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Electric Vehicles - Energy Management System to Recover Excess Power Generated by Fuel Cells

Shital Madhukar Nikam[1], Er. Ms. P.A. Desai[2]

[1]M.E. Student, Dept. of Electrical Engg., Matoshri College of Engineering and Research Center, Nashik, MS, India.
[2]Assistant Prof., Dept. of Electrical Engg., Matoshri College of Engineering and Research Center, Nashik, MS, India.

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Abstract - *This paper highlights an energy management of battery-Proton Exchange Membrane Fuel Cell (PEMFC) hybrid energy storage for electric vehicle. Generally, Fuel Cells (FCs) are not sufficient to satisfy the load demand, so batteries are added to make the system more sustainable. The system under study consists of fuel cells and battery bank storage to produce energy without interruption. The hybrid source is sized for feeding an electric vehicle of 3 kW. The mathematical model topology and the identification of each subsystem are presented. The power management control (PMC) is developed to supply electric vehicle without interruption. Two algorithms of PMC are developed in this paper. The first one, based on power balance, is used just to show the power flow between the different storage sources. The second one is proposed to recover fuel cells energy in case of energy excess. Expected results under MATLAB/Simulink are presented and discussed.*

Key Words: Electric Vehicle (EV), Fuel Cells (FCs), Proton Exchange Membrane Fuel Cell (PEMFC), Power Management Control (PMC), Direct Torque Control (DTC), MATLAB/Simulink.

1. INTRODUCTION

At present, the high pollution rate, the depletion of fossil resources and the increase in the price of these sources prompts us to exploit renewable energy sources such as solar, wind and others. The automobile contribute considerably in air pollution and the release of greenhouse gases, which is why the electric vehicle seems to be a good alternative to reduce these alarming effects.

Government of India launched the Faster Adoption and Manufacturing of (Hybrid and) EVs in India ("FAME India") in March 2015. India unveiled the 'National Electric Mobility Mission Plan (NMEEP) 2020' to address the issues of National energy security, vehicular pollution and growth of domestic manufacturing capabilities. Government of India has plans to make a major shift to EVs by 2030. India is a member of a multi-governmental forum Electric Vehicle Initiatives (EVI) which launched an EV 30@30 campaign in 2017, setting a goal of achieving 30% new EV sales by 2030 in member countries. Initiatives are taken in eight states in India: Andhra Pradesh, Delhi, Karnataka, Kerala, Maharashtra, Telangana, Uttar Pradesh and Uttarakhand.

Hybrid power system contains several energy sources and energy storage systems, to deal with the load demand and need satisfaction. Since 1839, fuel cells have attracted attention of several researchers and were developed for various applications. These renewable energy sources were and still of a great interest.

Automobile applications are dominated by proton exchange membrane fuel cells, thanks to its many advantages. However, in order to ensure the supply of the electric vehicle without interruption, the insertion of an additional source is necessary such as photovoltaic, supercapacitor and batteries. Nevertheless, the combination of several sources requires the introduction of management algorithms enabling to the vehicle to be supplied during all its operation.

This paper treated an energy management of battery-PEM fuel cell hybrid Energy Storage System for electric vehicle, where two strategies of management are proposed in order to improve the efficiency of the hybrid source. The first strategy ensures only the fed of the EV. The second one ensures the EV's supply with the exploitation of the excess power produced by the Fuel cell. The traction of the vehicle is ensured by an induction machine of 3 kW. The DC bus voltage is kept constant using Direct Torque Control (DTC) for its robustness and easiness to use. Each subsystem is identified and modeled under MATLAB/ Simulink. The two proposed systems are presented and simulation results are given and discussed.

2. PROPOSED SYSTEM MODEL

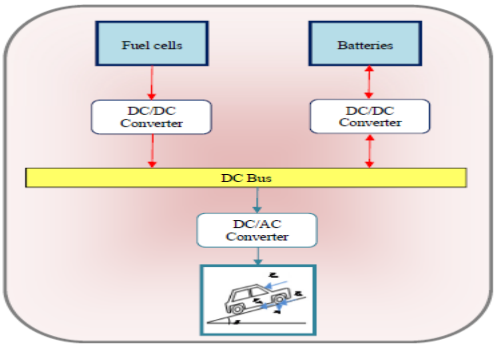

Fig - 1: Proposed system [1]

The global system consists of a proton exchange membrane fuel cell (PEMFC), two DC converters, a battery bank and an inverter supplying an electric vehicle.

2.1 PEMFC Model

The PEMFC model implements a generic model parameterized to represent most popular types of fuel cell stacks fed with hydrogen and air.

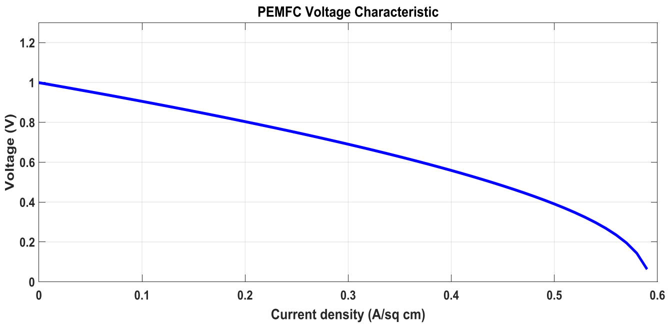

Fig - 2: PEMFC voltage characteristic.

It is observed that the cell voltage and efficiency present higher values for low current densities and power densities. On the other hand, for higher values of power, the efficiency and the voltage present smaller values. Therefore, when the designer of the control system wants to find the best operation point for the cell, he/she must take into account efficiency and voltage levels suitable for the application. Operating the cell in a constant current (which means constant power and voltage) is a good start point.

2.2. Battery Model

The battery behaves as complex impedance Z_{batt} with a resistance R_{batt} and a reactance X_{batt} to this disturbance. In order to determine the internal impedance of the battery (12 V, 100 Ah), obtained values are summarized in Table 1. These values change according to the battery state of charge. The battery bank is composed of eight lead acid batteries of 12 V, 100 Ah connected in series

Table - 1: Lead acid battery parameters (12 V, 100 Ah).

Parameters	Value
R_{batt}	0.704 Ohms
X_{batt}	0.072 ohms
C_{batt}	44.2 mF

2.3 DC/DC Converter Model

The DC/DC converter used boost chopper. It is inserted between the source and the inverter. The electrical schematic of the DC/DC boost converter is represented in Fig. 3, where D is the duty cycle which can be governed electronically.

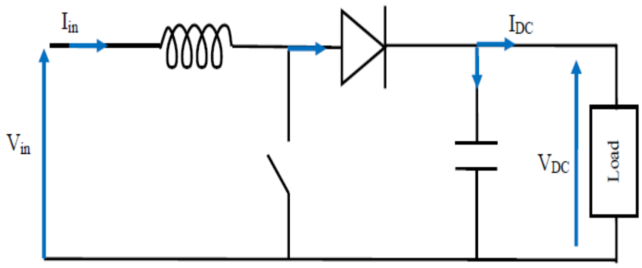

Fig - 3: DC/DC boost converter. [1]

The following equation gives voltage and current expressions of the DC/DC converter.

$$V_{DC} = \frac{1}{1-D} V_{in} \quad and \quad I_{DC} = (1-D) I_{in}$$

2.4 Three Phase Inverter Model

A three phase's inverter is inserted in the proposed system in order to drive the induction motor. The three phase inverter function is to convert the direct voltage into alternative one. Fig. 4 shows the electrical schematic of 3-phase inverter. The DC-AC converter is composed of 6 IGBTs (Insulated Gate Bipolar Transistors) to control the 3-phase motor. The aim of this kind of system is to manage the amplitude and frequency of the stator voltages. The stator phase voltages are expressed using,

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \frac{V_{DC}}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} S_a \\ S_b \\ S_c \end{bmatrix}$$

where: v_{as}, v_{bs} and v_{cs} are the three phase stator voltages, V_{DC} the DC link voltage and $S_{(a,b,c)}$ are the switching function.

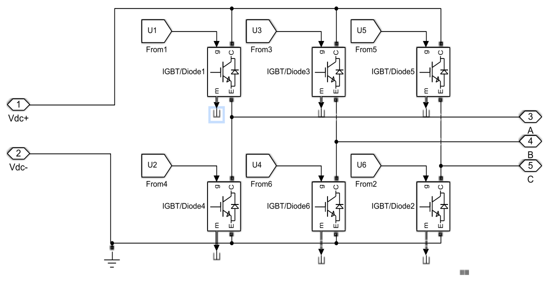

Fig - 4: Three phase inverter model.

2.5 Electric Vehicle Model

The first step in EV modeling is to produce an equation for the tractive effort. This is the force propelling the vehicle forward, transmitted to the ground. There are different types of forces occurred on EV.

i) The friction of the vehicle tires on the road causes the rolling resistance force noted by F_{tire}.

ii) The friction of the EV body moving through the air causes the aerodynamic drag force F_{aero}.

iii) The climbing force F_{slope} which depends on the road slope noted by F_{slope}.

The total resistive force is the addition of these forces. The parameters used for EV model are given in Table 2.

Table - 2: Parameters of the electric vehicle.

Parameter	Symbol	Value	Unit
Vehicle total mass	m	1300	kg
Rolling resistance force constant	f_r	0.01	--
Air density	ρ_{air}	1.2	Kg/m^3
Frontal surface area of vehicle	A_f	2.6	m^2
Tire radius	r	0.32	m
Aerodynamic drag coefficient	C_d	0.32	--

A vehicle speed profile is given in Fig. 5.

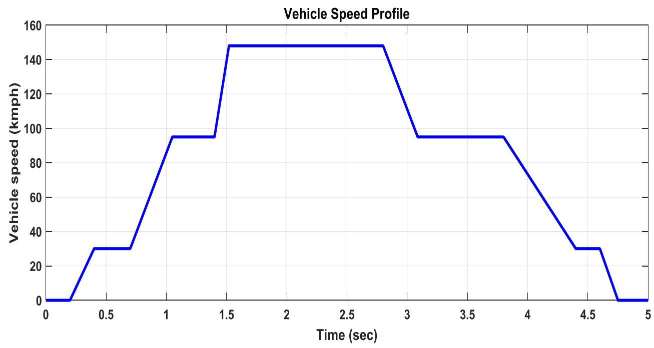

Fig - 5: Vehicle speed profile.

2.6 Induction Machine Model

The stator voltage equations can be represented in a stationary reference frame as,

$$V_{s\alpha} = R_s I_{s\alpha} + \frac{d\phi_{s\alpha}}{dt} \quad and \quad V_{s\beta} = R_s I_{s\beta} + \frac{d\phi_{s\beta}}{dt}$$

Following equations give the stator flux and electromagnetic torque equations,

$$\phi_{s\alpha} = L_s I_{s\alpha} + M I_{r\alpha} \quad and \quad \phi_{s\beta} = L_s I_{s\beta} + M I_{r\beta}$$

$$T_e = \frac{3PM}{2}(\phi_{r\beta} I_{s\alpha} - \phi_{r\alpha} I_{s\beta})$$

The parameters of the induction machine used are identified and summarized in Table 3.

Table - 3: Parameters of the induction machine.

Parameter	Symbol	Value	Unit
Shaft power	P_u	3	kW
Number of pole pairs	P	2	--
Stator resistance	R_s	1.76	Ω
Rotor resistance	R_r	1.95	Ω
Mutual Inductance	M	0.183	H
Stator (rotor) self inductance	$L_s = L_r$	0.01984	H
Inertia moment	J	0.02	$Kg\text{-}m^2$
Viscous friction	f	0.0001	$N.m.s^2$

3. SIMULATION RESULTS

The results to validate the proposed method and demonstrate the effectiveness of the control and the proposed energy management for electric vehicle are presented. In our work an induction motor of 3 kW is used as propulsion of EV.

The proposed algorithm operates properly in order to ensure the supply of the vehicle without interruption. It is noticed that till t = 1.3 sec, the energy produced from the PEMFC is quiet sufficient to supply the electric vehicle. In this mode (Mode 3), there is an excess of energy that is not explored because the batteries are fully charged. Mode 2, Mode 5 and Mode 6 represent respectively compensation mode, braking mode with batteries charging and braking mode with full charge of the battery (Fig. 6).

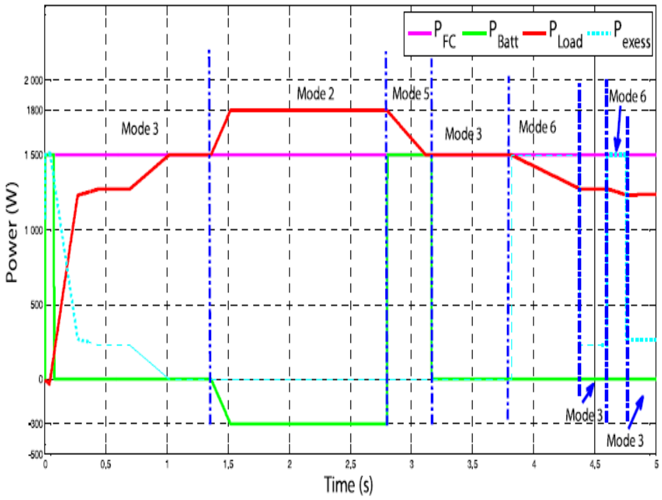

Fig - 6: Different powers generated in the global system.

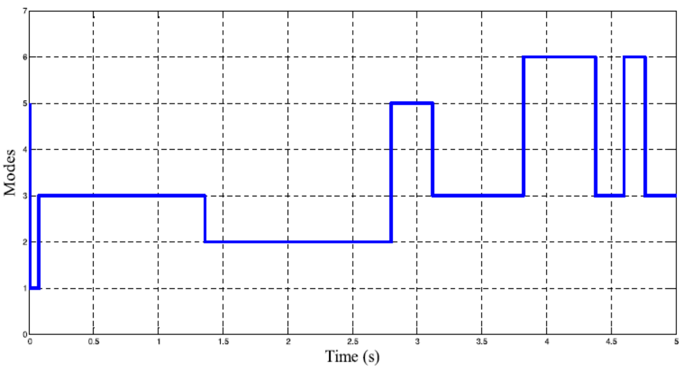

Fig - 7: Operating mode of the studied case [1].

The following Table 4 summarizes the solicitation of each source.

Table - 4: Different powers during each mode.

Modes	P_{excess} (%)	P_{batt} (%)	P_{load} (%)	P_{FC} (%)
Mode 3 (M3)	18	0	100	100
Mode 3 (M3)	0	0	100	100
Mode 2 (M2)	0	16.66	100	83.33
Mode 5 (M5)	0	-100	0	100
Mode 3 (M3)	0	0	100	100
Mode 6 (M6)	100	0	0	100
Mode 3 (M3)	18	0	100	100
Mode 6 (M6)	100	0	0	100
Mode 3 (M3)	22	0	100	100

The state of charge of the batteries is moving between the SOC_{max} and the SOC_{min} as illustrated in Fig. 8.

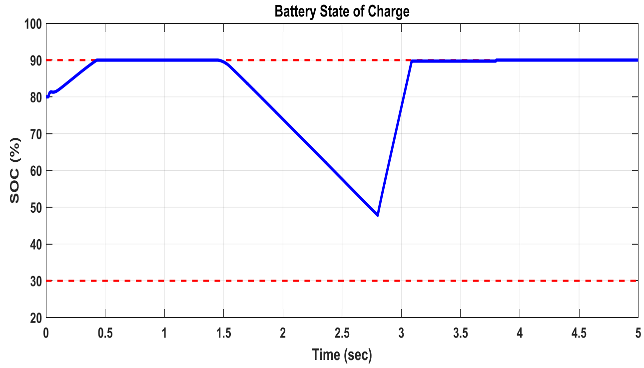

Fig - 8: Batteries state of charge.

The following figures (Fig. 9 - 12) illustrate the characteristics of the induction machine, where the stator current has a sinusoidal waveform and the electromagnetic torque reaches the load torque during all the functioning while keeping the flux constant.

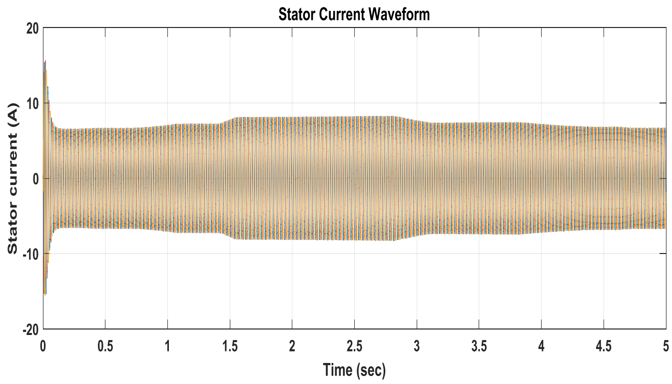

Fig - 9: Stator current waveform.

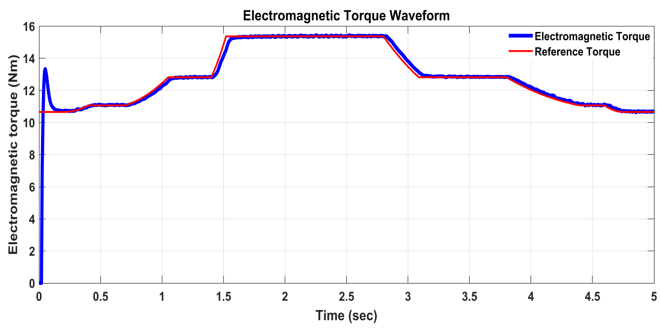

Fig - 10: Electromagnetic torque waveform.

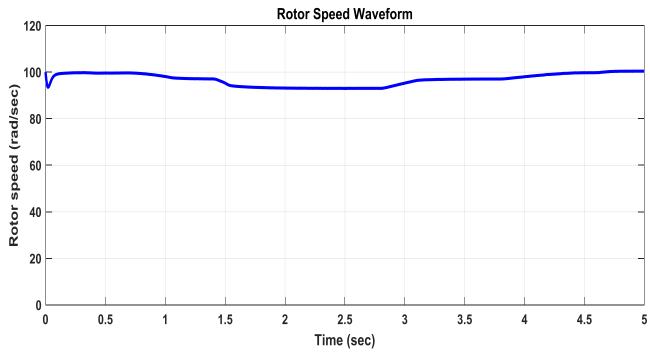

Fig - 11: Rotor speed torque waveform.

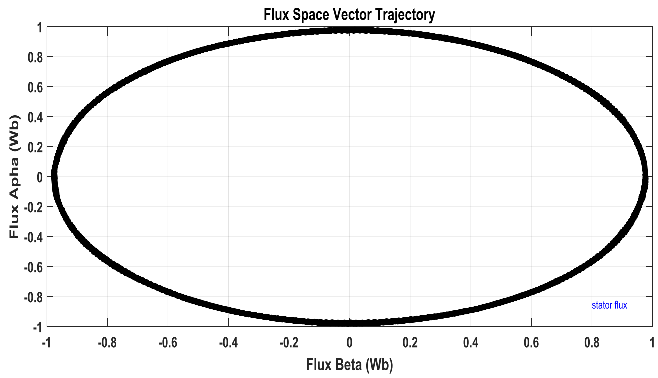

Fig - 12: Stator flux waveform in time domain and circular trajectory.

4. IMPROVEMENT IN THE MANAGEMENT STRATEGY

In this section an improvement of the management strategy is proposed (Fig. 13). This strategy allows us to recover the energy supplied by fuel cells in case of surplus energy when batteries are fully charged. This energy can be stored in super-capacitor or used to generate hydrogen in the electrolyzer.

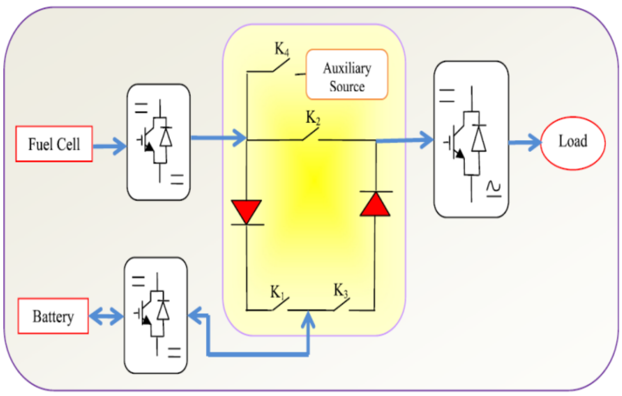

Fig - 13: The proposed system with for switches.

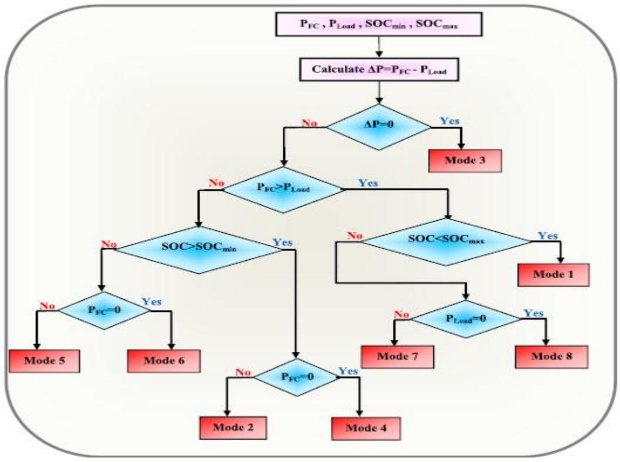

Fig - 14: The proposed energy management algorithm.

The proposed energy management algorithm is represented in Fig. 14. Depending on the different tests P_{Load}, P_{FC} and P_{batt}, the system operates in one of the following modes:

➢ Mode 1: The FC power produced is upper than the power of load ($P_{FC} > P_{Load}$) and the SOC of the batteries is inferior to the SOC_{max}, in this case, the excess energy is stored in batteries.

➢ Mode 2: The power supplied by FC is insufficient ($0 < P_{FC} < P_{load}$); in this case the power of batteries is added to satisfy the power demand. It's the compensation mode.

➢ Mode 3: The FC power's is sufficient as $P_{FC} = P_{Load}$.

➢ Mode 4: This mode is operating when no energy provides from the FC, so, batteries supply alone the load.

➢ Mode 5: The produced FC power is insufficient to supply the load and the battery is discharged ($SOC < SOC_{min}$); in this case the batteries charge.

➢ Mode 6: In this case, there is no FC energy production and batteries are discharged, the load is disconnected.

➢ Mode 7: In this mode, the FC power ($P_{FC} > P_{Load}$) is quite sufficient to supply the load and the excess energy will be stored in the auxiliary source.

➢ Mode 8: The load is disconnected ($P_{Load} = 0$) and the $SOC = SOC_{max}$ (battery charged), so the fuel cell energy is stored in the auxiliary source.

The different modes depend on the four switches K_1, K_2, K_3 and K_4. The block diagram of energy management and control strategy is given in Fig. 15.

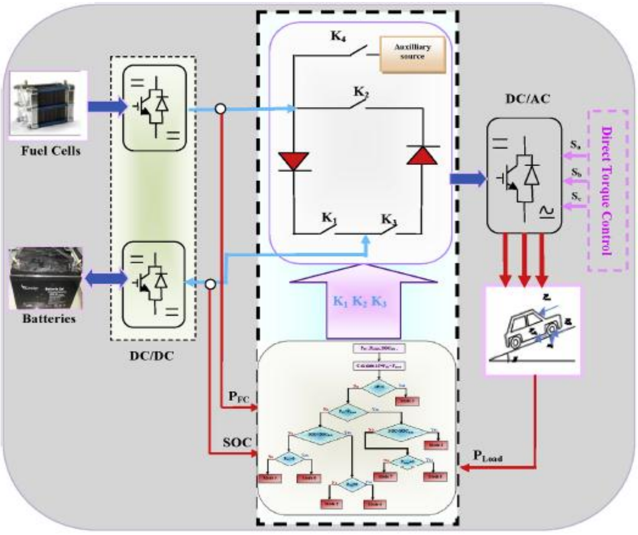

Fig - 15: Energy management and control strategy of the proposed system.

A same profile as in the first PMC algorithm is used and the different generated powers are shown in Fig. 16.

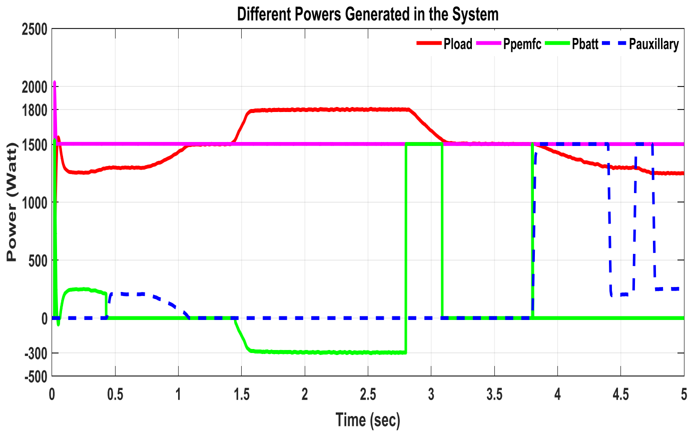

Fig - 16: Different powers generated in the global system.

The different modes obtained from the studied system are given in Fig. 17. The obtained results approve the reliability of the proposed algorithm and confirm its effectiveness.

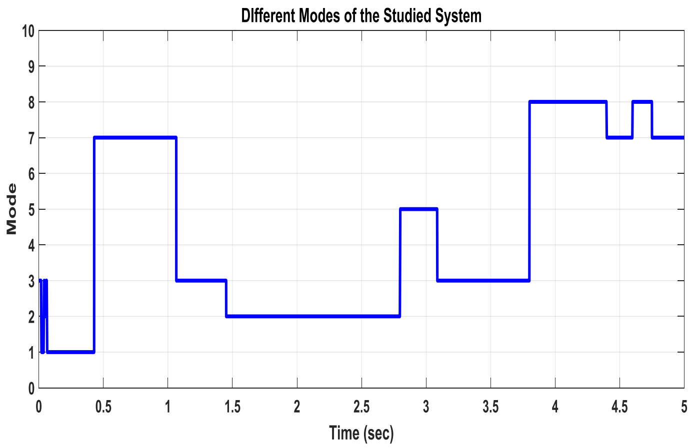

Fig - 17: Different modes of the studied system.

5. CONCLUSIONS

In this paper, a study of hybrid Fuel cells/Battery bank system supplying an electric vehicle is presented. An energy management was proposed to ensure the supplying of the electric vehicle; however, the appearance of excess energy in the first studied system pushed us to improve the energy management. The new strategy contains four switches. The forth one is dedicated to store the excess energy in an auxiliary source.

The simulation model of the hybrid system has been developed using MATLAB/Simulink. The results of the simulation allowed us to validate the proposed method and demonstrate the effectiveness of the control and the proposed energy management for electric vehicle.

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BIOGRAPHIES

Ms. Shital Madhukar Nikam is a M.E. (EPS) second year student of Electrical Engineering Department at Matoshri College of Engineering and Research Center, Nashik [MS], India.

Er. Ms. P A. Desai is an Assistant Professor at Electrical Engineering Department at Matoshri College of Engineering and Research Center, Nashik [MS], India.