Energy Management Strategy for Battery/Supercapacitor Electric Vehicle Applications

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Abstract- This paper presents an energy management strategy for a hybrid battery/supercapacitor electric vehicle application. The energy management strategy presented divides the load power between the different energy sources in such a way that all the sources work in their allowable range and at their highest efficiency. The proposed system is modeled in MATLAB/Simulink environment. The results shows that use of supercapacitor with battery reduce the stress on the battery and also improve the battery life by limiting the batterycurrent.

***Keywords— Battery*, Supercapacitor, Battery Ageing, Energy Management, Rule Based.**

I. INTRODUCTION

Transportation sector based on gasoline vehicles is causing a substantial percentage of the emission of greenhouse gases and other pollutants. Increasing demand of personal mobility, limited oil reserves and global warming issues are also few reasons for shifting towards Electric Vehicles (EVs). EVs are found to be the most promising solution to these problems because of their remarkable energy saving capabilities and potential interaction with renewable power grid [1-2]. Battery is the fundamental component of electric vehicle but using only a battery as an energy source is not a good idea. Battery has high energy density but low power density, which means it can store high energy in less mass but rate of giving out that power is low [3]. The nominal energy capacity of a battery fades over time due to several chemical processes taking place within the battery cells. How the battery is being used effect the rate at which capacity fades and thus is influenced by the on-board energy management strategy. Several factors such as deep depth-of-discharge, high or low temperature, high *c*-rates, extreme state-of-charge levels, etc., are generally acknowledged to promote capacity fade [4]. So when we need sudden high power battery seems to be a bad choice. Also battery's life is deeply affected by high discharge current [5]. Taking high current from battery deteriorates its life and results in high rate of battery ageing [6]. A hybrid system can be effective solution of these problems.

A hybrid system is a combination of energy sources which when used together can fulfill all the requirement of an efficient energy source [7]. A combination of supercapacitor and battery is taken in this paper. Supercapacitor is a very good energy storage device as they have high power density which means they can give power quite fast [8]. They can be charged very quickly and can survive for a long lifetime [9]. Thus supercapacitor when used with battery makes a system with a high energy density device and high power density device. This makes the system useful for both storing high power as well as supplying high power spontaneously. The use of the hybrid energy storage system (HESS) is not limited only for the shielding the distractive current spikes to the batteries but in addition, the HESS is an efficient storage system in the EVs [8].The basic block diagram of the hybrid system used is shown in Fig.1. It mainly consists of battery and supercapacitor connected to load through two DC/DC bidirectional converters.

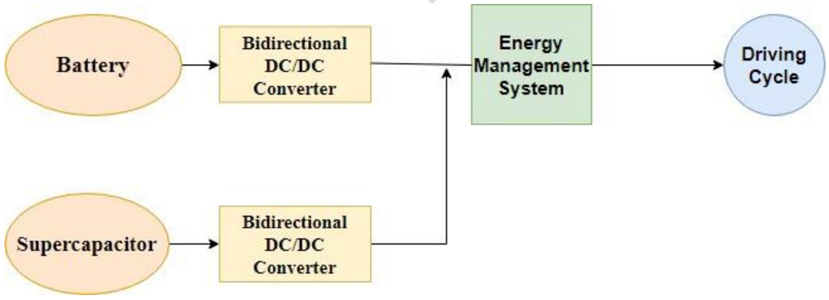

Fig. 1. Block Diagram to Show Parallel System of Battery and Supercapacitor

II. MODELING OF COMPONENTS

2.1 Modeling of battery

In the present work most common electric model of electrochemical batteries based on Thevenin equivalent is used. The equivalent circuit is shown in Fig. 2. This model uses two RC time constant which is particularly suitable for control applications. The model includes the following parameters:

1. R_o is the battery input resistance characterizing the charge/discharge energy losses of the battery cell.
2. R_1 and C_1 are the resistance and the capacitance that model the fastest electric dynamics (mostly during charging and discharging phases).
3. R_2 and C_2 are the resistance and the capacitances that model the slowest electric dynamics (mostly during slow charging and discharging phase and relaxation phase)
4. E_o is the electromotive force of the battery which can be measured as open circuit voltage.

All the equivalent circuit parameters are non linear and depends on the state of charge (SOC) and temperature [11].

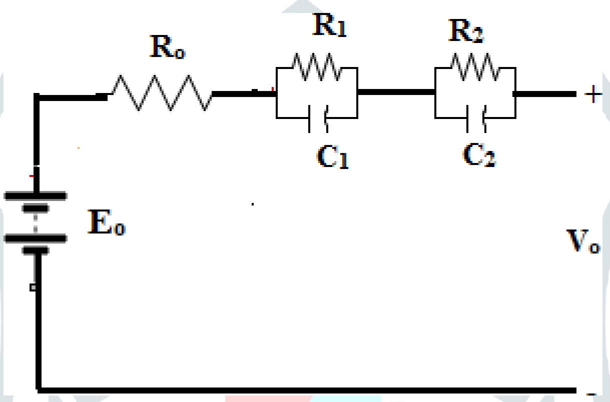

Fig. 2. Equivalent Circuit of Battery

The depth of discharging of battery is given by:

$$DOD = 1 - SOC \tag{1}$$

The state of charge is 1 when it is fully charged and is 0 when fully discharged. Thus we can say that DOD is 0 when battery is fully charged and is 1 when fully discharged. The internal resistance (R_o) of battery almost remains constant is affected by the state of charge and by temperature.

2.2 Modeling of Supercapacitor

Supercapacitors are high capacity capacitors which have capacitance higher than the basic capacitors [9]. The first order equivalent circuit of a supercapacitor cell is shown in Fig.3.

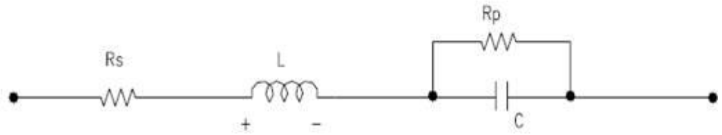

Fig. 3 First order circuit model of Supercapacitor

The circuit consis of four elements namely a capacitor, a series resistor, a parallel resistor and a series inductor. Series resistance which is also called the equivalent series resistance (ESR) contributes to energy loss during charging and discharging. Leakage current resistance which is the parallel resistance R_p also takes energy loss due to capacitor self- discharge. In a practical capacitor R_p is always much higher than R_s, that is why in high-power applications R_p can be neglected particularly.

The supercapacitor based on double layer technology consists of two porous electrodes which allow its surface area to reach two thousand square meters per gram. Thus capacitance and surface area have a non linear relationship between them. Because of this the electrical response becomes like a transmission line response. So the exact equivalent model of Supercapacitor is given in Fig. 4.

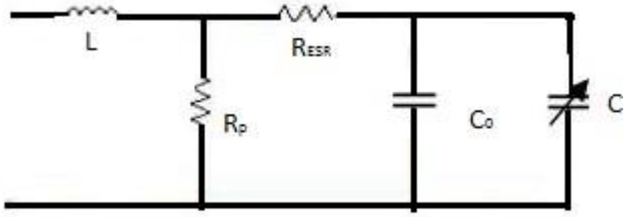

Fig. 4 Exact Equivalent circuit model of Supercapacitor.

The equivalent capacitance can be given by-

$$C_{cell} = C_0 + kVc \tag{2}$$

In high power applications like electric vehicles a number of supercapacitors are used. The equivalent capacitance is given by-

$$C_{total} = \frac{1}{\sum_{n=1}^{n} \frac{1}{C_n}} \tag{3}$$

Where n is the number of cells and C is the capacitance.

Total equivalent circuit resistance will be

$$R_{ESR} = n(R_{esr}) \tag{4}$$

The voltage across the terminals of Supercapacitor during charging is given by:

$$V_t(t) = V_r(t) + V_c(t) \tag{5}$$

Where V_c (t) is the terminal voltage of supercapacitor and V_r (t) is the voltage across internal resistance. V_r (t) is given by:

$$V_r(t) = R\, i(t) \tag{6}$$

The terminal voltage across Supercapacitor while discharging is given by-

$$V_t(t) = V_r(t) + V_c(t) \tag{7}$$

III.ENERGY MANAGEMENT STRATEGY

The energy management strategy plays an important role in any hybrid system which consists of two or more energy sources. In the present work battery and supercapacitor based hybrid energy storage system is used to improve the battery lifetime. Effectively splitting the load demand between the battery pack and supercapacitor pack is a major challenge. An efficient management and control strategy is required to extend and preserve energy storage life spans. Through this strategy power is divided between the energy sources in such a way that all sources work in their allowable range and at their highest efficiency. The energy management of the proposed hybrid system is done as per the following rules (Table I) :

Rule I: When $P_{demand} = P_{battery}$

In this case when required power is equal to the allowable power of battery, it will supply the load. In such cases there will be no charging of supercapacitor.

Rule II: When $P_{demand} > P_{battery}$ but $P_{demand} \le P_{battery} + P_{SC}$

(a) When $SOC_{bmax} < SOC_b < SOC_{bmin}$ and SOC_{SC} either normal or high

In this case when the required load power is more than the allowable power of battery and SOC of battery (SOC_b) is in normal range both supercapacitor and battery will share power. The battery will supply its maximum allowable power and deficit power will be shared by the supercapacitor.

(b) When SOC_b is in lower range (but more than allowable minimum) and SOC_{SC} either normal or high

In this case when SOC of battery is above minimum and required power is more than its capacity supercapacitor will come in to play and share the critical load. Such type of operation is allowed only in some critical conditions and load need to be cut before battery SOC touches to minimum value.

(c) When $SOC_b \le SOC_{b\_\min}$ and $SOC_{SC} \le SOC_{SC\_\min}$

In this case both battery and supercapacitor SOC are in minimum range so load will be cut because neither battery nor supercapacitor will be capable of supplying load.

Rule III: When $P_{demand} < P_{battery}$

(a) When $SOC_{bmax} < SOC_b < SOC_{bmin}$ and SOC_{Sc} Normal or low

In this case when the required power is less than the battery power and SOC of battery is in the defined range only battery will be sufficient to fulfill the load demand. The battery will supply the required power and the rest of the power will be used to charge the supercapacitor.

(b) When $SOC_{bmax} < SOC_b < SOC_{bmin}$ and SOC_{Sc} high

In this case when SOC of supercapacitor is near maximum (does not need charging) and demand power is less than battery power, battery will only supply the load and will not charge the supercapacitor.

Rule IV: When $P_{demand} = 0$

The battery will use its power to charge the supercapacitor. This happens because battery current cannot come to zero suddenly. If power required is zero at an instant battery power may not be zero that time. So with slowly decreasing battery power it will charge the supercapacitor until power comes to zero.

Table I: Rules for the Rule Based Energy Management Strategy

Condition	**Battery SOC Level**	**Supercapacitor SOC**	**Energy Sharing Source**
$P_{battery} < P_{demand} < P_{supercapacitor} + P_{battery}$	Normal or high	Normal or High	Battery and Supercapacitor both shares the load
	Low	Low	Load cut
$P_{demand} = P_{supercapacitor} + P_{battery}$	Normal or high	Normal or high	Battery and Supercapacitor both
$P_{demand} < P_{battery}$	Normal or high	Normal or Low	Battery shares the load and charge Supercapacitor
	Normal or high	High	Load shared by Battery; No charging of Supercapacitor
	Low	Any range	Load cut; No charging of Supercapacitor
$P_{demand} = 0$	Normal or High	Normal or Low	Supercapacitor charging
$P_{demand} = P_{battery}$	Normal or High	Any range	Load shred by Battery; No charging of Supercapacitor

IV. SIMULATION RESULTS

To validate the strategy described above MATLAB simulation is carried out for a period of 60 sec. An arbitrary high dynamic load profile comparable to standard driving cycles is chosen for simulation purposes which require sudden change in power demand. Being a high power density source, effectiveness of supercapacitor in power sharing can be reasonably tested with such load profiles. The power sharing is done on the basis of strategy explained above.

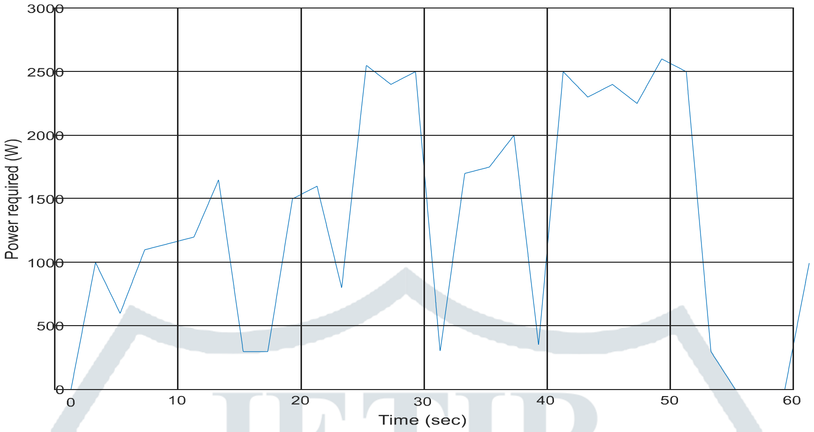

Fig. 4 Load Demand

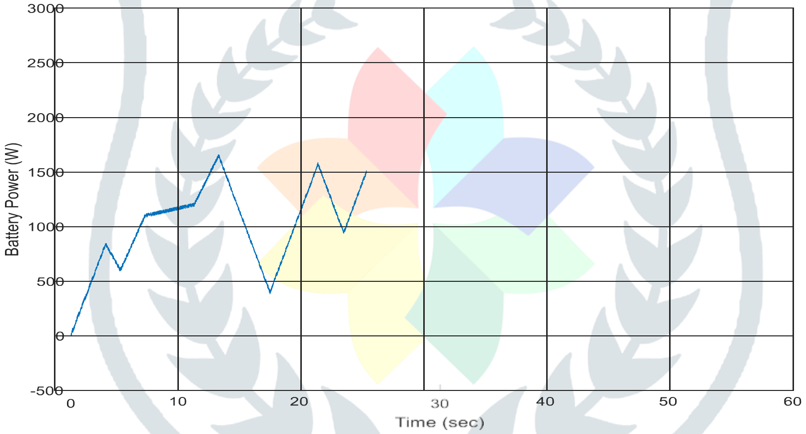

Fig. 5 Battery Power

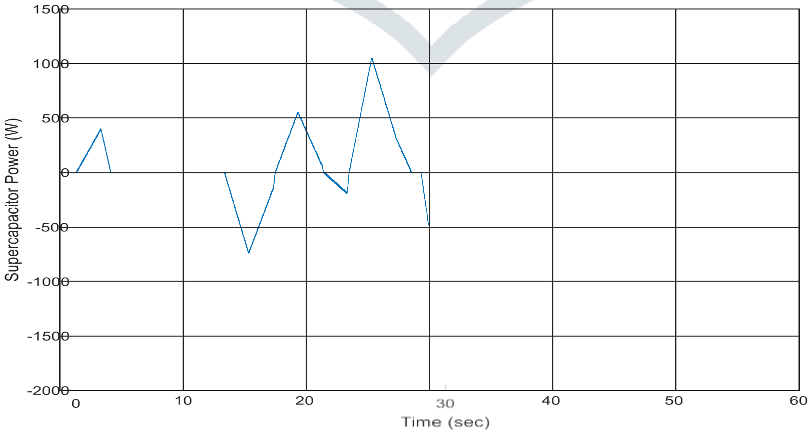

Fig. 6 Supercapacitor Power

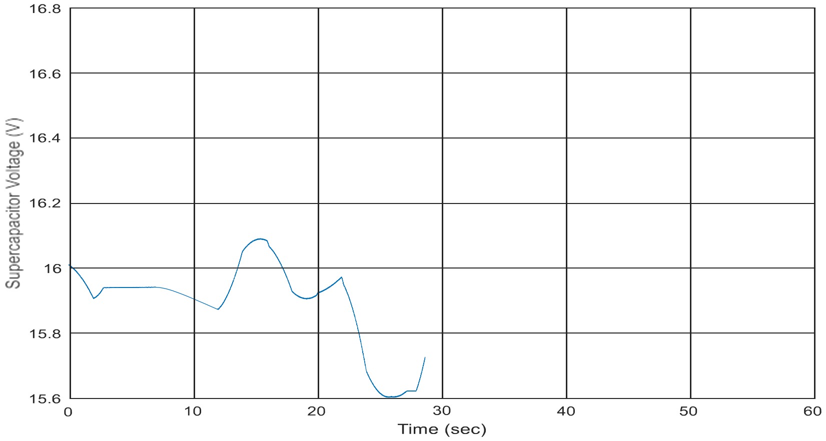

Fig. 7 Supercapacitor Voltage Profile

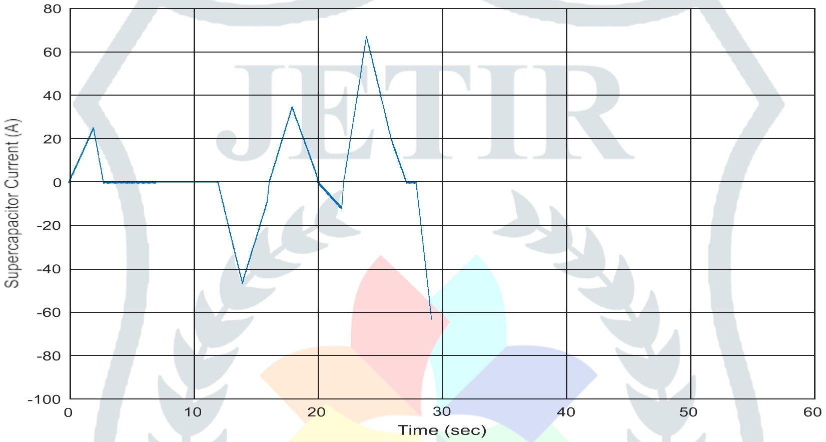

Fig. 8 Supercapacitor Current Profile

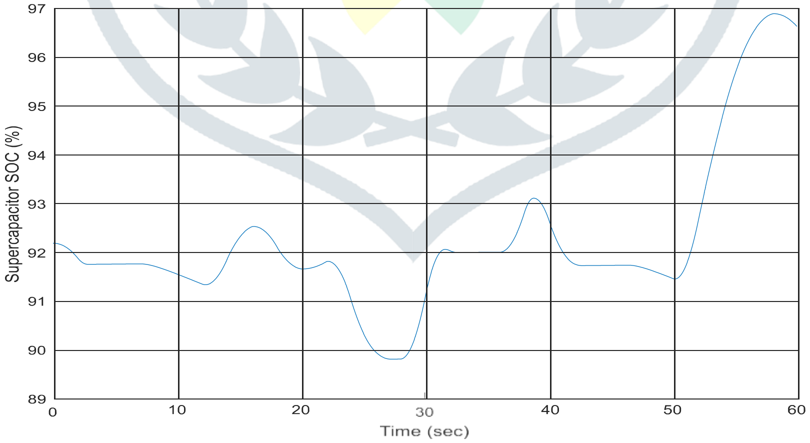

Fig. 9 State of Charge of Supercapacitor

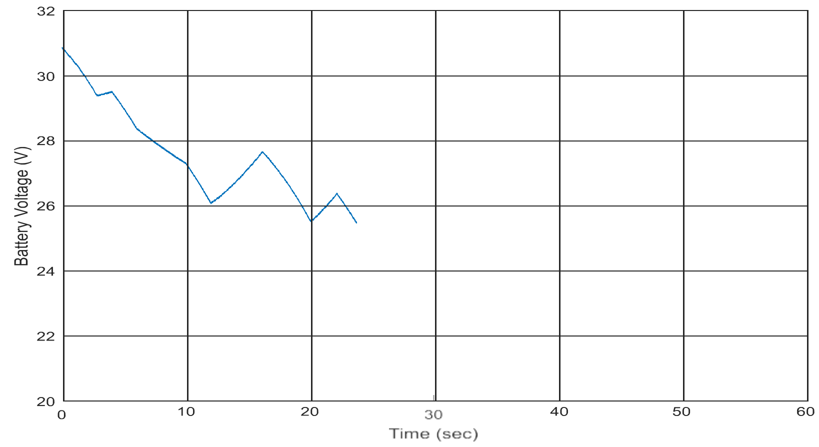

Fig. 10 Voltage Profile of Battery

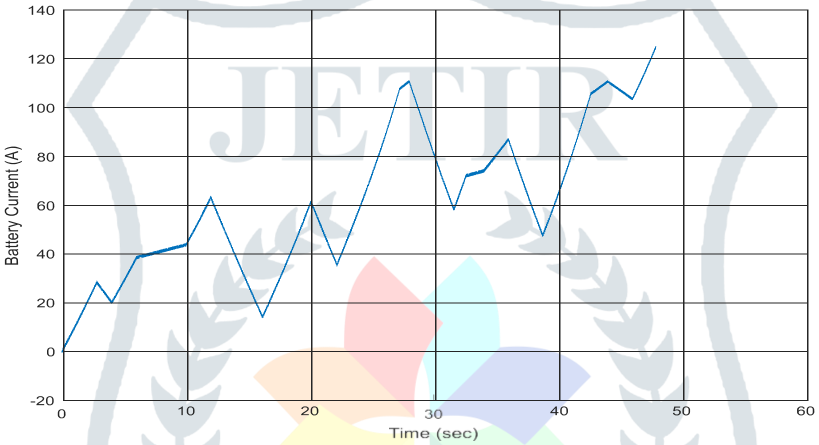

Fig. 11 Current Profile of Battery

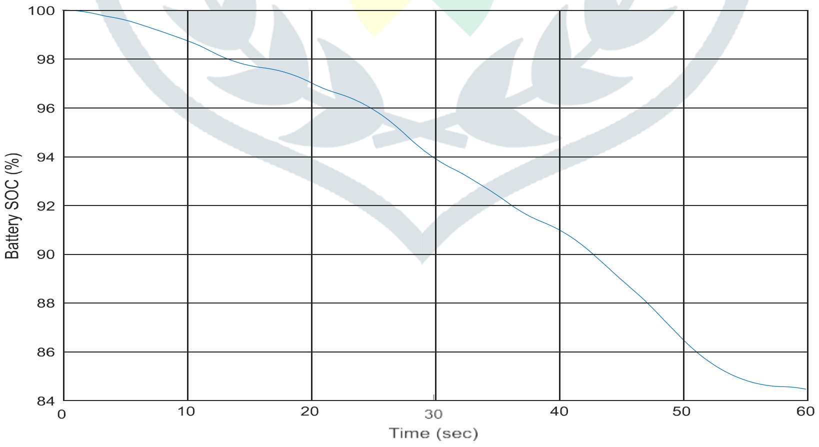

Fig. 12 State of Charge of Battery

Load power is shown in Fig. 4. The splitting of load power demand between the battery and supercapacitor based on above defined strategy are shown in Fig. 5 and Fig. 6. During initial time from 0 to 10 sec the power required is in the range of allowable battery power so only battery supplies power and supercapacitor will not shares any power. In the subsequent 10 seconds the required load power suddenly decreases to zero but battery power cannot decrease to zero instantaneously at such high rate so with the remaining power battery charges supercapacitor till its power reach to zero. During the period between 30 sec to 40 sec required load demand suddenly increases and thus supercapacitor comes into play. Fig. 6 shows that supercapacitor helps battery in meeting the load demand wherever sudden changes in load power take place. In the last 10 seconds i.e. from 50 to 60 sec, load power required is zero and thus charging of supercapacitor takes place.

The above results prove the importance of supercapacitor in electric vehicle application with battery. Use of supercapacitor decreases stress on battery and saves it from faster ageing as well as power do not get wasted. Supercapacitor voltage, current and SOC profile are presented in Fig. 7, Fig. 8 and Fig. 9 respectively. Similarly battery voltage, current and SOC profile are shown in Fig. 10, Fig. 11 and Fig. 12 respectively.

V. CONCLUSION

It has been shown that hybridizing battery electric vehicle with supercapacitors is an effective way to reduce the stress on the battery and improve the battery life. In the absence of supercapacitor battery would have been the only energy source which means whole of the load would have been on the battery and this would have resulted in high discharge current and stress on it. Thus using supercapacitor proves to be good for battery’s health and efficiency. Energy management strategy for splitting the load power demand between battery and supercapacitor is also presented. The proposed strategy shares the load demand between battery and supercapacitor in such a way that both work in their allowable range and at their highest efficiency.

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