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Fuzzy Logic-based Energy Management System in Hybrid Electrical Vehicle

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Abstract - Hybrid electrical vehicles (HEVs) are becoming more popular because of their high efficiency, lower cost, and pollution-free characteristics. Hybrid power sources are important for powering the vehicle for long run driving. Energy management is a critical issue in electrical vehicles that operate on hybrid power sources. An artificial intelligence based algorithms have shown significant contribution in the efficient EMSs for hybrid electrical vehicles. This article presents a Fuzzy logic-based EMS in the hybrid electrical vehicle that uses fuel cells, batteries, and internal combustion engines as the power sources. The proposed system provides efficient control of power flow in HEV based on the current battery state of charge (SOC), different vehicle dynamics and driving conditions. The suggested fuzzy management strategy shows the simple, reliable and efficient control of energy management in of the hybrid power source.

Keywords - Hybrid Electrical Vehicle, Fuzzy Logic, Energy Management, Battery Management

INTRODUCTION

The enormous increase in the global population and increase in living standards in developing countries leads to the increase in automobile vehicles. However, traditional vehicles operated on diesel/petrol are becoming less efficient and less popular because of the shortage of fossil fuel and the increase in air pollution caused by emission of hazardous gases. The traditional inter combustion engine-based vehicles emits CO2 which is the main root of global warming and air quality degradation. Recently, electrical vehicles have shown huge growth because of their pollution-free nature, lower cost, and efficiency. Still, deployment of the fully electric vehicle is challenging because of limited distance traveling capacity. In a single charge of the battery, the current electric vehicle can run about 150-200km which limits the driving capability of the vehicle for long-distance travel. Hybrid electric vehicles use a combination ICE and electrical power source for powering the vehicle to improve the HEV performance in critical conditions. The size and number of batteries is a major barrier in HEV, therefore researchers have focused on allied compact power sources for HEV along with batteries [1-3].

Several initiatives associated with fuel cells and their usage have been launched in recent years in the hunt for a clean car that protects the environment. Hydrogen is gaining traction as a viable alternative to conventional energy sources utilized in vehicles, such as gasoline. The fuel cell, which is powered by hydrogen, a renewable energy source, emits no emissions and has a high energy efficiency [4-5]. As a result, it can be regarded a renewable and sustainable energy source that helps to reduce greenhouse gas emissions.

The desire to reduce detrimental emissions of co2 and greenhouse gases has prompted the development of electric and hybrid vehicles that are fueled by non-polluting sources, particularly fuel cells. Fuel cells are currently widely employed in electric vehicles due to their high energy density, relatively low temperature, and, most importantly, excellent efficiency [6]. However, because of their slow dynamic, fuel cells are not always capable of responding to quick variations in the power supply when utilized as the sole source. For these

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reasons, especially in light of the vehicle's energy behavior and the fuel cell's dynamic characteristics, it will be necessary to integrate at least two sources of energy: one primary and one secondary [7-9].

As a result, it is necessary to use supplementary resources like batteries or ultra-capacitors. The major source is the fuel cell, whereas the auxiliary source is an energy storage device such as a super-capacitor, battery, or a combination of the two [10]. The storage system, which is employed as an auxiliary source in an HEV, should fulfill numerous functions. In reality, it enables the storage of energy and the reduction of losses during braking and repetitive descents. The storage system offers extra power to the primary source during accelerations and as a reversible source [11]. Various hybrid designed architectures of hybrid vehicles, as well as the accepted EMSs developed for each structure, have been the subject of numerous studies [12-13]. This perspective sheds light on the significance of EMS for multi-source vehicles. As a result, EMSs might be based on offline approaches with a specified mission profile [14] or online approaches with an uncertain velocity profile [15-16].

The fundamental goal of an EMS in a hybrid electric vehicle (HEV) is to attain power demand with the least amount of fuel, the least amount of pollution, and the best possible vehicle performance. The complicated construction of HEVs leads in difficulty in EMS. EMSs are important in assessing HEV fuel economy since they can properly forecast the power distribution of the engine and motors [17]. Fuzzy Rule-based EMSs are reliable and troublefree to set up. It can deal with both verbal and statistical data at the same instance. The settings of fuzzy logic control (FLC) are simple to alter, giving it a great degree of control freedom. Conventional, predictive, and adaptive fuzzy control are the three types of fuzzy rule-based EMS [18]. For the parallel HEV, Bathaee et al. [19] introduced a fuzzy-based torque controller. The desired battery SOC and ICE torque are used to determine the ICE operational points. Li et al. [20] introduced an FLC-based system for determining the power division between the ice and the battery so that the HEV engine can run efficiently and emit less pollution. Further, a fuzzy logic based EMS was utilized to determine the operation points of the engine and motor in the PHEV. It resulted in lower fuel usage as well as lower CO, CO2, HC, and NOx emissions [21]. EMSs for battery/ultra-capacitor electrical vehicles with multi-input converters based on fuzzy controller and rate limiter were presented by Akar et al. [22]. The battery's level of charge is regulated by a fuzzy controller, which smoothes the battery's power profile.

This article presents an efficient energy management scheme using a Fuzzy logic algorithm that selects the proper power source for the hybrid electric vehicle. The major contributions of this article are described as follow:

- Design of hybrid electrical vehicle models with hybrid power sources such as battery, FC and Internal combustion unit.
- Implementation of efficient control of hybrid power sources based on battery SOC, vehicle dynamics and different driving conditions for EMS for hybrid electrical vehicle.

The remaining article is structured as follows: Section II provides the details about the proposed energy management scheme of hybrid electrical vehicle. Section III focuses on the investigational results and discussions. Finally, section IV elaborates conclusions and future scope.

PROPOSED METHODOLOGY

The flow diagram of the proposed EMS scheme for HEVs is shown in Fig. 1. The proposed system provides the control of the fuel cell for the electrical vehicle based on the battery SOC and load power profile. While computing the load power profile various driving conditions and environmental conditions are considered such as the mass of the vehicle, airspeed, road inclination, ICE parameters, etc.

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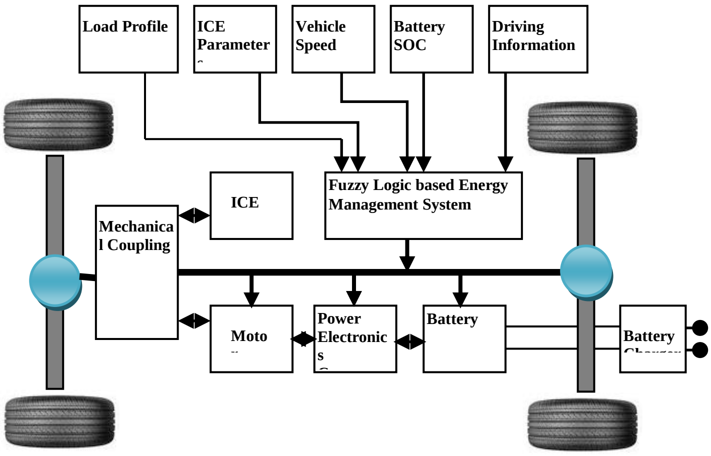

Fig. 1 Flow diagram of the proposed system

The Fuel Cell Stack block provides a generic model that represents hydrogen and air-fueled fuel cell stacks. The graphic below depicts an electrical model of a fuel cell that runs on a fuel flow rate. A basic model and a comprehensive model are the two blocks that make up the stack model. To transition between the two models, choose the level in the mask under Model detail level in the block dialogue box. The simulink model and corresponding circuit for the fuel cell are illustrated in Fig 2 and3.

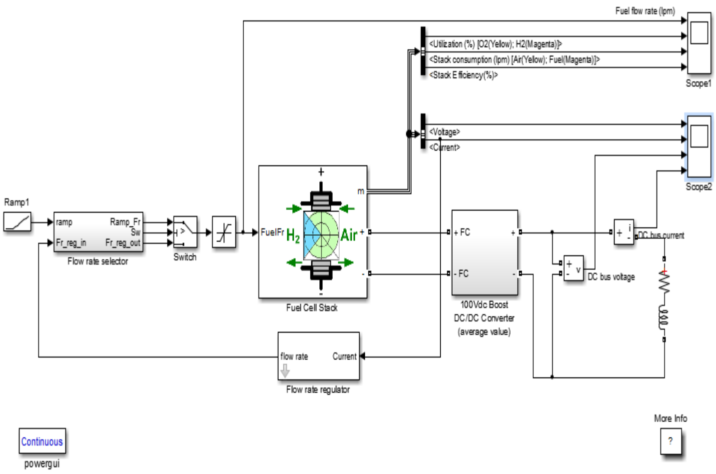

Fig. 2 Modellig of Fuel cell

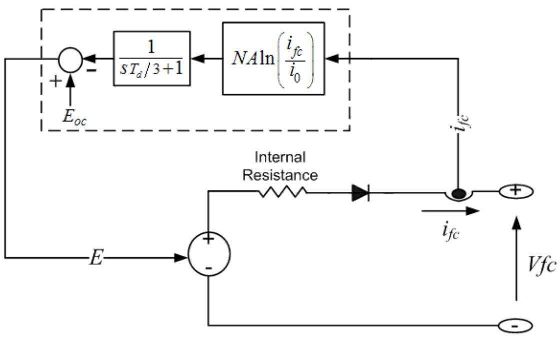

Fig. 3. Fuel cell equivalent circuit

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The performance of the single FC cell based on single FC current, voltage and power relationships is given in Fig. 4.

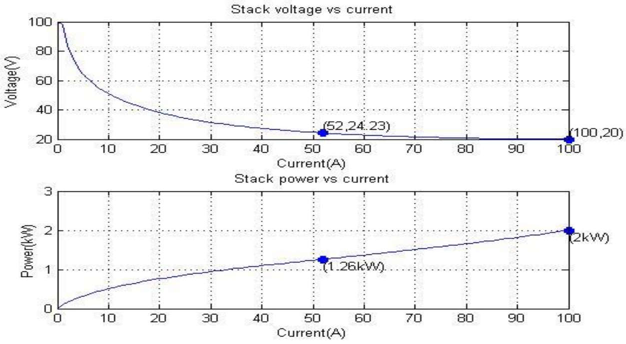

Fig. 4 Performance curve for single FC

The parameter selected for the simulation of the FC are described in the Table 1. The proposed system consider stack of 8 FCs to fulfill the power requirement.

Table 1: fuel cell simulation parameters

Parameter	**Specification**
Type of cell	Proton Exchange Membrane Fuel Cell (PEMFC)
Number of Cells	8
Nominal Stack efficiency (%)	55%
Voltage range	98- 100v
Working temperature (Celsius)	65 degree
Nominal Air flow rate (lpm)	300
Nominal air supply pressure (bar)	1 bar
Nominal fuel supply pressure (bar)	1.5 bar
H2	99.92%
O2	21 %
H2O	1 %

The battery block provides a generic dynamic model that characterizes rechargeable batteries. The battery specifications are given in table 2.

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Table 2. Battery specifications

Parameter	Value
Nominal Discharge Current (d)	1.3 A
Internal Resistance	2 mΩ
Rated Capacity	6.5 Ah
Nominal Voltage (a)	1.18 V
Maximum Capacity (b)	7 Ah (5.38 h * 1.3 A)
Exponential Capacity (e)	1.3 Ah
Nominal Voltage (a)	1.18 V
Capacity @ Nominal Voltage (a)	6.25 Ah
Exponential Voltage (e)	1.28 V
Fully Charged Voltage (c)	1.39 V

Equation 1 and 2 are used for modeling of the lithium-ion battery type considering charging (i*<0) and discharging (i*>0) mode.

$$f_1(it, i*, i) = E_0 - K\frac{Q}{Q-it}i* - K\frac{Q}{Q-it}it - A.e^{-B.it} \quad (1)$$

$$f_1(it, i*, i) = E_0 - K\frac{Q}{Q-0.1Q}i* - K\frac{Q}{Q-it}it - A.e^{-B.it} \quad (2)$$

The range of various input and output variables considered for energy management of HEV such as SOC, upload, and PFC are given in Table 3-4. Total twenty rules are constructed for the control action generation of fuzzy logic-based energy management of HEV as given in Table 5.

TABLE 3. INPUT VARIABLES FOR FUZZY BASED EMS FOR HEV

Input Variable	Level	Range (%)
SOC	VL	0-40
	L	30-60
	M	50-80
	H	70-100
Pload	N	-1000-0
	VL	0-500
	L	400-1000
	M	900-1500
	H	1400-2000

The membership equations for the battery SOC are described in Equations 3-6. The SOC is split into different variables such as very low (VL), Low (L), medium (M), and high (H) with trapezoidal membership function (TMF).

$$SOC_{VL}(x) = \begin{cases} 1 & 0 \le x \le 30 \\ \frac{40-x}{10} & 30 < x \le 40 \end{cases} \quad (3)$$

$$SOC_L(x) = \begin{cases} \frac{x-30}{15} & 30 \le x45 \\ \frac{60-x}{10} & 50 \le x \le 60 \\ 1 & 45 \le x \le 50 \end{cases} \quad (4)$$

$$SOC_M(x) = \begin{cases} \frac{x-50}{10} & 50 \le x \le 60 \\ 1 & 60 \le x \le 70 \\ \frac{80-x}{10} & 70 \le x \le 80 \end{cases} \quad (5)$$

$$SOC_H(x) = \begin{cases} \frac{x-70}{10} & 70 \le x \le 80 \\ 1 & 80 \le x \le 100 \end{cases} \quad (6)$$

The membership equations for the Load demand (PLoad) are described in Equations 7-11. The upload is divided into different variables such as no-load (N), very low (VL), Low (L), medium (M), and high (H) with trapezoidal TMF.

$$PLoad_N(x) = \begin{cases} 1 & -1000 \le x \le 0 \\ \frac{50-x}{50} & 0 \le x \le 50 \end{cases} \quad (7)$$

$$\mathrm{PLoad}_{VL}(x) = \begin{cases} \frac{x-50}{50} & 0 < x \le 50 \\ 1 & 50 \le x \le 400 \\ \frac{500-x}{100} & 400 \le x \le 500 \end{cases} \quad (8)$$

$$\mathrm{PLoad}_L(x) = \begin{cases} \frac{x-450}{50} & 450 < x \le 500 \\ 1 & 500 \le x \le 800 \\ \frac{1000-x}{200} & 800 \le x \le 1000 \end{cases} \quad (9)$$

$$\mathrm{PLoad}_M(x) = \begin{cases} \frac{x-900}{1000} & 900 < x \le 1000 \\ 1 & 1000 \le x \le 1400 \\ \frac{1500-x}{100} & 1400 \le x \le 1500 \end{cases} \quad (10)$$

$$\mathrm{PLoad}_H(x) = \begin{cases} \frac{x-1400}{100} & 1400 < x \le 1500 \\ 1 & 1500 \le x \le 2000 \end{cases} \quad (11)$$

TABLE 4. OUTPUT VARIABLES FOR FUZZY BASED EMS FOR HEV

Output Variable	**Level**	**Range (W)**
PFC	Z	0-100
	L	50-300
	M	250-500
	H	450-650

The membership equations for the FC power control variable (PFC) are described in Equations 12-15. The upload is divided into different variables such as zero (Z), Low (L), medium (M), and high (H) with TMF.

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$$PFC_Z(x) = \begin{cases} 1 & 0 \le x \le 50 \\ \dfrac{80 - x}{30} & 50 \le x \le 80 \end{cases} \quad (12)$$

$$PFC_L(x) = \begin{cases} \dfrac{x - 50}{50} & 50 < x \le 100 \\ 1 & 100 \le x \le 200 \\ \dfrac{300 - x}{50} & 250 \le x \le 300 \end{cases} \quad (13)$$

$$PFC_M(x) = \begin{cases} \dfrac{x - 250}{50} & 250 < x \le 300 \\ 1 & 300 \le x \le 450 \\ \dfrac{500 - x}{50} & 450 \le x \le 500 \end{cases} \quad (14)$$

$$PFC_H(x) = \begin{cases} \dfrac{x - 400}{100} & 400 < x \le 500 \\ 1 & 500 \le x \le 650 \end{cases} \quad (15)$$

TABLE 5. RULES FOR FUZZY BASED EMS FOR HEV

Fuzzy Rule Base		
Input		***Output***
SOC	***Pload***	***PFC***
VL	N	Z
VL	VL	L
VL	L	M
VL	M	H
VL	H	H
L	N	Z
L	VL	L
L	L	M
L	M	M
L	H	H
M	N	Z
M	VL	Z
M	L	L
M	M	L
M	H	M
H	N	Z
H	VL	Z
H	L	Z
H	M	L
H	H	L

SIMULATION RESULTS AND DISCUSSIONS

The anticipated system is simulated using MATLAB R2018b on the personal computer having a core i5 processor with 2.84 GHz speed and 8GB RAM. The schematic of the anticipated EMS system is illustrated in Fig. 5.

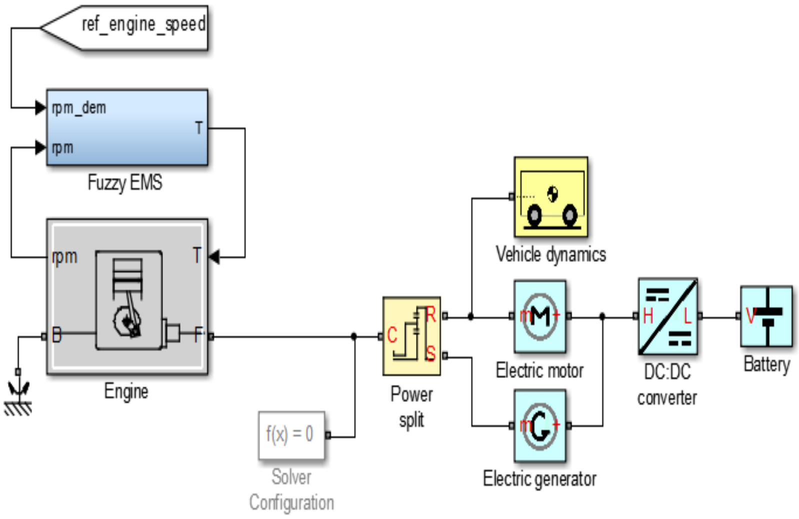
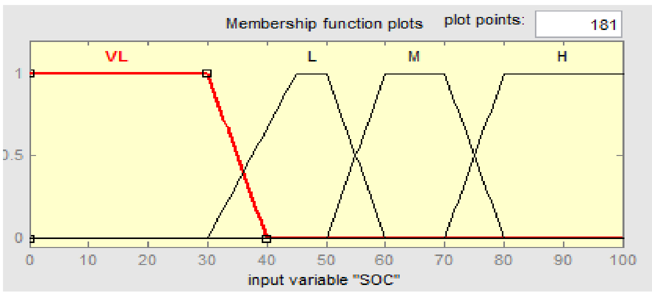


Fig. 5 Simulink schematic of the proposed system

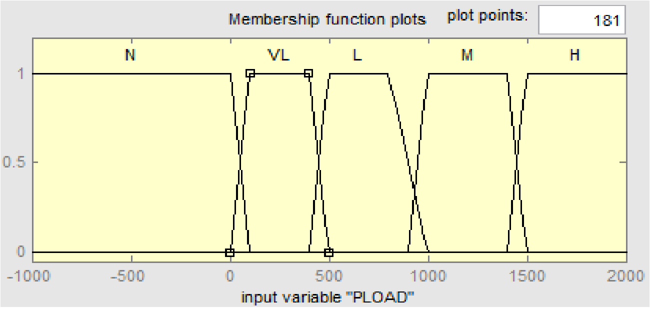
Table 6 gives a detailed description of the various electrical parameters and vehicle dynamics used for the simulation.

Table 6: Electrical parameter and vehicle dynamics specifications

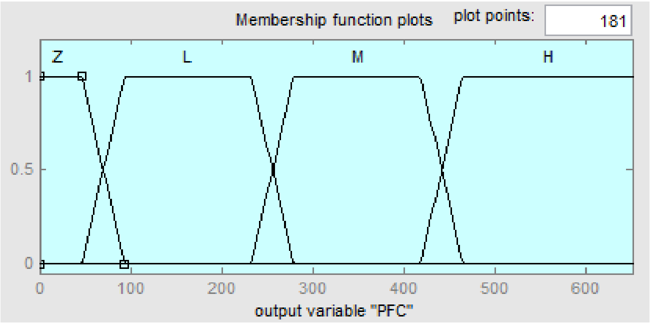
Parameter	**Value**	**Unit**
Battery Capacity	20	Ah
Battery Nominal Voltage (Max)	300	V
Converter Output Voltage	500	V
Motor Efficiency	94	%
Maximum Motor Torque	450	Nm
Motor Maximum Power	100	kW
Vehicle mass	1000	Kg
Tire radius	0.25	m
ICE Maximum Power	100	kW



a)



b)



c)

Fig. 3 Visualization of Fuzzy membership functions for input and output variables a) SoC b) PLoad c) PFC

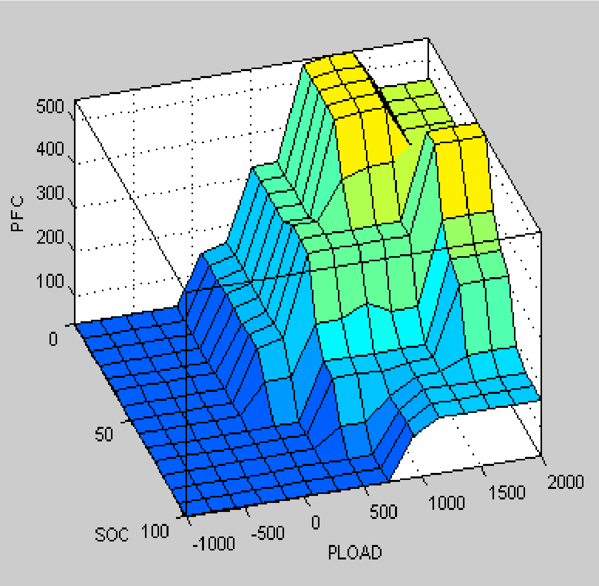


Fig. 6. Surface plot for SOC vs PFC vs PLoad

The visualization of Fuzzy membership functions for input and output variables and surface plot for SCO vs PFC vs PLoad is shown in Fig. 5 and 6. The surface plot depicts that when the load is higher and the battery SOC is lower then it shows the need of turning ON of fuel cell. When the plod is lower and SOC is higher then it indicates that the fuel cell can be turned OFF.

The consequences of the system is estimated for the different random SOC and PLoad condition that results in 96.00% accuracy. Some of the sample control conditions for distinct input conditions are illustrated in Fig. 7-8.

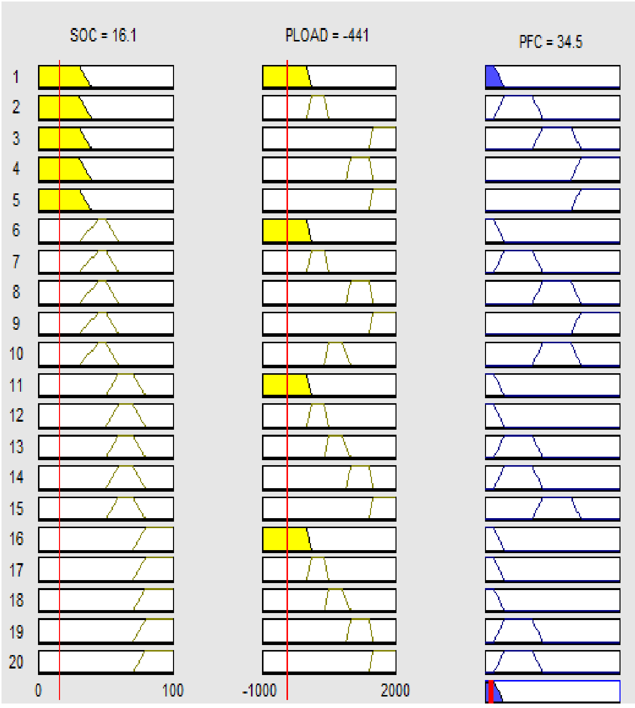


Fig. 7. Fuzzy rule viewer for very low PFC (34.5) for input variables SOC=16.1% and Pload=-441

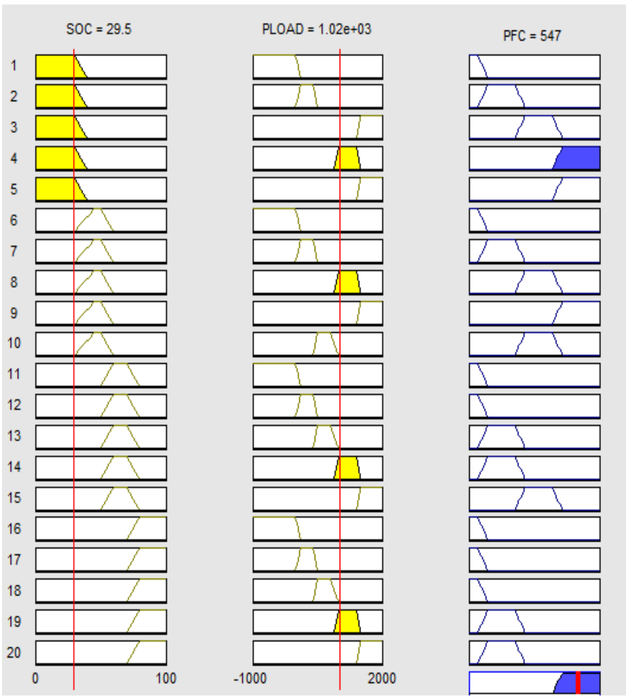


Fig. 8. Fuzzy rule viewer for very high PFC (547) for input variables SOC=29.5%, and Pload=1020

The outcomes of the proposed EMS model is authenticated for the different values of the SOC and Load demand and it is observed that it is able to provide the power to the HEV for longer duration as shown in Fig. 9. The system uses the FC power source in critical conditions only that helps to minimize the fuel cost.

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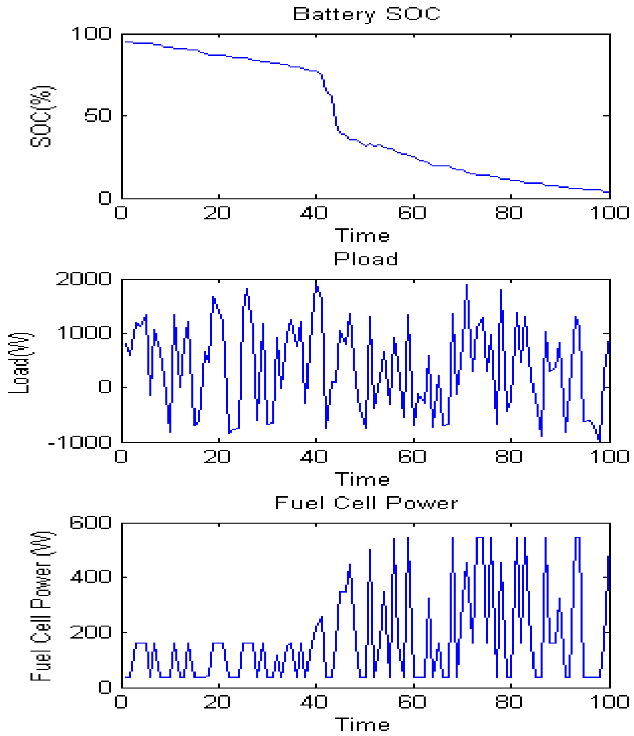

Fig. 9 Proposed EMS control scenario

CONCLUSIONS AND FUTURE SCOPE

Thus, this paper offers a fuzzy logic-based EMS for a hybrid electrical vehicle based on battery SOC, different vehicle dynamics and driving conditions. It provides the precise control of the FC power based on battery SOC and load profile by considering different vehicle conditions such as vehicle dynamics, atmospheric pressure, etc. The fuzzy logic-based EMS provides efficient and automatic control of the power flow in a HEV. The fuzzy logic based EMS provides simple rule base EMS that is simple to implement on the hardware platform and provides lesser computational efforts. It provides multi-objective control of the vehicle speed in various driving conditions. In the future, various renewable energy sources can be used to charge the battery.

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