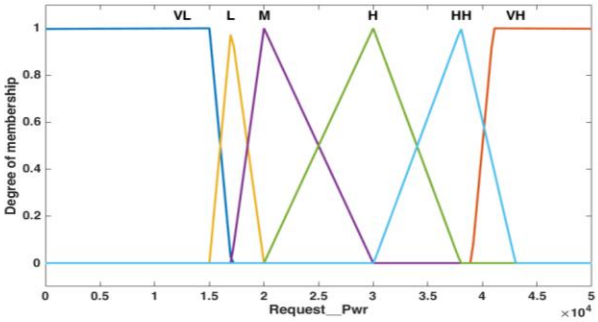


Figure 6. Membership Functions for total requested power.

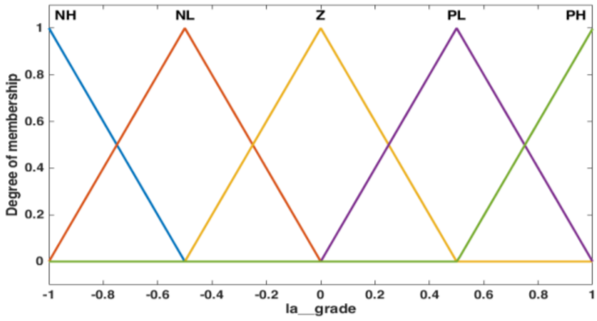


Figure 7. Membership functions for slope changes.

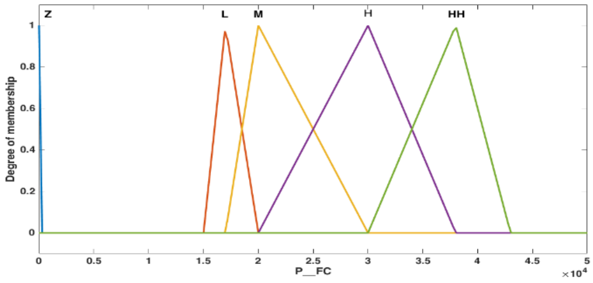


Figure 8. Membership Functions for the amount of power requested from the fuel-cell.

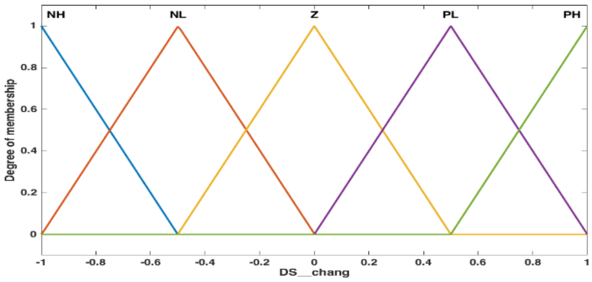


Figure 9. Membership functions for optimal speed change.

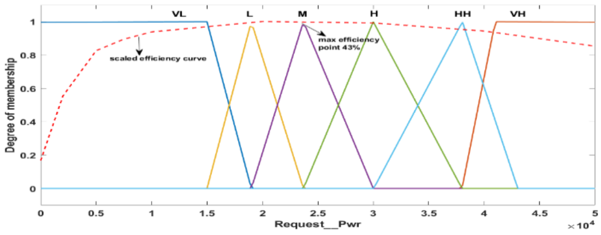


Figure 10. Designing the requested power membership functions based on the fuel-cell efficiency curve.

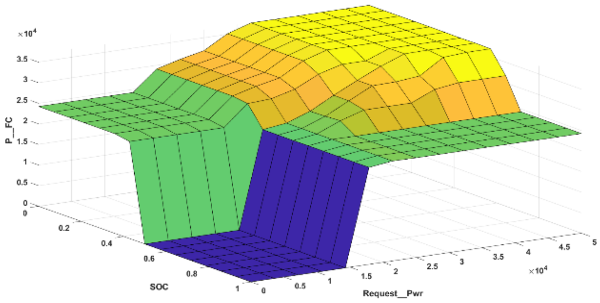


Figure 11. Fuzzy control surface 1 (input: total requested power and SOC, output: required power).

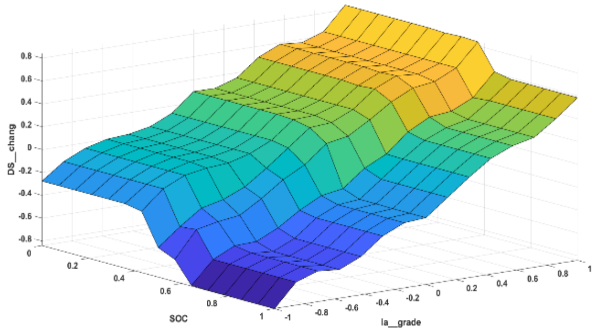


Figure 12. Fuzzy control surface 2 (input: slope and requested power changes, output of desired speed changes).

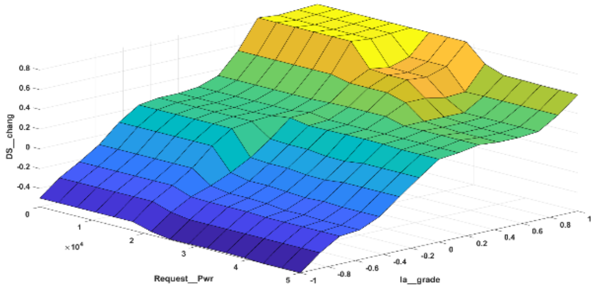


Figure 13. Fuzzy control surface 3 (input: slope and requested power changes, output: optimal speed changes).

The membership functions of the total requested power and the requested power from the fuel-cell are designed by considering the fuel-cell efficiency curve (as shown in Figure 10). According to Figure 10, the maximum fuel efficiency is 43% at 23.7 kW which corresponds to the medium membership function (M). The selection of the zero (Z) membership function in

Figure 10 indicates the controller's decision to turn off the fuel-cell.

According to Figure 11, in situations which the SOC is very high or in situations which the total power demand is very low, the power demand from the fuel-cell is zero and the fuel-cell is off. Figure 11 indicates the effect of Slope changes (la_grade) and battery charge level (SOC) changes on the desired speed changes (DS_Change). As shown in Figure 12, as the slope of the ahead path increases (or decreases), the desired velocity changes also increase (or decrease). Therefore, it can be said that the car has increased its speed before reaching the uphill and can have better power management when crossing it. According to Figure 12, when the charge level is low, the DS_Change is higher than when the charge level is high. On the other hand, considering that the M membership function represents the most efficient fuel-cell working points, in designing the rules, an attempt has been made to use this membership function as much as possible.

Figure 13 shows the effect of changes in the slope of the ahead path (la_grade) and the total requested power (Request_Pwr) on changes in the desired speed (DS_Change). As shown in Figure 13, as the slope of the path ahead increases (or decreases), the desired speed changes also increase (or decrease). Therefore, if the slope of the ahead road is reduced, the desired speed of the car (and consequently the requested power) will also be reduced, which can be said that this will reduce the braking effort of the car and therefore the fuel consumption to produce this excess power will be reduced. According to Figure 13, when the total requested power is low, the DS_Change is higher than when the charge level is high. This idea aimed to move the fuel-cell operating point toward the most efficient membership function (M).

3. Simulation of a fuel-cell hybrid vehicle in a real path

The road on which is considered to simulate the vehicle motion is the Yasuj-Lordegan route with a distance of 150 km, which can be seen in the diagram of the slope changes of this route in Figure 3. Slope information is available from maps. The maximum slope of the path is 14%.

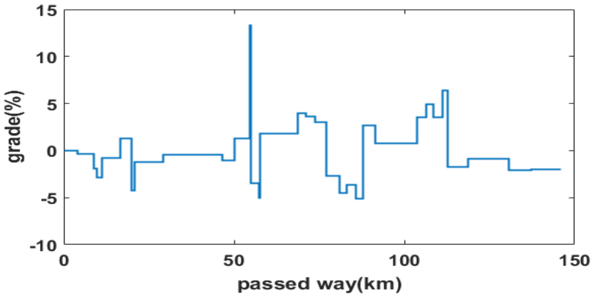


Figure 14. Changes in the slope of the Yasuj-Lordegan path.

According to Figure 15, the vehicle model built in Simulink environment using the advisor toolbox. The parameters used in the simulation model are shown in Table 1.

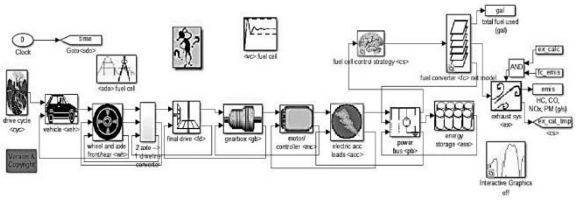


Figure 15. The simulation model of a fuel-cell hybrid vehicle in Simulink environment.

Table 1. Parameters of the fuel-cell vehicle.

Electric motor mass	kg 91	**Vehicle mass**	592 kg
Electric motor Peak eff	92%	**Fuel Converter**	300 kg
Electric Motor-max Power	75 kW	**Fuel cell-max Power**	50 kW
Transmission Mass	50 kg	**Fuel Cell-Peak eff**	43%
Transmission peak eff	97%	**Battery Pack -mass**	275 kg
Cargo Mass	136 kg	**Total Mass**	1444 kg

In the thermostatic control approach, the decision is made solely on the basis of the battery charge level and does not take into account the slope of the road. This is evident at km 53 of the route, which, as shown in Figure 16. The path has sever uphill in this location, but the fuel-cell is still off and the battery charge level decreases at a higher rate. The power produced by the battery is not enough to maintain the vehicle constant speed at this point. As a result, the speed of the car has decreased considerably.

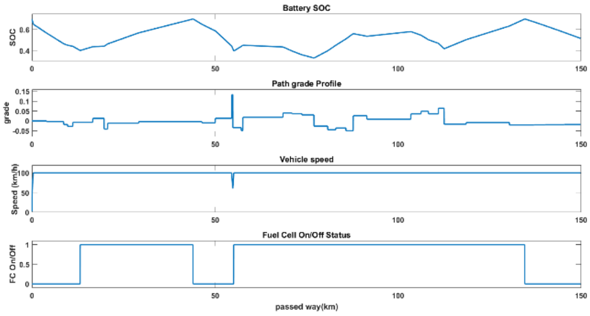


Figure 16. Simulation results of thermostatic control approach.

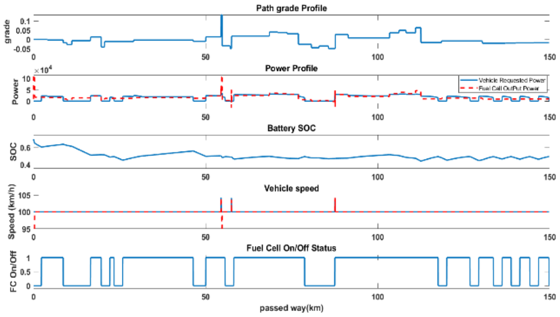


Figure 17. Results of simulation of the look-ahead fuzzy control approach.

The simulation results of the look-ahead fuzzy control approach are shown in Figure 17. The first diagram in Figure 17 shows the road slope changes. The second diagram shows two power profiles. The first profile, shown with a continuous line, shows the power required by the vehicle to move on the road considering the instantaneous path slope according to the first diagram in Figure 17 and with an optimum speed of 100 ± 10 km/h. The second profile, indicated by the dashed line, represents the output power of the fuel-cell, or in other words, the fuzzy controller output command. The third diagram in Figure 17 shows the changes in the battery charge level, the fourth diagram shows the changes in the desired speed and the fifth diagram shows the on and off condition of the fuel-cell.

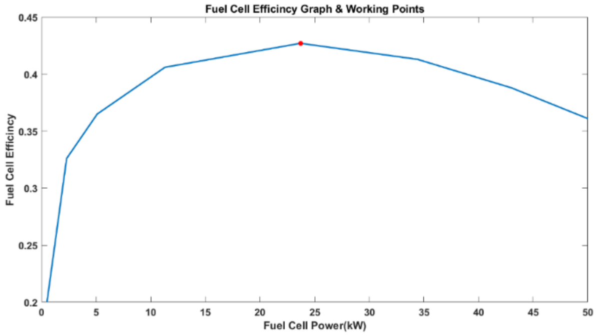
The look-ahead fuzzy controller has increased the vehicle's desired speed before reaching the uphill, thereby maintaining the fuel-cell operating point closer to the M membership function as it crosses the uphill. These conditions can be seen at km 53, 55 and 85 of the paths. On the other hand, this controller reduces the desired speed of the car before reaching the downhill, and as a result, the total requested power before reaching the downhill is reduced. This prevents excess power generation with lower efficiency conditions. These conditions can be seen at km 54 of the route.

2.1.1. Abbreviations and Acronyms

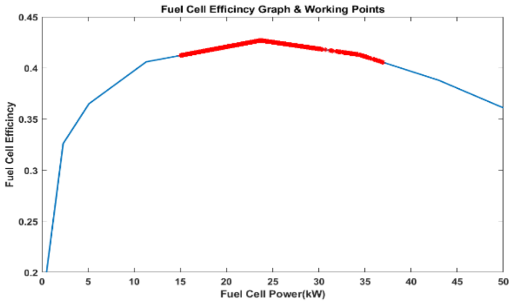
Define abbreviations and acronyms the first time they are used in the text, even after they have been defined in the abstract. Abbreviations such as ASME, SI, MKS, CGS, sc, dc, and rms do not have to be defined. Do not use abbreviations in the title or headings unless they are unavoidable.

4. Compare the performance of the controllers

In order to better understand the performance of the designed controllers, in this section, the fuel-cell operating points of the two controllers are reviewed in Figure 18. According to Figure 18, in thermostatic controller, the fuel-cell is switched on and off at only one point. In Figure 18 (A), the operating point is 23700 watts (maximum efficiency point). Fuel-cell operating points in look-ahead fuzzy controllers are shown in Figure 18 (B). In this diagram, the fuel-cell operation is not a single point and a relatively high efficiency interval (95 to 100% of the maximum efficiency) is considered for the authorized fuel-cell operating points.



A. Thermostatic controller (working point 23700 watts



B. Look-ahead controller

Figure 18. Comparison of fuel-cell working points in the designed controller’s performance.

Table 2. Comparison of the results of control approaches.

Control Approach	Hydrogen fuel consumption (lit)	Final battery charge	equivalent hydrogen Fuel consumption (lit)	equivalent gasoline Fuel consumption (lit)	time of travel (sec)	How long the fuel-cell is on
Thermostatic (power:23700watts)	104.3	53.4	110.9	7.51	5406	4035
Fuzzy Look-ahead	102.21	59.2	106.5	7.19	5354	3415

Although the fuel-cell in the thermostatic control approach in Figure 18 (A), at first glance, operates only at the maximum efficiency point, but according to Table 2, its operating time at this point is longer. According to Table 2, it can be said that if the fuel-cell operating points are moved to the right of the diagram (higher power), then the time of fuel-cell on will be decreased. Reducing the fuel-cell on time will reduce hydrogen fuel consumption. On the other hand, this (increasing the power of the fuel-cell operating point) reduces the efficiency of the operating point and can increase fuel consumption. Therefore, the importance of designing a look-ahead controller can be seen in the fact that the operating point of the fuel-cell is managed in a way that increases the power of the operating point to such an extent that fuel consumption is reduced.

Depending on the different performance of the controllers, the final battery charge at the end of the path will be different for each of them. To better compare fuel consumption, a parameter called hydrogen equivalent fuel consumption has been used. To calculate the equivalent hydrogen fuel consumption, the vehicle will use its fuel consumption to bring the battery charge level to the initial charge level without any movement. The amount of gasoline fuel consumption is more common in cars comparison. Therefore, the equivalent fuel consumption of gasoline is also calculated in Table 2. In other words, the energy per liter of gasoline is 42,600 joules per gram and the density of gasoline is 749 grams per liter. As a result, gasoline has 31,907,400 joules per liter of energy. The energy per liter of hydrogen is 120,000 joules per gram and the density of hydrogen is 18

grams per liter. As a result, hydrogen has 2,160,000 joules per liter of energy. Therefore, it can be said that the energy of 14.77 liters of hydrogen is equivalent to the energy of one liter of gasoline.

5. Sensitivity analysis of look-ahead fuzzy controller coefficients

In the next step, tried to optimize the internal structure of the look-ahead control, means the parameters of the look-ahead window length (n_2), distance between the start of window distance and the current point (n_1) and the gain coefficient of velocity changes (k_v). At first glance, it can be analyzed that the higher the instantaneous velocity, the larger $n_1$must be selected. In other words, the look-ahead window starts at a greater distance from the current position so that the previous control commands do not affect the look-ahead window. Also, the higher the information variance of the look-ahead window samples, the smaller n_2 should be considered, due to the fact that if the scatter of window point information is high, the average of this information may not well reflect the initial points of the window (for which the fuzzy controller is to decide). In fact, both parameters n_1 and n_2 should change dynamically based on the instantaneous speed and variance of the look-ahead window information. If the car increases its speed before an uphill, it can be said that the fuel energy has led to an increase in the car's kinetic energy, which decreases with the car entering the uphill. In other words, if we define a kinetic energy battery for the car, the look-ahead controller seeks to use this kinetic energy battery in the movement of the car. The lower the amplitude coefficient of velocity changes (k_v), the lower the considered kinetic energy battery capacity. On the other hand, a high coefficient of amplitude changes of speed (k_v) leads to an excessive increase in speed and kinetic energy of the car, which must eventually be lost by the brakes and converted into heat. In this case study, these three parameters were changed over a period of time, and the best values were selected that produced less equivalent fuel consumption. The results of the initial study examining the changes in these parameters are shown in Figures 19 to 21.

Table 3. The effect of control coefficients on equivalent hydrogen fuel consumption

Coefficient	Effect percentage
n_1	0.6
n_2	0.15
k_v	3.41

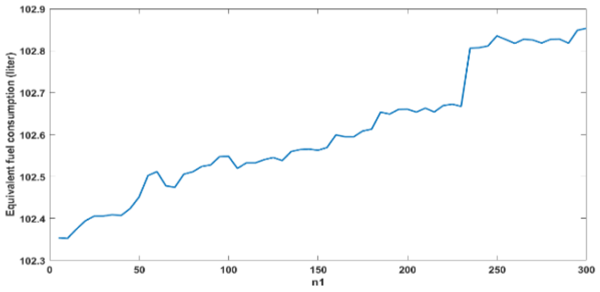


Figure 19. Equivalent Fuel changes to $\boldsymbol{n_1}$while $\boldsymbol{n_2}$ and $\boldsymbol{k_v}$ are constant.

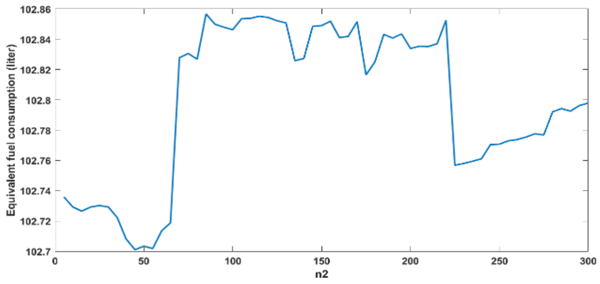


Figure 20. Equivalent Fuel changes to $\boldsymbol{n_2}$while $\boldsymbol{n_1}$ and $\boldsymbol{k_v}$ are constant.

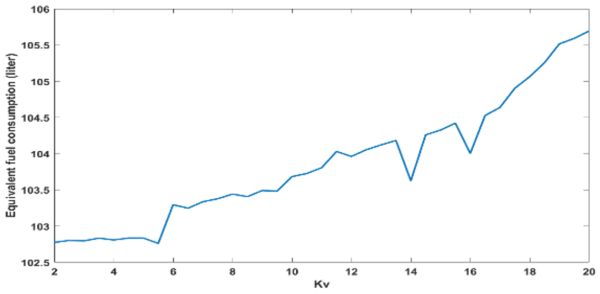


Figure 21. Equivalent Fuel changes to $\boldsymbol{k_v}$ while $\boldsymbol{n_1}$ and $\boldsymbol{n_2}$ are constant.

The effect of look-ahead fuzzy control coefficients on equivalent hydrogen fuel consumption is shown in Table 3, which the greatest effect belonging to the amplitude coefficient of velocity changes (k_v).

6. Conclusion

In this paper, the thermostatic controller is simulated as a basic method in the control of fuel-cell hybrid vehicles in which the fuel-cell works in its best efficient operating point. The simulation results showed that the look-ahead controller reduced fuel consumption by 3.96% and the travel time by 0.96% compared to the thermostatic controller.

If the car increases its speed before an uphill, it can be said that the fuel energy has led to an increase in the car's kinetic energy, which decreases when the car enters the uphill. In other words, if we define a kinetic energy battery for the car, the look-ahead controller seeks to use this kinetic energy battery in the movement of the car.

On the other hand, the look-ahead controller has been able to reduce the travel time by 0.87% by increasing the desired speed before the uphill. The internal structure of the look-ahead unit was also studied to improve the performance of fuzzy look-ahead control and the effect of the parameters of look-ahead window length (n_2), window start distance to the current point (n_1) and speed amplitude coefficient (k_v) in reducing hydrogen equivalent fuel consumption were studied.

The influence of n_2, n_1 and k_v parameters on the fuel consumption of hydrogen equivalent for moving the studied vehicle in the simulated 150 km distance are equal to 0.15%, 0.6% and 3.41%, respectively.

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