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Energy management based hybrid fuel cell/battery for electric vehicle using type 2 fuzzy logic controller

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***Abstract*—Electric vehicles and renewable energy are currently viewed as completely complementary clean energy technologies. In this paper, a renewable energy management system based on a hybrid smart vehicle is used, combining the energy from the fuel cell and the energy from the storage devices according to the driving cycle response and long-distance autonomy. Thus, the use of fuel cells and storage batteries in the automotive sector is expected to play a major role in addressing the issue of sustainable mobility in the long run. In a hybrid vehicle, the electrical motor is hopped-up by a electric cell aided by a secondary energy supply. The latter is either a battery or a supercapacitor. The resulting hybrid architecture offers a degree of freedom in the management of energy flows and in the sizing of the powertrain. This paper proposes and designs a type-2 fuzzy logic controller based on the intended motor torque and battery state of charge (SOC_{Bat}), with the goal of regulating the requested energy consumption while increasing or maintaining driving performance characteristics. This proposed Type-2 fuzzy controller is implemented and evaluated in the onboard hybrid power system simulation model. The results show that the management algorithm can improve its intervention during cycle change and power system efficiency by decreasing variance in battery state of charge. Simulations reveal that the new method is well suited for various driving cycles and severe operational ircumstances.**

Keywords- Power Management; Type 2 Fuzzy Logic Controller; Fuel Cell; Battery ; Hybrid Energy; Electric Vehicles

I. INTRODUCTION

Significant climatic changes, such as global warming and poor air quality, have recently threatened all life on Earth, raising concerns around the world about enormous gas emissions as well as energy issues. Thermal electric vehicles are becoming intelligent vehicles in this context, giving a possible solution to environmental challenges by improving energy efficiency and system reliability. Following this trend, pure electric vehicles powered by renewable energy sources are being proposed to optimize energy management using artificial intelligence approaches [1].

Energy storage system integration plays a critical role in processes like grid stability, reliable power supply, and pumping systems, as well as in electric vehicles with hundreds of miles of range. In order to maintain the energy balance and thereby simply improve the power quality while keeping the cost into consideration, a number of energy management approaches have been developed in the literature [2]. Battery energy storage systems have been selected as the energy storage system and implemented in many applications.

Several research of energy management systems have recently been conducted on hybrid cars. Based on numerous input variables [3], Montazeri-gh et al.[2] developed the rule to increase energy savings. It is typically advised to use a neural network (NN)-based machine learning (ML) technique to address multi-objective energy management problems. Using the sampling optimization method, Genther et al. [1] looked at the possibility of reducing the price of fuel cell automobiles.

According to the research described in [4], a novel hybrid power management system that combines an external energy reduction technique with an adaptive neuro-fuzzy inference system (ANFIS) and functions as an adaptive control system is proposed. In order to maximize the performance of an on-the-spot crossbreeding physical science system made up of an HT-PEM cell and a Li-ion battery, [5] proposes a scaling strategy. The Gray Wolf Optimizer (GWO) method was suggested by Djerioui et al. This strategy's goal is to control the fuel cell/battery hybrid power source [6]. On the other hand, Hong investigated an energy management strategy based on the dynamic tracking coefficient for hybrid vehicles; this strategy can keep the efficiency of the hybrid fuel cell power system at a high level.

The aforementioned battery-only energy storage technique has a number of drawbacks, such as a brief life cycle, a low power density, and a high cost [7]. In contrast to batteries, supercapacitors have a number of benefits including a high power density, a lengthy life cycle, and a broad operating range. By supporting the battery during times of increased power demand and extending its life, these complementary qualities can be combined in a hybrid storage system, which will ultimately increase the driving range.

For the adequate flow of energy all told parts of the electrical vehicle, the adoption of a hybrid energy storage system needs a strong energy management technique that is complete by employing a type-2 symbolic logic controller strategy [8].

The use of a type-2 fuzzy logic controller method enables a robust energy management technique, which is necessary for the sufficient flow of energy in all components of the electric vehicle [8]. This strategy is one of the best for handling the internal relationships of a complex model because of its strong nonlinearity, enormous amounts of data handled in parallel, and great robustness [9], [10]. According to our research, a fuel cell serves as the major energy source for the suggested Energy Management of Hybrid Power System fuel cell/Battery Based dc/dc converter, while batteries serve as the secondary energy source for the system.

This revised version of the article is structured as follows: in section 2, we'll go over the hybrid electric vehicle configuration and its design parameters. A brief on the modeling of the hybrid source fuel cell and battery will be introduced in Section 3. Section 4 discusses the type 2 fuzzy logic principle. The type 2 fuzzy logic-based power management is discussed in section 5. Section 6 presents the simulation results and commentary. The work done in the conclusion is summarized in Section 7. Future work in section 8.

II. Hybrid Electric Vehicle Configuration

Figure 1 depicts the schematic for the on-board hybrid power system. It is a fuel cell and battery-powered direct current power system. A DC bus is connected to the fuel cell system by a unidirectional DC/DC boost converter. The battery is connected to the DC bus by a non-isolated bidirectional DC/DC converter. The electric motor load is connected to the DC bus by a three-phase voltage inverter. The traction chain's parts will be assessed to make sure they work well together. In addition, type 2 fuzzy logic is used to distribute and manage energy between the energy sources and the traction motor and the auxiliary services of the vehicle.

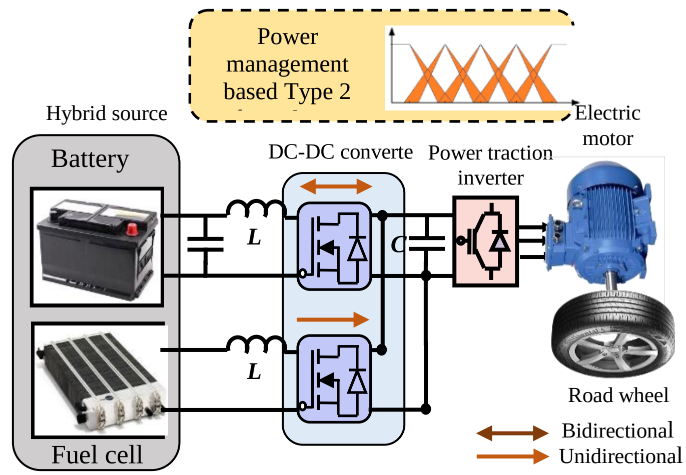

Figure 1. Configuration of the hybrid electrical vehicle's powertrain

III. Hybrid Source Modeling

A. *Model of Fuel Cell*

Since it is the best fuel cell type for transportation, the Proton Exchange Membrane Fuel Cell (PEMFC) is used in this work. The high cost and limited lifetime of fuel cells are the fundamental obstacles to their widespread commercialization [11], [12]. The electrical circuit shown in Figure 2 can be utilized as a suitable substitute to replicate the dynamical behavior of a fuel cell.

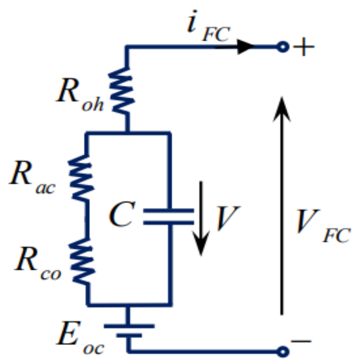

Figure 2. Electric circuit of the fuel cell

You may write the fuel cell output voltage as follows:

$$V_{FC} = E_{OC} - V - R_{oh} I_{FC} \quad (1)$$

With:

$$\frac{dV}{dt} = \frac{1}{C} I_{FC} - \frac{1}{\tau} V \quad (2)$$

Where:
V: represents the dynamical voltage across the equivalent capacitor.
C: is the equivalent electrical capacitance.
R_{oh}: is the ohmic resistance.
E_{oc}: is the open-circuit voltage.
τ: is the fuel cell electrical time constant,
It defined as follows:

$$\tau = (R_{ac} + R_{oc}) C \quad (3)$$

The fuel cell's output voltage can also be stated as follows:

$$V_{FC} = V_{cell} N_{cell} \quad (4)$$

Where:
N_{cell}: is the number of cells in the stack.

In the event of an open circuit, the fuel cell might be regarded as a source of voltage. This voltage has a perfect level that is lowered by the way it functions. The theoretically reversible voltage, also known as open circuit voltage (OCV), or ideal voltage output, E, is present inside the cell [13]. The formula for this voltage is:

$$E_{cell} = E_{0-cell} + \frac{RT}{2F} \ln\left(p^*_{H_2} \sqrt{p^*_{O_2}} R_{ac} + R_{oc} \right) - E_{d-cell} \quad (5)$$

Where:
R: is a gas constant,
T: is temperature in Kelvin,
F: is Faraday's constant,
p^*: is the partial pressure of the noted species, all of which are positive.
Furthermore,

$$E_{0-cell} = E^0_{0-cell} - k_E (T - 298) \quad (6)$$

Where:
E_{0-cell}: is the reference potential at standard temperature and pressure (298 K, 1 atm),
k_E: is a constant, both positive.
The final element of the OCV is the equation:

$$E_{d-cell} = \lambda_e i \left(1 - e^{-\frac{t}{\tau_e}} \right) \quad (7)$$

Where:
λ_e: is a constant,
i: is the cell current,
τ_e: is fuel and oxidant flow delay, all positive.

These equations are used to determine the fuel cell's stated power, abbreviated PFC, and to identify an accurate mathematical model that corresponds to it [14].

B. *The Battery Model*

The battery can be modeled by the simplified electrical diagram as shown in Figure 3.
Where:

$$V_{Bat} = E_{Bat} + R_{Bat} I_{Bat} \quad (8)$$

The battery capacity C_{Bat} can be calculated as follows [15]:

$$C_{Bat} = C_0 \frac{1.67(1 + 0.005\,\Delta T)}{1 + 0.67\left(\frac{I_{Bat}}{I_0}\right)} \quad (9)$$

The battery's charge level is indicated as [16]:

$$SOC_{Bat} = 1 - \frac{Q}{C_{Bat}} \quad (10)$$

With:

$$Q = I_{Bat} \times t \quad (11)$$

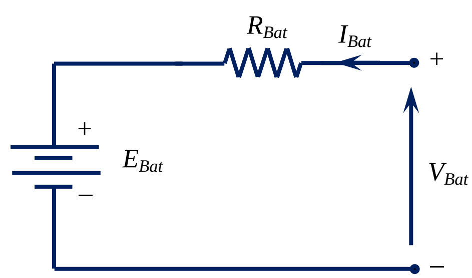

Figure. 3. Electric circuit of the battery

A static bidirectional buck-boost device [17] connects the battery on to the DC bus. Figure 4 shows the diagram of this topology with the tactic of control the battery by a customary standard setting.

As a result, the two power sources—battery and fuel cell—cooperate to satisfy the driving cycle's energy needs while also taking into account the fuel cell's capacity changes and the battery's dynamics during charging and draining [18]. The following equation links the provided and desired powers at a specific time:

$$P_{Load} = P_{Bat} + P_{FC} \quad (12)$$

Where:
P_{Load} : is the power demand of the drive cycle.
P_{FC}: is the power supply from fuel cell.
P_{Bat}: is the power supply from battery pack.

As battery efficiency varies with respect to discharge and charging of the battery, it is essential to model these two stages separately and hence study their dynamics. So, we can written as [19]:

$$P_{Load} = P_{Bat-dch}\eta_{dch} + \frac{P_{Bat-ch}}{\eta_{ch}} + P_{FC} \quad (13)$$

where:
$P_{Bat-dch}$: is the discharge power provided by the battery, which by sign convention is positive.
P_{Bat-ch}: is the charge power going into the battery, which by sign convention is negative.
η_{dch}: is the battery discharge efficiency.
η_{ch}: is the battery charge efficiency.

Similarly equation (10) is modified with respect to battery discharge and battery charge efficiency as:

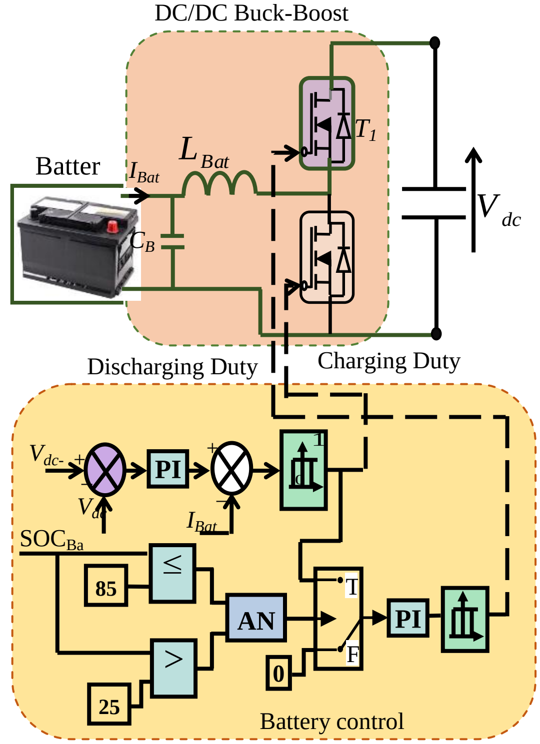

Figure 4. Battery control using a classical controller

$$SOC = 1 - \frac{P_{Bat-dch}}{Q_{Bat}}\Delta k - \frac{P_{Bat-ch}}{Q_{Bat}}\Delta k \quad (14)$$

The energy that flows out of and into the battery can be determined during each driving cycle based on the charging and discharging power. In order to determine the number of battery cycles in each simulation, this energy is compared to the battery's total energy capacity for the charging and discharging phase. The value of the total number of cycles is crucial in determining the battery's cost and remaining life [19], [20].

IV. Conception of Type-2 Fuzzy Logic Systems

A. *Type 2 Fuzzy Logic Structure*

The popularity of Type 1 FLSs prompted the creation of Type 2 FLSs based on FSs. The same fundamental elements that make up a Type 1 FLS also exist in a Type 2 FLS: a Fuzzifier, a Rule-Base, an Inference Engine, and finally an Output Processor.

In contrast to Type 1 FLS, which restart the defuzzification process in the last step, the Output Processor adds a step in the Type 2 scenario such that a Type 2 FS is first converted into a comparable Type 1 FS [21]. This strategy is put into practice using the type reduction (TR) technique, which will be covered later in this work. The interdependence of the aforementioned blocks is shown in Figure 5.

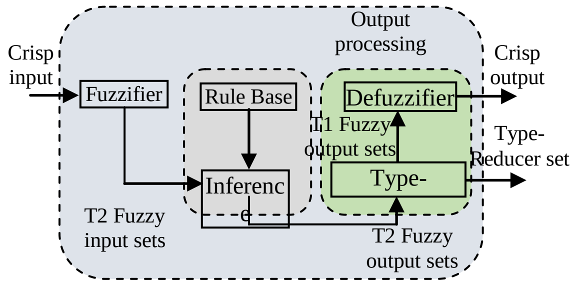

Figure 5. Topology of Type 2 Fuzzy Logic algorithm

B. *Rule Establishment of Type 2 Fuzzy Control Energy Management Strategy*

The dual-input single-output sugeno fuzzy inference model is used by the T2-FL in this work to implement fuzzy control in a power management system. This fuzzy approach is more adaptable for systems with nonlinearities, time-varying processes, hysteresis, and other complex processes [5] because it does not necessitate a precise mathematical representation of the managed system. The state of charge SOC_{Bat} of the battery pack and the required energy of the engine P_{Load} are the fuzzy controller's inputs, and the output power of the fuel cell PFC is its output.

The fuzzy logic of the power hybrid source built in this study is as follows and is based on the Sugeno fuzzy controller. For ease of control during the driving cycle, all input and output membership functions were of the trapezoidal and triangular types. It is important to guarantee the vehicle's power requirements during the entire driving operation. The working range of the hybrid multi-source should be optimized by this energy management system in order to increase the powertrain's efficiency and, consequently, the economy [22].

In order to fully use the energy stored and absorbed by the battery to increase its lifespan, the battery pack's SOC_{Bat} should be kept close to the predicted value. The output power of the fuel cell should be decreased when SOC_{Bat} is large and P_{Load} is low, and raised when SOC_{Bat} is small and P_{Load} is high. The fuzzy controller rules developed using the aforementioned ideas, as well as literature and experience, are shown in Table 1 [23]. As the approach for clarification, the area center equivalent effect is used in Figure 6, which shows the three-dimensional relationship between the input and output for this energy management system.

The power distribution between the fuel cell and the battery can be realized using the existing fuzzy control energy management approach. The designed non-uniformly distributed membership functions are depicted in Figures 7 and 8 respectively, taking into account the actual meaning of each input P_{Load} , SOC_{Bat}, and output PFC.

The following equation specifies the variation interval of the input and output quantities:

$$\begin{cases} SOC_{Bat} \in [0,1] \\ P_{Load} \in [-3,10] \\ P_{FC} \in [0,10] \end{cases} \tag{15}$$

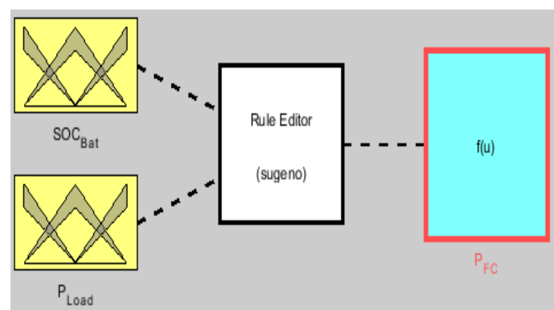

Figure 6. Final structure of fuzzy power management system

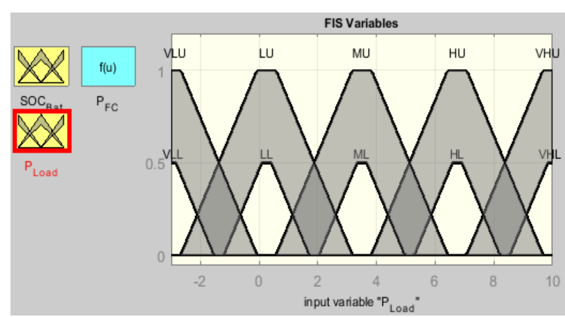

Figure 7. Input's membership function P_{Load}

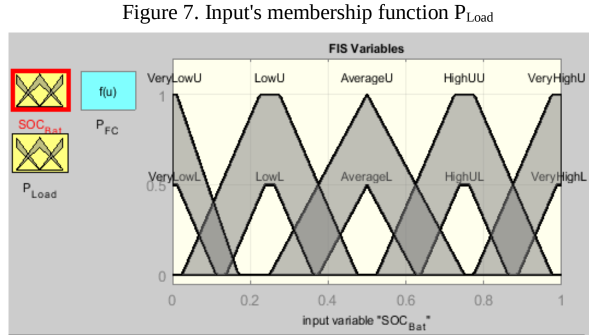

Figure 8. Input's membership function SOC_{Bat}

The T2-FLC had two inputs, power demand and SOC_{Bat}, and one FC power fraction output [24]. The user mental object is inputted within the sort of a group of rules. A rule-base is employed to tell the FLC what the output should be reckoning on a group of input conditions. All rules employed in the system are often seen in Table 1. The following examples are accustomed explain how fuzzy rules is defined using the linguistic labels in Tables 1.

If SOC_{Bat} is High and P_{Load} is Low then PFC is Medium:

– More power than necessary is provided by the fuel cell technology.

– The storage system is relatively overloaded and can also provide additional energy to meet the total demand.

If SOC_{Bat} is Very Low and P_{Load} is Average then PFC is High:

– The current values of the input and output quantities comply with the current, torque and speed limits and references.

– Then, it is necessary to ensure more energy utilizing the fuel cell to provide the motor and these accessories as well as the charging of the battery at the same time.

TABLE I. RULES FOR THE PROJECTED ELECTRIC VEHICLE'S TYPE 2 FUZZY MANAGEMENT

P_{FC}		SOC_{Bat}				
		VL	L	M	H	VH
P_{Load}	VL	M	M	L	L	VL
	L	H	H	M	M	L
	A	H	H	H	M	L
	H	VH	VH	H	H	M
	VH	VH	VH	H	H	H

C. Structure for simulation Blocks

While the vehicle is in motion, the fuel cell and the batteries provide different types of energy according to different control strategies. The battery can supply the torque demanded by the engine at start-up and this helps the fuel cell which takes a while to get ready [25]. The motor may need a relatively large instantaneous power in some cases such as the parking position of the vehicle uphill and for other reasons.

Figure 9 displays the algorithm that is integrated into the simulation model, is composed of the power limitation rule but also of all the securities. As long as the batteries have not reached a minimum discharge or maximum charging voltage limit, then the battery current will be limited between 0 A and the limiting value. Both autonomous charging and electric braking are used to recharge the batteries [26].

The sub-blocks used in the main management block are illustrated in Figure 10, these are the measurement, supervision and battery energy management block. The power management approach's major purpose is to monitor battery power generation and keep battery SOC between the minimum and most values to make sure improved charging potency.

This technology limits the fuel cell's output power within a specific range and adjusts the output power to meet the engine power demand in order to reduce power consumption [27]. The fuel cell decides whether to turn on or off based on the battery's state of charge and the power required by the load, allowing the battery to operate at peak efficiency for a prolonged period of time.

The examined system also includes numerous control loops based on a straightforward traditional PI regulator, such as the motor current limiting loop, the created torque, and currents delivered by the sources, in addition to our management method.

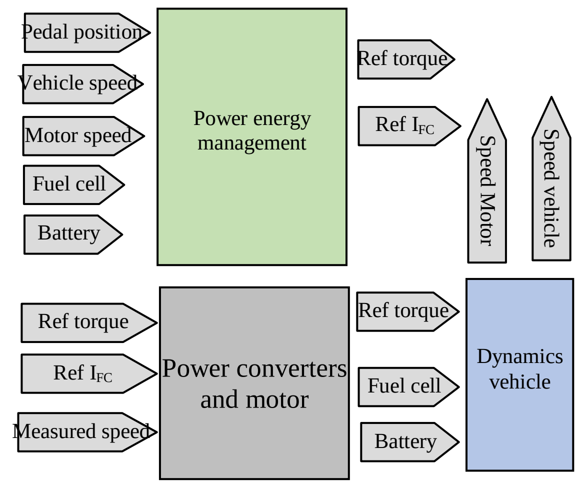

Figure 9. Schematic of global hybrid power management system

D. Power Management

With the event of large-scale hybrid electrical vehicles, energy management systems area unit thought-about to be the best artificial algorithms ever developed. The management systems embrace measuring instrumentation, acquisitions and paired computers associate degreed area unit supported by advanced management technology to make an intelligent autonomous system [28].

To meet high performance necessities all told aspects, energy management is of nice importance within the intelligent vehicle. On the one hand, with the increasing penetration level of electrical vehicles, the dispatchable energy consumption are going to be comparatively less as a result of the introduction of renewable energy has the characteristics of high uncertainty and intermittence [29], [30].

In order to realize the time period supply-demand balance between the on the market power and therefore the demanded power of a vehicle, effective methods for programming the energy generated should be designed to permit the combination of the energy resources place in situ [31]. On the opposite hand, versatile and manageable masses will act with the electrical vehicle through the intelligent system that is a crucial link to confirm time period balance [32]. Energy management within the intelligent vehicle consists of optimizing the potency of energy use by coordinating the assorted manageable units of the electrical vehicle through economical communication computer code and advanced management techniques to confirm the safe, stable, reliable and economical operation of the total electrical vehicle [33]. The flow chart of the management logic for power management is shown in Figure 11. Some logic threshold constraints mix with AN T2-FLC during this flow chart, forming AN integrated management strategy to see the mode switch between the battery and therefore the cell [34].

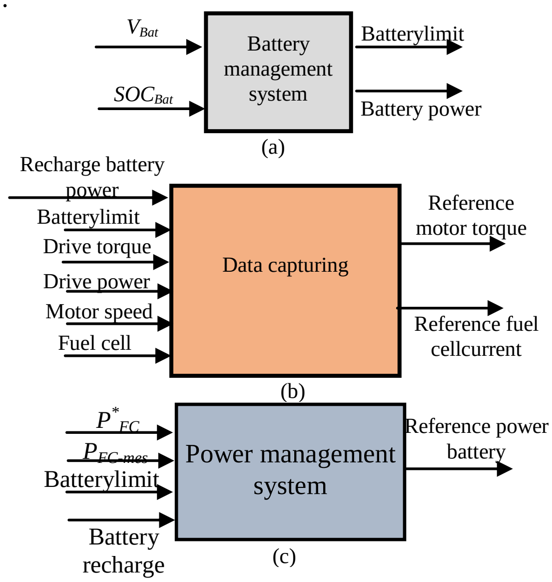

Figure 10. Schematic of global hybrid power management system, (a) battery management, (b) Data capturing, (c) power management

V. Type 2 Fuzzy Logic Power Management Strategy

An energy management approach is necessary to maximize the energy efficiency of the powertrain components while retaining a suitable quantity of energy in the storage devices. The only way to effectively reduce energy usage without sacrificing vehicle performance is to put in place an efficient control technique [35]-[37].

The system employed in this investigation is shown in Figure 1. There are two energy sources in this system: a primary source (the fuel cell) and a secondary source (the battery). In conclusion, improved energy allocation between the vehicle's engine and auxiliary services during operation and, on the other hand, not neglecting the battery's level of charge, are the first steps in achieving optimal energy management [38].

In this article, five vehicle operating modes havebeen adopted in accordance with the selected hybrid configuration.

Mode 1: during this mode, the motor operates at full power during acceleration or uphill driving since the demand for energy is highest, both switches T1 and T2 is turned OFF. The body diode of upper switch T1 starts conducting as shown in Figure 12. In this situation, both the battery and the fuel cell supply energy to the motor. It should be noted that this mode requires a fully charged battery and a full hydrogen tank [39]. This scenario, according to the following equation, can also help power the motor:

$$P_{Load} = P_{Bat} + P_{FC} \quad (16)$$

The following equations represent the relationship between the current voltage magnitudes of the mesh of the buck boost circuit for the bidirectional buck boost converter:

$$\frac{dV_{Bat}}{dt} = \frac{I_{Bat}}{C_{Bat}} \quad (17)$$

$$\frac{dV_{dc}}{dt} = \frac{V_{dc}}{R_{Bat}C_{bus}} - \frac{V_T}{R_{Bat}C_{bus}} - \frac{I_{L_{Bat}}}{C_{bus}} \quad (18)$$

Mode 2: medium speed, in this case the fuel cell has two roles depending on the power required. The first role ensures the distribution of energy to the motor and the second role is to charge the battery if the latter is less than 25% [40].

$$P_{FC} = P_{Load} + P_{Bat} \quad (19)$$

The figure 13 illustrates the mode (2) of power generation, based on the before-mentioned equations.

Mode 3: low power generation mode shown in Figure 14, at this point the battery is the storage device responsible for feeding the motor with energy [41].

The SOC_{Bat} of the battery must be greater than 85% in order to ensure the traction energy as well as the energy of the auxiliary services of the vehicle. The motor receives the converter output voltage. As this converter runs in boost mode, it has the ability to raise the battery voltage to drive the motor ahead.

$$P_{Load} = P_{Bat} \tag{20}$$

Mode 4: the regenerative braking illustrated in Figure 15, the battery absorb the energy coming from the motor, which works in this case as a generator [42]. We can write:

$$P_{Load} = -P_{Bat} \tag{21}$$

According to Figure 14, the two diodes are reverse biased and the upper switch T1 is turned ON while the bottom switch T2 is turned OFF. The converter operates in buck mode during this period. The equations that describe how the energy-recovering brake mode operates are as follows:

$$L_{Bat}\frac{dI_{L_{Bat}}}{dt} = -V_{Bat} + V_{dc} \tag{22}$$

$$\frac{dV_{dc}}{dt} = -\frac{V_{Bat}}{R_{Bat}C_{Bat}} - \frac{V_{dc}}{R_{Bat}C_{Bat}} - \frac{I_{L_{Bat}}}{C_{Bat}} \tag{23}$$

Mode 5: this mode corresponds to the shutdown of the system where the two hybrid sources are available for the maintenance check and for regeneration. The battery can be connected to an energy charger and even to other operating modes such as V2G mode (vehicle to grid) where the battery can play a dual role by charging and discharging operation. While the fuel cell can get its regeneration by charging the tank with hydrogen [43], while:

$$P_{Load} = 0 \tag{24}$$

Figure 16 shows the power management strategy used in mode (5).

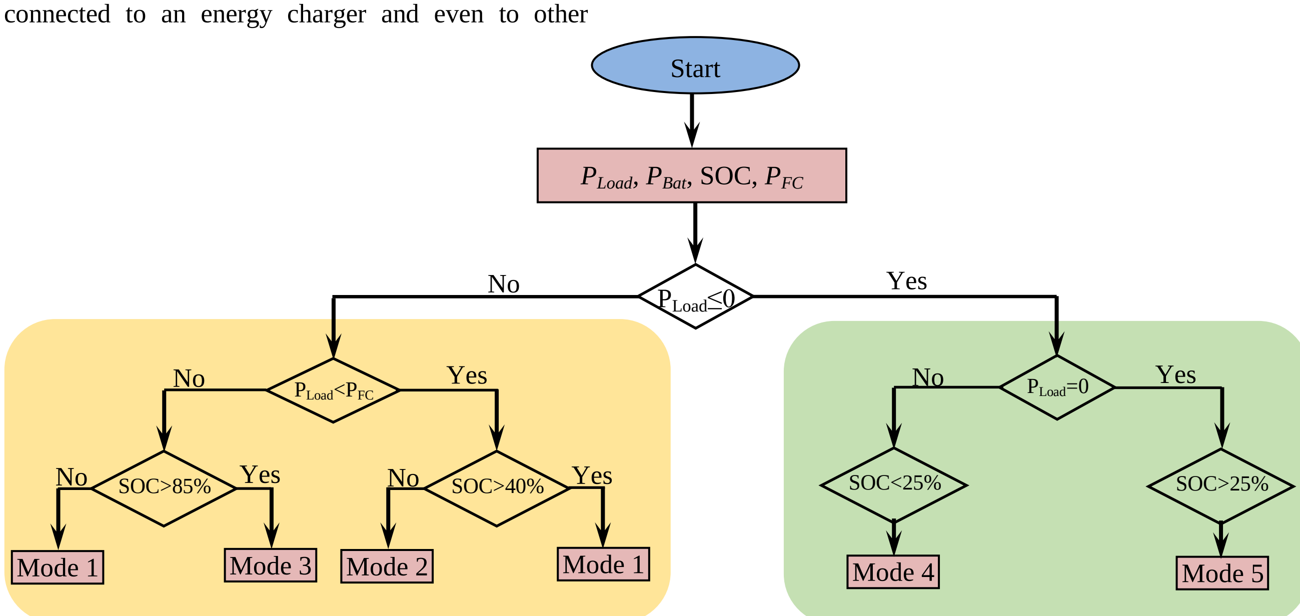

Figure 11. The procedure flowchart of T2-FLC

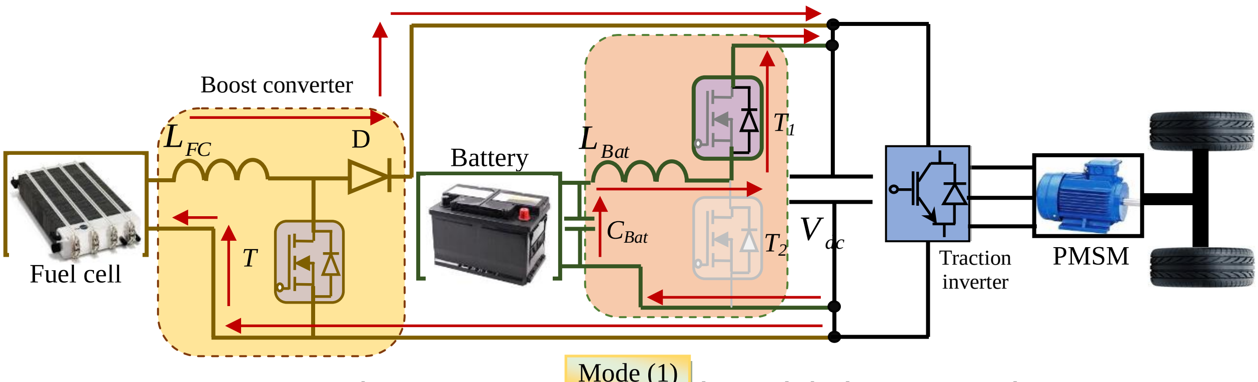

Figure 12. The power management approach utilized to provide the electric car is in Mode 1

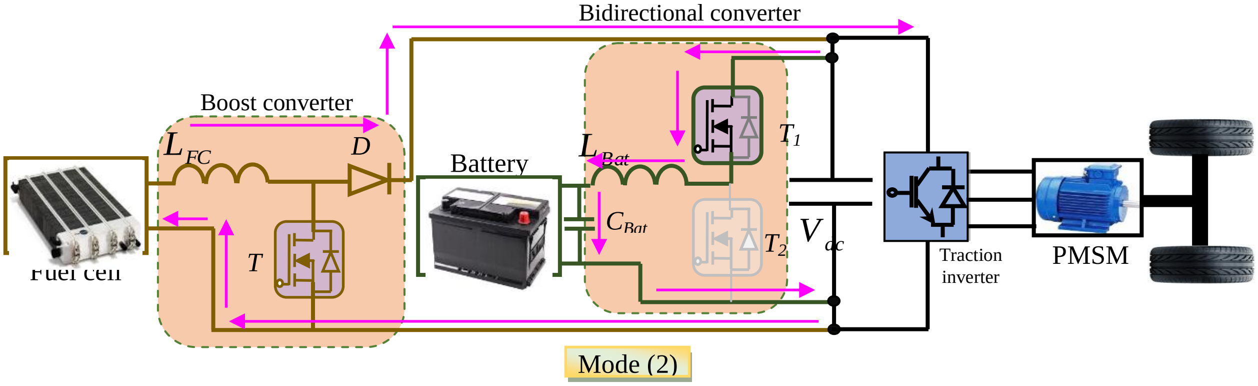

Figure 13. The second mode of the power management system was employed to supply the electric car at a medium pace

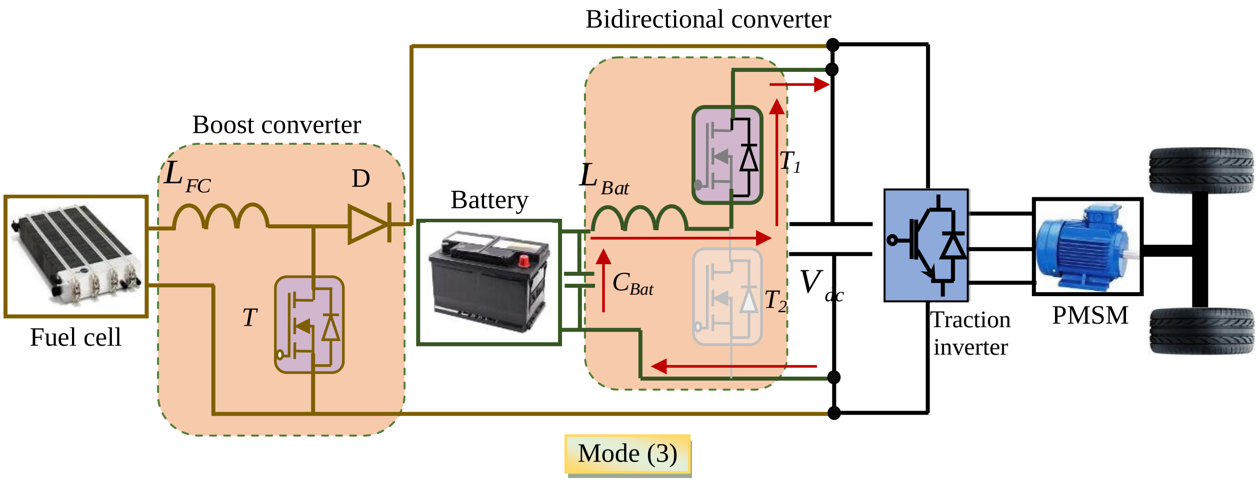

Figure 14. The electric vehicle's power management technique is in low mode

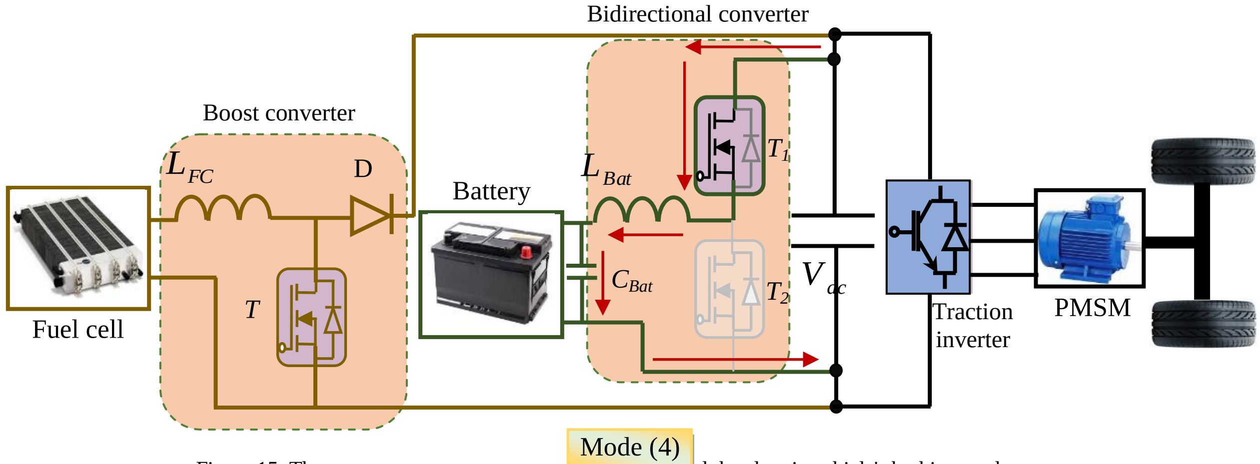

Figure 15. The power management approach utilized to fuel the electric vehicle's braking mode

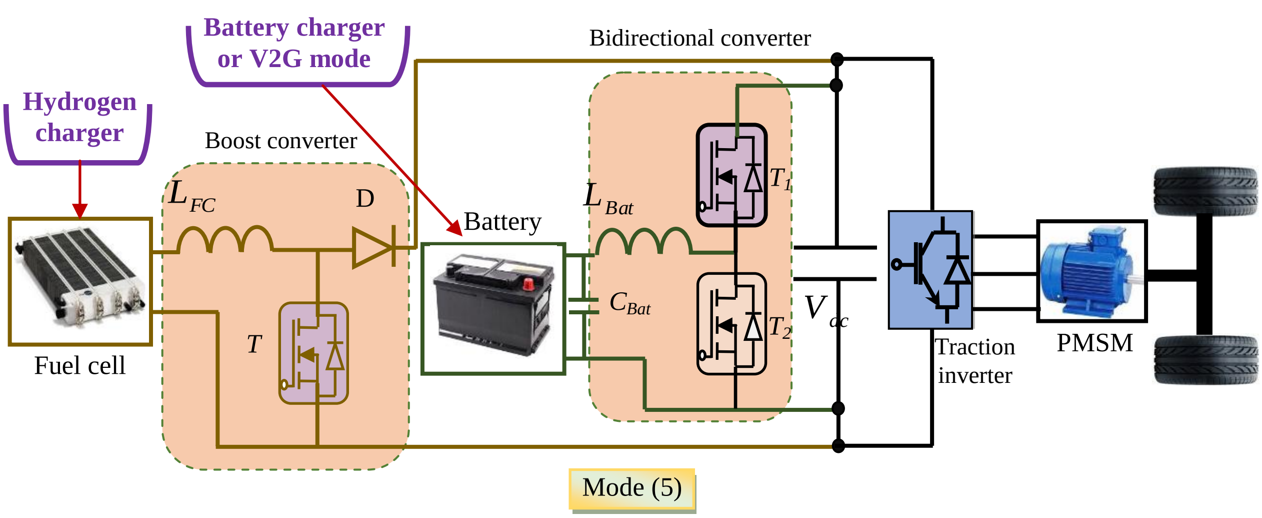

Figure 16. Modes (5) of the power management strategy used for fed the electric vehicle

VI. Simulation Results and Discussion

The suggested model has been validated under various operating scenarios pertaining to the vehicle's state and the hybrid system's characteristics. Tools from MATLAB/Simulink were used to simulate the EV model. As a result, this part provides and examines the results obtained utilizing the suggested models. It focuses on the efficiency of power control and system management, as well as the speed of the electric vehicle. Table 2 summarizes the motor, fuel cell, and battery specifications.

For the control method shown in Figure 17.a, the DC link voltage is maintained at about 240 volts. Energy management in hybrid vehicles must employ a multi-scheme operation because each technique is chosen based on crucial variables. For example, based on the real life of the input sources, management can be utilized to maximize the life of the source or lower the duty cycle of the battery and the battery. Furthermore, the management algorithm is dimensioned and validated on various driving cycles. In Figure 17.b, the DC bus current is depicted. By comparing how the bus current reacts to the motor's instantaneous power, we can see that current behaves similarly to power.

The electromagnetic torque generated by the motor is shown in Figure 18.b. The same figure also shows the motor's rotational speed. The motor speed is shown in Figure 18.c during a variety of driving cycles. This cycle represents a typical urban automobile drive. In order to observe how the hybrid sources respond to these speed changes, this driving cycle takes into account the speed of acceleration, deceleration, braking, and pausing. Figure 19 shows that the battery's state of charge is still clearly within the range that is thought to represent excellent performance. The battery and fuel cell voltage at the voltage regulators' output is shown in Figure 20 (a) and (b).

No matter how the load changes, these voltages don't change. This voltage is anchored directly to the DC bus, as you may remember. When braking, the increase in recuperation energy quickly becomes challenging to control, and the battery voltage goes above the preset limitations. It is important to take recovery energy limits into account to prevent battery overcharging. Figure 21 depicts the reference power, which consists of the electric traction motor's power as well as the power of all the vehicle's auxiliary devices, battery power, and fuel cell power output. This figure shows how the car brakes when the load is negative, even though the fuel cell PFC's output power cannot be negative. The power for the load is provided by a hybrid energy source (FC/Battery). As would be expected, the battery is the first component to respond to a reference change. In the presence of slight speed variations, battery power output remains at low levels. The contribution of the fuel cell is more needed during acceleration or braking. The frequency of the fuel cell is extremely low. In order to charge the storage system and ensure driving in the event of a significant power demand, the fuel cell raises its output at the conclusion of the cycle while the vehicle is stationary. The energy management system's contribution to the power balance is depicted in the same figure. Even if the reference and delivered power have a control delay. The simplicity of design and ease of application for real-time execution are advantages of these algorithms. The acquired findings show the effectiveness of the algorithms employed to solve these types of situations.

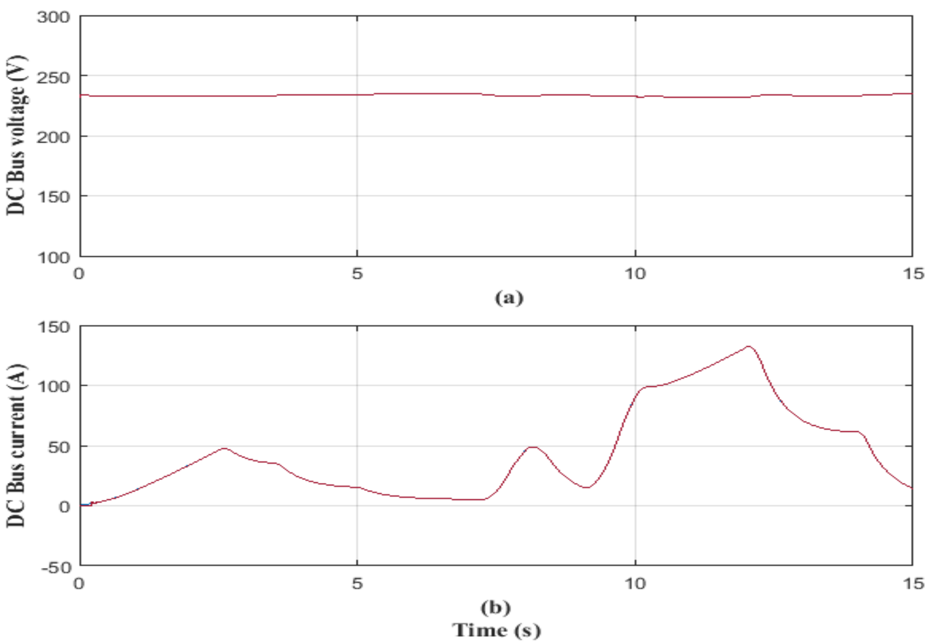

Figure 17. Characteristics of DC bus, (a) voltage, (b) current

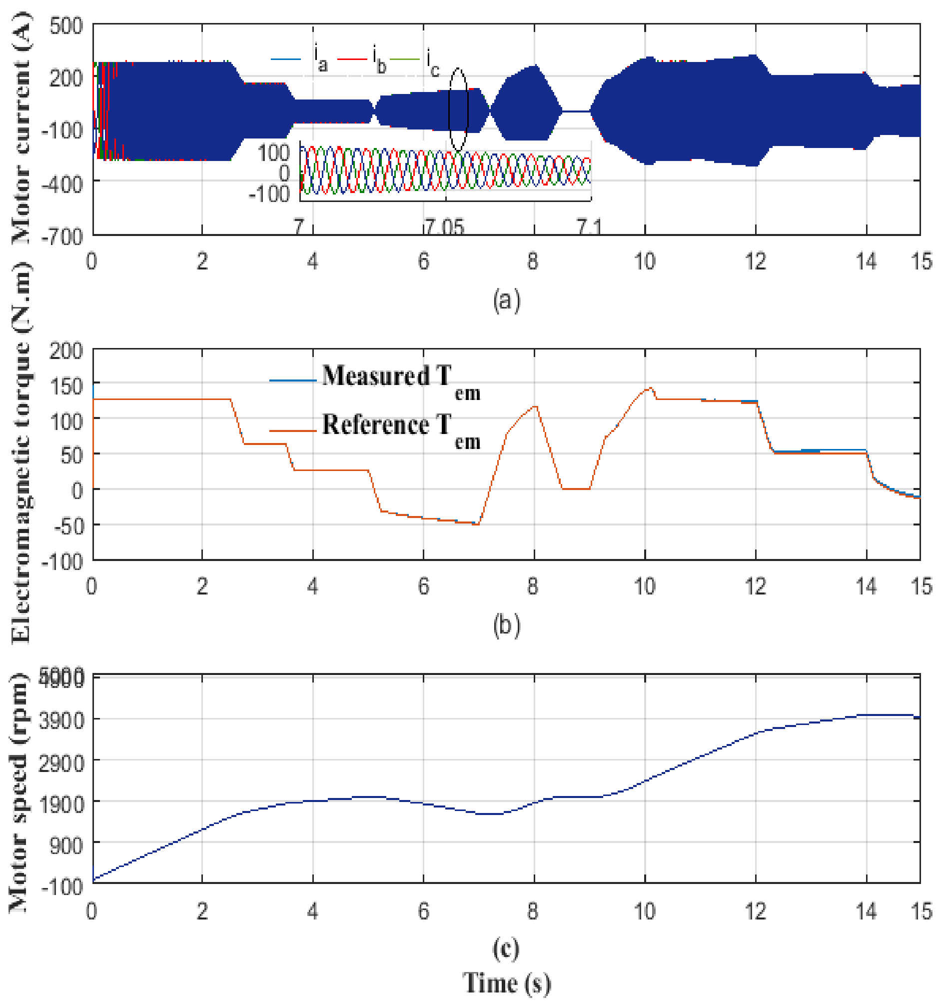

Figure 18. Motor characteristics, (a) motor stator currents, (b) Electromagnetic torque developed by the motor, (c) Mechanical motor speed

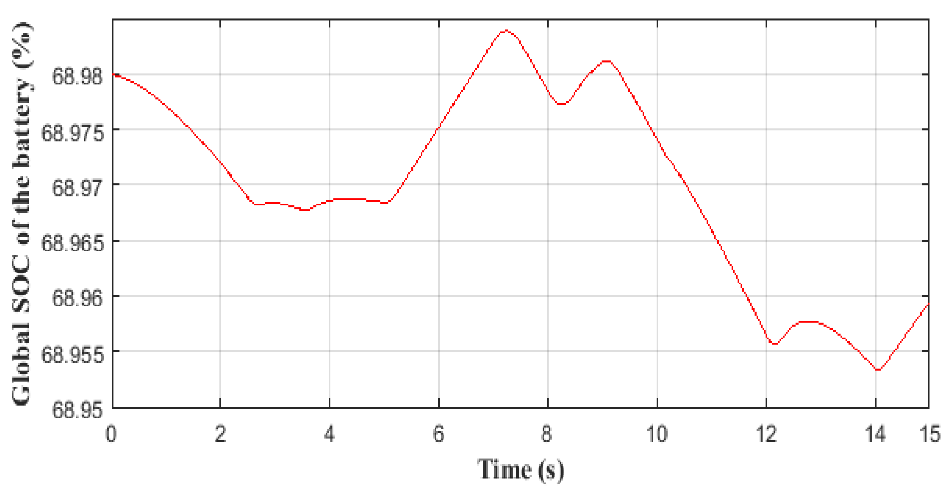

Figure 19. Battery status of charge response

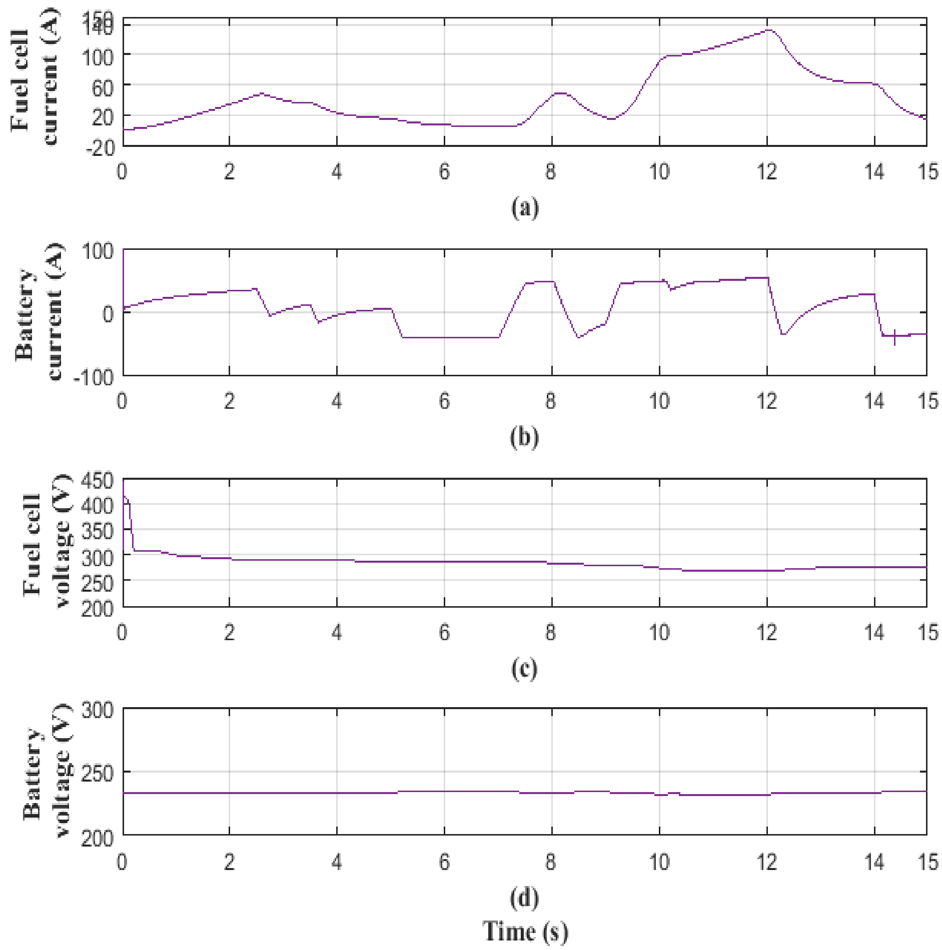

Figure 20. Electrical characteristics of hybrid sources, (a) fuel cell current, (b) battery current, (c) fuel cell voltage, (d) battery voltage

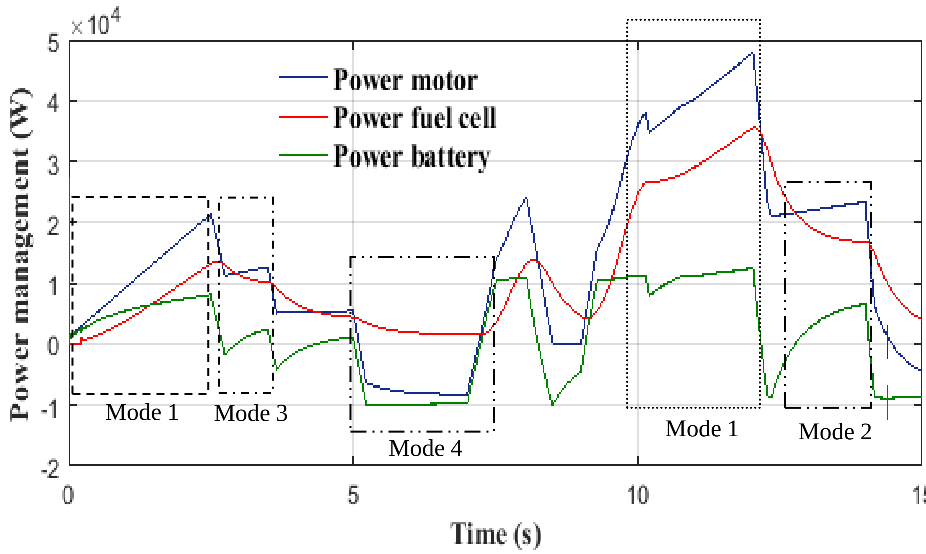

Figure 21. Fuel cell and battery power delivering the requested load

VII. Conclusion

This study focused on creating a type 2 fuzzy logic controller-based intelligent power management system for a fuel cell and battery-powered hybrid electric car. Due to its connection to language variables, T2-FLC avoids the need for mathematical models and is simple for consumers to understand. Additionally, it is simple to deploy in real-time on a test platform for experimental electric vehicles.

Because the battery can be continuously charged during driving cycles or in the event of electric braking, the FLC strategy is used to organize the operation of energy sources according to demand. The battery can provide enough power for the motor during start-up, and the fuel cell comes into operation and charges the battery after a brief delay. It can serve as a primary source to meet energy needs and it can recharge batteries, which are regarded as secondary sources.

The designed power management system's primary goal is to limit SOCBat fluctuation in order to lengthen battery life and lower component power losses. The power controller makes sure that the brake and accelerator pedal inputs from the driver are consistently satisfied, that the battery is sufficiently charged throughout driving cycles, and that the hybrid vehicle's fuel usage is maximized.

The energy management tactics of hybrid fuel cell and battery vehicles are better suited to the T2-FLC methodology. The simulation findings are good, and the suggested technique can be utilized on a real-world model and as a guide for similar research. The work carried out in this article opens up new avenues for future work which concern various strategies for real-time a reinforcement learning algorithm that selects adequate actions on vehicle parameters in real time to optimize both driving and comfort.

VIII. Future Work

In future works, can possibly add the supercapacitor in energy storage system to get better results, especially in terms of efficiency and performance.

Besides, can add other parameters as: state of charge of supercapacitor in to power management system for better results.

References

[1] Koulali, M., Mankour, M., Negadi, K., & Mezouar, A. (2019). Energy management of hybrid power system PV Wind and battery based three level converter. TECNICA ITALIANA-Italian Journal of Engineering Science, 63(2-4), 297-304.

[2] Corcau, J. I., Dinca, L., Grigorie, T. L., & Tudosie, A. N. (2017, June). Fuzzy energy management for hybrid fuel cell/battery systems for more electric aircraft. In AIP Conference Proceedings (Vol. 1836, No. 1, p. 020056). AIP Publishing LLC.

[3] Luca, R., Whiteley, M., Neville, T., Shearing, P. R., & Brett, D. J. (2022). Comparative study of energy management systems for a hybrid fuel cell electric vehicle-A novel mutative fuzzy logic controller to prolong fuel cell lifetime. International Journal of Hydrogen Energy, 47(57), 24042-24058.

[4] Bissey, S., Jacques, S., & Le Bunetel, J. C. (2017, May). La logique floue au coeur d'un algorithme d'optimisation de la consommation d'énergie électrique d'une habitation individuelle. In Conférence des Jeunes Chercheurs en Génie Electrique (JCGE).

[5] Belhadj, S., Belmokhtar, K., & Ghedamsi, K. (2019). Improvement of energy management control strategy of fuel cell hybrid electric vehicles based on artificial intelligence techniques. Journal Européen des Systèmes Automatisés, 52(6), 541-550.

[6] Araria, R., Berkani, A., Negadi, K., Marignetti, F., & Boudiaf, M. (2020). Performance analysis of DC-DC converter and DTC

based fuzzy logic control for power management in electric vehicle application. Journal Européen des Systèmes Automatisés, 53(1), 1-9.

[7] Nair, N., Gasbaoui, I., & Ghazouani, A. E. K. (2018, May). An Efficiency Fuzzy Logic Controller Power Management for Light Electric Vehicle Under Different Speed Variation. In IFIP International Conference on Computational Intelligence and Its Applications (pp. 106-118). Springer, Cham.

[8] Pérez-Pimentel, Y., Osuna-Galán, I., Avilés-Cruz, C., & Villegas-Cortez, J. (2018). Power supply management for an electric vehicle using fuzzy logic. Applied Computational Intelligence and Soft Computing, 2018.

[9] Xin, W., Zheng, W., Qin, J., Wei, S., & Ji, C. (2021). Energy management of fuel cell vehicles based on model prediction control using radial basis functions. Journal of Sensors, 2021.

[10] Antão, R. J. M. M. (2016b). Type-2 fuzzy logic: uncertain systems' modeling and control. Ria.ua.pt. http://hdl.handle.net/10773/18041

[11] Valverde, L., Rosa, F., Bordons, C., & Guerra, J. (2016). Energy management strategies in hydrogen smart-grids: a laboratory experience. international journal of hydrogen energy, 41(31), 13715-13725.

[12] Stanton, K., Lai, J. S. J., & Nelson, D. Dynamic PEM Fuel Cell Model for Power Electronics Design with Temperature Consideration. Unpublished.

[13] Jbari, H., Askour, R., & Idrissi, B. B. (2022). Fuzzy logic-based energy management strategy on dual-source hybridization for a pure electric vehicle. International Journal of Electrical & Computer Engineering (2088-8708), 12(5).

[14] Mohamed, N., Aymen, F., Altamimi, A., Khan, Z. A., & Lassaad, S. (2022). Power Management and Control of a Hybrid Electric Vehicle Based on Photovoltaic, Fuel Cells, and Battery Energy Sources. Sustainability, 14(5), 2551.

[15] Belhaj, F. Z., El Fadil, H., El Idrissi, Z., Intidam, A., Koundi, M., & Giri, F. (2021). New Equivalent Electrical Model of a Fuel Cell and Comparative Study of Several Existing Models with Experimental Data from the PEMFC Nexa 1200 W. Micromachines, 12(9), 1047.

[16] Mtolo, S. N., & Saha, A. K. (2021). A Review of the Optimization and Control Strategies for Fuel Cell Power Plants in a Microgrid Environment. IEEE Access.

[17] Karthikeyan, V., Tiwari, A. K., & Kandasamy, C. (2022). Real time hardware implementation of discrete sliding mode fuzzy controlled buck converter using digital signal processor. International Journal of Electrical & Computer Engineering (2088-8708), 12(5).

[18] Jarry, T., Lacressonnière, F., Jaafar, A., Turpin, C., & Scohy, M. (2021). Modeling and Sizing of a Fuel Cell—Lithium-Ion Battery Direct Hybridization System for Aeronautical Application. Energies, 14(22), 7655.

[19] Carignano, M., Roda, V., Costa-Castelló, R., Valiño, L., Lozano, A., & Barreras, F. (2019). Assessment of energy management in a fuel cell/battery hybrid vehicle. IEEE access, 7, 16110-16122.

[20] Reddy, N. P., Pasdeloup, D., Zadeh, M. K., & Skjetne, R. (2019, June). An intelligent power and energy management system for fuel cell/battery hybrid electric vehicle using reinforcement learning. In 2019 IEEE transportation electrification conference and expo (ITEC) (pp. 1-6). IEEE.

[21] Wahib, A., Samir, G., Hatem, A., & Abdelkader, M. (2019). Energy management strategy of a fuel cell electric vehicle: Design and implementation. International Journal of Renewable Energy Research (IJRER), 9(3), 1154-1164.

[22] Li, Q., Chen, W., Li, Y., Liu, S., & Huang, J. (2012). Electrical power and energy systems energy management strategy for fuel cell/battery/ultracapacitor hybrid vehicle based on fuzzy logic. Fuel Cell, 43, 514-525.

[23] Li, D., Xu, B., Tian, J., & Ma, Z. (2020). Energy management strategy for fuel cell and battery hybrid vehicle based on fuzzy logic. Processes, 8(8), 882.

[24] Araria, R., Negadi, K., & Marignetti, F. (2019). Design and analysis of the speed and torque control of IM with DTC based ANN strategy for electric vehicle application. Tecnica-Ital J Eng Sci, 63, 181-188.

[25] Araria, R., Negadi, K., Boudiaf, M., & Marignetti, F. (2020). Non-linear control of dc-dc converters for battery power management in electric vehicle application. Przegląd Elektrotechniczny, 96.

[26] Xun, Q., Liu, Y., & Holmberg, E. (2018, June). A comparative study of fuel cell electric vehicles hybridization with battery or supercapacitor. In 2018 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM) (pp. 389-394). IEEE.

[27] Li, Q., Chen, W., Liu, S., You, Z., Tao, S., & Li, Y. (2012). Power management strategy based on adaptive neuro-fuzzy inference system for fuel cell-battery hybrid vehicle. Journal of Renewable and Sustainable Energy, 4(1), 013106.

[28] Ferrara, A., Okoli, M., Jakubek, S., & Hametner, C. (2020). Energy management of heavy-duty fuel cell electric vehicles: Model predictive control for fuel consumption and lifetime optimization. IFAC-PapersOnLine, 53(2), 14205-14210.

[29] Showers, S. O., & Raji, A. K. (2022). State-of-the-art review of fuel cell hybrid electric vehicle energy management systems. AIMS Energy, 10(3), 458-485.

[30] Badji, A., Abdeslam, D. O., Becherif, M., Eltoumi, F., & Benamrouche, N. (2020). Analyze and evaluate of energy management system for fuel cell electric vehicle based on frequency splitting. Mathematics and Computers in Simulation, 167, 65-77.

[31] Mohamed, N., Aymen, F., Ali, Z. M., Zobaa, A. F., & Abdel Aleem, S. H. (2021). Efficient power management strategy of electric vehicles based hybrid renewable energy. Sustainability, 13(13), 7351.

[32] Habib, M. (2015). Rule-Based Energy Management Strategy Optimized Using PSO for Fuel Cell/Battery Electric Vehicle. International Journal on Energy Conversion (IRECON), 3(1).

[33] Hu, X., Liu, S., Song, K., Gao, Y., & Zhang, T. (2021). Novel Fuzzy Control Energy Management Strategy for Fuel Cell Hybrid Electric Vehicles Considering State of Health. Energies, 14(20), 6481.

[34] Ghaderi, R., Kandidayeni, M., Soleymani, M., Boulon, L., & Chaoui, H. (2020). Online energy management of a hybrid fuel cell vehicle considering the performance variation of the power sources. IET Electrical Systems in Transportation, 10(4), 360-368.

[35] Al-Flehawee, M., & Al-Mayyahi, A. (2022). Energy management for hybrid electric vehicles using rule based strategy and PI control tuned by particle swarming optimization algorithm. International Journal of Electrical & Computer Engineering (2088-8708), 12(6).

[36] Surgenor, B. W., Salah, M., Abdelhafez, E., Hamdan, A., & Hamdan, M. Performance Comparison For Hybrid Fuel Cell/Battery Vehicle Utilizig Different Power Management Control Strategies.

[37] Motapon, S. N., Dessaint, L. A., & Al-Haddad, K. (2013). A comparative study of energy management schemes for a fuel-cell hybrid emergency power system of more-electric aircraft. IEEE transactions on industrial electronics, 61(3), 1320-1334.

[38] Liu, J., Wang, Z., Hou, Y., Qu, C., Hong, J., & Lin, N. (2021). Data-driven energy management and velocity prediction for four-wheel-independent-driving electric vehicles. eTransportation, 9, 100119.

[39] Xiao, W., Wang, L., Liu, D., & Zhang, W. (2019, October). An optimized energy management strategy for fuel cell hybrid vehicles. In IOP Conference Series: Materials Science and Engineering (Vol. 612, No. 4, p. 042088). IOP Publishing.

[40] Li, Y., Deng, X., Liu, B., Ma, J., Yang, F., & Ouyang, M. (2022). Energy management of a parallel hybrid electric vehicle based on Lyapunov algorithm. eTransportation, 100184.

[41] Saib, S., Hamouda, Z., & Marouani, K. (2017, October). Energy management in a fuel cell hybrid electric vehicle using a fuzzy logic approach. In 2017 5th International Conference on Electrical Engineering-Boumerdes (ICEE-B) (pp. 1-4). IEEE.

[42] Zhang, H., Qin, Y., Li, X., Liu, X., & Yan, J. (2020). Power management optimization in plug-in hybrid electric vehicles subject to uncertain driving cycles. eTransportation, 3, 100029.

[43] Xin, W., Xu, E., Zheng, W., Feng, H., & Qin, J. (2022). Optimal energy management of fuel cell hybrid electric vehicle based on model predictive control and on-line mass estimation. Energy Reports, 8, 4964-4974.

APPENDIX

TABLE II. PARAMETERS OF BATTERY BACK, FUEL CELL AND ELECTRIC MOTOR

Parameters	Symbol	Values
Battery		
Battery voltage	V_{bat}	216 V
Rated capacity	Q	150 Ah
Rated power	P_{bat}	50 kW
Fuel cell		
Type	PEMFC	------
Electric motor		
Motor	PMSM	------
Pole pairs	P_p	4
Resistance of stator	R_s	0.0083 Ω
Flux linkage	ψ	0.0711 Wb
d axis inductance	L_d	0.000174 H
q axis inductance	L_q	0.000292 H
Inertia moment	J	0.003 kg.m^2
Viscous friction	f	0.0002 N.m.s^2