International Journal of Technical Innovation in Modern Engineering & Science (IJTIMES)
Impact Factor: 5.22 (SJIF-2017), e-ISSN: 2455-2585
Volume 4, Issue 09, September-2018

EFFECT OF REGENERATIVE BRAKING ON THE HYDROGEN CONSUMPTION OF FUEL CELL ELECTRIC VEHICLE

Aditi Swarnkar[1], Jai Kumar Maherchandani[2]

[1] Department of Electrical Engineering,College of Technology and Engineering,
Maharana Pratap University of Agriculture and Engineering, Udaipur, India,

[2] Department of Electrical Engineering, College of Technology and Engineering,
Maharana Pratap University of Agriculture and Engineering, Udaipur, India,

Abstract*— This paper presents the effect of regenerative braking on the hydrogen consumption of fuel cell electric vehicle (FCEV). The hydrogen consumption of Fuel Cell/Battery/Supercapacitor (FC/BATT/SC) electric vehicle is compared for regenerative braking and non-regenerative braking (non-RB) cases. Frequency splitting operational state control strategy (FSOSCS) is used for the energy management of FC/BATT/SC configurations. Simulation is carried out in MATLAB/Simulink environment. The results indicate that use of regenerative braking causes improved battery state of charge (SOC level), increased voltage of supercapacitor, improved transient performance and reduced stress on fuel cell, thus resulting in reduced hydrogen consumption.

***Keywords*— Driving cycle, fuel cell electric vehicle, hydrogen consumption, regenerative braking.**

I. INTRODUCTION

The tremendous rise in population has resulted in the increase in the number of conventional internal combustion engine (ICE) vehicles. Moreover the harmful gases produced by these vehicles are causing harm to both environment and mankind [1]. Hence, such a scenario calls for the need of the alternative sources of energy used for the propulsion purposes. The electric vehicles specifically the fuel cell electric vehicles (FCEVs) are comparable to the ICE vehicles in terms of range and possess better efficiency. Also FCEVs are clean energy sources as the electrochemical reaction in the fuel cell involves the direct conversion of hydrogen and oxygen to produce electricity for propulsion purposes and the byproducts produced are water and heat which are clean and do not involve any combustion [2, 3]. However these FCEVs have poor power density thus cannot withstand sudden transients present in the load and also they cannot absorb the energy produced during braking resulting in more hydrogen consumption [4, 5]. Hence the fuel cell is not operated alone and it is used in hybridization with energy storage sources (ESSs) namely battery and supercapacitor to fulfil the transients load demand and to absorbs regenerative braking energy. The regenerative braking (RB) is important aspect which influences the performance of FCEV. The kinetic energy produced during braking is stored in the battery and supercapacitor in the form of electrical energy to supply the transient load demand in future [6-9]. Thus improves the conversion efficiency of the FCEV, increases the driving range which eventually enhances fuel economy and reduces hydrogen consumption [10].

In the present work, hydrogen consumption of FC/BATT/SC configuration for both regenerative braking (RB) and non-regenerative braking (non-RB) cases is compared. In RB case the load power is negative during braking which indicates that load returns back power to the system. For non-RB case, the load power always remains positive even in the case of braking. Both these cases are compared to show that the regenerative braking helps in reduced hydrogen consumption as more energy is stored in the ESSs compared to non-RB case. Hence less amount of hydrogen is used as most of the transient load is handled by the supercapacitor and the battery. Moreover use of regenerative braking improves the state of charge (SOC) of the battery and voltage of the supercapacitor.

The paper is organized as follows: section 2 consists of the system description and modeling of the fuel cell/battery/supercapacitor electric vehicle; section 3 explains methodology used to present the impact of regenerative braking; section 4 describes the simulation result and finally the presented work is summarized in section 5.

II. SYSTEM DESCRIPTION AND MODELING OF HYBRID FUEL CELL/BATTERY/SUPERCAPACITOR CONFIGURATION

A. System Description

The Fig 1 depicts the hybrid configuration of fuel cell/battery/supercapacitor (FC/BATT/SC) electric vehicle. The fuel cell is the main source of supply which is connected to boost converter to boost up the fuel cell voltage equal to the dc bus voltage. Battery is connected to the buck-boost converter for charging and discharging operation and the supercapacitor is connected directly to the dc bus which delivers the power to the load.

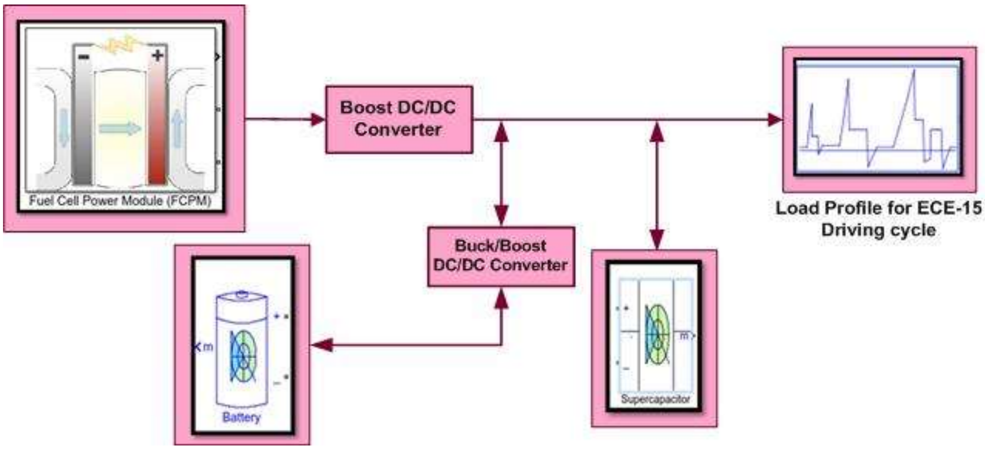

Fig. 1: Block Diagram of fuel cell/battery/supercapacitor configuration.

B. Modeling of fuel cell

The modeling of fuel cell is carried out using MATLAB/Simulink software [11]. The fig. 2 shows the typical polarisation characteristics of 12.5KW fuel cell. The activation and ohmic region in the polarisation curve indicates the voltage drop across the fuel cell due to the various losses including activation loss and ohmic loss.

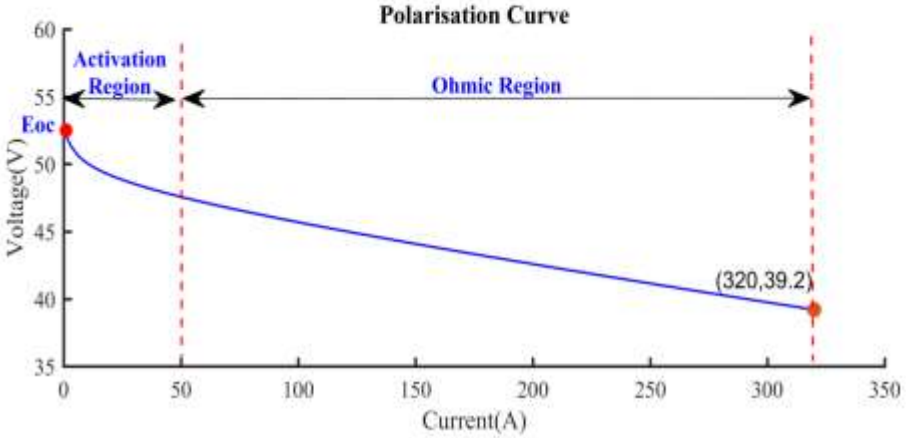

Fig. 2: Polarisation curve of 12.5KW PEM fuel cell obtained from simulation results.

C. Modeling of Battery

The generic model of Li-ion battery is modeled in MATLAB/Simulink environment [12]. This model is based on the equations developed by the Shepherd which allows study of various parameters of battery like terminal voltage, open circuit voltage, internal resistance, discharge current and state-of-charge (SOC). This model is applicable for the study of the behaviour of battery during both charging and discharging conditions. The typical discharge characteristic of lithium ion battery of 40Ah capacity is shown in Fig. 3. This characteristic is divided into three regions namely exponential region, nominal region, discharge region.

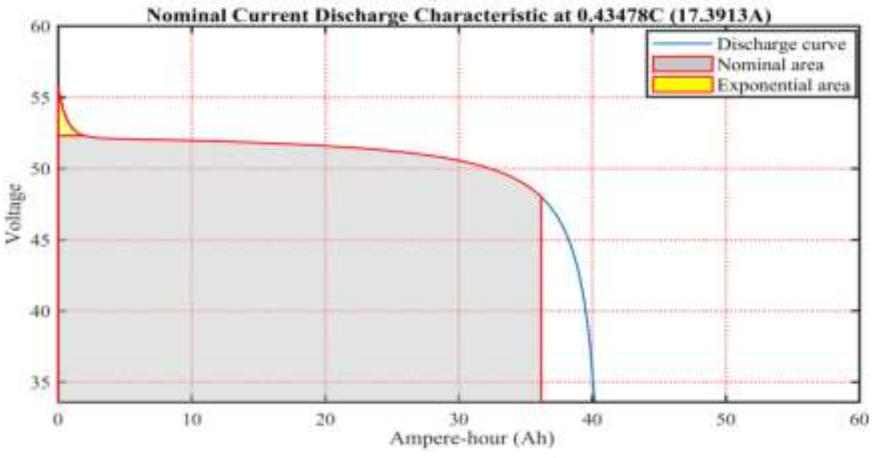

Fig. 3: Nominal discharge characteristics of lithium-ion battery.

D. Modeling of Supercapacitor

The generic model of supercapacitor based on Stern model is studied in MATLAB/Simulink environment [13]. The Fig. 4 shows the typical charging characteristic of 15.6 F supercapacitor at different current.

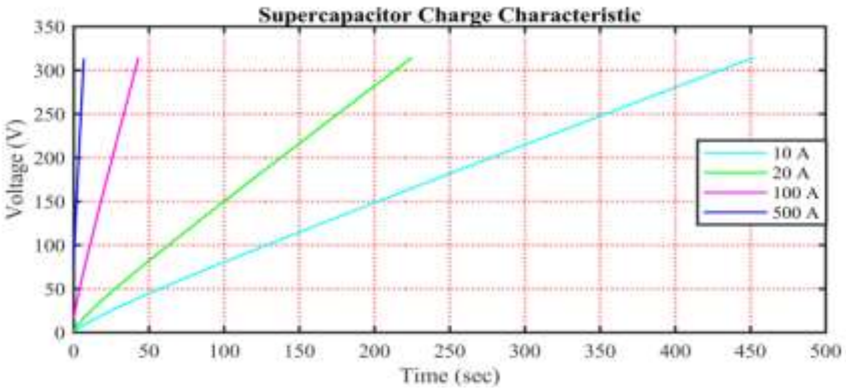

Fig. 4: Charging Characteristics of Supercapacitor.

III. METHODOLOGY

A. Load Profile

The effect of regenerative braking is studied by comparing the regenerative and non-regenerative braking cases based on the load profiles. The Fig. 5 shows the load profile for the non-regenerative braking (non-RB) and regenerative (RB) case having the peak load power of 10 KW. In the non-RB case the load power remains always positive it means that no power is returned back to the system. However in RB case the load power is negative during braking which indicates that power is returned back to the system. Hence fuel cell/battery/supercapacitor hybrid configuration is simulated for both the cases. The energy management between fuel cell, battery and supercapacitor is carried out using frequency splitting operational state control strategy (FSOSCS).

(a)

(b)

Fig. 5 (a) Load profile without regenerative braking. (b) Load profile with regenerative braking.

B. Energy Management Strategy

The Fig. 6 shows the frequency splitting operational state control strategy (FSOSCS) which provides the fuel cell reference power (P_{ref}) based on the load power (P_L) and battery state of charge (SOC) levels. This reference power is divided by fuel cell voltage to provide fuel cell reference current. This reference current is compared with the actual fuel cell current to generate the duty cycle of boost converter. The charging and discharging of battery and supercapacitor are controlled by the dc bus regulation as shown in Fig. 7. The priority of both charging and discharging is given to the supercapacitor as it handles the most of the sudden transients present in the load demand. At the time of charging the supercapacitor is charged first above the reference voltage (270V), then the battery is charged based on its state of charge.

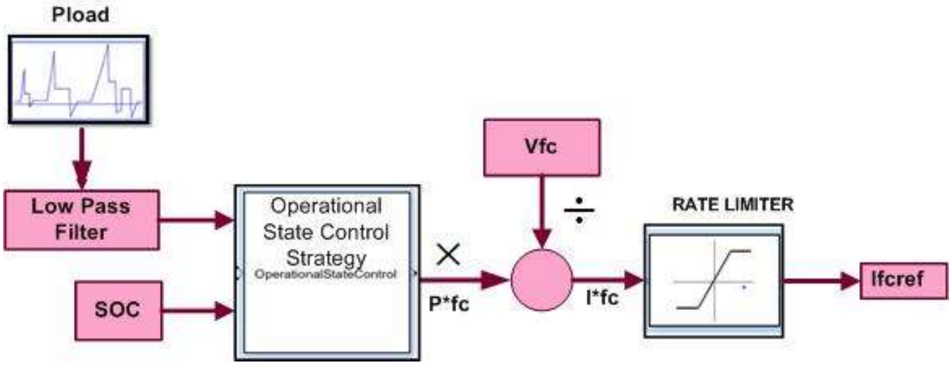

Fig. 6 Block diagram of frequency splitting operational state control strategy.

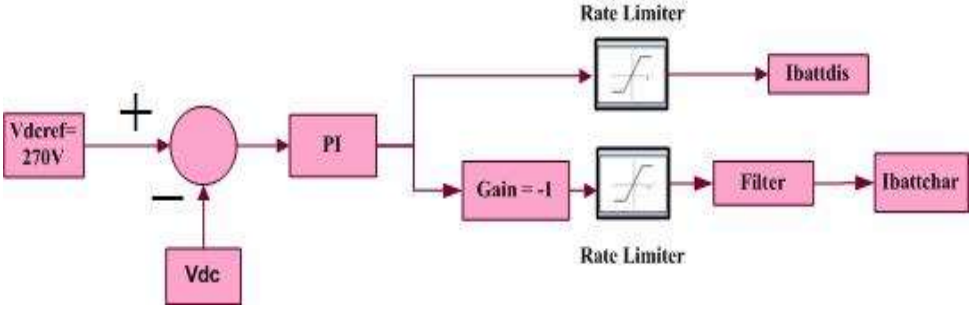

Fig. 7 Dc bus regulation for the control of battery and supercapacitor.

Table I shows that there are 11 operating states based on three battery SOC levels namely high, normal and low and the load power.

TABLE I

OPERATING STATES OF FREQUENCY SPLITTING OPERATIONAL STATE CONTROL STRATEGY

Battery SOC levels	**State**	**Load power**	**Fuel cell reference power (P_{fcref})**
High (SOC > 90%)	1	$P_L < P_{fcmin}$	P_{fcmin}
	2	$P_{fcmin} \le P_L < P_{fcmax}$	P_L
	3	$P_L \ge P_{fcmax}$	P_{fcmax}
Normal (60%≤SOC≤ 85%)	4	$P_L < P_{fcmin}$	P_{fcmin}
	5	$P_{fcmin} \le P_L < P_{fcopt}$	P_{fcopt}
	6	$P_{fcopt} \le P_L < P_{fcmax}$	P_L
	7	$P_L \ge P_{fcmax}$	P_{fcmax}
Low (SOC ≤ 60%)	8	$P_L < P_{fcmin}$	$P_L + P_{battchar}$
	9	$P_{fcmin} \le P_L < P_{fcopt}$	$max(P_L + P_{battchar}, P_{fcopt})$
	10	$P_{fcopt} \le P_L < P_{fcmax}$	$P_L + P_{battchar}$
	11	$P_L \ge P_{fcmax}$	P_{fcmax}

IV. RESULTS

The effect of regenerative (RB) and non-regenerative braking (non-RB) on the hydrogen consumption for FC/BATT/SC configuration is studied with the help of MATLAB/Simulink. The Fig. 8 shows the load power sharing between fuel cell, battery and supercapacitor for the non-RB case. It clearly indicates that at the time of braking, load do not provide energy back to the system. Thus both battery and supercapacitor absorbs the energy from the only source i.e. the fuel cell. So the fuel cell has to meet not only the load demand but also provide extra power to charge battery and supercapacitor resulting in the more hydrogen consumption.

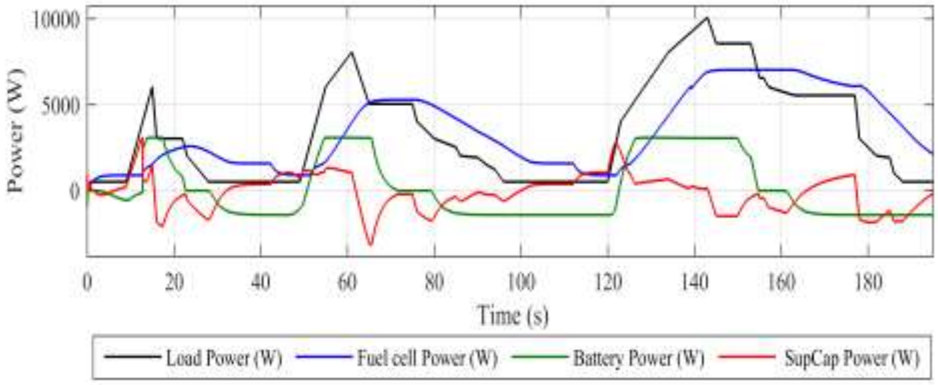

Fig. 8 Load power sharing between fuel cell, battery and supercapacitor for non-regenerative braking case.

The Fig. 9 shows the power sharing for regenerative braking (RB) case. During braking operation, the load returns energy back to the system. Hence this braking energy is used to charge the battery and supercapacitor which results in higher battery SOC level and increased supercapacitor voltage as shown in Fig. 10 and Fig. 11 respectively. Thus during acceleration, the energy storage sources (ESSs) has enough energy to meet the transient load demand. So, eventually the fuel cell operates at reduced power as compared to the non-RB case which results in the reduction of hydrogen consumption as shown in Fig. 12 and Fig. 13 respectively.

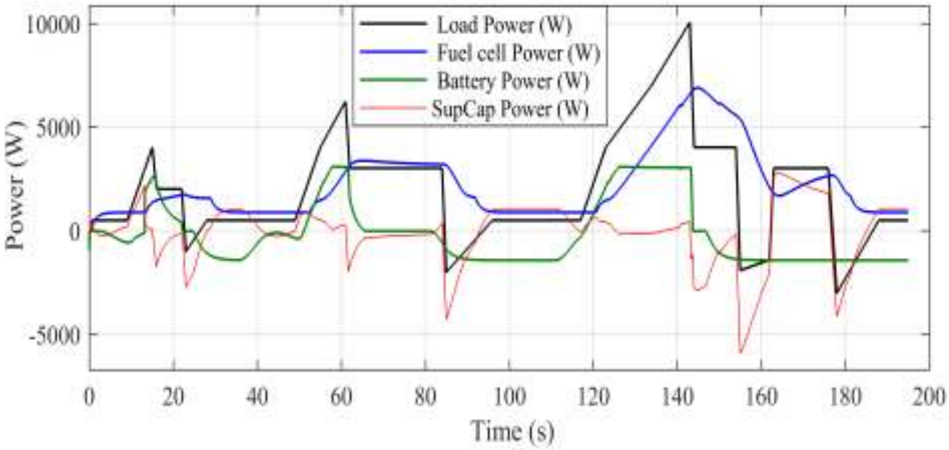

Fig. 9 Load power sharing between fuel cell, battery and supercapacitor for regenerative braking case.

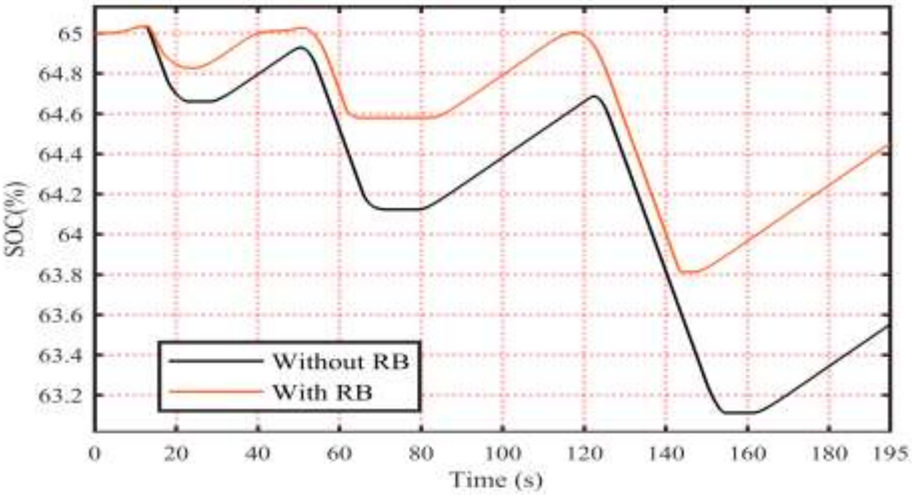

Fig. 10 Improved battery SOC level

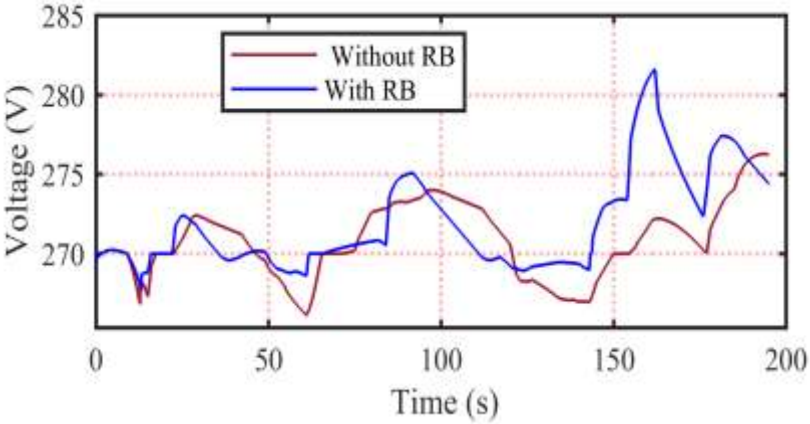

Fig. 11 Improved voltage of supercapacitor.

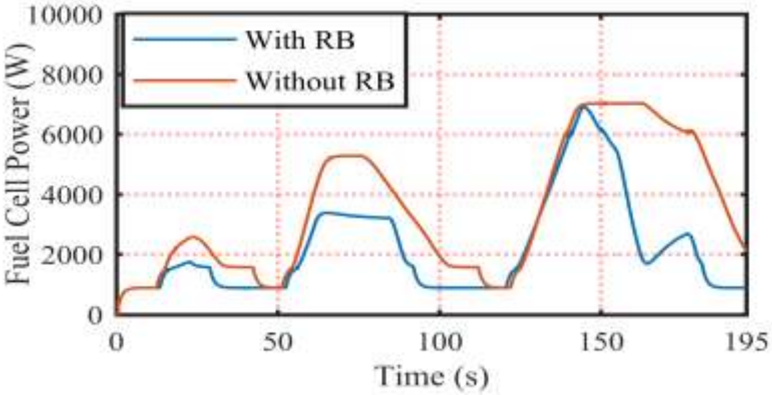

Fig. 12 Reduced fuel cell power for regenerative braking case.

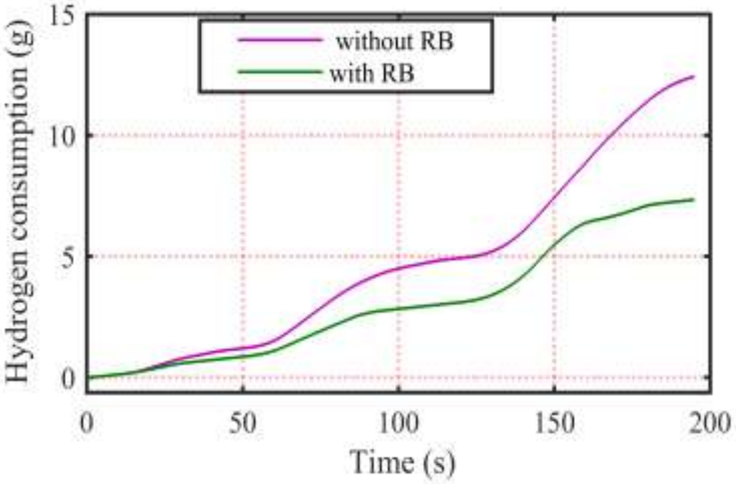

Fig. 13 Reduced hydrogen consumption for regenerative braking case.

V. CONCLUSIONS

In this paper the effect of regenerative braking on the hydrogen consumption of the fuel cell electric vehicle is presented using MATLAB/Simulink software. The regenerative braking (RB) and non-regenerative braking (non-RB) cases are compared for FC/BATT/SC configuration in terms of battery SOC level, supercapacitor voltage, fuel cell power and hydrogen consumption. The energy management strategy used is frequency splitting operational state control strategy (FSOSCS). The results showed that the higher battery SOC level, increased supercapacitor voltage and improved transient performance is achieved in RB case as compared to the non-RB case. The fuel cell also needs to supply less power as compared to the non-RB case which results in the further reduction of hydrogen consumption. Hence the regenerative braking helps in the reduction of hydrogen consumption in fuel cell electric vehicle.

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