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Energy management strategy for Fuel cell hybrid electric vehicle using fuzzy logic control

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Abstract: Fuel cell hybrid electric vehicles have gained widespread recognition as one of the most promising transportation applications due to its zero emissions, minimal noise, and high efficiency. This study proposes a fuel cell-based hybrid electric vehicle energy management approach. Lithium-ion batteries are used as a backup energy source. Our suggested strategy is grounded in fuzzy logic and tries to reduce hydrogen consumption while enhancing the robustness of power sources by taking into account both the battery's state of charge and their dynamic constraints. The fuel cell power is produced by the fuzzy logic controller using the load power and battery state of charge as inputs. The simulation model of the hybrid electric vehicle and its energy management strategy are established using MATLAB/Simulink. The simulation results show the correct functioning of our model.

Keywords- **Energy management, Hybrid vehicle, Fuel cell, Fuzzy logic, DC/DC converter, Ultra capacitor, Battery.**

I. INTRODUCTION

Decarbonizing transportation is turning out to be one of the biggest challenges the international automotive industry is currently facing. This is because of a number of factors, such as the rise in greenhouse gas and particulate emissions that not only affect the climate but also people, the rise in pollution, the rapid depletion of oil, issues with energy security and dependence on foreign sources, and population growth. There is an urgent need for significant advancements in low and ultra-low carbon technology and vehicles.

Road vehicle electrification will be crucial in the development of low-carbon transportation options, and a longer-term technology is probably going to utilise hydrogen as an energy vector [7].

While a fuel cell hybrid vehicle (FCHV) is in use, a fuel cell serves as the primary power source, with a battery or ultra-capacitor serving as the auxiliary power source. The FCHV has made extensive use of this hybrid power distribution technique. As a result, much study has been done on the hybrid power distribution mode of FCHV, with their main areas of interest being the energy management strategy of controlling the fuel cell system and energy storage system.

The fundamental difficulty with hybrid vehicles is balancing the power from the fuel cell and the auxiliary power source(s). To solve this problem, an Energy Management System (EMS) is required for efficient energy transmission from the power drive to the wheels. EMS maintains and regulates fuel usage, enhances performance, and extends the life of FCHEVs [2].

The main benefits of fuel cells include decreased greenhouse gas emissions, high reliability, flexibility in installation and operation, development of renewable energy sources, decreased demand for foreign oil, and improved environmental quality.

Due to its simplicity and efficiency in real-time control, the fuzzy logic technique is employed in this study to put various energy management tactics into practise and boost FCHV's economy and optimize their dynamic performance.

II. ENERGY MANAGEMENT SYSTEMS

In the literature, numerous researchers have proposed a variety of EMSs. According to optimization theory EMSs can be classified as rule based EMSs and optimization based EMSs. The rule-based EMSs include the deterministic rule-based EMSs and the fuzzy ruled based EMSs. Deterministic rule-based EMSs are usually designed through the methods, which include lookup tables, filter-based control (FBC), and wavelet transform. Deterministic rule-based EMS designed through look-up tables are used to control the operating point of energy sources. The main feature of the strategy is to set the operating points of devices according to load demand and devices operating states. Filter based EMSs are considered as one of the simplest control strategies due to its superior robustness and low computation complexity [1]. Similar to FBC, wavelet-based energy management strategies control power allocation by frequency division. Although rule-based EMSs are frequently utilised, their effectiveness mostly depends on the expertise and engineering background of the researchers.

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System control can be developed linguistically using fuzzy control (FC). Relative to other control applications, FC is provided as a method to obtain an EMS for FCHEVs fairly regularly. The system's freedom may be to blame for this. FC essentially defines input-output relations as static, nonlinear relations. Nonetheless, dynamics can be taken into account by referring to variables as a quantity of stored energy or a rate of change. The State of Charge (SOC) of the battery, the SOC of the ultra-capacitor (UC), and the load power requirement are all included in the proposed FC systems. UC maintains DC bus voltage at desired value [2]. Fuzzy controller gives reference power correction for battery bank and fuel cell power. The nonlinear nature of fuzzy controller is used to reduce voltage ripple on power converter level.

III. HYBRID ELECTRIC VEHICLE ARCHITECTURE AND MODELS

This hybrid HEV system employs two energy sources and exchanges power through a DC bus, as shown in Fig. 1. A unidirectional DC/DC buck converter is used to link the main source, a fuel cell, to a DC bus. To maintain a steady DC voltage, a secondary source of lithium-ion battery is used and coupled to the DC bus via a bidirectional converter. With their high power density and ability to store readily available energy, UC is connected to the DC bus using a bidirectional converter. This helps to keep batteries below safe resistive heating limits and prolong the life of the BT [3].

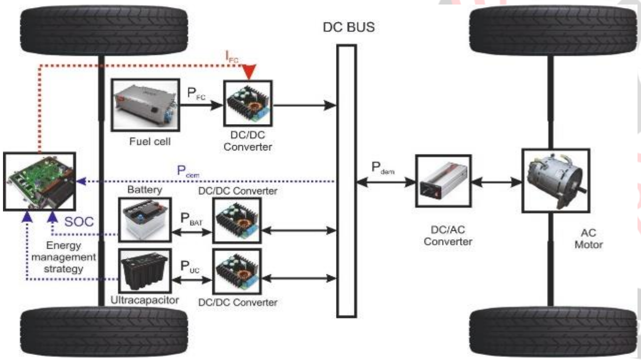

Fig.1: Architecture of the fuel cell hybrid electric vehicle.

The vehicle is propelled by a synchronous permanent magnet motor (PMSM) supplied by a DC bus through an inverter.

For split power demanded by the load efficiently taking into account the characteristics of each source to increase their lifetime and minimize fuel consumption, an energy management strategy based on fuzzy logic is developed.

Electric Vehicle Model

All the forces acting on a vehicle in motion is represented in Fig.2. The equation that represents the dynamic of the vehicle is presented as follows [5].

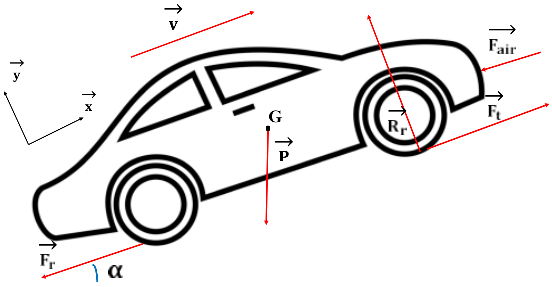

Fig. 2: Forces applied to the vehicle.

The aerodynamic force $\overrightarrow{Fair}$ affects the performance of the vehicle during the acceleration along the x axis according the equation (1).The gravitational force $\vec{P}$ and the resistance of the wheels on the floor $\overrightarrow{Fr}$ are also given by the equations (2) and (3) respectively [5].

$$\overrightarrow{F_{\text{air}}} = -\frac{1}{2}\rho_{\text{air}} V^2 A C_x \vec{x} \dots\dots\dots\dots (1)$$

$$\vec{P} = -M_v g \sin\alpha \vec{x} \dots\dots\dots\dots\dots (2)$$

$$\overrightarrow{F_x} = -P C_x \cos\alpha \vec{x} \dots\dots\dots\dots\dots.. (3)$$

From the Fig.2, we observe that the equation of F_t is taken only on the x axis, so according to the preceding equations, we can present the mechanical tensile force F_t by the expression as follow:

$$F_t = M_v \frac{dv}{dt} + \frac{1}{2}\rho_{air} V^2 A C_x + M_v g \sin\alpha + M_v g C_r \cos\alpha \dots\dots\dots. (4)$$

The expression of the motor power P_m required to advance the vehicle is given by the equations (5) and (6).

$$P_m = v.F_{\text{t}} \dots\dots\dots\dots\dots\dots\dots\dots (5)$$

$$P_m = v\left(M_v \frac{dv}{dt} + \frac{1}{2}\rho_{air} V^2 A C_x + M_v g \sin\alpha + M_v g C_F \cos\alpha\right) \dots\dots\dots (6)$$

Battery model

In this work, we use the lithium-ion battery because of its better response compared to other types of batteries, long lifetime and its wide use in transport. The battery is modeled using a simple controlled voltage source in series with a constant resistance, as shown in Fig.3 [5].

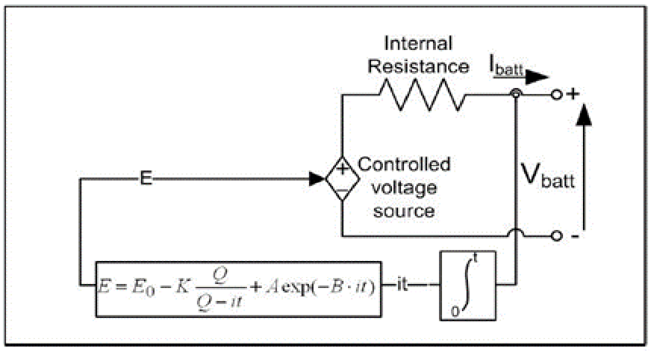

Fig. 3: Non-Linear battery model.

The parameter (V_{batt}) figured in the Fig.3 can be calculated

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by two different equations. If the current is positive, then the battery is in discharge mode as shown in equation (7) and if the current is negative, the battery is in charge mode described by equation (8).

$$V_{\text{diacharge}} = E_0 - R.i - K \frac{Q}{Q-it} \cdot (it + i^*) + A\exp(-B.it) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

$$V_{\text{eharge}} = E_0 - R.i - K\frac{Q}{it - 0.1Q} \cdot i^* - K\frac{Q}{Q-it}.it + A\exp(-B.it) \ldots\ldots\ldots (8)$$

The SOC of battery is determined using equation (9)

$$SOC_{\text{bett}} = 100\left(1 - \int \frac{i_{(0)}dt}{Q}\right) \qquad \ldots\ldots\ldots\ldots\ldots\ldots(9)$$

Fuel cell model

The fuel cell is an electrochemical device that generates electrical energy and heat through a chemical reaction. The advantages of fuel cells over the incumbent technologies are numerous, for example, high energy efficiency, the electrical energy is produced without pollutant emissions, low noiselevels and good performance [3].

Fig.4 shows the model of the fuel cell available in MATLAB/ Simulink. This model consists of three blocks (A, B, C) and an electrical part consisting of internal resistance, a diode, and a variable voltage source.

The fuel cell total voltage and total power are expressed respectively by equations (10) and (11).

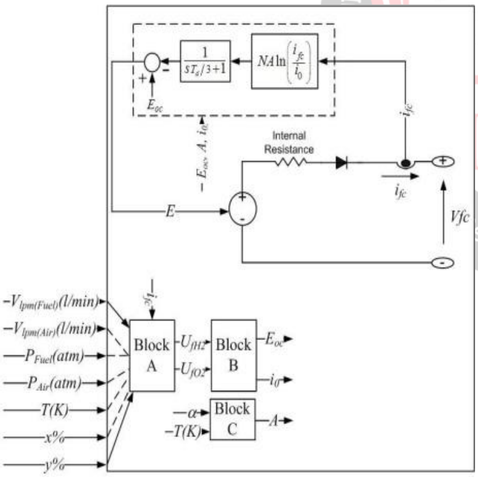

Fig. 4: Model of the fuel cell

$$Vfc = Ncell.Vcell \qquad (10)$$

$$P_{fc} = V_{fc}.I_{fc} \qquad (11)$$

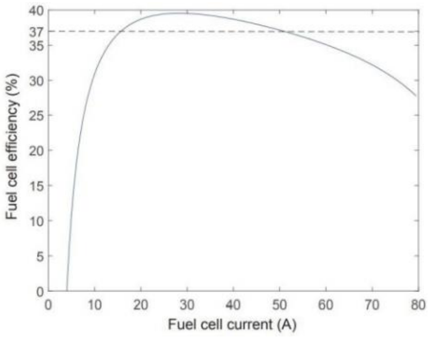

Fig. 5: Fuel cell efficiency curve.

The flow rates of oxygen and hydrogen are calculated respectively by equations (12) and (13) in block A.

$$U_{O_2} = \frac{60000RTNI_{fc}}{zFP_{air}V_{lpm(air)}O_2\%} \ldots\ldots\ldots (12)$$

$$U_{H_2} = \frac{60000RTNI_{f}c}{zFP_{f\text{ uel}}V_{lpm(f\text{ fuel})}H\%} \ldots\ldots (13)$$

Block B calculate the values of the open circuit voltage (E_{oc}) and the exchange current (i_0) Block C calculate the value of the slope A.

The Fig.5 shows the fuel cell efficiency curve. This curve is characterized by a maximum efficiency zone.

Thus, in order to reduce the consumption of hydrogen it is interesting to use the fuel cell within this maximum efficiency zone.

DC/DC converter model

The fuel cell is connected to the DC bus via a unidirectional DC/DC boost converter. The structure of the boost converter is represented in Fig.6 [5].

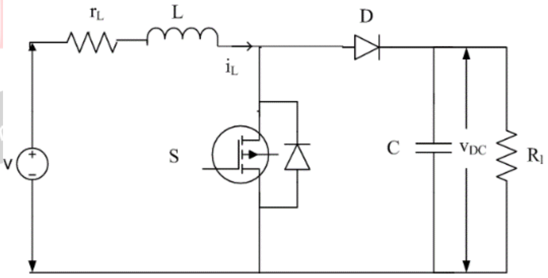

Fig. 6: DC/DC boost converter.

DC/AC inverter model

The electrical machine type used in this work is a permanent magnet synchronous motor (PMSM). It is more and more used in electric vehicles due to the high power density, high efficiency, and it's used as motor or generator depending on the torque imposed by the drive cycle of the vehicle.

The PMSM is supplied through a DC bus by a DC/AC inverter which is controlled by EMS signals [9].

UC system model

The UC is chosen as a second energy source because of its considerably high power densities and its unlimited number of charge/discharge compared to the battery. Moreover, it is robust and maintenance free [6]. The model of a UC cell equivalent circuit illustrated in Fig. 7 is composed of a capacitance C $_{cell}$, a series resistance r_s corresponding to the charge and discharge resistance, a parallel resistance r_p consisting of the self-discharge losses.

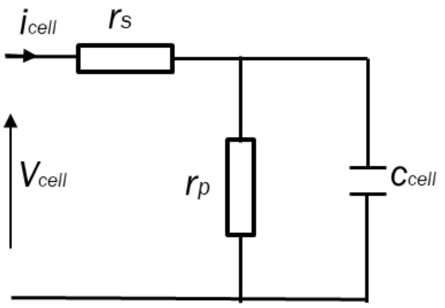

Fig. 7: Equivalent circuit of UC bank.

The modelling of the UC units is detailed by the following equations:

$$V_{\text{cell}} = r_s i_{cell} + \frac{1}{C_{cell}} \int \left(i_{cell} - \frac{V_{C_{cell}}}{r_p} \right) \ldots\ldots\ldots.(14)$$

$$V_{UC} = n_{UC} V_{cell} \ldots\ldots\ldots\ldots\ldots(15)$$

IV. FUZZY LOGIC CONTROL

Fuzzy Logic Control (FLC) provides a way of dealing with imprecision and nonlinearity in complex control situations. The special features of a FLC make it perfectly suitable for the power management in a FCHEV. One of the main reasons to use fuzzy logic is that FCHEV control has a highly nonlinear behaviour and identifying a proper mathematical model of the overall system presents serious difficulties. The FLC algorithm should manage the hybrid power system according to the load profile and efficient operation. FLC can be used for these purposes by examining different inputs. These inputs together with the fuzzy rules generate the desired control signals. The operation of the control strategy can be split into three different function blocks: 1) Satisfy the load demand. 2)

Ensure the stability of the dc-link voltage and mitigate its fluctuations. 3) Control the SOC of the UC bank and BT bank.

Membership Functions

Fig. 8 and 9 illustrate the membership functions of the input and output. Input variables are Load power and SOC, output Variables are Battery power correction term and FC reference power

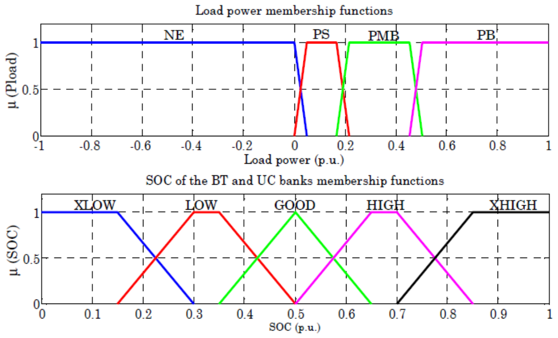

Fig.8: Input Membership Function

The FC system power is 0.8 KW when it is OFF, 7.78 KW (average value of the non negative component of the EUDC power demand) when AV, 18 KW when MED and 30 KW when MAX. The hold functions keep the FC system operation unmodified. The BT power correction term is mapped in the physical domain using a constant value. This parameter is calculated as a function of the energy change in the UC bank from the point in which it has a SOC equal to 0.2 or 0.8 to the one in which the SOC is 0.5. It has been assumed that the total energy could be recovered or consumed in 7.5 s

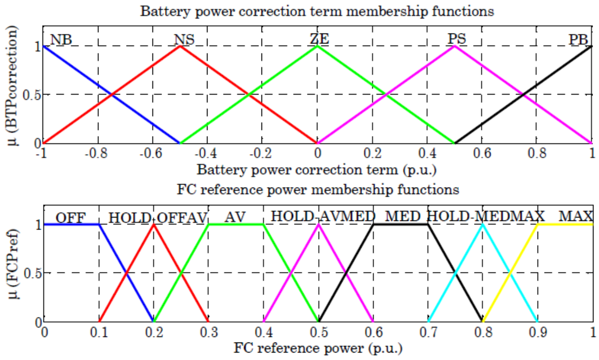

Fig.9: Output Membership Function

Rules definition

The rules specified in the FLC comply with the following priority order [9]:

- The SOC of the UC bank must always be “Good” (this power source should be able to deliver or absorb energy in every situation). If the SOC of the UC bank is “Good”, the stability of the dc-link voltage is ensured.
- Minimize the changes in the FC system operation.
- Store as much energy as possible coming from the load in regenerative operation.
- The response time of the two sources must be low;
- Protect the battery against deep-discharge, by using the fuel cell to charge the battery at acceptable levels.

Protect the battery against overcharging because of repeated braking, by limiting the battery charge and using it to support the fuel cell during high power

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demands of the load.

		SOC		
		L	M	H
Pdem	N	VL	VL	VL
	ZE	L	VL	VL
	L	L	VL	VL
	M	M	L	VL
	H	H	M	L

.

Table 1: Rules of Fuzzy Logic Control

- Reduce hydrogen consumption through minimal use of the fuel cell.

The last step in FLC process is the de-fuzzification, which consists to convert the fuzzy value to non- fuzzy output. Fig 10 shows the detailed representation of the controller together with the input and output variables

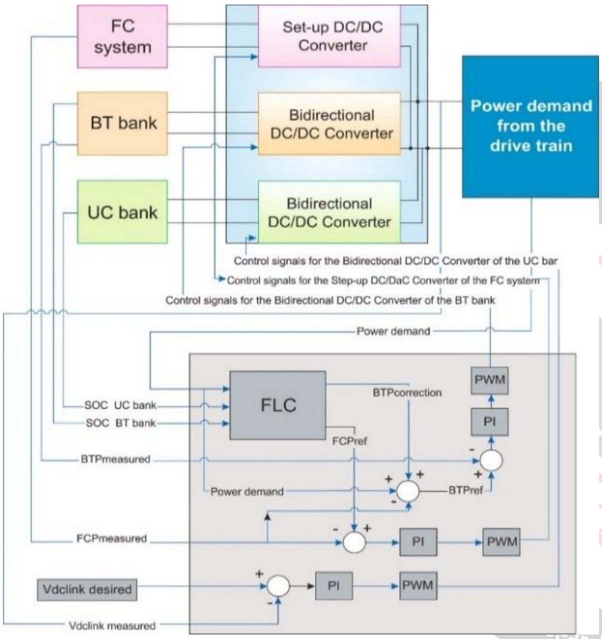

Fig. 10. Detailed representation of the controller

V. RESULTS

For simulation of electric propulsion system of the vehicle we have consider one fuel cell with 30 kW of power, a 30 kW rechargeable battery pack, five 48 V and 165 F ultra-capacitor units connected in series, a power distribution unit (PDU), a unidirectional converter for connecting the fuel cell to the PDU, a bidirectional converter to connect the UC and battery to the PDU, a 24 V auxiliary battery charger (2 × 12 V), a main battery charging module from 230 V (AC), two 33 kW electric motors mounted on the rear wheels, two motor inverters, Command and control modules for the propulsion system. For simulation purpose we have consider Extra Urban Driving Cycle (EUDC) driving cycle. Complete simulation is executed in Matlab/ Similink. The maximum step size of the solver is set to 10 μs for reliable operation.

Experimental results are shown in Fig.11,12 and 13 which shows the power distribution among FC, UC and BT with respect to load power demand.

Each figure consists of four plots. First plot shows power demand based on EDUC cycle and vehicle speed. Second plot shows power consumed from each source. Third and fourth plot shows voltages and currents of respective sources. From the results we observed that the extra-urban cycle driving autonomy was 2 h 50 min at an average speed of 70 km/h. The maximum imposed speed was 120 km/h.

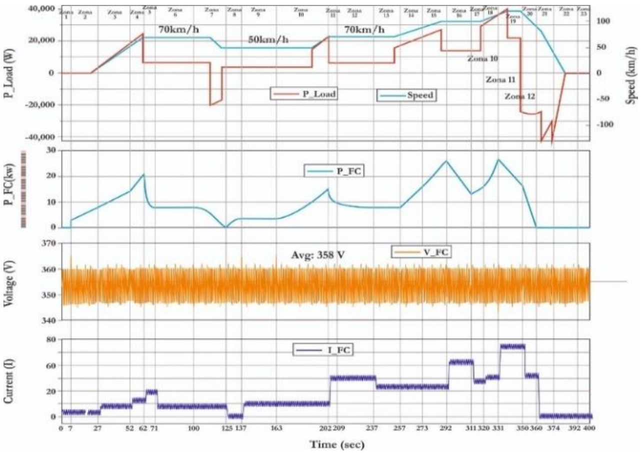

Fig. 11 Power consumption for Ultra-capacitor for load power demand coverage on EUDC

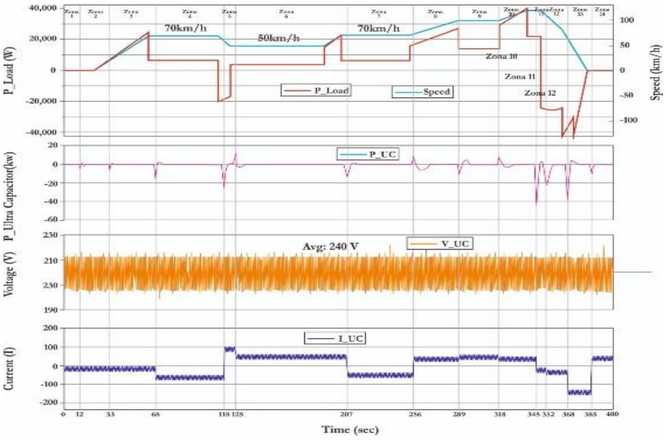

Fig 12. Power consumption for Fuel cell for load power demand coverage on EUDC

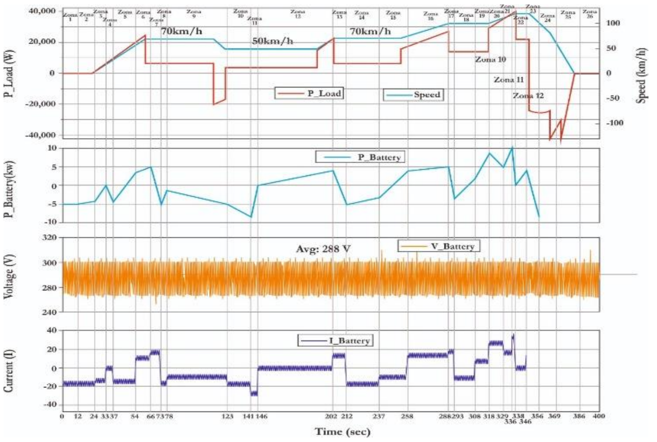

Fig.13 Power consumption for Battery for load power demand coverage on EUDC

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VI. CONCLUSIONS

In this study a FC, UC and BT power train with fuzzy logic based energy management strategy is proposed. This hybrid power-train exhibits a satisfactory performance under EUDC driving cycle. The FC is considered a primary source in whole system and BT bank is secondary source. Therefore BT bank is able to recover the energy coming from regenerative breaking or supply power when the power demand is positive and greater than FC system. On the other hand UC bank takes care of the DC link voltage stability by supplying fast variation transient and peak power when the two other sources are not able to meet the power requirements.

With the help of FLC we are able to satisfy power demand of FCEV at the same time SOC of BT and UC is maintained within acceptable limits. DC link is satisfied around its desired value and the energy recovered is maximized.

The findings given here help to further technological understanding and provide a practical answer to the problem of energy management in a hybrid fuel cell electric vehicle.

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