Towards Sustainable Mobility: Comparative Study of Energy Management Strategies in Fuel-Cell Hybrid Electric Vehicles

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ABSTRACT

The global shift towards fuel cell hybrid electric vehicles (FHEVs) is motivated by rising fuel costs and environmental concerns related to emissions. This study evaluates two energy management strategies in a hybrid electric vehicle equipped with a proton exchange membrane fuel cell (PEMFC) as the primary power source and a lithium-ion battery as a secondary source. A traditional proportional-integral (PI) strategy and an intelligent fuzzy logic-based control (FLC) strategy are compared to optimize energy flow and minimize fuel consumption. Both algorithms studied generate the reference power of the PEM fuel cell for each state of charge level of the Li-ion battery and the required power of the vehicle. Simulation results, using the NYCC drive cycle, demonstrate that the fuzzy logic-based control strategy mitigates voltage fluctuations, reduces battery discharging, and hydrogen consumption, thereby improving transient response.

I. Introduction

The growing concern about climate change, increased environmental awareness, the diminishing availability of fossil resources, and rising fuel costs strengthen the need for a transition towards sustainable development through the adoption of eco-friendly vehicles powered by clean energy sources. Faced with these pressing challenges, it is imperative to seek clean and efficient propulsion solutions to preserve our advancements in mobility. Therefore, the development and mastery of propulsion systems constitute significant areas of research [1, 2].

Fuel Cell Electric Vehicles (FCEVs) are perceived as a promising alternative to conventional vehicles. These vehicles harness hydrogen, a renewable energy source, to ensure a substantial driving range. However, in the case of a single-source FCEV, the fuel cell must cater to all the power requirements of the vehicle, which can result in significant fluctuations due to its slow response and limited dynamic capability, consequently reducing its lifespan [3]. Faced with this challenge, numerous researchers have proposed hybridizing fuel cells with supercapacitors and/or batteries to overcome the drawbacks associated with slow dynamics and to implement energy recovery [4, 5].

In a hybrid power system, energy management strategy (EMS) plays a fundamental role. In this context, several methods of energy management are studied and developed with the aim of ensuring the vehicle's propulsion power, efficiently regulating the flow of energy from energy sources, minimizing fuel consumption, and increasing the lifespan of the power system [6]. In the literature, EMS can be divided into three categories: optimization-based strategies, frequency-based strategies, and rule-based strategies [7]. Optimization-based EMS can further be divided into local optimization strategies (such as predictive control, optimal control theory, Pontryagin's minimum principle, etc.) and global optimization strategies (such as linear programming, dynamic programming, Particul swarm optimisation, etc.) [8-10]. Frequency-based strategies can be classified into classical strategies (such as frequency separation, adaptive filters, etc.) and advanced strategies (such as methods based on wavelet transform, etc.) [11, 12]. Finally, rule-based EMS can be divided into deterministic strategies (such as PI control, state machines, etc.) and strategies based on artificial intelligence (such as fuzzy logic, neural networks, etc.) [13-15].

To enhance the EV performance and address the previously mentioned challenges, this study investigates and contrasts two energy management strategies, with their respective advantages outlined below. The first strategy is grounded in the classical PI control approach, while the second relies on a fuzzy logic-based management strategy. Both methods are applied to the battery-fuel cell hybrid power system illustrated in Figure 1. Results obtained through Matlab/Simulink clearly demonstrate the effectiveness of these energy strategies across various driving scenarios. To achieve these objectives, this article is structured into five sections: Section 1 provides an introduction. In Section 2, a modeling of the studied system is presented. Section 3 provides explicit details regarding the proposed energy management strategies. Simulation results, generated using Matlab/Simulink, are presented in Section 4. Lastly, a conclusion of this work summarizes and validates the proposed strategies.

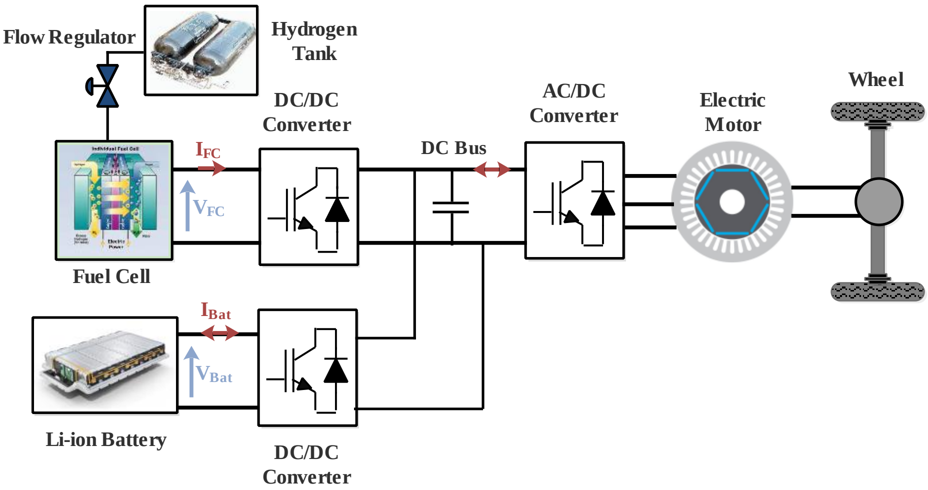


Figure 1. Block diagram of proposed fuel cell hybrid EV.

II. System Modelling

II.1. Vehicle Modelling

A vehicle under the influence of various external forces is shown in Figure 2.

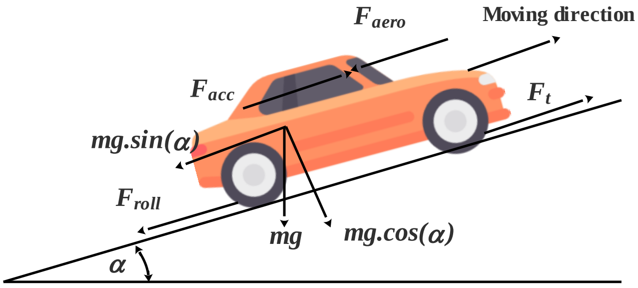


Figure 2. External forces applied to the EV.

The different forces acting on the vehicle are defined as follows [12, 16]:
Rolling resistance force:

$$F_{roll} = mgf_{ro}\cos(\alpha) \tag{1}$$

Slope force:

$$F_{slope} = mg\sin(\alpha) \tag{2}$$

Aerodynamic drag force:

$$F_{aero} = \frac{1}{2}\rho_{air}A_f C_d (v+v_w)^2 \tag{3}$$

Acceleration force:

$$F_{acc} = k_m m\frac{dV_e}{dt} = k_m m\gamma \tag{4}$$

The total tractive force (*Ft*) is the sum of all the different forces and is given by:

$$F_t = F_{tire} + F_{aero} + F_{slope} + F_{acc} = mgf_{ro}\cos(\alpha) + \frac{1}{2}\rho_{air}A_f C_d (v+v_w)^2 + mg\sin(\alpha) + k_m m\gamma \tag{5}$$

The required power of the electric vehicle can be given by:

$$P_m = v.F_t = v.\left[mg\left(f_{ro}\cos(\alpha)+\sin(\alpha)\right) + k_m m\gamma + \frac{1}{2}\rho_{air}A_f C_d (v+v_w)^2\right] \tag{6}$$

II.2. Fuel Cell Modelling

PEM fuel cells are electrochemical devices that produce electrical energy and heat via a chemical reaction. They offer several advantages over existing technologies, such as exceptional energy efficiency, the generation of electric power without emitting pollutants, minimal noise levels, and impressive overall performance [17].

The voltage of the used PEMFC V_{FC} is given by [6, 18]:

$$V_{FC} = N_{cell}\left(E_n - V_{act} - V_{ohmic} - V_{con}\right) \tag{7}$$

Where N_{cell} is the number of cells, E_n is the Nerst voltage, V_{act} is the activation losses, V_{ohmic} is the ohmic losses and V_{con} is the concentration losses.

The Nernst voltage is determined as follows:

$$E_n = \begin{cases} 1.229 + (T-298)\dfrac{-44.43}{zF} + \dfrac{RT}{zF}\ln\left(P_{H_2}P_{O_2}^{\frac{1}{2}}\right) & T \le 100^\circ C \\ 1.229 + (T-298)\dfrac{-44.43}{zF} + \dfrac{RT}{zF}\ln\left(\dfrac{P_{H_2}P_{O_2}^{\frac{1}{2}}}{P_{H_2O}}\right) & T > 100^\circ C \end{cases} \tag{8}$$

The different losses can be expressed as follows:

$$V_{ohmic} = R_{ohm}I_{FC} \tag{9}$$

$$V_{act} = A\ln\left(\frac{I_{FC}}{i_0}\right) \tag{10}$$

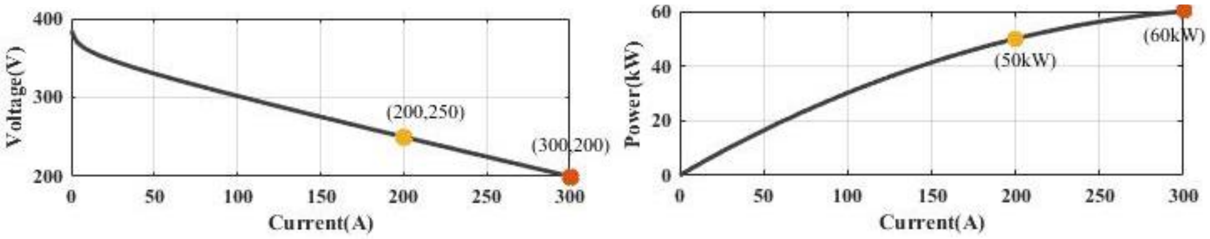
$$V_{act} = \frac{RT}{zF}\ln\left(1-\frac{I_{FC}}{I_{L\max}}\right) \tag{11}$$

The rates conversion of hydrogen H_2 and oxygen O_2 are calculated as follows:

$$Uf_{H_2} = \frac{60000RTNI_{FC}}{zFP_{fuel}V_{fuel}x\%} \tag{12}$$

$$Uf_{o_2} = \frac{60000RTNI_{FC}}{2zFP_{air}V_{air}y\%} \tag{13}$$

Figure 3 shows the PEMFC stack characteristics (Stack voltage vs current) and (Stack power vs current).



(a) (b)

Figure 3. PEMFC stack : (a) Stack voltage/current; (b) Stack power current.

II.3. Battery Modelling

In this subsection, we focus on the representation of the Li-ion battery. It's conceptualized as a straightforward model, comprising a controlled voltage source in series with a constant resistance. The voltage across this battery model is determinable through two separate equations. This approach simplifies the complex behavior of Li-ion batteries, making it easier to integrate into various simulations and analyses. [16, 19]:

$$V_{discharge} = E_0 - R.i - K\frac{Q}{Q-it}.(it+i^*) + A\exp(-B.it) \tag{14}$$

$$V_{charge} = E_0 - R.i - K\frac{Q}{it-0.1Q}.i^* - K\frac{Q}{Q-it}.it + A\exp(-B.it) \tag{15}$$

The state of charge of the battery can be obtained using as follows:

$$SOC_{bat} = 100\left(1 - \int \frac{i_{(t)}dt}{Q}\right) \tag{16}$$

Where R is the battery internal resistance, Q is the battery capacity, E_0 is the Li-ion battery constant voltage, it is the actual battery charge, and i^* is the filtered battery current.

II.4. Boost and Buck-Boost converters model

In this work, an active parallel configuration is adopted, which involves connecting each source to the DC bus through a DC-DC converter, as shown in Figure 4. A bidirectional Buck-Boost converter, enabling power flow in both directions, was used on the Li-ion battery side, while a conventional Boost converter was used on the PEM fuel cell side. A dual PI control loop is employed to keep the DC bus voltage close to its setpoint and regulate the power of the Li-ion battery, as shown in Figure 5a. A PI controller is applied to manage the power of the PEM fuel cell stack by adjusting the current to its reference value, as illustrated in Figure 5b. The mathematical model of these converters can be described by the following system of equations [20]:

$$\begin{cases} \dfrac{dI_{FC}}{dt} = \dfrac{1}{L_1}V_{FC} - \dfrac{1-u_1}{L_1}V_{DC} \\ \dfrac{dI_{bat}}{dt} = \dfrac{1}{L_2}V_{bat} - \dfrac{1-u_{23}}{L_2}V_{DC} \\ \dfrac{dV_{DC}}{dt} = \dfrac{1-u_1}{C}I_{FC} + \dfrac{u_{23}}{C}I_{bat} - \dfrac{1}{C}I_{DC} \end{cases} \tag{17}$$

$$u_{23} = \begin{cases} 1-u_2 & i_{batref} > 0 \quad (discharging\ mode) \\ u_3 & i_{batref} < 0 \quad (charging\ mode) \end{cases} \tag{18}$$

Where u_1, u_2 and u_3 denotes the duty cycles of switch S_1, S_2 and S_3, respectively.

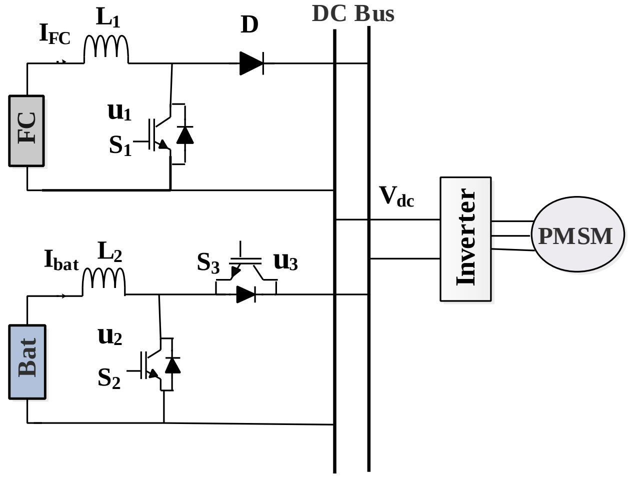
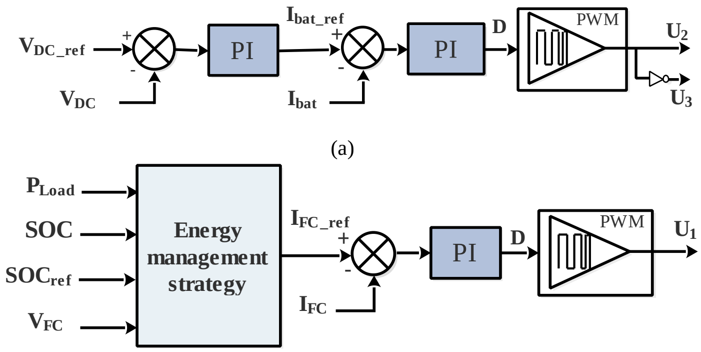


Figure 4. Li-ion battery and fuel cell with their associated converters.



(a)

(b)

Figure 5. (a) DC bus voltage and Li-ion battery current control. (b) fuel cell current control.

The detailed specifications of the studied vehicle are given in Table 1.

Table 1. Specifications of the studied vehicle.

Specifications	**Item**	**Value**
Vehicle Structure	Vehicle total mass (m)	1325 kg
	Gear ratio (G)	5.2
	Air density (ρ_{air})	1.2 kg/ m^3
	Frontal area (A_f)	2.57 m^2
	Tire radius (r)	0.3 m
	Drag coefficient (C_d)	0.3
PEMFC stack	Nominal power	50 kW
	Number of cells	358 cell
	Nominal stack efficiency	55 %
Li-ion battery	Nominal voltage	250 V
	Rated capacity	48 Ah

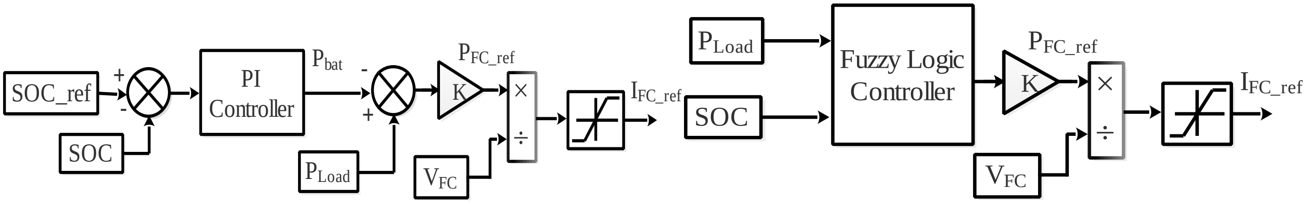
III. Energy Management Strategies

III.1. Classical PI Strategy

This approach employs a PI controller to regulate the SOC of the Li-ion battery, as illustrated in Figure 6(a). The output from the PI controller corresponds to the Li-ion battery power, which is subsequently subtracted from the load power to determine the PEM fuel cell reference power. The concept of this strategy is to maintain the SOC at a reference level. Specifically, when the Li-ion battery's SOC falls below the reference SOC, the fuel cell supplies nearly all of the required power. Conversely, when the battery's SOC exceeds the reference SOC, the fuel cell operates at a lower power level, while the battery provides the full power. This method is relatively straightforward to implement, with its performance primarily influenced by the parameters of the PI controller [21].

III.2. Fuzzy Logic Energy Management Strategy

We opted for a fuzzy logic control-based EMS due to its adaptability, effectiveness, and ability to function without precise mathematical models, as depicted in Figure 7(b). The inputs for the fuzzy logic controller include the state-of-charge (SOC) of the Li-ion battery and the load power (Pload). The output parameter is the reference value for the PEMFC stack power. In this fuzzy logic control-based EMS, the PEMFC stack is operated in a manner that prevents it from operating in the low-efficiency zone, thereby enhancing its overall efficiency [13, 22]. The fuzzy logic rules associated with this energy management approach have been devised and are presented in Table 2.



(a) (b)

Figure 6. Energy management strategies. (a) Classical PI control. (b) Fuzzy logic control.

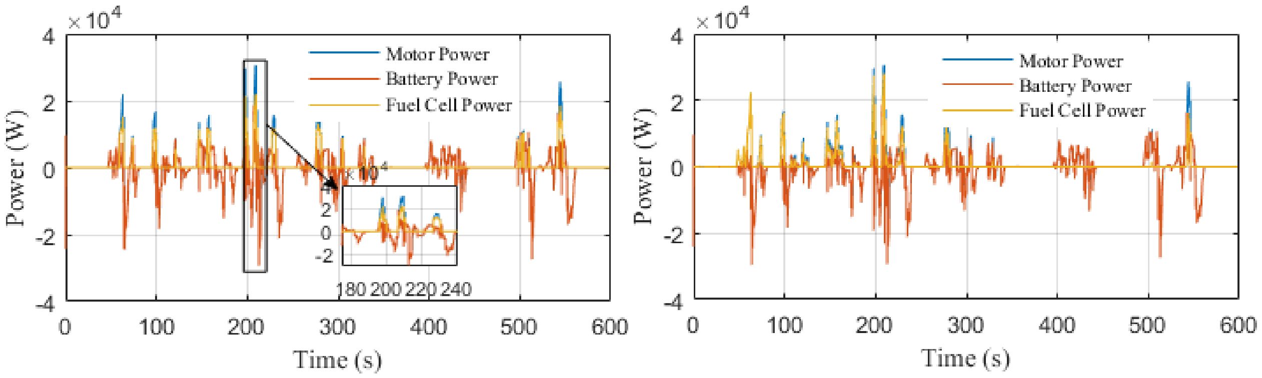
Table 2. Proposed fuzzy logic control rules

Number	SOC	P_{Load}	P_{FC}	Numbre	SOC	P_{Load}	P_{FC}
1	L	N	ZE	10	L	M	H
2	M	N	ZE	11	M	M	L
3	H	N	ZE	12	H	M	VL
4	L	VL	L	13	L	H	VH
5	M	VL	ZE	14	M	H	M
6	H	VL	ZE	15	H	H	VL
7	L	L	M	16	L	VH	VH
8	M	L	VL	17	M	VH	H
9	H	L	ZE	18	H	VH	L

IV. Simulation and Results

To evaluate the efficiency of the two energy management strategies for fuel cell/battery electric vehicles, namely the classical PI control strategy and the proposed fuzzy logic management strategy, we utilize the New York City Cycle (NYCC) driving cycle in our study. The performance assessment of these EMSs is conducted via simulations using Matlab/Simulink. All tests begin with identical initial conditions to ensure the same conditions for comparison.

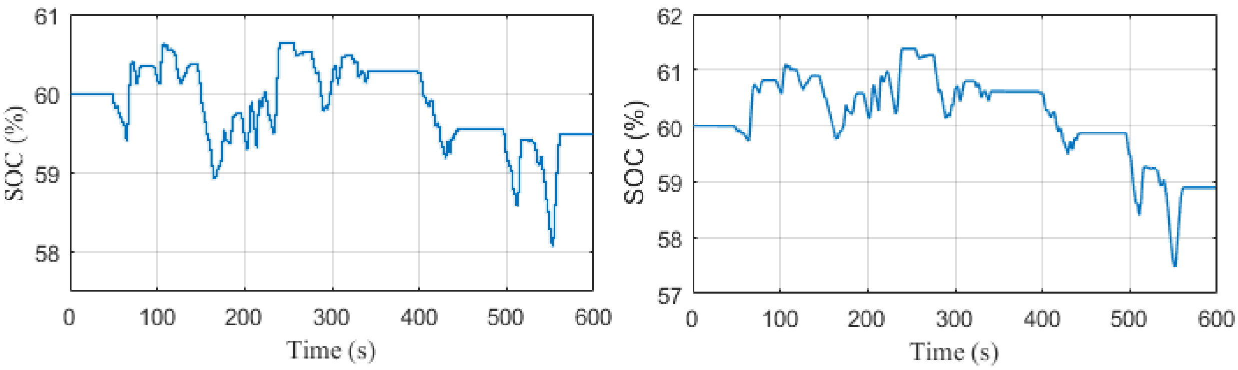
The power of PEM fuel cell stack, Li-ion battery and motor are presented in Figure. 7. The results show the effectiveness of the proposed fuzzy logic control-based EMS to perfectly allocate the energy among the sources.



(a) (b)

Figure 7. Electric vehicle power under NYCC : (a) Proposed fuzzy logic control strategy; (b) Classical PI control strategy.

Figure. 8, shows the Li-ion battery state of charge evolution during the NYCC driving cycle. It can be seen that the fuzzy logic control management strategy has reduced the battery discharge.



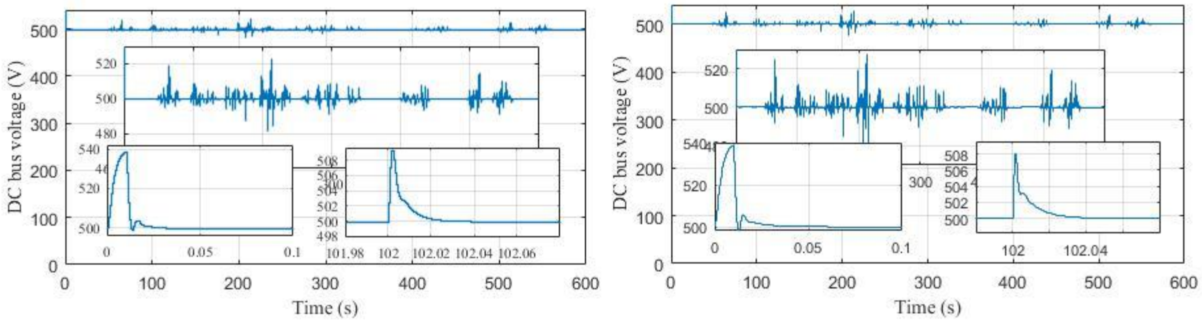
(a) (b)

Figure 8. Li-ion battery SOC under NYCC : (a) Proposed fuzzy logic control strategy; (b) Classical PI control strategy.

Figure. 9, depicts the DC bus voltage of the two EMSs during the NYCC driving cycle. It can be noticed that the measured DC bus voltage in the two cases follows the reference but with differing behavior. therefore, the fuzzy logic control management strategy achieved a faster transient response and reduced the DC bus voltage ripples.

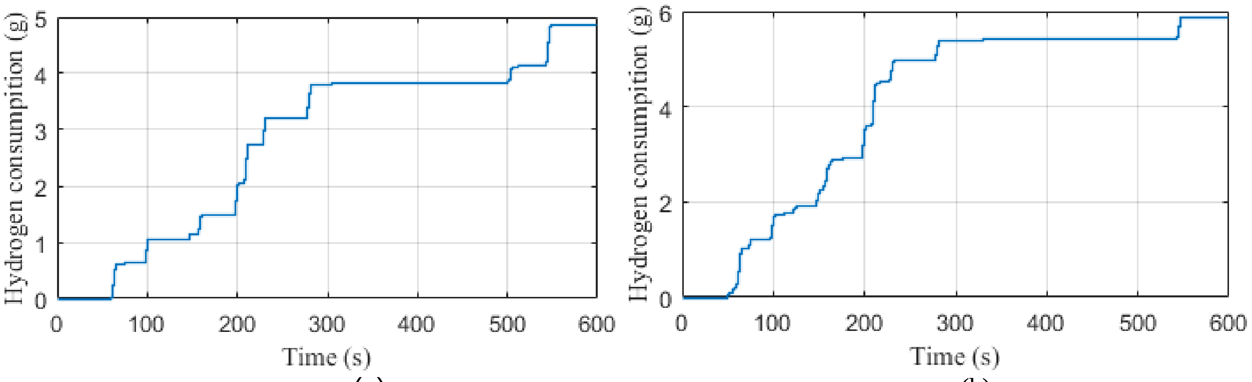
Figure. 10, depicts the hydrogen consumption of the electric vehicle during its movement. It can be clearly seen that the fuzzy logic control-based EMS consumes less hydrogen than conventional PI control strategy.

Figures. 7(a)-(b), 8(a)-(b), 9(a)-(b), 10(a)-(b) and Table 3, show that the proposed fuzzy logic control management strategy achieved faster transient response, reduced DC bus voltage ripples, reduced battery discharge and hydrogen consumption these results contribute in enhancing vehicle performance.



(a) (b)

Figure 9. DC bus voltage under NYCC : (a) Proposed fuzzy logic control strategy; (b) Classical PI control strategy.



(a) (b)

Figure 10. Hydrogen consumption under NYCC : (a) Proposed fuzzy logic control strategy; (b) Classical PI control strategy.

Table 3. General comparison between classical PI strategy and proposed fuzzy logic control strategy

	Classical PI Control Strategy	**Fuzzy Logic Control Strategy**
State of charge (%)	60 – 58.89	60 – 59.5
Response time (s)	0.045	0.025
Ripple (V)	28	21
Hydrogen consumption (g)	5.88	4.88

V. Conclusion

This paper presents a comparative study of two energy management strategies for fuel cell hybrid electric vehicles. These strategies use the demand power and the Li-ion battery SOC as two input parameters, and the reference power of the PEMFC stack as the output parameter. The study aims to compare these techniques according to the SOC of the battery, the hydrogen consumption and the dynamic response in order to choose the most suitable strategy. Both strategies are validated through simulations of the NYCC driving cycle test. The results obtained demonstrate that the proposed fuzzy logic management strategy outperforms the conventional proportional-integral control strategy in all aspects, including DC bus voltage fluctuations, battery discharge, hydrogen consumption, and response time, providing a more accurate and optimal solution.

References

[1] E. A. Nanaki and C. J. Koroneos, "Climate change mitigation and deployment of electric vehicles in urban areas," Renew. Energy, vol. 99, pp. 1153-1160, 2016. doi: 10.1016/j.renene.2016.08.006

[2] D. Rekioua, K. Kakouche, P. O. Logerais, and T. Rekioua, "Power control-based fuzzy and modulated hysteresis methods for micro-grid using a photovoltaic system," International Conference on Smart Grid (icSmartGrid), IEEE, 2023, pp. 1-6. doi: 10.1109/icSmartGrid58556.2023.10170869

[3] A. Oubelaid, K. Kakouche, N. Belbachir, T. Rekioua, M. Bajaj, F. Jurado, and S. Kamel, "Efficient driveline architecture and torque distribution strategy for dual traction machines electric vehicles," in 2023 5th Global Power, Energy and Communication Conference (GPECOM), IEEE, 2023, pp. 86-91. doi: 10.1109/GPECOM58364.2023.10175710

[4] F. Tao, L. Zhu, Z. Fu, P. Si, and L. Sun, "Frequency decoupling-based energy management strategy for fuel cell/battery/ultracapacitor hybrid vehicle using fuzzy control method," IEEE Access, vol. 8, pp. 166491-166502, 2020. doi: 10.1109/ACCESS.2020.3023470

[5] M. E. Şahin and F. Blaabjerg, "PV powered hybrid energy storage system control using bidirectional and boost converters," Electr. Power Components Syst., vol. 49, no. 15, pp. 1260-1277, 2022.

[6] K. Kakouche, A. Oubelaid, S. Mezani, T. Rekioua, M. Bajaj, F. Jurado, et S. Kamel, "Energy Management Strategy of Dual-Source Electric Vehicles Based on Fuzzy Logic Control Considering Driving Cycles," in 2023 5th Global Power, Energy and Communication Conference (GPECOM), IEEE, 2023, pp. 92-97. doi: 10.1109/GPECOM58364.2023.10175709

[7] A. Benhammou, H. Tedjini, Y. Guettaf, M. A. Soumeur, M. A. Hartani, O. Hafsi, and A. Benabdelkader, "Exploitation of vehicle's kinetic energy in power management of tow-wheel drive electric vehicles based on ANFIS DTC-SVM comparative study," Int. J. Hydrogen Energy, vol. 46, no. 54, pp. 27758-27769, 2021. doi: 10.1016/j.ijhydene.2021.06.023

[8] L. Tribioli, M. Barbieri, R. Capata, E. Sciubba, E. Jannelli, and G. Bella, "A real-time energy management strategy for plug-in hybrid electric vehicles based on optimal control theory," Energy Procedia, vol. 45, pp. 949-958, 2014. doi: 10.1016/j.egypro.2014.01.100

[9] N. Kim, S. Cha, and H. Peng, "Optimal control of hybrid electric vehicles based on Pontryagin's minimum principle," IEEE Trans. Control Syst. Technol., vol. 19, no. 5, pp. 1279-1287, 2010. doi: 10.1109/TCST.2010.2061232

[10] M. A. Abdelshafy, H. Hassan, and J. Jurasz, "Optimal design of a grid-connected desalination plant powered by renewable energy resources using a hybrid PSO-GWO approach," Energy Convers. Manag., vol. 173, pp. 331-347, 2018. doi: 10.1016/j.enconman.2018.07.083

[11] J. Snoussi, S. Ben Elghali, M. Benbouzid, and M. F. Mimouni, "Auto-Adaptive Filtering-Based Energy Management Strategy for Fuel Cell Hybrid Electric Vehicles," Energies, vol. 11, p. 2118, 2018. doi: 10.3390/en11082118

[12] J. P. F. Trovão, M. A. Roux, É. Ménard, and M. R. Dubois, "Energy-and power-split management of dual energy storage system for a three-wheel electric vehicle," IEEE Trans. Veh. Technol., vol. 66, no. 7, pp. 5540-5550, 2016. doi: 10.1109/TVT.2016.2636282

[13] K. Kakouche, T. Rekioua, S. Mezani, A. Oubelaid, D. Rekioua, V. Blazek, L. Prokop, S. Misak, M. Bajaj, and S. Ghoneim, "Model Predictive Direct Torque Control and Fuzzy Logic Energy Management for Multi Power Source Electric Vehicles," Sensors, vol. 22, no. 15, p. 5669, 2022. doi: 10.3390/s22155669

[14] D. Rekioua, Z. Mokrani, K. Kakouche, T. Rekioua, A. Oubelaid, P.O. Logerais, ... & S.S.. Ghoneim. (2023). Optimization and intelligent power management control for an autonomous hybrid wind turbine photovoltaic diesel generator with batteries. Scientific Reports, 13(1), 21830.

[15] A. U. Rahman, S. S. Zehra, I. Ahmad, and H. Armghan, "Fuzzy supertwisting sliding mode-based energy management and control of hybrid energy storage system in electric vehicle considering fuel economy," J. Energy Storage, vol. 37, 102468, 2021. doi: 10.1016/j.est.2021.102468

[16] K. Kakouche, A. Oubelaid, S. Mezani, D. Rekioua, and T. Rekioua, "Different Control Techniques of Permanent Magnet Synchronous Motor with Fuzzy Logic for Electric Vehicles: Analysis, Modelling, and Comparison," Energies, vol. 16, no. 7, p. 3116, 2023. doi: 10.3390/en16073116

[17] C. H. Zheng, N. W. Kim, and S. W. Cha, "Optimal control in the power management of fuel cell hybrid vehicles," Int. J. Hydrogen Energy, vol. 37, no. 1, pp. 655-663, 2012. doi: 10.1016/j.ijhydene.2011.09.091

[18] Z. Abdin, C. J. Webb, and E. MacA. Gray, "Modelling and simulation of a proton exchange membrane (PEM) electrolyser cell," Int. J. Hydrogen Energy, vol. 40, no. 39, pp. 13243-13257, 2015.

[19] D. Rekioua, K. Kakouche, T. Rekioua, and Z. Mokrani, "Control a Photovoltaic/Wind Turbine/Diesel Generator with Storage Battery," in 21st International Conference on Renewable Energy and Power Quality (ICREPQ'23), Madrid, Spain, 2023. doi: 10.24084/repqj21.342

[20] M. E. Şahin and F. Blaabjerg, "A Hybrid PV-Battery/Supercapacitor System and a Basic Active Power Control Proposal in MATLAB/Simulink," Electronics, vol. 9, p. 129, 2020.

[21] S. N. Motapon, L. A. Dessaint, and K. Al-Haddad, "A comparative study of energy management schemes for a fuel-cell hybrid emergency power system of more-electric aircraft," IEEE Trans. Ind. Electron., vol. 61, pp. 1320-1334, 2013. doi: 10.1109/TIE.2013.2257152

[22] Y. Zhang, C. Zhang, Z. Huang, L. Xu, Z. Liu, and M. Liu, "Real-Time Energy Management Strategy for Fuel Cell Range Extender Vehicles Based on Nonlinear Control," IEEE Trans. Transp. Electrif., vol. 5, pp. 1294-1305, 2019. doi: 10.1109/TTE.2019.2958038