Performance Evaluation of Electric Vehicle Using Hybrid Energy Storage System

Minal R. Rade, J. A. Mane, and O. N. Buwa

Abstract The fuel efficiency and performance of novel vehicles with electric propulsion capability are largely limited by the performance of Energy Storage System. The battery system choice is a crucial item but no single type of energy storage element fulfils high energy density, high power delivery capacity, low cost per unit of storage, long cycle life, low leakage, and so on at the same time. One of the best solution is to use a Hybrid Energy Storage System. The main objective is to design of a hybrid electrical energy storage system which gives substantial benefits against battery issues such as reduction in battery stress. Also to maintain battery current as constant as possible during transients to limit battery stress. On the other hand supercapacitor has capability to charge as fast as possible without exceeding maximum current from regenerative breaking and to discharge most of its stored energy during acceleration. Adding supercapacitor bank will assist the battery during vehicle acceleration and hill climbing and with its quick recharge capability, it will assist the battery in capturing the regenerative breaking energy. This significant advantage a battery-supercapacitor energy storage system gained attention. Battery and supercapacitor sizing includes the most important and difficult steps is, the determination of the numbers of batteries and supercapacitor connected in series and parallel. The power management is essentially the optimal distribution of power between battery and supercapacitor. With supercapacitor added into the hybrid energy storage system, battery workload is reduced, which leads to significant extension of battery life.

Keywords Electric vehicle · Hybrid energy storage system · Supercapacitor · Battery · DC-DC converter

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1 Introduction

Nowadays, world is changing due to advent of numerous new technologies and innovations in EV. By 2030 all conventional vehicles will be fully electric. In Electric Vehicle energy storage system is a key ingredient as it affects the efficiency and driving performance [1]. The battery is the main power source available in the market. As vehicle is subjected to different time varying power demands battery has to supply large current which affects the battery performance and life. Also battery has limitations of power density and limited driving range [2]. Therefore no single element (battery) can fulfil the all desirable characteristics. Increasing size of battery to fulfil required power it will cause increase in cost and weight. The midway is hybridization that allows two different energy storage elements of different characteristics such as high energy density and high power density i.e. battery and supercapacitor (SC) respectively. So it gives efficient Hybrid Energy Storage System (HESS) [3–7]. In that battery is used to supply low and average power and supercapacitor is for peak power so as to battery current maintained as constant as possible. Thus efficiency and performance of an EV can be improved [8]. EV requires high power in dynamic condition which requires high power density and energy density source. So proper distribution of power between battery and supercapacitor requires more attention. To handle power split between two energy sources power electronic converter are used. For enhancing performance of energy sources DC/DC converters are used [9]. By using hybrid energy source not only workload on battery reduces but also overall performance improves [10]. Second another important point is proper sizing of energy storage system. It is critical as it related to cost of EV. This paper presents optimal sizing of battery and supercapacitor for pure EV based on theoretical formulas. The paper contents are as follows. The Sect. 2 Summarizes Hybrid Energy Storage System. Section 3 gives HESS Sizing. The Sect. 4 describes Overall System Structure, The Sects. 5, 6 and 7 estimates Power management algorithm, Simulation results and conclusion respectively.

2 Hybrid Energy Storage System

Figure 1 shows the Regon plot of specific energy verses specific power for all Hybrid energy technologies. Li–S have high energy density than the other technology also it have higher thermal runway onset temperature. This makes it suitable for EV applications. On the other hand supercapacitor has high power density than other. Combining these two technologies gives efficient energy storage System [11].

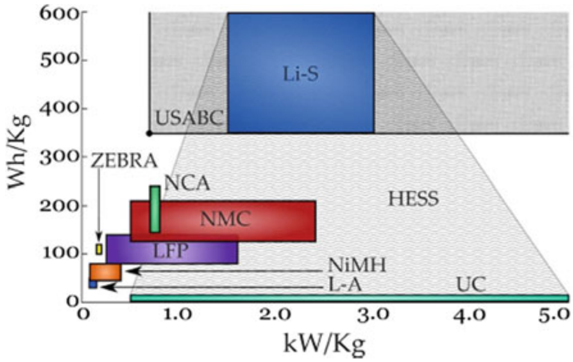

Fig. 1 Regon plot [11]

2.1 Battery

There are various batteries available as energy storage. Due to advancement in Li-based battery technology these are most popular in case of electric drive vehicles as it has high energy density and allows EV to have longer driving cycle. Conventional Li-ion battery has theoretical specific energy of 387 Wh/kg but commercially it is only up to 240 Wh/kg. Li Air (Li_2O_2) and $Li-S$ based technology have been gaining very high theoretical specific energy of 3582 and 2567 Wh/kg respectively [12, 13].

2.2 Supercapacitor

Supercapacitor is a double layer capacitor. Its electrical Characteristics are stable and operates on wide range of temperature. It have fast charging and discharging, also SC can meet other USABC goals such as specific power and life cycle which is suitable for EV applications. According to U.C Davis Institute study SC can maintain a specific energy and specific power of 30 and 10 Wh/kg and 3395 and 2540 W/kg respectively [11].

3 HESS Sizing

In pure electric vehicle sizing of energy storage system is the key point. Sizing should be such that it will meet all vehicle dynamics. Mainly two parameters have to consider namely nominal voltage and Ah rating of battery and nominal voltage and capacitance in case of SC. These specifications can be meet by reconfiguring series–parallel combinations. For desired bus voltage number of cells are connected in series and for desired energy number of cells are in parallel. Number of series connected cells N_{Bat_S} and $N_{SC}-s$ can be calculated by Eqs. 1 and 2 [14].

$$N_{Bat\_S} = \frac{V_{bus}}{V_{celbat}} \tag{1}$$

$$N_{SC\_S} = \frac{V_{bus}}{V_{SC}} \tag{2}$$

where V_{bus} is required system bus voltage and V_{celbat} and V_{SC} are the nominal voltage of battery cell and SC cell respectively. Capacitance of supercapacitor is given by Eq. 3

$$C_{series} = \frac{C_{sc}}{N_{SC}} \tag{3}$$

where C_{series} equivalent capacitance of series connected supercapacitor.

Therefore required No. of supercapacitors in parallel is given by

$$N_{SC\_P} = \frac{C_{defined}}{C_{series}} \tag{4}$$

where $C_{defined}$ is required capacitance to fulfil load profile. Energy and Power for both energy storage elements can be calculated

$$P_{te} = F_{te} * v_{vehicle} \tag{5}$$

$$Power_{SC} = \frac{V_{SC}^2}{4ESR} \tag{6}$$

$$BatteryAhrating = \frac{E}{V_{Nominal}} \tag{7}$$

$$E = \frac{P_{te}}{\eta_{DT}} * \left(\frac{ZEV\,Range}{3600^{*} v_{vehicle}}\right) \tag{8}$$

ZEV Range is Zero Emission Vehicle. The desired ZEV is 60 miles on a level road.

$$E_{SC} = 1/2CV^2 \tag{9}$$

where

ESR is the Equivalent Series Resistance of supercapacitor

F_{te} = Tractive force (N) P_{te} = Tractive power (W) P_{SC} = SC power (W)

$v_{vehicle}$ = Vehicle velocity (m/s)

η_{DT} = Drivetrain efficiency
E_{SC} = Energy required (Wh)
$V_{Nominal}$ = Battery Nominal Voltage (Volt).

4 Overall System Structure

Figure 2 presents the structure of overall system which is considered for study. The multiple converter topology is used. It allows complete control over both energy sources. It composed of two energy storage elements: Battery and Supercapacitor. The DC/DC Unidirectional boost converter for battery and DC/DC bidirectional buck/boost converter for Supercapacitor. DC link voltage value is kept constant as its output. The overall system is controlled using PID controller. Figures 3 and 4 shows unidirectional boost converter used for battery and bidirectional buck/boost converter for Supercapacitor. PID Controllers consist of gains, differentiation and

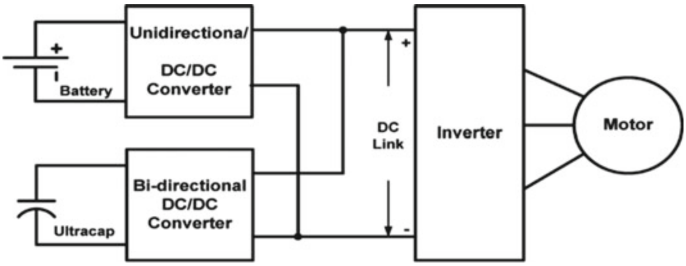

Fig. 2 Overall structure of system

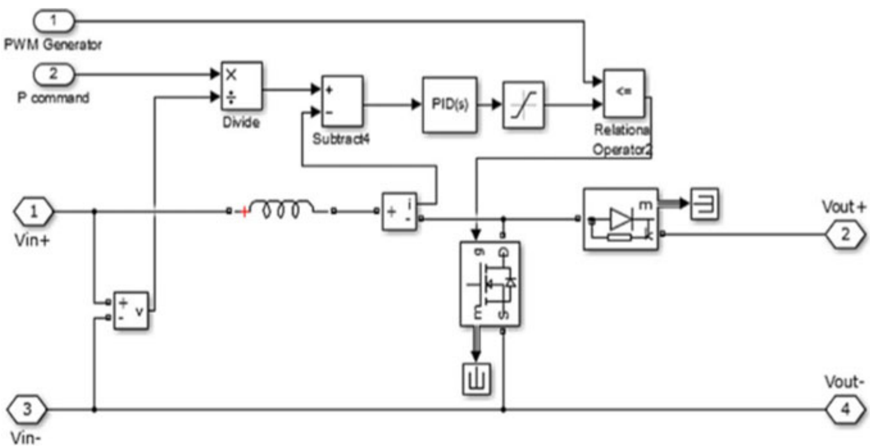

Fig. 3 Unidirectional boost converter

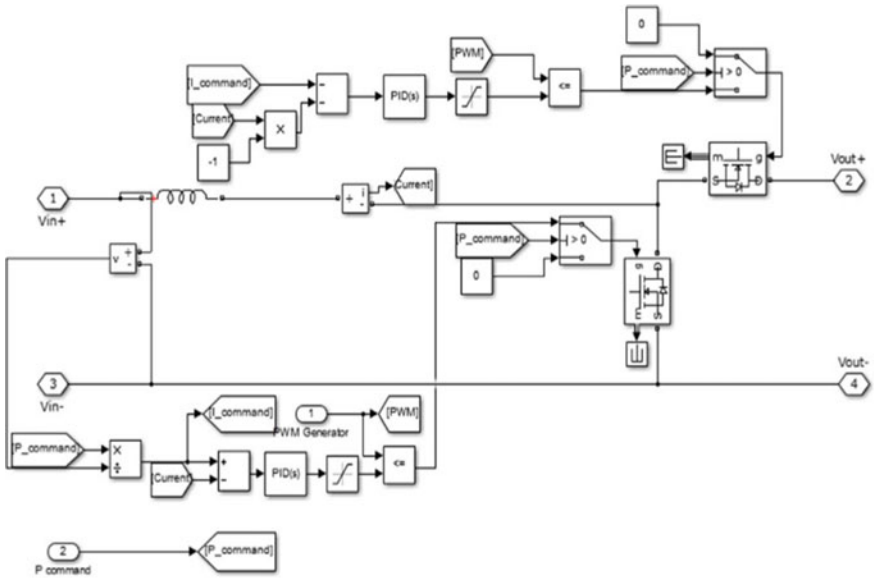

Fig. 4 Bidirectional buck/boost converter

integration parameters. By tuning these parameters control signal is produced and sent to the DC/DC converters in order to control desired amount of energy needed for the vehicle range.

5 Power Management Algorithm

Figure 5 shows flow diagram representing the power management algorithm. When the system begins to operate, controller reads all parameters such as battery, supercapacitor voltage and DC link voltage and current of battery and supercapacitor. All the variable values are limited to their respective limits by controller. Then it compares with power requirement profile. If profile values exceeds predefined values then system will not operate. If demand of current is high at starting and in case of acceleration and if battery is insufficient to supply power with predefined values of current and voltage supercapacitor will assist battery to fulfil power requirement at that particular time to reduce high current extraction from battery.

If the power requirement is average or within the limits then only battery will provide power. In case of deceleration supercapacitor will accept power from system and get charged. The limitation of rate of rise/fall of current in the inductors protects the lithium-ion battery against fast changing power.

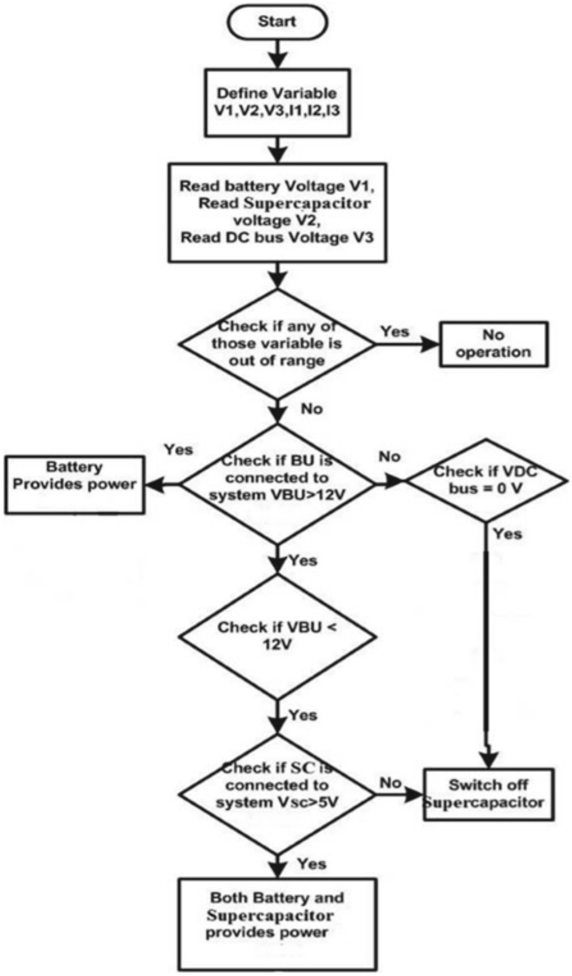

Fig. 5 Power management algorithm

6 Simulation Result

In order to evaluate the behaviour of the studied system here directly its power requirement profile is considered is as shown in Fig. 6 MATLAB Simulink model of HESS is as shown in Fig. 7 and Table 1.

Figures 8 and 9 Shows the voltage, current and % SOC of Battery and supercapacitor respectively. Figure 10 shows the power supplied by Battery and supercapacitor respectively. It is observed that when the power requirement is high at starting almost up to 3 s battery is insufficient to provide power alone to the system, so in that case supercapacitor provides power with battery. After that from 3 to 6 s power requirement is moderate in that case battery is able to provide power alone without extracting high current. For that period power supplied by supercapacitor is zero. For the period

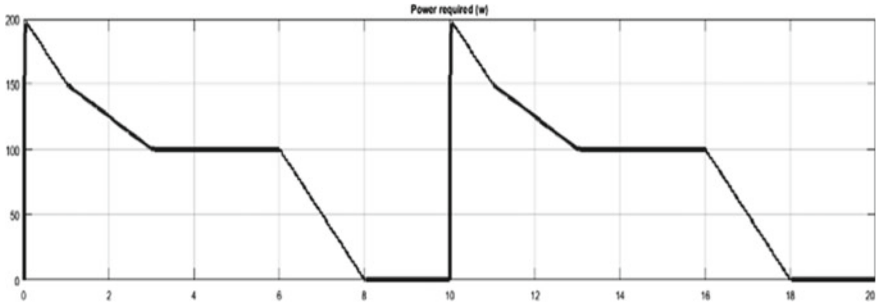

Fig. 6 Power requirement profile

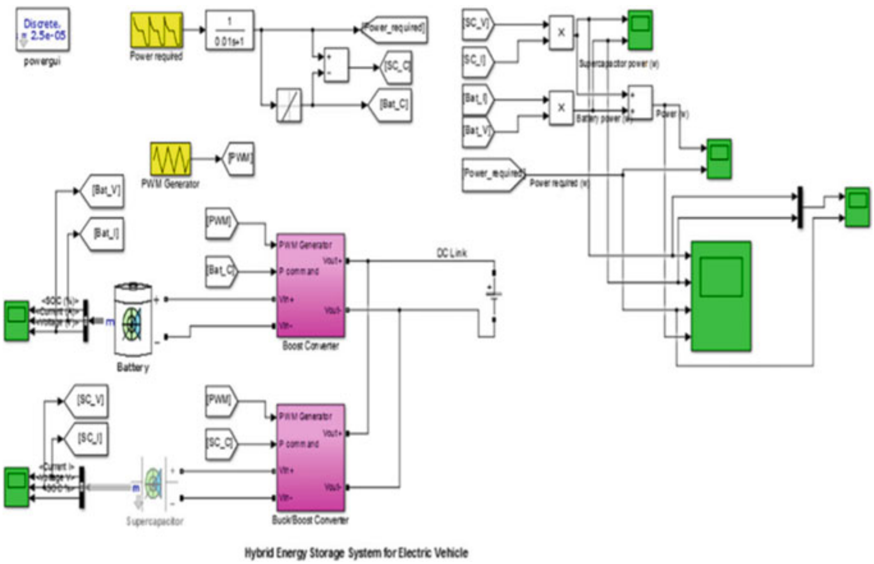

Fig. 7 MATLAB simulink model of HESS

Table 1 Specifications of energy storage device used

Device	Specifications
Supercapacitor module	5.4 V, 100 F
Battery Pack	7.4 V, 2.2 Ah @ 100% SOC
DC link voltage	12 V

from 6 to 8 s there is deceleration in that case regenerative power is recovered in supercapacitor and it get charged. For the period 8–10 s there is no power requirement from the system, so supplied by both battery and supercapacitor is zero. Also

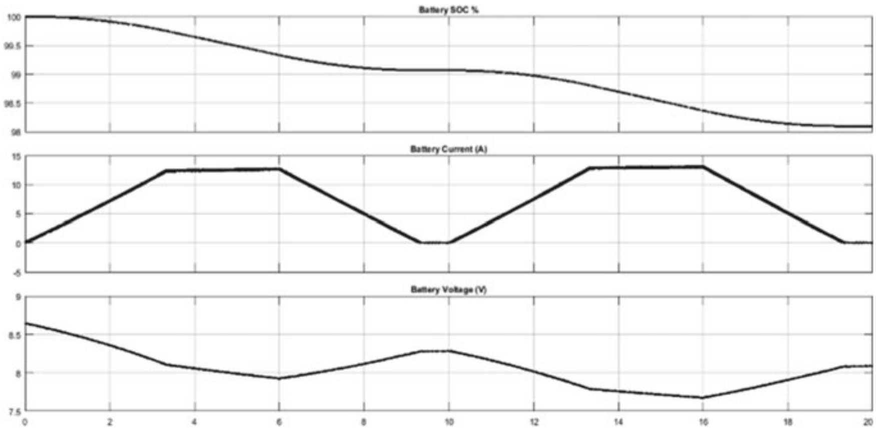

Fig. 8 Voltage, current and % SOC of battery

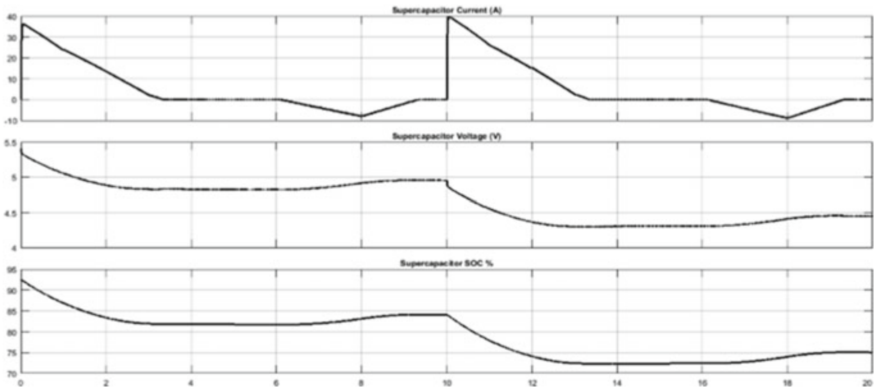

Fig. 9 Voltage, current and % SOC of supercapacitor

it is observed that battery is current is maintained as constant as possible in case of vehicle dynamics which is more important to extend battery life.

Figure 10 Shows the Power supplied by battery and Supercapacitor and Fig. 11 shows the combined power supplied by both supercapacitor and battery. From this it is observed that power requirement from the system is exactly fulfil by using hybrid energy storage elements i.e. battery and supercapacitor

7 Conclusion

From the MATLAB Simulink model of the HESS it is concluded that sizing of hybrid energy storage system for required power plays important role in pure electric

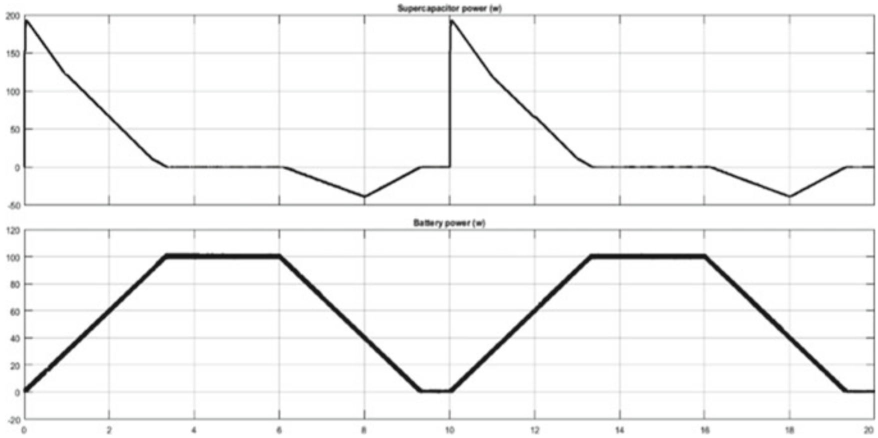

Fig. 10 Power supplied by battery and supercapacitor

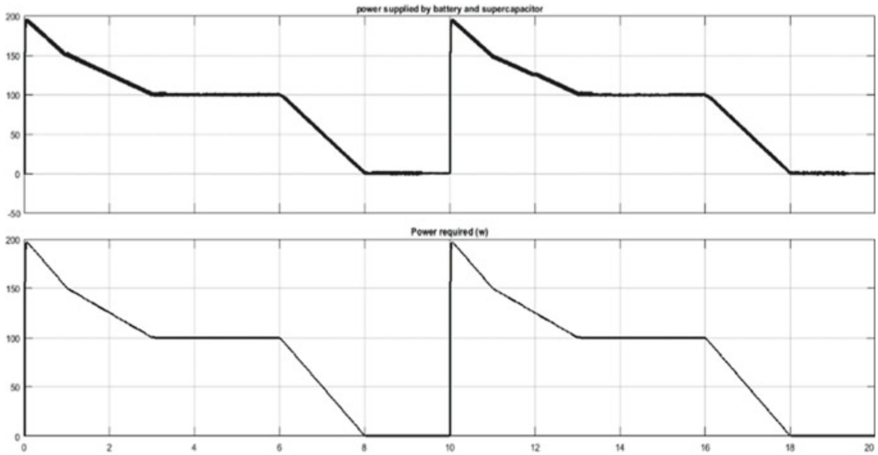

Fig. 11 Combine power supplied by battery and SC and power required

vehicle. The main challenge is to calculate number of series and parallel combination of individual energy storage element. Power required by the system is exactly fulfil by using Hybrid Energy storage system and DC/DC converter discussed in this paper. The battery current is maintained as constant as possible as peak current is supplied by auxiliary energy storage element i.e. Supercapacitor so battery life is significantly increased.

Future Scope

Design of MATLAB Simulink model with BLDC motor which is not considered in this paper. Design of On-board battery charger for the given system.

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