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Analysis of the control strategies for fuel saving in the hydrogen fuel cell vehicles

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ABSTRACT

A hydrogen fuel cell vehicle requires fuel cells, batteries, supercapacitors, controllers and smart control units with their control strategies. The controller ensures that a control strategy predicated on the data taken from the traction motor and energy storage systems is created. The smart control unit compares the fuel cell nominal output power with the vehicle power demand, calculates the parameters and continually adjusts the variables. The control strategies that can be developed for these units will enable us to overcome the technological challenges for hydrogen fuel cell vehicles in the near future. This study presents the best hydrogen fuel cell vehicle configurations and control strategies for safe, low cost and high efficiency by comparing control strategies in the literature for fuel economy.

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Introduction

On account of find a way out the global warming problem in the world, it is utmost importance to minimize demand for fossil fuels and reduce emissions [1–9]. Thanks to sustainable fuel nature of hydrogen, hydrogen fuel cell vehicles (HFCEVs) are inevitably more advantageous than other conventional vehicles. Since the energy efficiency of the hydrogen fuel cell is high, replacing the internal combustion engines with hydrogen fuel cell vehicles will contribute to the developing technology. With this precaution, the trend towards hydrogen fuel cell vehicles in the transportation sector is increasing rapidly [8–12]. In general, hydrogen fuel cells are environmental friendly technology that transforms incoming hydrogen into electricity and contributes to renewable energy [13–23]. They are promising and renewable energy sources with high energy efficiency and low emissions [24–26].

The hydrogen fuel cells are designed to take the place of conventional internal combustion engine vehicles [11,27–29]. In addition to these advantages, there are disadvantages of having lower power density and slower power response [26,30,31]. In order to reduce these disadvantages, supercapacitors (SCAPs) and batteries (BATs), energy storage systems, can be used together with the fuel cell (FC) [20,26,32–34].

However, to achieve the advantages of HFCEVs and to mitigate disadvantages is needed that robust control strategies. The ability of the batteries to have higher energy than the supercapacitors and the supercapacitors to have higher power

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than the batteries should be used appropriately in the control strategies [20,26,31,32,35–41]. Moreover, it is necessary to design controllers when these control strategies are developed. For this, the design of the electronic power circuits in the system should increase the efficiency of the system and satisfy other needs [42–46]. Controllers control the flow and sharing of energy in energy storage systems by supplying energy from the system [47–52].

Proper control of the power and energy variables is required to control the vehicle's equivalent hydrogen consumption and maintain the efficiency of the vehicle along the way. To achieve high charging efficiency, the battery (BAT) must operate at the optimum operating range and a control strategy must be designed for it [31,42,53–55]. The current, voltage and power ratings of an FC must be adjusted by checking BAT charge status of the BAT. In addition, to achieve good system performance, the supercapacitor (SCAP) control strategy must be identified and must have a gradual control cycle with the FC control strategy [24,26,32,33,52,56–62]. In order to apply these control strategies to FC and hybrid vehicles, a controller should be used to establish and implement a control strategy based on data from the traction motor, FC, BAT and SCAP. After determining the characteristics of all these energy storage technologies according to the energy and power demand of the vehicle (P_{demand}) and establishing a system, it is necessary to apply the control strategies and make comparisons between them and determine the most appropriate one in terms of many features.

The first part of the study describes the vehicle configuration and gives an overview of various control strategies and then, these control strategies are examined, compared and interpreted. In the last section, the results are presented in an explanatory manner.

The configuration of the vehicle

As developments in the automotive sector increase, automakers are beginning to produce vehicles that are technologically advanced. It is necessary to determine their configuration before launching these vehicles to the market. The configuration of the hydrogen fuel cell vehicle (HFCEV) is clearly indicated in Fig. 1. In this configuration, the control mechanism has consisted of FC, BAT, SCAP, DC/DC converter and inverter [30]. In addition, the vehicle composes of three-phase traction motor, auxiliary devices, DC-bus, and energy storage systems. The power-energy changes and balances required by the vehicle are provided by the healthy functioning of all these elements. The control strategy should be determined to prevent any damage to the system from occurring.

The primary energy source for HFCEV is FC [32,63,64]. FC converters serve as an intermediate layer for connecting FC to the DC-bus [60–64]. FC converter maintains the voltage regulation of BAT [65–68]. The battery generates extra power for both the DC-bus and FC when the fuel cell's power (P_{FC}) is not enough. BAT converter is operated to preserve the voltage regulation of SCAP [20,39–41,69]. SCAP controls DC-bus voltage and it generates specific power that FC and BAT cannot generate to provide the vehicle's sudden power demand. SCAP converter is involved in regulating a DC link voltage [69–74]. The inverter is used to produce any desired output voltage for the traction motor and to control the output of FC-BAT-SCAP.

Control strategies of the hydrogen fuel cell vehicles

Control mechanisms in HFCEVs usually include FC, BATs and SCAPs. Various controllers have been developed and applied to provide energy management in the vehicle. The most common control strategies used by these controllers are given below.

1. Peaking Power Source Strategy (PPSS)
2. Operating Mode Control Strategy (OMCS)
3. Fuzzy Logic Control Strategy (FLCS)
4. Equivalent Consumption Minimization Strategy (ECMS)

When control strategies are defined, common characteristics should be considered in common, and the main backbone of control strategies must be shaped accordingly. The strategy should be established by determining the current and power limit values for the charge and discharge states of BAT. In the event of sudden charging and discharging of SCAP, the

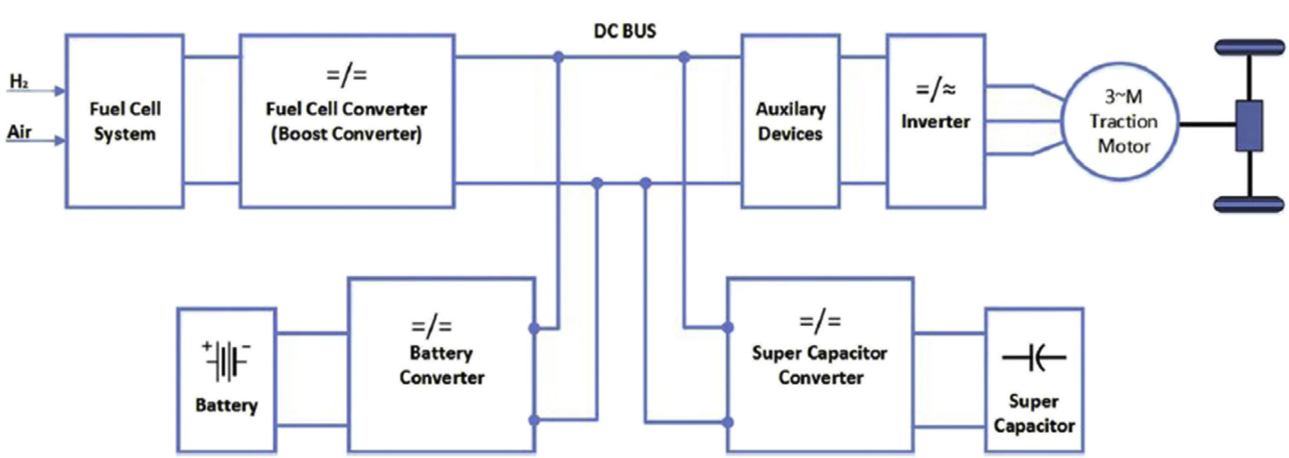

Fig. 1 – The configuration of the vehicle [Adopted from Ref. [11]].

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intervals of the current changes should be determined and prevented from being damaged. In addition, the charge and discharge times of the selected BAT and SCAP should be in accordance with the reference values in terms of efficiency. Fig. 2 generally demonstrated the system of energy control.

Control strategies required for different mechanisms of this system should be determined. For the vehicle energy management to be efficiently controlled, these strategies must be correctly identified and tested for feasibility. The energy control system should control the energy exchange among FC, SCAP and BAT, as well as the power demanded by the system. Furthermore, DC/DC converters, DC/AC inverters, auxiliary power units and traction motor should also be included in the system control [55,75].

Peaking power source strategy (PPSS)

In a HFCEV configuration, there are FC, pedals, traction motor, peaking power source (PPS), a vehicle controller, motor controller, electronic interface, wheels and the signals for the transmission between them. The vehicle controller controls power and torque according to commands from the gas and brake pedals. The traction motor acts as a generator with the command from the brake pedal and stores energy in the PPS that can supply its energy from FC while P_{FC} is greater than P_{demand} [76,77]. The control strategy that ensures this is the peaking power source strategy (PPSS). The configuration of a hydrogen fuel cell vehicle using the PPS strategy is shown Fig. 3.

PPSS should be determined so as to ensure that P_{demand} is maintained at all times by keeping the energy of FC and the PPS in the optimum working zone. The power control strategy is determined according to the acceleration and deceleration of the vehicle. Accordingly, if braking energy is required for the vehicle, the regenerative braking energy [57,78,79] is stored in the PPS. If the command from the driver contains moving and accelerating energy, then the power and energy levels produced by FC and the PPS are compared. According to the magnitude of the demanded power, the energy changes between FC and PPS meet the vehicle power requirement. The vehicle provides the energy requirement either from FC or with the PPS, or both, according to the demand from the driver.

While the PPS power is calculated as

$$P_{pps} = \frac{P_m}{\psi_m} - P_{fc}, \tag{1}$$

the energy changes in the PPS are as follows:

$$E = \int_t \left(P_{pps-ch} - P_{pps-dch}\right) dt. \tag{2}$$

Where P_{pps} is PPS nominal power, P_m is the traction motor power, ψ_m is the traction motor efficiency, P_{fc} is FC power, E is the energy exchange of PPS, P_{pps-ch} is the power of the PPS in the charging state, $P_{pps-dch}$ is defined as PPS discharge power.

PPSS controls the operation of FC in the optimum working zone [76,77]. It also allows the traction motor to control the output power so that the system responds quickly to the power demand.

Operating mode control strategy (OMCS)

The OMCS controls power sharing and power variances between FC and BAT [30]. The difference of power between the vehicle and FC gives BAT its power (see Fig. 4). When determining the control strategy, the OMCS refers to P_{demand}, the

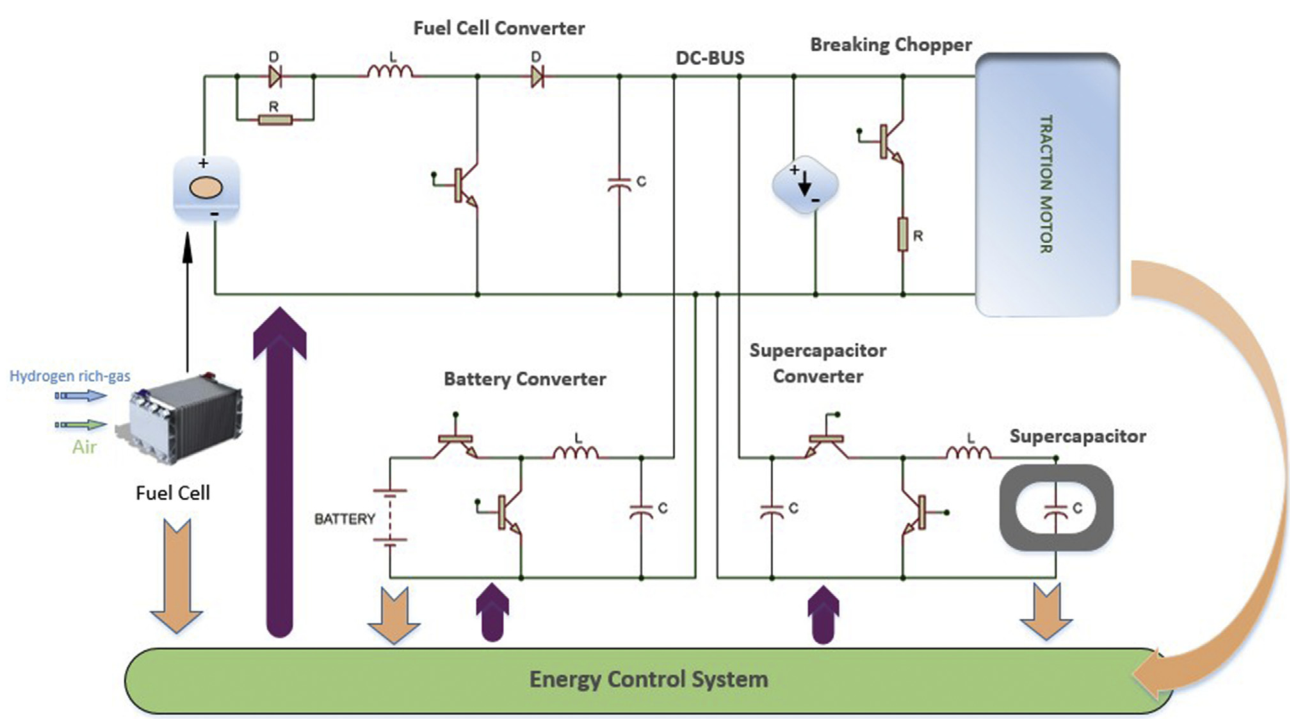

Fig. 2 – The energy control system of HFCEV.

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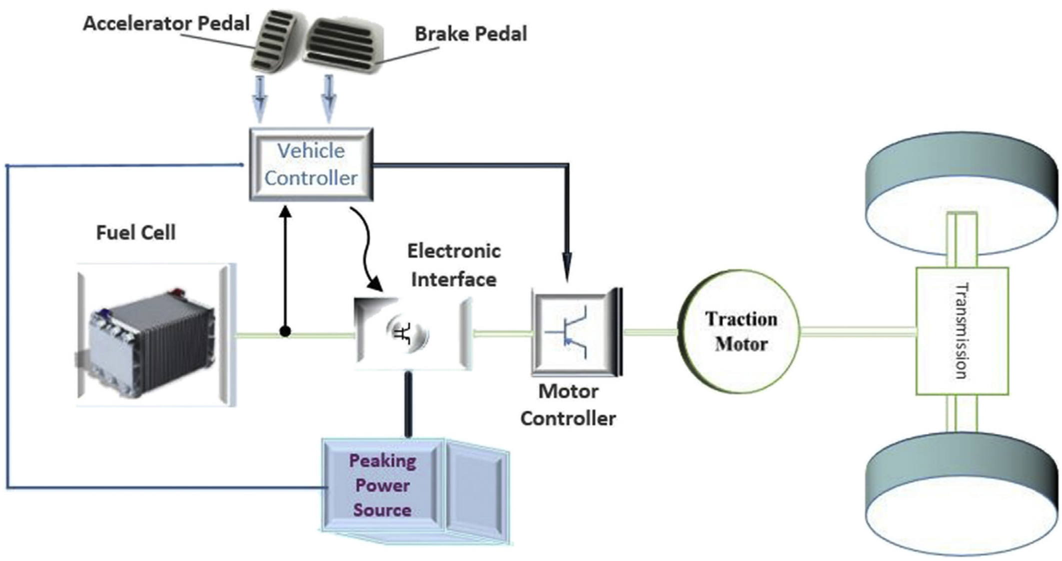

Fig. 3 – The configuration of a hydrogen fuel cell vehicle using the PPSS.

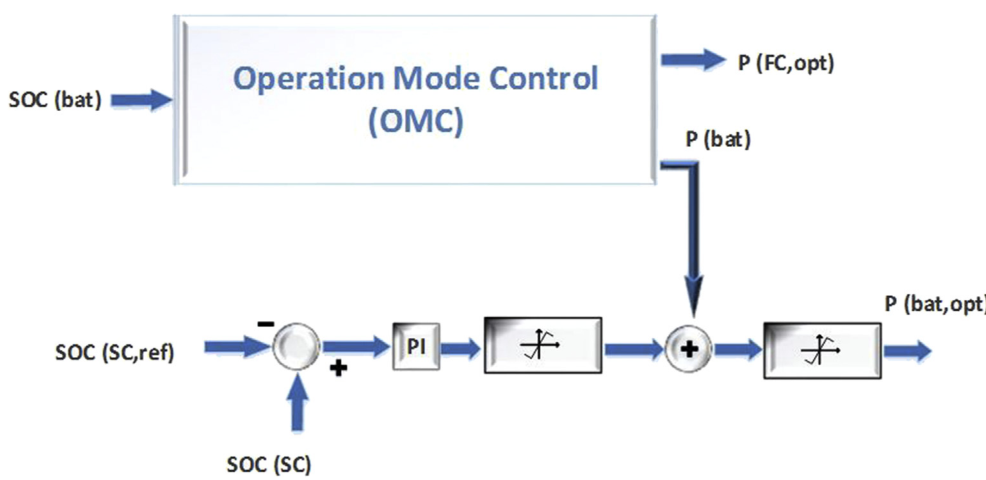

Fig. 4 – Operation Mode Control Strategy (OMCS).

vehicle speed, the power of BAT (P_{BAT}) and the balance P_{FC}. The most important feature of this control strategy is to be able to determine the operating mode in case of three charging states: fast charge mode, discharge mode and charge mode [30,80–82]. When selecting these operating modes, P_{demand}, vehicle speed, SCAP and BAT state of charge are taken into account.

The power demanded by the vehicle (P_{demand}) in the discharge mode may be less or more than the nominal P_{FC}, depending on the acceleration. If P_{demand} is lower than the nominal P_{FC}, the system's energy is provided by FC. If P_{demand} is in excess of the nominal P_{FC}, the energy of the system is provided both from FC and from BAT. In charging mode, P_{demand} is the nominal P_{FC}, and FC provides both the power demand and charges BAT. In the fast charge mode, P_{demand} is much smaller than the nominal P_{FC}. In this mode, FC provides both P_{demand} and the power to all units that require extra energy. It also charges BAT.

Fuzzy logic control strategy (FLCS)

FLCS aims to provide power control between energy storage systems in order to increase system efficiency and fuel economy in HFCEVs [30,51,83–86]. According to this strategy, DC/DC converter power (P_{DC}) ought to minimum, middle or maximum level relative to the energy of FC and BAT [87–90]. In this strategy, the system that performs this operation is the fuzzy logic controller [91–93]. The entire mechanism of FC vehicle to be controlled and the functions that these mechanisms work together and the fuzzy logic control strategy rules are determined [48]. The fuzzy logic control strategy configuration to which all these rules apply is demonstrated in Fig. 5.

BAT voltage, SCAP voltage, and P_{demand} are the inputs of FLC. Moreover, the optimum P_{BAT} and P_{FC} are the outputs. FLC is designed to adjust the P_{DC} according to BAT and SCAP voltages. In addition, it provides P_{demand} while at the same

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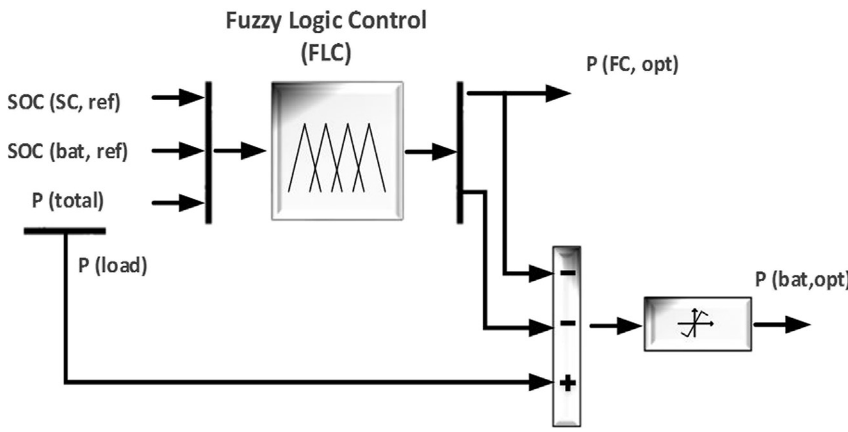

Fig. 5 – Fuzzy Logic Control Strategy (FLCS) configuration.

time apportioned power between BAT and SCAP. Table 1 shows the determined rules for FLCS.

In this table, the power levels of BAT and SCAP SOCs are given as low (L_{SOC}), middle (MD_{SOC}), and maximum (X_{SOC}) respectively. In addition, the vehicle power demand levels are low power (P_L), middle power (P_{MD}), and maximum power (P_X). Finally, the power levels of the DC/DC converter are given minimum (DC_{min}), middle (DC_{middle}), and maximum (DC_{max}).

When the power levels of BAT and SCAP SOCs are low (L_{SOC}), P_{DC} ought to be maximized (DC_{max}). While BAT and SCAP power levels are high (X_{SOC}), P_{DC} must be at either the minimum level (DC_{min}) or the middle level (DC_{middle}), depending on P_{demand}. The aim is to maintain the optimum power levels of BAT and SCAP while meeting P_{demand} and is to allow operation at a nominal P_{FC}.

Table 1 – The determined rules for the Fuzzy Logic Control Strategy (FLCS).

Battery SOC	Supercapacitor SOC	Power demand	The power of DC/DC converter
L_{SOC}	L_{SOC}	P_L	DC_{max}
L_{SOC}	L_{SOC}	P_{MD}	DC_{max}
L_{SOC}	L_{SOC}	P_X	DC_{max}
L_{SOC}	MD_{SOC}	P_L	DC_{max}-DC_{middle}
L_{SOC}	MD_{SOC}	P_{MD}	DC_{max}-DC_{middle}
L_{SOC}	MD_{SOC}	P_X	DC_{max}
L_{SOC}	X_{SOC}	P_L	DC_{max}
L_{SOC}	X_{SOC}	P_{MD}	DC_{max}
L_{SOC}	X_{SOC}	P_X	DC_{max}
MD_{SOC}	L_{SOC}	P_L	DC_{max}
MD_{SOC}	L_{SOC}	P_{MD}	DC_{max}
MD_{SOC}	L_{SOC}	P_X	DC_{max}
MD_{SOC}	MD_{SOC}	P_L	DC_{middle}
MD_{SOC}	MD_{SOC}	P_{MD}	DC_{middle}
MD_{SOC}	MD_{SOC}	P_X	DC_{max}-DC_{middle}
MD_{SOC}	X_{SOC}	P_L	DC_{middle}-DC_{min}
MD_{SOC}	X_{SOC}	P_{MD}	DC_{middle}-DC_{min}
MD_{SOC}	X_{SOC}	P_X	DC_{middle}
X_{SOC}	L_{SOC}	P_L	DC_{max}
X_{SOC}	L_{SOC}	P_{MD}	DC_{max}
X_{SOC}	L_{SOC}	P_X	DC_{max}
X_{SOC}	MD_{SOC}	P_L	DC_{middle}-DC_{min}
X_{SOC}	MD_{SOC}	P_{MD}	DC_{middle}-DC_{min}
X_{SOC}	MD_{SOC}	P_X	DC_{middle}
X_{SOC}	X_{SOC}	P_L	DC_{min}
X_{SOC}	X_{SOC}	P_{MD}	DC_{min}
X_{SOC}	X_{SOC}	P_X	DC_{middle}-DC_{min}

Equivalent consumption minimization strategy (ECMS)

In HFCEVs, ECMS can be used to control changes in vehicle performance when energy storage resources such as BATs and SCAPs are used in addition to FC. To determine and manage a vehicle's energy control system, ECMS was first developed by Paganelli et al. [94]. If P_{demand} is supplied by BAT, the battery will need to be charged and will supply it from FC. Equivalent hydrogen consumption in FC will be converted into fuel consumption in BAT, and the strategy will be determined according to the amount of hydrogen consumed. All this energy exchange ought to be managed by a control strategy that includes auxiliary power units and powertrains [95–97]. The control loop, which also contains a PI controller, is shown in Fig. 6.

What we need to do here is to create important equations. Equivalent hydrogen consumption in ECMS depends on equivalent hydrogen consumption of BAT and FC [96,98–116]. Equivalent hydrogen consumption of FC (C_{fc}) is given in the following equation.

$$C_{fc} = \alpha \cdot P_{fc}^2 + \beta \cdot P_{fc} + \gamma \tag{3}$$

Equivalent hydrogen consumption of FC (C_{fc}) will be calculated when the fuel cell power (P_{fc})and its corresponding coefficients (α, β, γ) are substituted in the equation [30].

When BAT is expressed equivalent hydrogen consumption (C_b),

$$C_b = \begin{cases} \dfrac{P_b C_{fc,avg}}{\eta_{dch}\eta_{ch,avg}P_{fc,avg}}, & P_b \geq 0 \\ \dfrac{P_b \eta_{ch}\eta_{dch,avg}C_{fc,avg}}{P_{fc,avg}}, & P_b < 0 \end{cases} \tag{4}$$

the power of BAT (P_b), the mean hydrogen consumption of FC ($C_{fc,avg}$), the charging and discharging efficiencies of BAT (η_{ch},η_{dch}) , the mean charging and discharging efficiencies of BAT ($\eta_{ch,avg}$,$\eta_{dch,avg}$) and the mean power of FC ($P_{fc,avg}$) must be taken into account [95,96].

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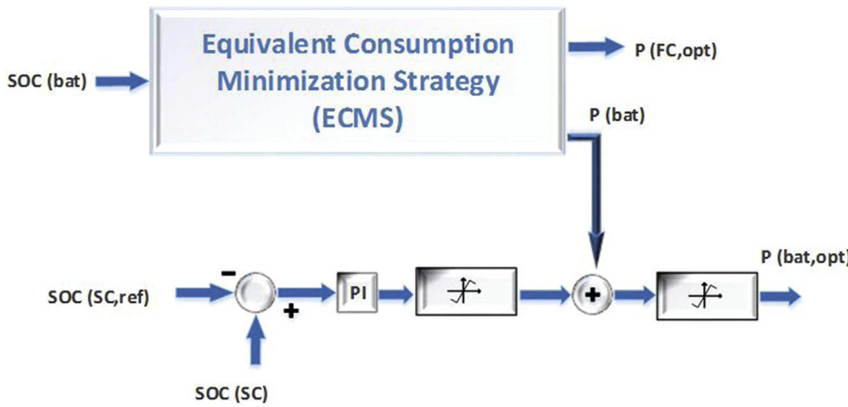

Fig. 6 – Equivalent Consumption Minimization Strategy (ECMS).

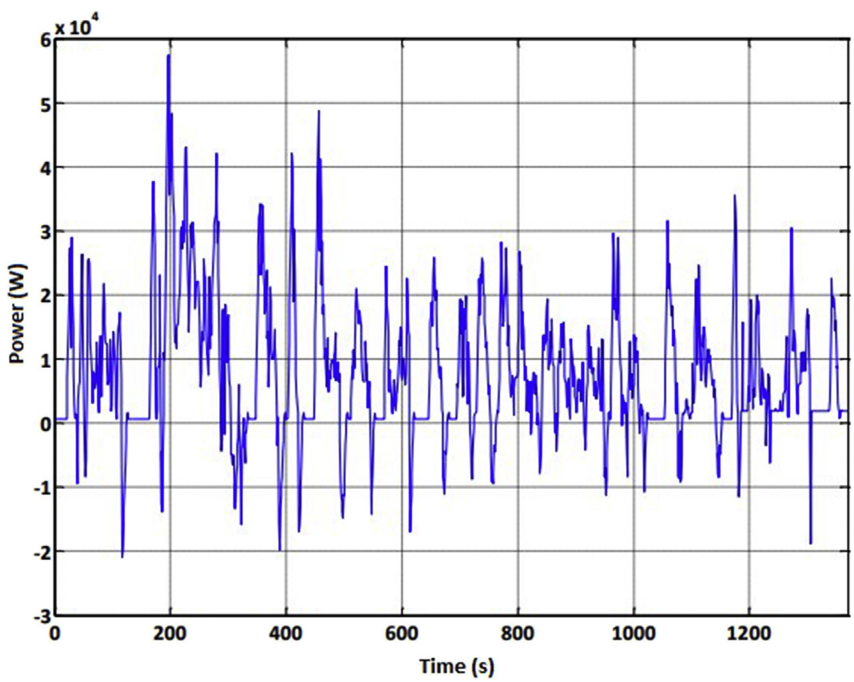

Fig. 7 – The power demand of a light-duty hydrogen fuel cell vehicle (UDDS driving-cycle).

Finally, the total equivalent hydrogen consumption (C_T) of HFCEV can be calculated as

$$C_T = C_{fc} + \kappa C_b. \tag{5}$$

As in Refs. [95] and [117], κ, known as the penalty coefficient, is calculated as follows.

$$\kappa = 1 - 2\mu \frac{(SOC - 0.5(SOC_H + SOC_L))}{SOC_H - SOC_L} \tag{6}$$

In this equation, BAT state of charge is indicated by SOC, BAT high state of charge by SOC_H, BAT low state of charge by SOC_L, and the balance coefficient of SOC by μ.

Finally, the control of SCAP equivalent hydrogen consumption (C_{sc}) can be done with the PI controller because it is small enough to be ignored to compared to that of FC with BAT [30,96,99]. Once the PI controller has checked SCAP state of charge and adapted it, it adds the power of SCAP to BAT power obtained by ECMS. Thus, the ECMS converts the electricity consumption of BAT and SCAP into the equivalent hydrogen consumption. Furthermore, ECMS can use electricity energy provided by energy storage systems such as BAT and SCAP as hydrogen from FC, if necessary, with the concept of equivalent fuel consumption [118].

Results and discussions

The control strategies that can be developed in HFCEVs, which usually include FCs, BATs and SCAPs, are very important in

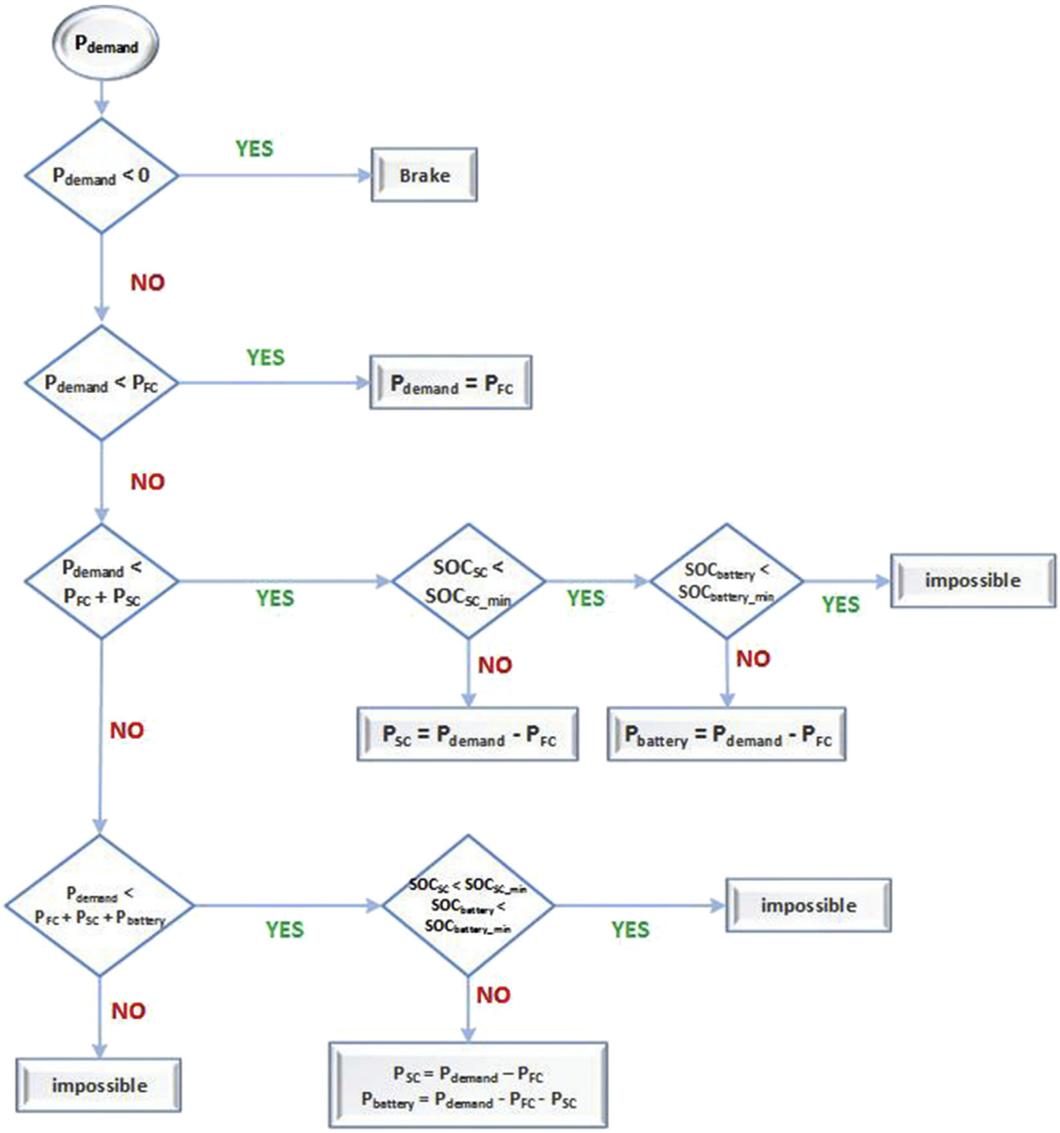

Fig. 8 – The flowchart of the power systems.

terms of energy efficiency and fuel economy. According to P_{demand} when P_{FC} and efficiency drops, SCAP and BAT will be taken into operation and driving efficiency of the vehicle will be stabilized and fuel saving will be ensured. Fig. 7 shows a light-duty HFCEV's power demand, based on urban dynamometer driving schedule (UDDS) [119].

Respectively, FC, SCAP, and BAT provide P_{demand}. Direct use of FC for traction is more efficient in terms of energy, so FCs are used as the primary source. The strategy for maintaining power division and charging is based on the fact that BATs have greater energy density and SCAPs have higher power density [26,38–41,60]. Furthermore, since SCAP is easily rechargeable and dischargeable when compared to BAT, BAT is solely energized in the event of high power demand. The design of the control electronics between the power systems is shown in Fig. 8.

The power of the circuit components present in the system should be considered for analyse P_{demand} in the flowchart. In this figure, BAT state of charge is indicated by $SOC_{battery}$, BAT minimum state of charge by $SOC_{battery\_min}$, SCAP state of charge by SOC_{SC} and SCAP minimum state of charge by SOC_{SC_min}.

If P_{FC} is greater than P_{demand}, the electric power generated from FC is used primarily. However, if P_{FC} is less than P_{demand}, the nominal power is supplied from FC and the remainder is supplied from SCAP. If P_{demand} exceeds the total P_{FC} and P_{SC}, BAT enters the circuit. While these operations are performing, BAT and SCAP should be set to work in the state of charge range. If BAT and SCAP are not properly charged, undesirable conditions may occur in the control electronics. If P_{demand} is lower than P_{FC} and the vehicle is braking, the secondary energy storage system can be charged with FC remaining energy. While the vehicle recharges BAT in the weak deceleration, it recharges SCAP in the strong deceleration. Thus the control electronics are designed.

Control electronics of the control strategies mentioned in the study are often designed in this way. According to P_{demand}, BAT/SCAP power changes working with FC have been

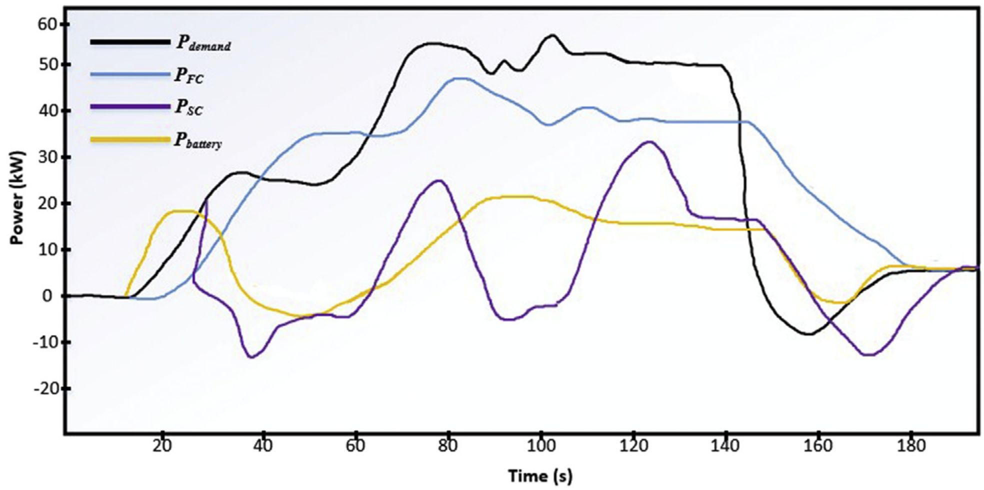

Fig. 9 – The waveforms of the power changes in a light-duty hydrogen fuel cell vehicle.

Table 2 – Control strategies in the vehicle that consume hydrogen for about 300 s.

The control strategies	FC hydrogen consumption (kg)	Eq. hyd. consumption of the hybrid (kg)	The computation time (s)
PPSS	3.89	15.37	3492
OMCS	3.90	36.55	1052
FLCS	3.92	17.67	7732
ECMS	3.82	5.76	777

determined. The power demand in a light-duty HFCEV and the waveforms of the power changes that occur in FC, BAT, and SCAP are plotted in Fig. 9.

P_{FC} followed P_{demand} as seen. However, since the rate of power increase is limited at the points where sudden changes occur, some of the power needed is provided from BAT and SCAP [120]. The maximum P_{demand} here is about 58 kW and P_{FC} is about 45 kW. BAT and SCAP provide the required peak value when the vehicle is accelerating, and store regenerative power during vehicle braking.

According to these power changes in the vehicle, it is possible to make a comparison of the control strategies applied. All of these control strategies in HFCEVs give similar results. SCAP converter control keeps the DC bus voltage set point. The alterations on FC voltage are observed due to changes in power supply, BAT and SCAP voltages. The fuel that the vehicle will consume during driving range will affect P_{FC}, $P_{battery}$ and P_{SC}. The goal of every control strategy that is compared is to be able to create a most efficient and stable vehicle cycle with minimal fuel consumption. As P_{demand} increases so do the fuel consumption. Since the fuel of HFCEV is hydrogen, the amount of hydrogen consumed by the vehicle for about 300 s applied to it by various control strategies, the equivalent hydrogen masses and the computation times are given in Table 2 [30].

ECMS gives the best results on hydrogen consumption from control strategies. Equivalent hydrogen consumption in an HFCV with ECMS applied is much lower than in other strategies. At the same time, PPSS keeps the operation of FC in the optimum working zone, allowing the system to respond quickly to the responded power demand according to the output power and to save fuel. In an FLCS applied vehicle, all mechanisms and functions should be defined and the rules to be established according to this function should be determined [30]. Because of the fact that the control design in FLCS is more complicated, the computation time is higher than in other control strategies. Therefore, some major parameters and logic rules in FLCS should be selected correctly and appropriately according to the requirements of the vehicle.

Conclusion

This article focuses on the comparison of various control strategies with energy control system of the vehicle, using BATs and SCAPs together with FC to reduce the disadvantages of FC, such as the lower power density and less power response of FC, as well as the advantages of FC in HFCEVs. For the development of appropriate control strategies, it should be benefited from BAT's high energy density and SCAP's high power density. Furthermore, various control strategies developed to provide the vehicle's energy control system to increase efficiency, reduce costs and save fuel. In sudden loads, the efficiency and lifetime of FC, BAT and SCAP are reduced. Power sharing is carried out by means of appropriate control strategies in order to avoid the inconveniences that may occur during instantaneous and major power changes. In the various control strategies compared here, FC is firstly mainly used. The power exchanging between FC and BAT, and the way SCAP monitors the DC-bus voltage, makes the control strategies different from each other. FC converter, BAT converter and SCAP converter connect these components to the DC bus. DC/DC converters provide voltage regulation to allow power sharing between each energy storage system. This power sharing is done by determining various control strategies according to P_{demand}. Requests from the driver such as acceleration, deceleration, sudden braking and stopping of the vehicle are evaluated by means of electronic controllers and are implemented by means of control strategies created.

Almost all of the control strategies described in this article have similar results. When comparing all of them, the most preferred control strategy among them was ECMS. According to P_{demand} in a light-duty HFCEV, it has been found that FC's hydrogen consumption and BAT-SCAP's equivalent hydrogen consumption are minimizing in ECMS. In the view of computation time, it was determined that computation time of the FLCS is much higher than that of the other control strategies. Since the FLCS has a rather complex structure compared to the other three control strategies, both the computation time is long and it requires serious changes in its parameters when applied to different tools. However, since PPSS, OMCS and ECMS are simple in terms of their parameters and structures, they can easily be applied to different HFCEVs with minor modifications. In addition, the PPSS keeps P_{FC} at the optimum working point and allows it to respond promptly as the vehicle demands it. However, the OMCS controls the conditions of the vehicle such as acceleration, deceleration, stopping and separates into three different modes. It works according to these modes, reducing the equivalent hydrogen consumption of the vehicle. When all these comparisons are evaluated, the following conclusions and recommendations should be taken into consideration:

- It would be more appropriate to use FC with limited storage capacity in HFCEVs together with energy storage systems such as BAT and SCAP instead of using it alone.
- In HFCEVs, power sharing should be performed by determining appropriate control strategies between FC, BAT and SCAP for advance the lifetime and efficiency of the energy control systems.
- The most preferred control strategy among the compared control strategies is ECMS. This is because ECMS has superior features such as keeping the equivalent hydrogen consumption at a minimum level, being the simplest by parameters, being able to be applied in many vehicles and keeping the performance of the vehicle at a high level.
- In future work, creating and controlling their control mechanisms in combination with ECMS, using dual-way DC/DC converters, which is particularly useful to provide the sudden and large power demands of the vehicle, will convert many of the disadvantages to advantage.
- Safe, low-cost and highly efficient control strategies that will enhance the workings of the future, especially those that will come from above the technological challenges of HFCEVs, should be established. Most importantly, the hydrogen consumption in terms of the fuel economy must be minimized. These strategies to be developed will contribute greatly to the future 'Green Energy' and 'Hydrogen Economy'.

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