

## Hybrid Energy Storage System for Electric Vehicle

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Received: 06th October 2019, Accepted: 20th November 2019, Published: 31st December 2019

### Abstract

Majority of the electric vehicles (EV) available commercially are powered by electrochemical batteries which have their own limitations related with cost, size, lifecycle and power density. A vehicle is supposed to perform satisfactorily under various dynamic conditions and on different road terrains requiring high torque and high motor current many times. The battery which is not a high power device is forced to deliver these high currents. Consequently, it results in reduction of battery life as well as low vehicle mileage per charging. This paper presents a hybrid energy storage system (HESS) for EV which involves coordinated usage of battery and ultra-capacitor (UC) based on the shared bus topology. One boost converter and a bidirectional buck boost converter are employed to create the active parallel configuration. The proposed scheme is simulated in Matlab/Simulink environment and tested at different operating conditions. Simulation results prove the effectiveness of the proposed scheme in overcoming the limitations of battery alone EV.

### Keywords

Electric Vehicle, Energy Storage System, Battery, Ultra-Capacitor, PMDC Motor, Converter.

### Introduction

EV are believed to be an important means for reducing both, the greenhouse gas emission and energy consumption of global transport. They are potentially more fuel efficient than comparable internal combustion engines. The energy required by an EV is supplied by the battery which is the high energy density storage device. Various dynamic operating conditions like starting, acceleration, running on a positive ramp etc. requires high torque and therefore high motor current. Drawing of high current from battery reduces its life. Therefore, in order to fulfill the tractive requirements of the vehicle, the on-board batteries strength may be increased but this demands higher cost, more space and increased maintenance. Secondly, the regenerative braking causes repeated cycles of charging and discharging of the battery and leads to a depletion in the battery life.

The shortcomings of battery have attracted the researchers to develop a HESS for electric vehicle. UC is an energy storage device with high power density and therefore, it can be a good companion with the battery. Proper coordination between them will satisfy both high energy density as well as high power density requirement of an EV. However, due to different performance characteristics of battery and UC, direct connection between them is not possible [1]. Many HESS topologies are proposed in literature for the hybridization of more than one energy storage devices [2-5]. Parallel active topology enables independent control over the power flow of the battery and UC. It is also called as shared bus topology. During regenerative braking, the kinetic energy of the electric vehicle can be transferred to the supercapacitor or the battery by using appropriate switching algorithm for interfacing converters. This harvested energy can be used during acceleration and also for avoiding deep discharge of the battery [4]. The system efficiency can be improved by maintaining optimum dc bus voltage if HESS is designed to have the boosting features by connecting the dc/dc converter output in series with UC [5].

This paper proposes a HESS composed of battery, UC, one boost dc/dc converter and one bidirectional dc/dc converter with buck-boost feature, driving a PMDC motor. The control scheme ensures that the peak power demand of the load is shared by UC while base load is shared by battery. High pass and low pass filters along with tunable PI controller are implemented to ensure tight dc bus voltage regulation under various load conditions.

### Proposed Method

The proposed drive scheme consists of three major components as shown in Fig. 1(a). They are unidirectional dc/dc boost converter, bidirectional buck- boost converter and a PMDC motor. The unidirectional converter is used as interface between the battery and dc link while the bidirectional converter is used to connect the UC with dc link. The non-isolated type bidirectional converter is shown in Fig. 1(b).

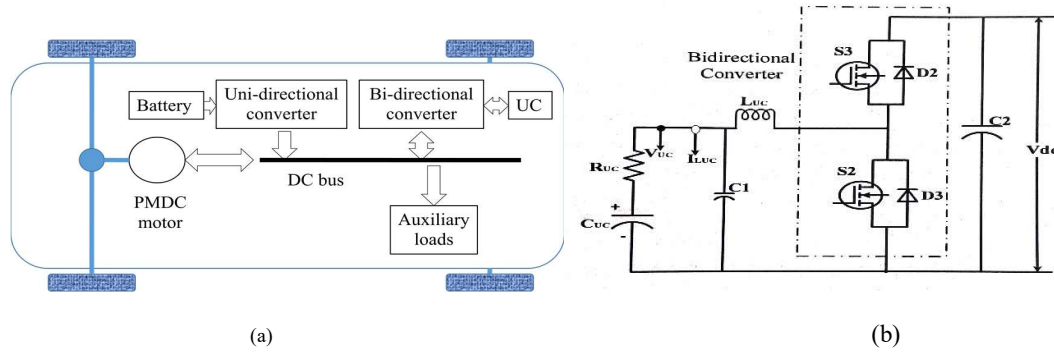


Figure 1: (a) Proposed HESS, (b) Half Bridge Bidirectional DC/DC Converter

With the linear control mechanism opted in the present work, peak shaving of the high motor current as seen from the battery terminals is achieved during starting and acceleration. A PI controller is used along-with the current limiting function to implement the power sharing.

The scheme is based on shared bus topology which isolates the battery from ripple content in the PMDC motor current. Frequently applied regenerative braking demands repeated charging and discharging of the static voltage source. In case of a battery only system, it suffers from the drawback of shorter battery life. In the proposed scheme, the repeated charging/discharging is managed by the bidirectional dc/dc converter that acts as an interface between UC and dc bus and is taken up by the UC, which leads to the extension of battery life.

**A) Selection of battery and UC**

Batteries have been used as a primary source of energy in EVs. Different types of batteries are available in the market. To maintain low price of the vehicle, lead acid battery is commonly used in e-rickshaw. In luxurious cars the lithium ion and lithium polymer batteries are preferred due to their merits like high life cycle, high efficiency, low self-discharge rate and high energy density compared to weight [6]. Such batteries account for about a third of the cost of the electric car.

Supercapacitors are promising charge storage device which have the capability to deliver peak current over short duration. In recent past, hybrid supercapacitors are suggested which provide improved performance in energy density without compromising on their power density [7]. Table 1 presents a comparison between various performance indices of battery and UC.

Parameters	Lead acid battery	Nickel metal Hydride Battery	ZEBRA Battery	Li-ion Battery	UC
Specific power(W/Kg)	75-150	80-400	150-200	250-1600	500-100,000
Energy Density(Wh/L)	50-80	60-150	135-180	250-500	10-30
Specific Energy(Wh/kg)	30-50	45-80	100-120	126-210	2.5-15
Cycle life	500-1000	1200-2000	>2500	1000-2000	>100,000
Self-discharge(%/day)	0.29-0.51	1-1.43	15	0.1-1.29	20-40
Cost(\$/kWh)	100-150	150-250	100-200	300-600	300-2000

Table 1: Comparison between Batteries and UC [8]

**B) Selection of Motor**

Electric motors are the work horse in EV. In earlier decades, a dc series motor was the only choice for high starting torque applications including traction. After the invention of power electronic controllers and advanced control methodologies, the industry popular cage type induction motor found place in vehicles. Thereafter, modern motors like permanent magnet synchronous motor (PMSM), brushless dc motor (BLDC), switched reluctance motor (SRM) and permanent magnet dc motor (PMDC) became the preferred choice of researchers and technocrats for EV [4,5,9]. The former three motors require the use of rotor position sensor and inverter for their operation which are not needed in PMDC motor.

**C) Converter Selection**

As shown in Fig. 1(a), the proposed scheme has two different converters. The unidirectional dc/dc boost converter interfaces the dc bus with the battery while the bidirectional dc/dc buck-boost converter controls the power transaction between dc bus and UC. To maintain the DC link voltage around the rated voltage of PMDC motor is one of the main objectives of this HESS. The battery connected unidirectional converter boosts up the low value of battery voltage so as to maintain the dc link voltage. For any drop in dc link voltage due to loading effect, the UC converter operates in boost mode to restore the dc link voltage back to the rated value. During regenerative braking operation, the dc bus voltage tends to increase therefore, UC converter must operate in buck mode so as to charge the UC with the excess energy available on the DC bus.

Unlike isolated topology, the non-isolated type bidirectional converter does not require a transformer and therefore has the advantages of light weight and compact size [1]. The half bridge topology of this converter allows flow of current in both the directions with less number of switching devices and reduced overall switching loss. The proposed scheme has implemented a half bridge, non-isolated type bidirectional dc/dc converter as shown in Fig. 1(b). Table 2 gives its switching sequence in different modes of operation. The selection of filter components L and C is based on the ripple content in the output voltage. Reduction in weight and size of the inductor can be achieved selecting a smaller value of L. The critical inductance in boost converter which represents its minimum value to ensure the operation as converter is given by [10].

$$L_{CRBOOST} = \frac{T_S * R_{LOAD}}{2} (1 - D)^2 D = \frac{1}{2} \left( \frac{V_{DC} - V_{UC}}{V_{UC} * I_{L_{UC}}} \frac{V_{UC}^2}{V_{DC}} T_S \right) \quad (1)$$

Critical inductance in buck converter is given as,

$$L_{CRBUCK} = \frac{(1-D)V_{DC}}{2I_A} T_S \quad (2)$$

Therefore, the value of UC converter's inductor is given by,

$$L_{UC} = Max \left[ \frac{1}{2} \left( \frac{V_{DC} - V_{UC}}{V_{UC} * I_{L_{UC}}} \frac{V_{UC}^2}{V_{DC}} T_S \right), \frac{(1-D)V_{DC}}{2I_A} T_S \right]$$

The capacitor value for UC converter can be obtained from following equations,

$$C_1 = \frac{\Delta L_{UC}}{8\Delta V_{UC}} T_S ; \quad C_2 = \frac{V_{DC} D}{R_L \Delta V_{DC}} T_S \quad (3)$$

Switching state	S2	D2	S3	D3	Power flow
Boost Mode 1	ON	NC	OFF	NC	UC to DC link
Boost Mode 2	OFF	C	OFF	NC	
Buck Mode 1	OFF	NC	ON	NC	DC link to UC
Buck Mode 2	OFF	NC	OFF	C	

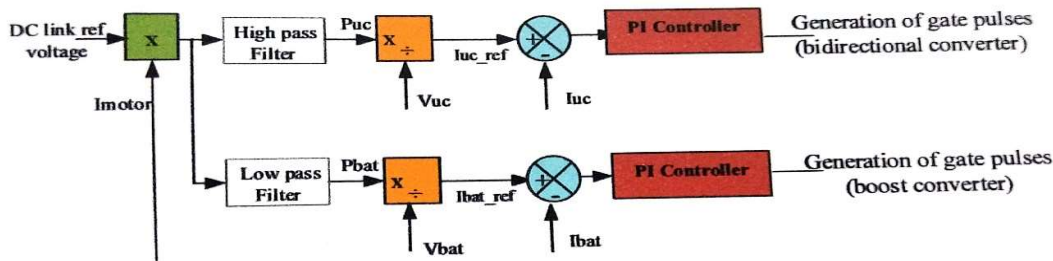
**Table 2: Operating Modes of Bidirectional DC/DC Converter**

Where NC = normally conduction, C = Conducting

**Control Aspects of Proposed Method**

The control scheme is designed for three modes of power transaction:(i) battery motoring, (ii) braking and (iii) starting/acceleration mode. During the first mode of operation, the traction motor is fed by the battery alone and the motor operates in steady-state. During braking, the regenerated power from the motor is used to charge the UC and its interfacing converter acts in buck mode. The third mode of operation demands heavy motor current. This results in the drop in dc bus voltage. The load requirement is therefore shared by both, such that the peak power demand is supplied by UC and battery delivers only steady state power.

A closed loop control is implemented with tuneable PI controller. It is designed to (i) ensure a constant dc bus voltage under varying load conditions and (ii) enforce the UC and battery currents to track well their references. The reference current for battery is generated from steady state power supplied by battery during normal operation. It is then compared with battery current and the error is minimized by using PI controller as shown in Fig. 2. Similarly, reference current for UC is generated from transient power demanded during starting and acceleration.



**Figure 2: Control Scheme**

**Simulation Results and Discussion**

The proposed HESS of Fig. 1 is simulated in MATLAB software for the hybridization of UC with battery. The battery has a rated voltage of 12V. It is elevated by boost converter to maintain the dc bus voltage at 25V and the UC is charged upto 16.2V. The battery power is limited by a limiter block and it is ensured that the transient power is supplied to the dc bus by the UC alone. The proposed HESS is tested under following operating conditions. Simulation results for each of them are presented in Fig. 3(a) to Fig. 3(h).

**A) Starting/Acceleration from Rest**

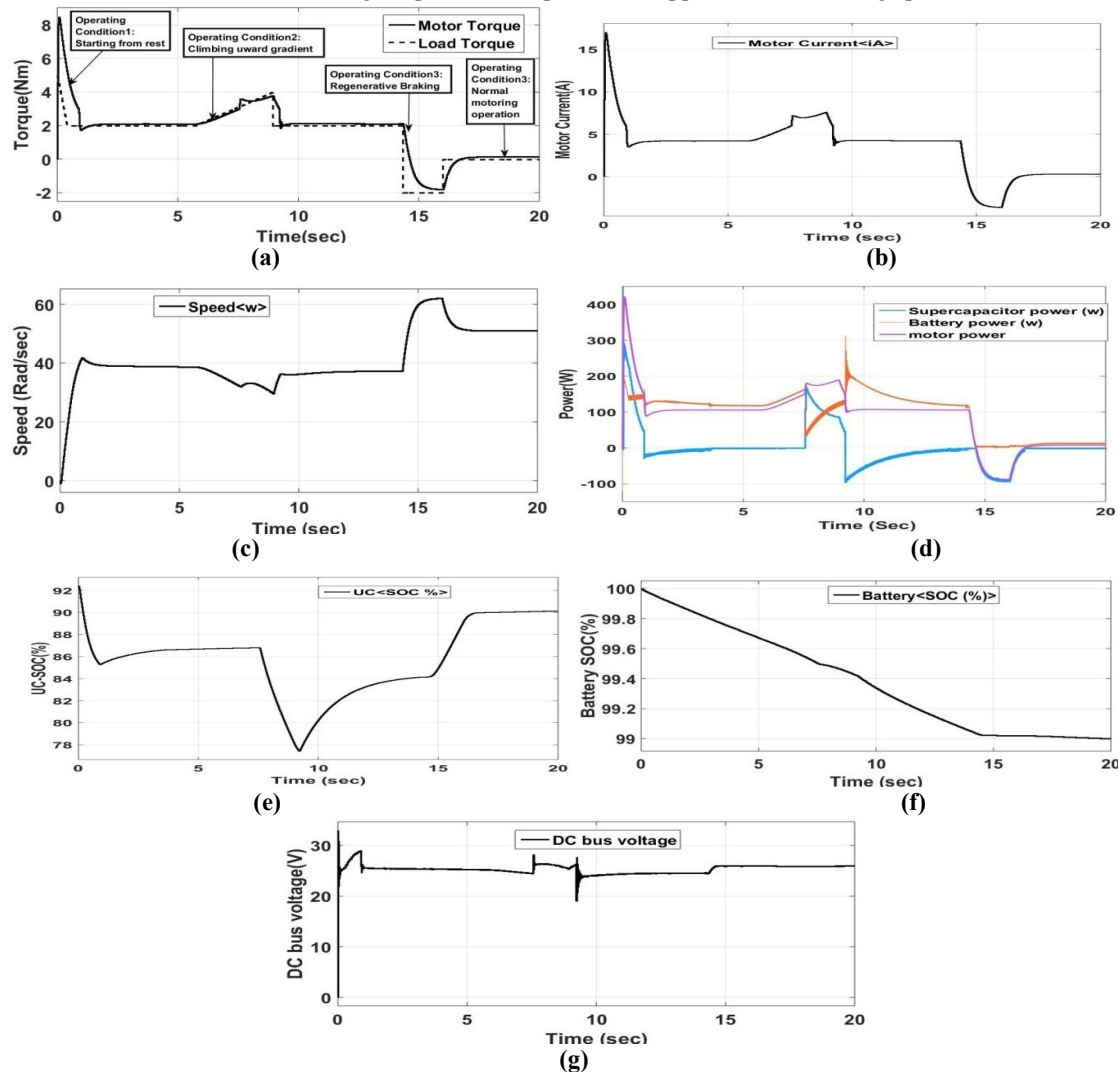
In vehicles, during starting condition, the stiction demands very high starting torque to accelerate the motor from rest. This effect is simulated by applying a 5Nm load torque at zero speed and thereafter reducing it to 2 Nm at 0.4s. During this period, it is observed that, the overall power requirement of the motor is shared by battery as well as UC which discharges rapidly to 83% of its state of charge (SOC). The motor accelerates gradually and reaches to its steady state speed in 2.5s. At steady state, battery alone feeds power to the motor.

**B) Running on a Positive Ramp**

It is assumed that the EV is climbing on a road having a non-linearly rising slope from 5.72s to 8.94s. This condition is simulated by applying a dynamic torque increasing from 2 to 4 Nm. The lagging of motor torque behind the load torque results in a speed drop of 25%. From Fig. 3(d), it is observed that, the transient rise in load torque activates the inner control loop of Fig. 2 and to relieve the battery from draining rapidly, the peak power is supplied by UC. In this process, it discharges at a faster rate reaching to 72% of its SOC. Thereafter, during steady state, the battery supplies power to the motor as well as UC for charging.

**C) Regenerative Braking**

At 14.3s, the vehicle is assumed to run on a downward slope with continuously rising speed at a constant rate. This condition is simulated by assuming a constant negative dynamic torque of 2 Nm from 14.3s to 16s. The speed rises above normal value and the tractive machine acts as a generator. The kinetic energy of wheels is converted into electrical energy and is used to charge the on board capacitor thus increasing its SOC. Due to reversal of motor current, a braking torque is developed which opposes the increasing speed of the vehicle.



**Figure 4: Simulation Results at Different Operating Conditions (a) Torques (Nm), (b) Motor Current (A), (c) Motor Speed (r/s), (d) Powers (W), (e) SOC of UC in %, (f) SOC of Battery in %, (g) DC Bus Voltage (V)**

The simulation results indicate the performance of proposed scheme during starting, running, regenerative braking and steady state condition. The control scheme designed to maintain a constant value of dc bus voltage generates required switching pulses for the converter devices and ensures appropriate direction of power flow. Although the bus voltage is fixed at motor voltage rating, it is observed that, it tends to deviate during dynamic conditions. The charging and discharging of UC attempts to maintain its SOC but due to unidirectional power flow permitted for the battery, its SOC reduces continuously with service. However, it is obvious that due to shaving of peak load on the battery, the drop in its SOC in the proposed HESS is less as compared to battery only system.

### Conclusion

A HESS consisting of battery and UC are proposed for the EV in this paper. The control system is designed to ensure that the battery supplies base load power while peak power demanded during dynamic conditions is provided by UC. The regenerated power from the PMDC machine is used for charging of UC as and when the vehicle runs under the influence of its kinetic energy. These measures minimize the excessive power drain from battery and reduce its repeated charging/discharging. Consequently, it will lead to enhanced battery life and improved mileage of the vehicle per charging. Though, this work is not focused on speed control, the speed of PMDC motor can be controlled by varying the dc bus voltage. The simulation results presented for different operating conditions reflect the feasibility and effectiveness of proposed scheme.

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