RESEARCH PAPER

Sizing Scheme of Hybrid Energy Storage System for Electric Vehicle

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Abstract

Energy storage system (batteries) plays a vital role in the adoption of electric vehicles (EVs). Li-ion batteries have high energy storage-to-volume ratio, but still, it should not be charged/discharged for short periods frequently as it results in degradation of their state of health (SoH). To resolve this issue, a conventional energy storage system (ESS) is being replaced by hybrid ESS (HESS). The requirement of high-voltage energy sources is increasing with the increasing number of performance based EVs. High-voltage storages are usually difficult to design due to the involvement of higher rating devices; hence, there is a need to create a method to modularize the storage. Modularization can be implemented using lower rating converters to decouple the ultra-capacitors (UCs) and batteries from the load, reducing the cost of storage. This article proposes a fully active series–parallel HESS topology which uses a set of UCs deployed in conjunction with the batteries. UCs provide the advantage of quick and frequent charging/discharging without degrading the battery SoH and are also used to absorb most of the energy generated due to regenerative braking. The major source of energy is Li-ion cells which provide the energy required to run the vehicle, whereas the UCs will provide above-average energy required by the motor. The proposed topology is managed by rule-based energy management systems (EMS), which considers pre-decided threshold parameters of various storage devices. Firstly, a power-based method to find the specifications of UCs and batteries is described which provides specifications for ESS hybridization. The proposed method, which is based on the prescribed set of limiting values of current and voltages, tries to maintain the UC voltage and battery current within range. This method reduces the above-average peaks of the required current from the batteries. Similarly, while recharging due to the regenerative braking, the proposed method removes the above-average peaks of the charging current of UCs. The proposed topology along with the EMS provides better state of charge (SoC) levels, giving a 38.6% increase in SoH levels of the batteries.

Keywords BMS · UC · Regenerative braking · Hybrid Energy Storage · Sizing · SoC · SoH

1 Introduction

The increasing concern of environmental degradation and depleting fossil fuels drive us towards the alternative options of transport (Höök and Tang 2013; Panday and Bansal 2014; Products 2010). This transport mode must be as efficient as its counterparts while being robust and environmentally clean (Van Mierlo 2018). This results in exploring the potential of EVs, hybrid electric vehicles

(HEVs) and plug-in hybrid electric vehicles (PHEVs) as a future mode of transport. The EVs are propelled by battery-driven electric motors, whereas the HEVs are powered by both battery and ICE (Çağatay Bayindir et al. 2011). The powertrain of these HEVs can be in series, parallel, split mode, etc. (Chan et al. 2010; Veer et al. 2019).

The performance of any type of EV (XEV) is highly dependent on the ESS (battery) which is a very costly component (Hannan et al. 2017). The stored energy must be retained for a prolonged period and should be made available at the driver's will. The ESS should be able to get charged and discharged multiple times with great ease without its life degradation. The uptime of the storage must be very high between the replacements, which means that the required mileage of the storage should be very high. Traditionally, the electricity was stored in the lead-acid

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batteries (Budde-Meiwes et al. 2013; Ecker et al. 2015; Palinski 2017; Sieg et al. 2019). Though many new types of batteries like ammonia-based batteries, hydrogen fuel cells, and methanol-based batteries are currently under development (Al-Zareer et al. 2017, 2018; Bicer and Dincer 2017; Hacatoglu et al. 2015), most of the electric car manufacturers currently prefer to employ Li-ion batteries. These Li-ion batteries get charged quickly, discharged as and when required, deliver high energy to storage ratio, and can satisfy substantial power requirements.

The battery management system (BMS) actively manages the voltage and current of batteries to keep them in the pre-defined limits. Active and passive balancing are essential processes carried out by BMS (Kane et al. 2016; Lelie et al. 2018; Serrao et al. 2011; Wu et al. 2015; Xing et al. 2011). The batteries of EVs can be charged from the wall outlets and by the power generated during regenerative braking. Regenerative braking is a complex mechanism, which produces power while braking the vehicle (Panchal et al. 2018). Braking does not occur frequently, but whenever it happens, it will produce massive power per unit time, i.e., a considerable amount of energy will be pushed directly into the batteries in a short time. Similarly, during peak traffic period (a common start-stop scenario), there is a high battery discharge in a short interval of time at each start of the vehicle. Both scenarios can lead to damage of the battery chemical properties. The frequent start-stop situations are not suitable for good battery health (Brandl et al. 2012; Panchal et al. 2017; Xu et al. 2011) and are known to age the battery faster (Barcellona and Piegari 2020; Zilberman et al. 2020). Degrading SoH presents problems in SoC estimation (Singh et al. 2020).

To save the batteries from the abovementioned scenarios, there is a crucial need to deploy a device with batteries which can get charged/discharged very quickly, virtually for infinite times. This makes the energy storage a hybrid storage. Additionally, this device should have a high-power dissipation as well as absorption capacity per unit mass. The UCs are well suited for these kinds of applications (Burke and Zhao 2015; Horn et al. 2019; Kouchachvili et al. 2018). These specific types of capacitors have a very different chemical design than the traditional capacitors. The capacitance values of UCs vary from some farads to tens of hundreds of farads. They can absorb and discharge a large amount of charge in a brief period and can do this frequently for extended periods. The energy-power characteristics of various storages are given in the Ragone plot (Fig. 1). The high-power density of UCs and high energy density of Li-ion batteries can be combined to improve the performance of existing HESS. Several topologies to design a HES are presented in literature and can be classified into two major categories (Zimmermann et al. 2016).
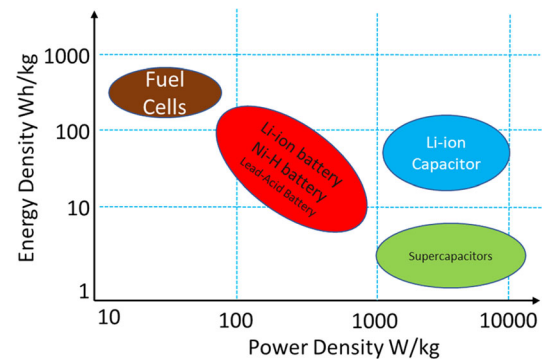

Fig. 1 Ragone plot of various storages devices (Ronsmans et al. 2015)

These categories, namely passive S (P-HES) and active HES (A-HES), are defined based upon the number of power electronics devices used. The categorization also illustrates the level of energy control and optimization in individual elements of the HESS. In a typical P-HES, various energy storage devices are connected in parallel to load without any power electronic decoupling between them. In such cases, due to the significant differences in the charging and discharging curves of the various storage elements, proper optimization is not possible. All the fluctuations in load voltages pass directly to the storage devices degrading the battery life. Therefore, the inclusion of power electronic devices is necessary to reduce the fluctuations reaching to battery modules (Fig. 2).

The level of control and optimization in A-HES depends on the number of DC-DC converters included. A-HES is further classified as semi-active (SA-HES) and fully active (FA-HES). SA-HES topology employs only one DC-DC converter. When this converter is connected before all the parallel-connected storages, voltage fluctuations of UCs will be same as that of battery; hence, this scheme (parallel SA–HES or PSA-HES) is not a very good improvisation over the P-HES. Battery SA-HES (BSA-HES) and capacitor SA-HES (CSA-HES) are further improvisations over PSA-HES. BSA-HES has a DC-DC converter for the battery while CSA-HES has a DC-DC converter for the capacitor. Both topologies aim to restrict the fluctuations due to one storage on the other. But, in both these connections, one of the storage devices remains in direct contact with the load which results in high fluctuation so there is further scope for improvement.

FA-HES better controls the energy flow as compared to SA-HES and can optimize power through each device. FA-HES consists of two main topologies which can be differentiated based on the arrangement of multiple DC-DC converters with respect to each other. Cascaded FA-HES (CFA-HES) has two or more DC-DC converters connected in parallel to each other. In battery CFA-HES (BCFA-HES) topology, the UCs are decoupled from DC-DC
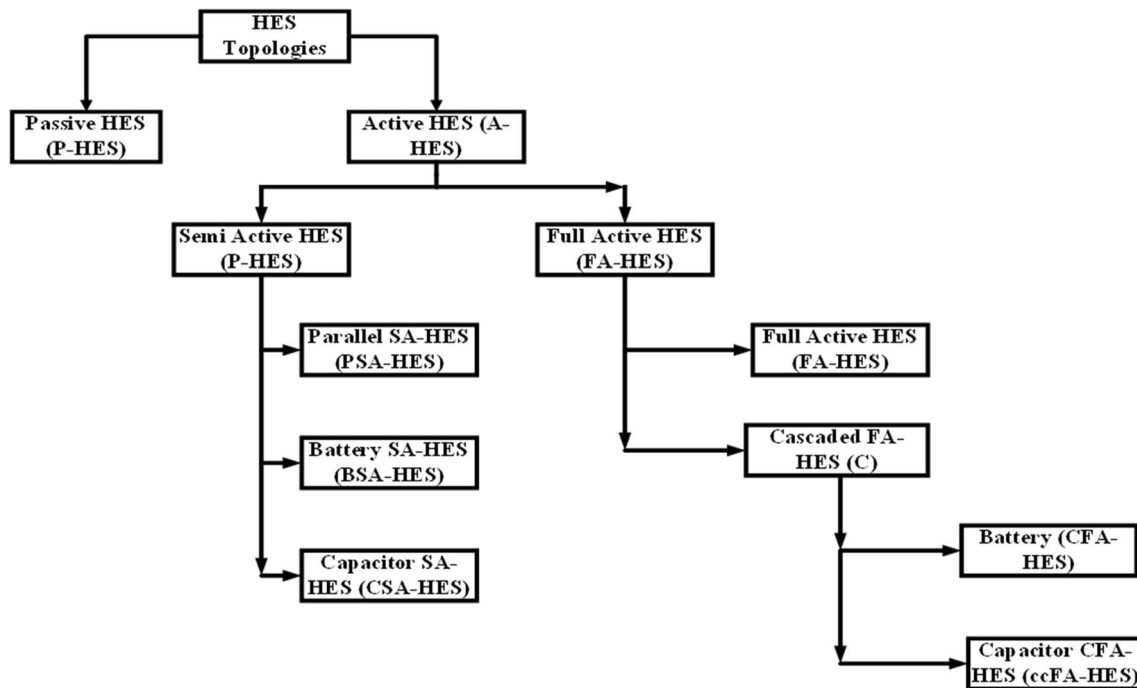
Fig. 2 HES topologies (Zimmermann et al. 2016)

converter, and the battery is further decoupled from UCs using another DC-DC converter. Conversely, in capacitor CFA-HES (CCFA-HES) topology, the batteries are decoupled from the load with a DC-DC converter. Then capacitors are decoupled with batteries by another DC-DC convertor. In these CFA-HES topologies, one of the used storages controls the voltage of the load, and the other tries to follow this voltage. Parallel FA-HES (PFA-HES) is another topology in which all the storage devices are decoupled from the load using separate DC-DC converters. The number of DC-DC converters is directly proportional to the number of separate storage devices used in PFA-HES. The advantage of PFA-HES over CFA-HES is the requirement of simpler DC-DC converters and better control of the energy flow.

Increasing requirement of storage voltage in EVs requires creating standard battery and UC modules. These modules can be combined in different ways to create larger storages. This creates a requirement of a specialized EMS with dedicated converters for each energy storage device. In the proposed method, a series–parallel FA-HES is discussed. A DC-DC converter is used along with each parallel combination of UC and battery modules to provide a stable voltage to DC voltage line. This article describes a linearly expandable method of using UCs in a hybrid series–parallel combination. The UCs decrease the peak power absorbed and dissipated from the battery modules and hence save the batteries from degrading. This article

proposes an EMS, which combines BMS and current management system.

1.1 Research Gap

From the above literature review, following research gaps are observed.

- The existing HESS design strategies are difficult to use for high-voltage storages.
- High-voltage storages require high-voltage battery modules as well as capacitor modules.
- To control the energy flow through the high-voltage storages, heavy and costly DC-DC converters with higher ratings are required.
- The existing strategies also lack the implementation techniques for pack level hybridization/modularization.

This article tries to attempt solving a few of these issues and contributes the following.

1.2 Proposed Novelties

- The manuscript provides a fully active series–parallel HESS technique.
- The proposed strategy provides a method for making high-voltage storages using low voltage battery and UC modules, i.e., pack level hybridization. This enables the designer to use lower rating DC-DC converter modules thus saving in weight, cost, and losses.

- The proposed rule-based EMS along with the modularized storage modules reduces the voltage and current fluctuations through the battery. This keeps the storage balanced, providing controlled charge/ discharge characteristics and temperatures.
- The proposed HESS strategy along with the proposed EMS provides better battery SoH levels after several charge–discharge cycles, compared to conventional methods. This will increase the timespan between battery replacements, thereby decreasing the maintenance cost.

1.3 Organization of the Article

The second part of this article tells the reader about the environment, proposed methodology, and specifications for the simulations of the hybrid storage. In the third part, rigorous analysis and obtained results using the proposed method are discussed. And lastly, the conclusion of the article is drawn.

2 Proposed Methodology

The main aim of the proposed method is to limit the peak absorption and dissipation of the Li-ion batteries to a predefined limit given by the manufacturer to avoid battery health degradation. The value can be updated in the EMS as per the manufacturer or based on other parameters concerning the battery health. This part illustrates the circuit layout and the component specifications of the proposed scheme, after which the simulation environment is portrayed, followed by the parameter estimation and EMS description.

2.1 Circuit Layout

The proposed method includes battery modules placed in series with each other in voltage additive polarity (Fig. 3). One UC module is connected in parallel to each battery module, aiming to nullify local above-average peaks in the currents of the individual battery modules. Another UC module is connected across the circuit, to eliminate any leftover peaks in the load current. Here, assuming almost constant voltage to the load with the help of EMS, the model will consider the load power requirement/supply as a direct function of current passing through the battery. The model will then limit the current through the batteries if it goes above the threshold value in any direction.

2.2 Environment for Software, Hardware, and Real-Time Simulations

The driving cycle used here is "Indian Driving Cycle" as depicted in Fig. 4 (Bindu and Thale 2018). The proposed strategy is simulated in the MATLAB environment using Simulink and Simscape Tools. To validate the sanctity of any method, its real-time validation is a must. The HEVs are highly nonlinear and complex in nature. Due to lack of financial resources as well as tedious and risky nature of physical test setups, the team chose to use the real-time FPGA and embedded system-based MicroLabBox testing setup. It leverages the power of different microprocessors and floating-point digital signal processing technologies present today. The proposed methodology is simulated in MATLAB and then validated in real time using hardware in loop (HIL) testing setup as shown in Fig. 5. The MicroLabBox has a vertical resolution of only 10 V; hence, exact waveform of signals with large amplitude cannot be displayed directly. Therefore, the signal magnitude is further divided by 100 to step it down to display on DSO in real time. Figure 4 represents the power requirements of the driving cycle, with current requirements and its real-time replica for the first 500 s in Fig. 6. The replica shown is only for 500 s which is the time range limit of the DSO. The oscilloscope provides results of the validation runs. The vehicle parameters are mentioned in Appendix Table 1.

A finitely chargeable battery model is used in the simulation, which comprises of a series internal resistance and a charge-dependent voltage source defined by $V = V_{nominal}*SoC/(1-beta*(1-SoC))$. The beta coefficient is decided by the total chargeable capacity. The UC model used has a system/combination of a voltage-dependent capacitor with series resistors and capacitors. These parameters were provided based on the actual values of the UCs available in the market.

2.3 Battery and capacitor specifications

The LiFePO$_4$ Li-ion cells are used in series and parallel combinations to create a battery module. These modules will be capable of supplying the current through parallel combination while simultaneously providing the given voltage due to series connections, hence supplying enough energy for a driving cycle. Similar is the case for the UC cell. Table 1 depicts all the specifications.

2.4 Linearization and sizing of the HES system

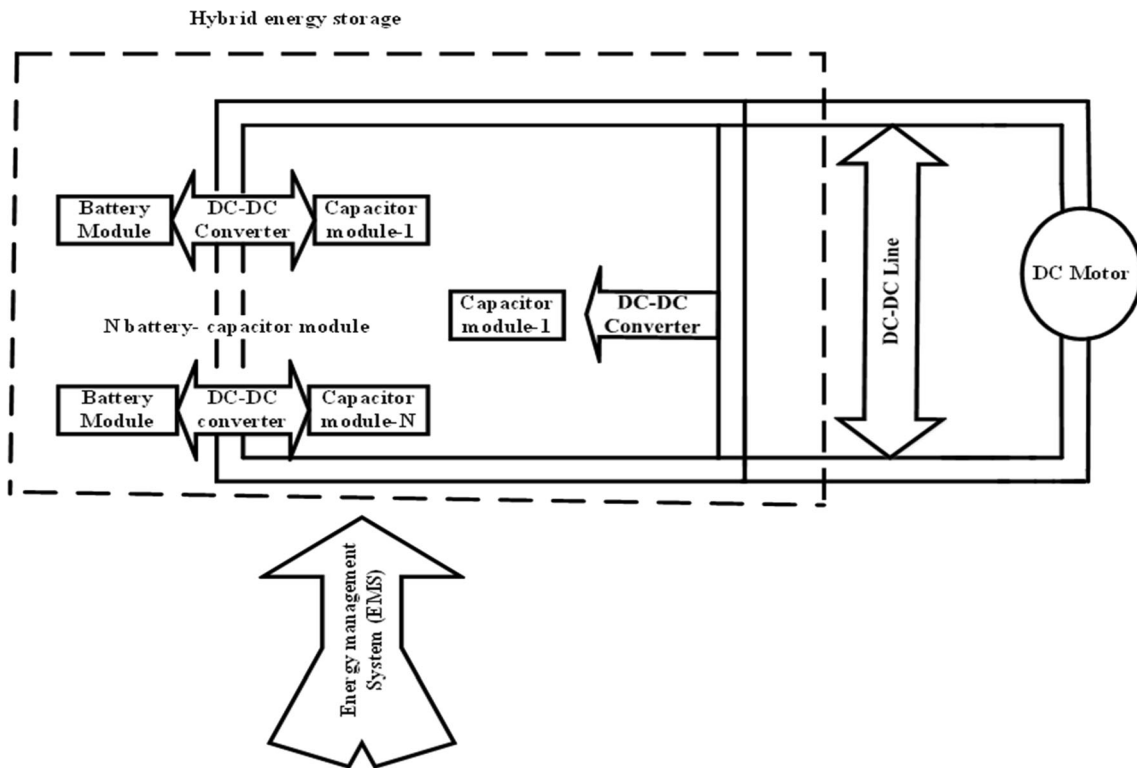The proposed method helps to find the specifications of components required to design a multiple capacitor-battery
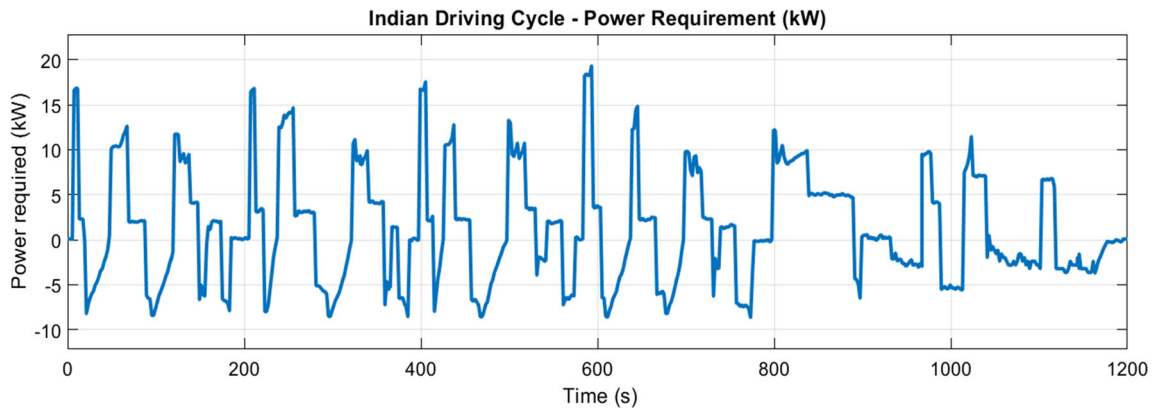
Fig. 3 Proposed circuit diagram

Fig. 4 Indian driving cycle—power requirements

(HES) system sufficing the highest peak requirements. A novel approach was needed because the capacitors can only store a small amount of energy but deliver/absorb power at a high rate. While the batteries can store a high amount of energy but cannot deliver/absorb power at a high rate. The linearization method defines the minimum number of Li-ion/UC cells required to form a single module, given the internal resistance and voltage rating of an individual cell. For proper torque, the power requirements should also be known beforehand to decide the number of modules of both capacitors and batteries. The derived voltage value for each module will determine the number of individual cells

in series and parallel combination. The specification of the LiFePO$_4$ and UC cell is provided in Table 1.
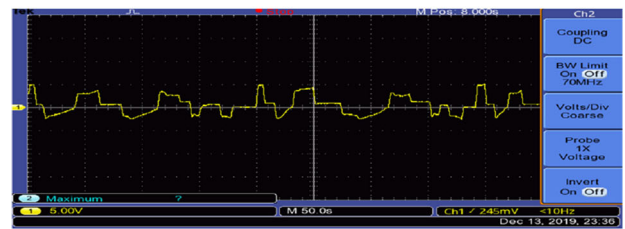
2.4.1 Sizing *of Battery Module*

This article designs a generic 48 V, 14kWh, and 292 Ah battery, made of 3.3 V LiFePO$_4$ cells. For a battery module, the specifications in Table 1 decide the number of cells in series and parallel.

$$N_{\text{BS}} = \frac{V_{\text{BM}}}{V_{Li} - cell} \tag{1}$$

Fig. 5 Simulation and real-time testing equipment Setup
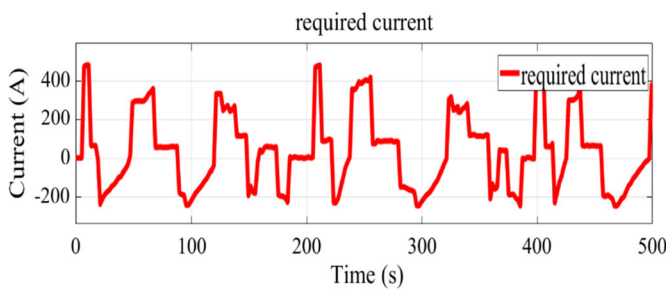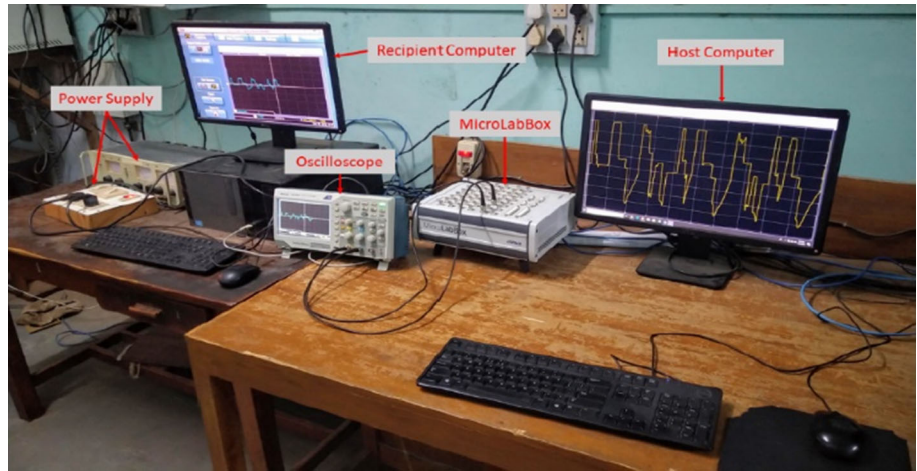
(a) Simulated required current

(b) HIL results of required current

Fig. 6 Current requirement of the driving cycle (0 – 500 s)

Table 1 Specifications of LiFePO$_4$ and UC cell (Maxwell Technologies Inc. 2014; Panasonic 2018)

Specifications	LiFePO4 cell	UC cell	Units
Nominal voltage	3.3	2.7	V
Nominal capacity	2.5	N.A	Ah
Internal resistance	6	0.29	mΩ
Weight	0.076	0.51	Kg
Rated capacitance	N.A	3000	F
Energy storage	8.25	3.04	Wh
Max. charge current	2200	–	mA
Max. discharge current	5200	–	mA

Therefore, at least 16 cells are placed in series into each module of 48 V, which accounts for the voltage drop across the internal resistances and interconnects. The current capacity of the module is the next parameter to be considered which needs to be 292Ah. For a single LiFePO$_4$ cell at 3.3 V, the energy stored at a safe level is 8.5Wh.

$$\text{Current rating (for one hour)} = \frac{W_{Li-\text{cell}}}{V_{Li-\text{cell}}} \tag{2}$$

The safe limit of the maximum current considered here is 2A.

$$N_{BP} = \frac{I_{BM}}{I_{Li-cell}} \tag{3}$$

Hence, each module will have 146 cells in parallel.

$$\text{Total number of cells} = N_{BP} \times N_{BS} \tag{4}$$

A total number of cells per module come out to be 2336. The net resistance of the module should also be known to simulate the design accurately. The rated internal resistance of each LiFePO$_4$ cell is 6 mΩ per cell.

$$\text{Net resistance per battery module} = \frac{N_{BS}}{N_{BP}} \times R_{int} \tag{5}$$

The net resistance calculated for the given specifications is 0.66 mΩ of each battery module. This value is minimal due to the high number of parallel connections. The graph in Fig. 4 represents the Indian driving cycle on a 48 V battery where maximum power requirement goes about 14kWh. But for safe operation within limits, battery modules must be clipped from the discharging after 90% of the nominal power capacity is dissipated. This limits the batteries to provide only 12.5kWh of the 14kWh storage capacity. As the dynamics of the vehicle will change

according to the road conditions and terrain, an upper limit for real-life scenarios must be given, or else the EMS would not be able to properly manage the battery in cases of severe load conditions and very demanding drivers. The safe limits chosen take into consideration that the threshold values should be less than that. While all the abovementioned values are in nominal terms, to extend the battery life, the voltage of batteries must remain in the 20% to 80% of nominal voltage values. The value of SoC is hence normalized between the operating (20%–80% of nominal) battery voltages ("Appendix" 1) and is used through the rest of the article. Suppose for the given vehicle design, a net of 140 V is required across the total batteries. It means that 3 individual battery modules, each of 48 V, in series combination would be enough to provide 140 V. The power requirement and the threshold limits will also be linearly multiplied by 3.

2.4.2 Sizing of the Capacitor Module

As per the proposed strategy, we need to design two different capacitor modules, one for placing in parallel of every individual battery module and the other for putting across the series combination of all the battery modules. All the capacitors will charge and discharge very quickly and change the voltage rapidly across its terminals. A DC-DC bidirectional converter placed at every connection of the capacitor module prevents the battery modules from getting impacted by the voltage fluctuations.

The UCs are rated to work within the voltage fluctuations of 100% to 50% of nominal voltage. The mean of the voltage range of the UC module should be equal to V_{BM}

$$V_{BM} = \frac{V_{UCM} + \frac{V_{UCM}}{2}}{2} \tag{6}$$

$$V_{UCM} = \frac{4}{3} \times V_{BM} \tag{7}$$

Equation (7) results that 62 V UC module is required in parallel with each battery module and 186 V UC module across the load.

Moving on to the sizing, a 62 V UC module ($C_{int}F$) with the minimum safe voltage limit 31 V is to be designed. Another UC module ($C_{ext}F$), placed across the whole circuit, should be able to handle thrice the voltage values taken for the before mentioned UC module. The maximum voltage for this module will be 62*3, i.e., 186 V, and the minimum voltage should be 93 V.

Considering that the maximum voltage will appear due to the series combination of the individual UC cell with a nominal voltage of 2.7 V, the number of cells required can be calculated as:

$$N_{UC_{int}} = \frac{V_{UC_{int}}}{V_C} \tag{8}$$

$$N_{UC_{ext}} = \frac{V_{UC_{ext}}}{V_C} \tag{9}$$

C_1 requires 23 and C_2 requires 79 capacitors cells in series, respectively. Following this, to find the number of UC cells needed in parallel, an analysis of the energy above the safe battery level should be considered. From Fig. 4, for a 48 V battery module, 160,500 Ws energy is needed. Therefore, for a 140 V configuration, 481,500 Ws of energy will be required. The energy requirement values are obtained from the integration of power required in the driving cycle.

$$E_{UC} = \frac{1}{2}\left(3 \times C_{int} \times \left(V_{UC_{int}}^2 - \left(\frac{V_{UC_{int}}}{2}\right)^2\right)\right.$$
$$\left. + C_{ext} \times \left(V_{UC_{ext}}^2 - \left(\frac{V_{UC_{ext}}}{2}\right)^2\right)\right) \tag{10}$$

$$C_{int} + 3 \times C_{ext} = 111.34 \tag{11}$$

Any designer would want to use a capacitor module which can be used for making both $C_{int}\&C_{ext}$. Hence, assuming there are $N_{UC_{ex}}\&N_{UC_{int}}$ number of similar UC modules in the external (C_{ext}) and internal (C_{int}) capacitors, respectively. Then, let the number of cells in each of the modules be N. Referring to C_{int}, N can be given a value of 23. As C_{ext} requires 69 cells, $N_{UC_{ex}}\&N_{UC_{int}}$ can be 3 and 1, respectively. Hence, the relation between $C_{ext}\&C_{int}$ is:

$$\frac{C_{int}}{3} = C_{ext} \tag{12}$$

Hence, the values of C_{int} and C_{ext} are 100F and 33.33F, respectively. The capacitors taken into consideration are 3000F, 0.29 mΩ capacitors. Sixty-nine capacitors in series combinations make a 33.33F capacitor module, which brings the net capacitance to 3000/69, i.e., 43.5F. Accounting for the I^2R losses, a capacitor of this value can be very well used instead of creating a separate 33.33F capacitor. Similarly, a 3000/23, i.e., 130F capacitor, can be used instead of making 100F. The total resistance of the 130F capacitor is 0.29 mΩ*23, i.e., 6.67 mΩ, and that of 43.5F capacitor is 0.29 mΩ*69, i.e., 20 mΩ. This method applies to any appropriate voltage levels required in various vehicles according to their power requirements. Varying the number of modules will produce a discrete range of output voltages.

2.5 Current Limiting and Voltage Control

Voltage and current control are the main parts of any power supply design. This module does the logical part of

converting the driver's accelerator actuation to an electrical signal for the motor. In this design, the EMS assumes that the batteries are the central power supply unit of the vehicle, and UC modules are the main power absorbers for the regenerative braking of the vehicle. The UC modules also help to supply above-average requirements of the load. The current drawn from the battery module must be limited to the maximum discharge current level of the module (which is 292A). The capacitors should supply any current that is required above this level unless their voltage level goes below the 31 V mark. The battery provides current if the capacitor voltage falls below 50% of the nominal voltage level.

During regenerative braking, as mentioned before, a large amount of current will suddenly flow into the storage unit. The capacitors will handle this current until their voltage goes above the maximum 62 V. After this, batteries should absorb any more current supplied to the storage system. The flowchart in Fig. 7 represents the current limiting and voltage control method. It starts with sensing the UC module's voltage and maintaining it under the given range of 100% and 50%.

2.6 Case 1: UC Voltage Between 100 and 50% of Nominal Voltages

In this case, the UC modules are in the optimal voltage range. The battery provides all the current up to 292A for acceleration, above which the capacitors provide the remaining required current. While regenerative braking, the UC module will absorb the current till the 200A, after which the battery module will absorb the surplus. The threshold values are calculated based on the number of parallel connections per module and the current capacity of each parallel connection.
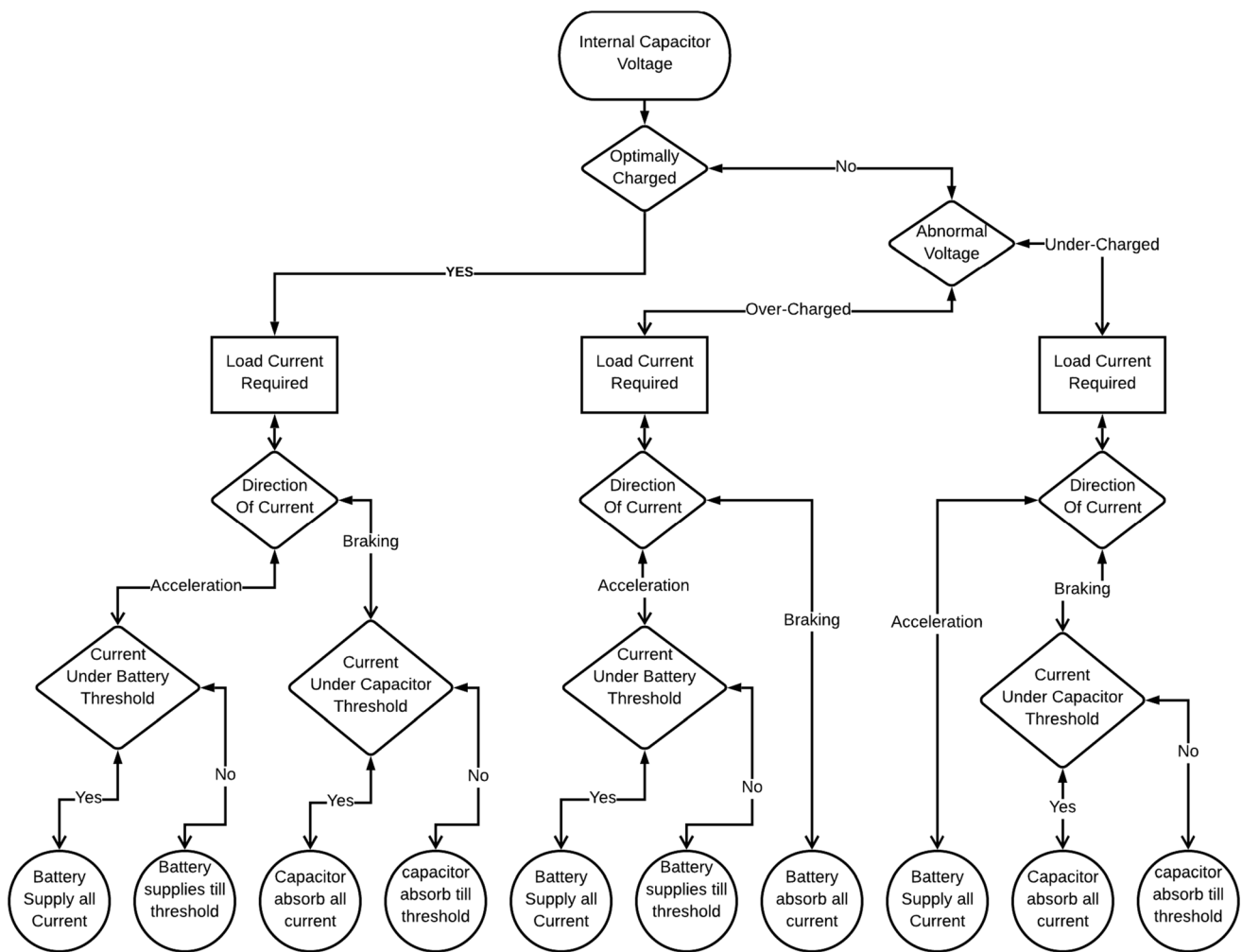

Fig. 7 Proposed energy management system

2.7 Case 2: UC Voltage Greater than 100% of Nominal Voltage

In this case, the UC modules are on the verge of over-charging. Hence any current from the regenerative braking must not enter the UC module. The battery will absorb all the current from the regenerative braking. The current requirements of the load will be fulfilled, as in case 1.

2.8 Case 3: UC Voltage is Less than 50% Nominal Voltage

In this range, the UC module is undercharged and will not be able to provide any current. Hence battery will have to supply any amount of current required by the load. The regenerative braking will work the same as in case 1.

2.9 SoH comparison

The chemical properties of any battery change over time. The aging occurs due to the various charging and dis-charging events that take place during the life of the battery. The manufacturer of batteries designs a maximum charge capacity for the batteries. But due to aging over time, the batteries lose some part of this capacity. The remaining capacity of the batteries is inversely proportional to the change in SoC over the observation time interval. Then the SoH of a battery can then be defined as a ratio of residual charging capacity (C_{residue}) and specified charging capacity ($C_{\text{Specified}}$).

$$C_{\text{residue}} \propto \frac{1}{SoC_{t_1} - SoC_{t_2}} \tag{13}$$

$$SoH = \frac{C_{\text{residue}}}{C_{\text{specified}}} \tag{14}$$

To compare different EMS, the ratio of respective SoH can be taken, which will eventually result in an inverse of the ratio of change in SoC due to respective methods over time.

3 Results and Analysis

The proposed system with identified circuit parameters is simulated in MATLAB and then tested in real time using MicroLabBox hardware test setup for various operating conditions. In the section, below results are presented and analyzed. In all the following figures, HIL results are represented by 'H' and MATLAB simulations are represented by 'S,' wherever required.

3.1 Comparison of HES Performance with and Without Regenerative Braking

EMS is not enabled in this case to showcase the effects of regenerative braking. In the absence of regenerative braking, the voltage and hence the charge content of the batteries will deplete faster compared to regenerative braking enabled. When regenerative braking is enabled, net power provided to the vehicle is the addition of power supplied by the batteries and power gained from regenerative braking. As the net power taken by the vehicle is the same for both the cases, the batteries will have to work harder in the case when regenerative braking is not enabled. Hence net fall in the SoC level will be less in case of regenerative braking as observed in Fig. 8a. A similar effect on the voltage levels is also observed in Fig. 8b.

Capacitor-aided storage modules also show a similar trend. The MATLAB simulation for capacitor-aided storages, along with their real-time results for the first 500 s are shown in Fig. 9, displaying the exact correspondence of the current and the voltages of various components. The current through the capacitors with regenerative braking enabled (Fig. 9b shows positive spikes, conveying that capacitors are charging. The capacitor will stay charged due to frequent braking in the case of regenerative braking enabled, while it would drain to 50% of the nominal voltage level, in the other case (Fig. 9d).

3.2 Comparison of HES Performance With and Without Using UCs

EMS is not enabled in this case to showcase the effects of UCs. The use of UC modules is relevant for the proposed method as the aim is to decrease the usage of batteries at high current supply or absorption rates. The energy supplied or absorbed by the capacitors will supplement the batteries in meeting the power requirement of the vehicle.

For a demonstration of this idea, a 48 V battery module designed earlier is used in parallel with the 62 V capacitor module (Figs. 10 and 11). Figure 10 provides the insight of the before mentioned idea. The current through batteries is significantly less when capacitors are used while the battery current shows huge spikes when used without capacitors. Similar trends are shown in Fig. 11b representing a repetition of the driving cycle four times. In the case of not using the capacitor and no limits on the discharge and charge current to the battery, it is evident that the battery module is supplying an excess of 400A to the load and absorbing around 200A while regenerative braking scenarios. After using capacitors, the maximum current supplied by the battery limits to under 300A. Similarly, the charging current is also decreased significantly. These

Fig. 8 Battery voltage with and without enabling regenerative braking

(a) Battery SoC

(b) Battery Voltage
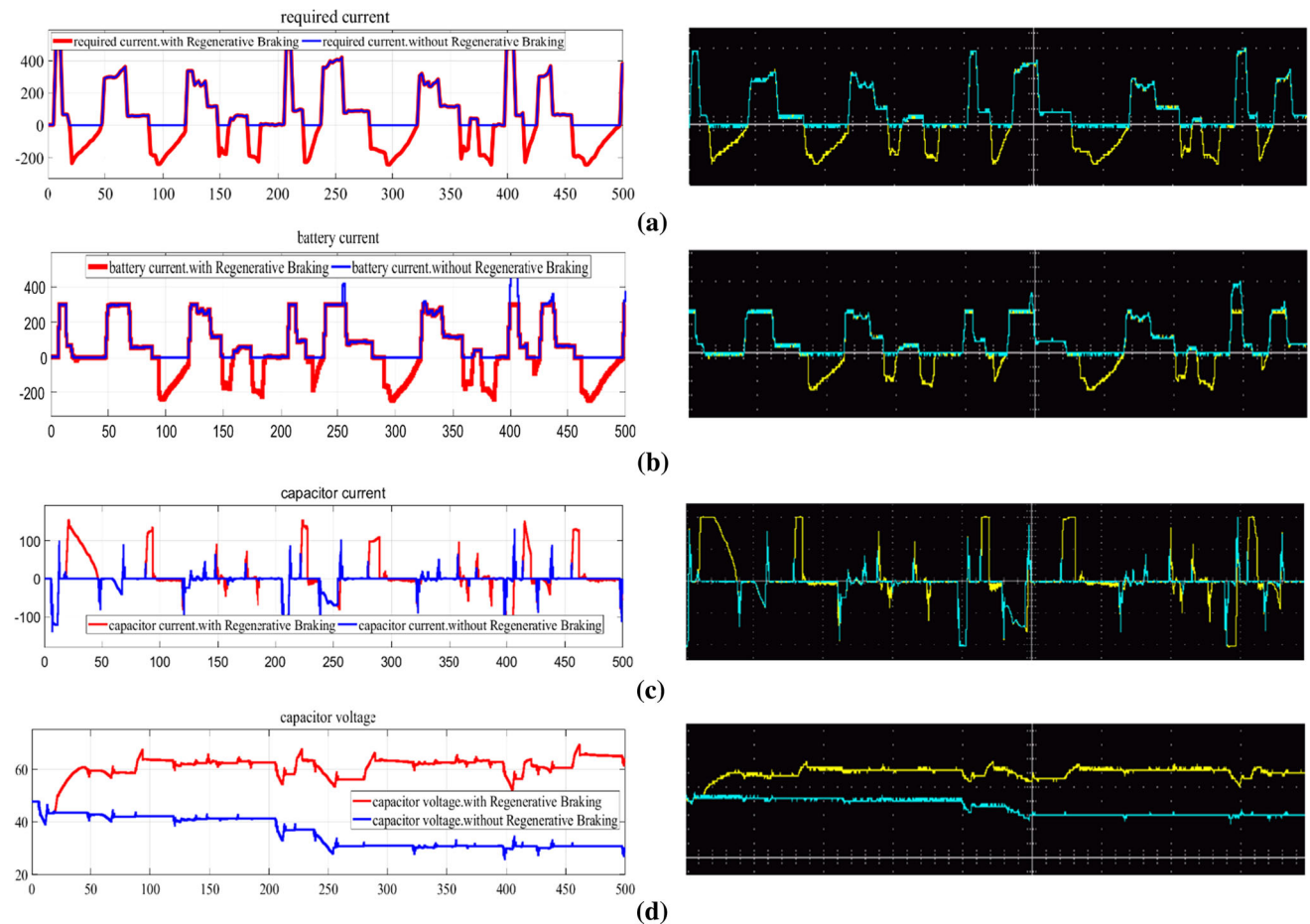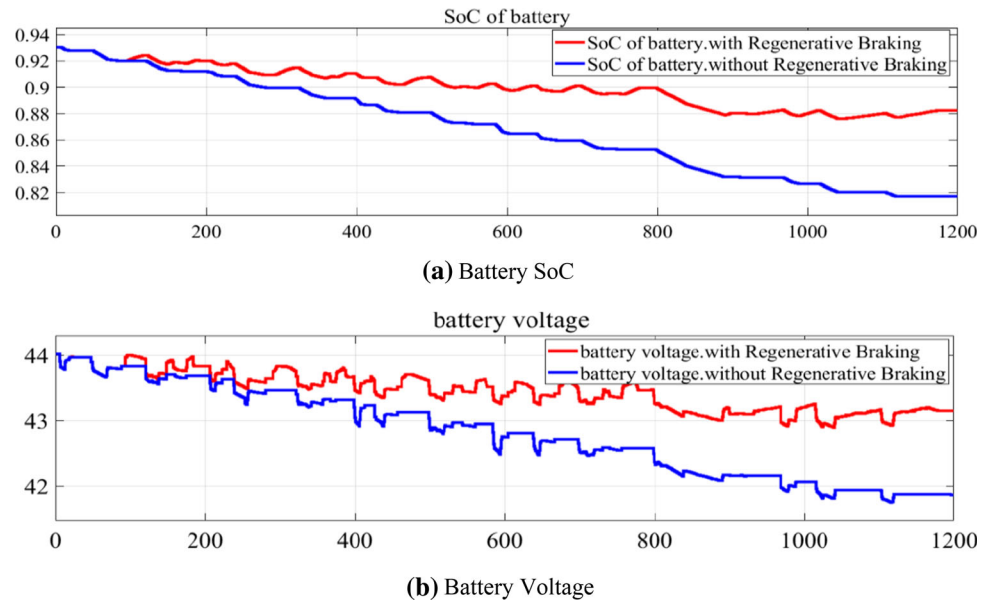

(a)

(b)

(c)

(d)

Fig. 9 HES performance with and without regenerative braking (with real-time results)

limitations save the batteries from degrading its SoH as well as minimize the voltage fluctuations (Fig. 11c). The voltage of the battery (Fig. 11c) enables the reader to visualize the amount of voltage drainage over repetitive driving in the two given scenarios.
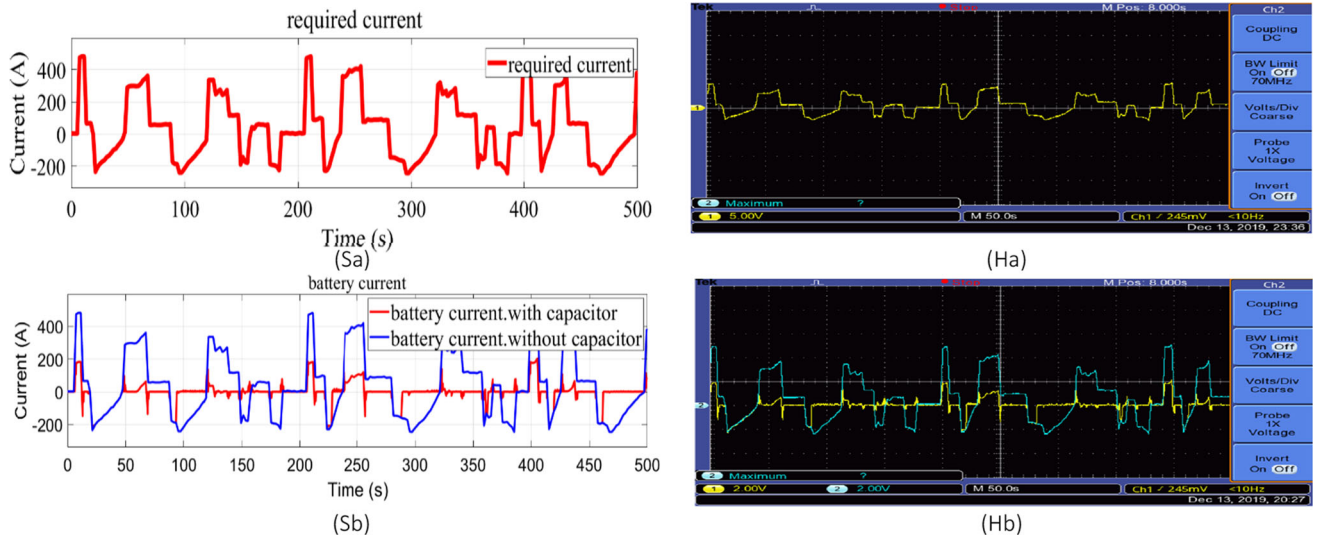
Fig. 10 Comparison of HES performance with and without ultra-capacitors
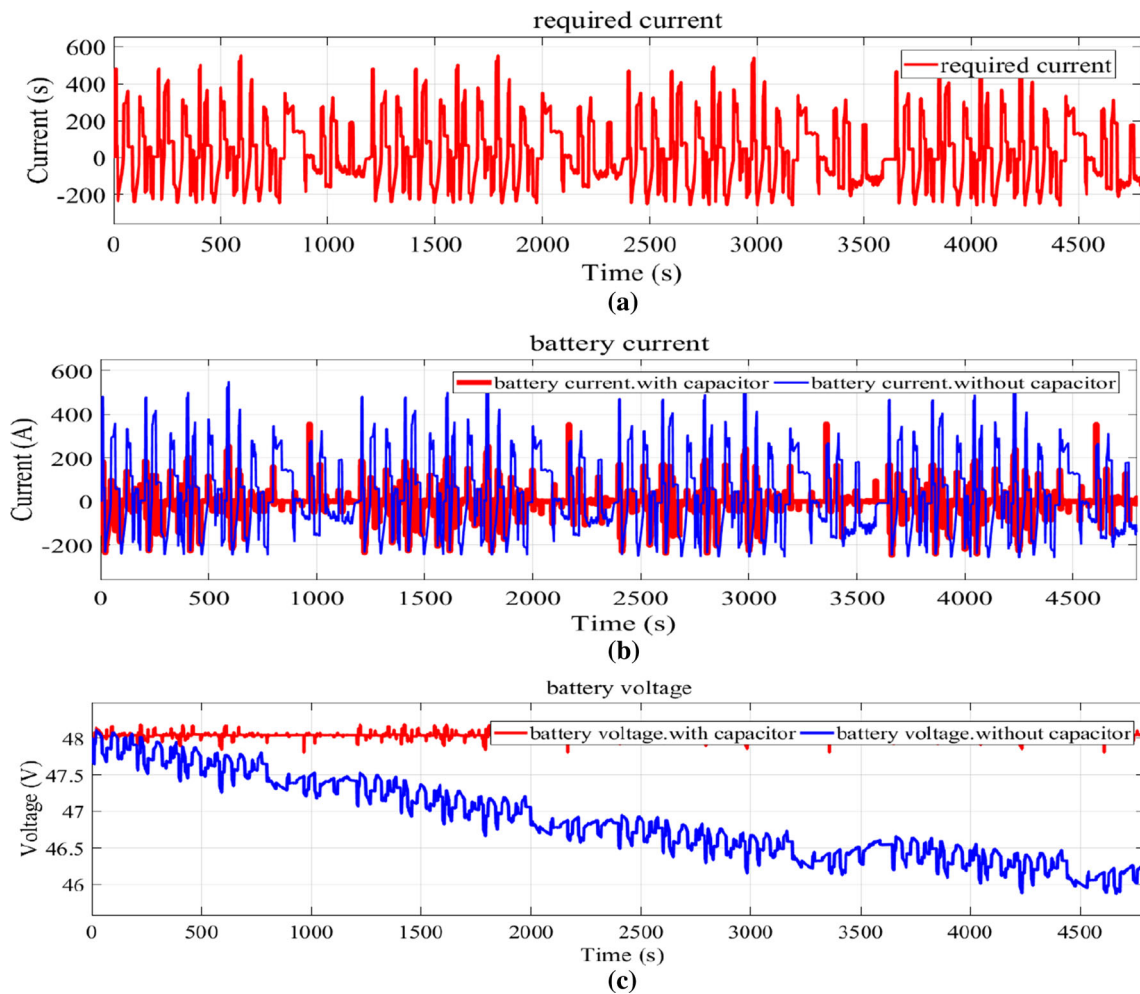
Fig. 11 Comparison of battery performance with and without ultra-capacitors

3.3 Simulation of the Proposed Circuit Design

The proposed method consists of multiple capacitors and battery modules connected, as explained in the "circuit layout" section. The current form of the Indian driving cycle is used for the load (EV) simulation (Figs. 6 and 13a). All the parameters, defined in the "Linearization and Sizing" section as well as the EMS, are applied to the MATLAB components. Figures 12 and 13 show the power and current fluctuations, respectively, with their real-time HIL results for 500 s. The EMS manages current in both directions (Fig. 13). Any positive current represents current supplied by the storage, while regenerative braking causes the negative flow of current. Here, reconsidering the facts that were taken care of when designing the battery module, a current limit of 292A is applied to the discharge current of the battery, while the current required above the 292A mark is supplied by the capacitor module. Similarly, a limit of 200A is applied to the charging current of the capacitor, while the excess of which will be readily absorbed by the battery module. Figure 13 shows current limiting by the EMS in the proposed method.

Then the model is run for the driving cycles repetitively to see the dynamics of the battery voltage over the cycles (Fig. 14). The voltage is also managed by the EMS (Fig. 14). It shows fewer fluctuations when compared to methods without capacitor modules and EMS. The combination of capacitors and EMS readily removes peaks from the battery module voltages.

The main aim was to limit the power input and output of the battery modules. Limiting current and voltage levels automatically control the power to a safe level, and the capacitor modules will do all the power input and output over and above the safe limits. The power limiting is observable in Fig. 12. The net power required at any given point in time is the same as in Fig. 12b, where no capacitors are used. Usage of capacitors as a secondary storage unit for energy limits the power requirements from the battery to a lower level. Figure 12a shows the peaks of the required power from the battery are removed and flattened. At the same time, the capacitors provide all the excess requirements.

3.4 Justification of Using Multiple Converters

A comparison of the proposed method and methods with similar storage capacity but a lesser number of converters are provided in Fig. 15. For the analysis, three storages with a different number of converters are chosen. The three cases compared are as follows: First one is the proposed storage, the second is storage with no external converter across DC bus, and the third storage is without any converter. In all cases, the storages have been charged with a constant 50 A current and then can discharge through a constant load of what rating (internal resistance 10 Ω). From Fig. 15, it is observable that the proposed storage retains higher and constant SoC levels for a longer time. As the number of converters decreases, the voltage stability decreases, and the SoC levels go down quickly than the
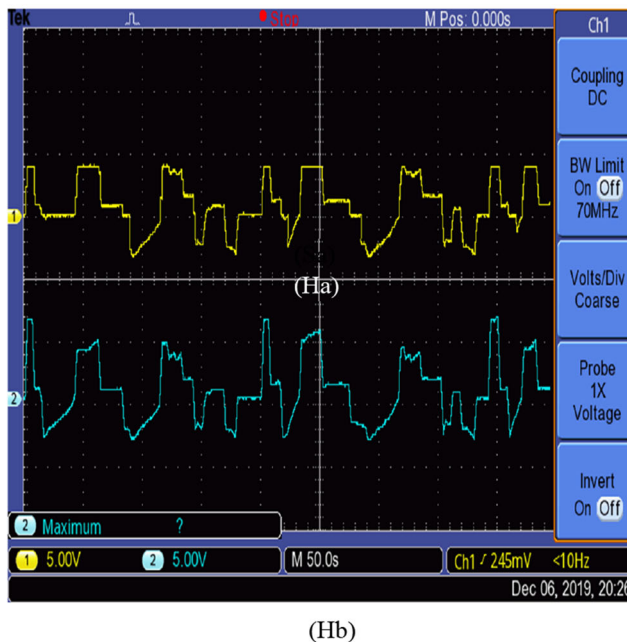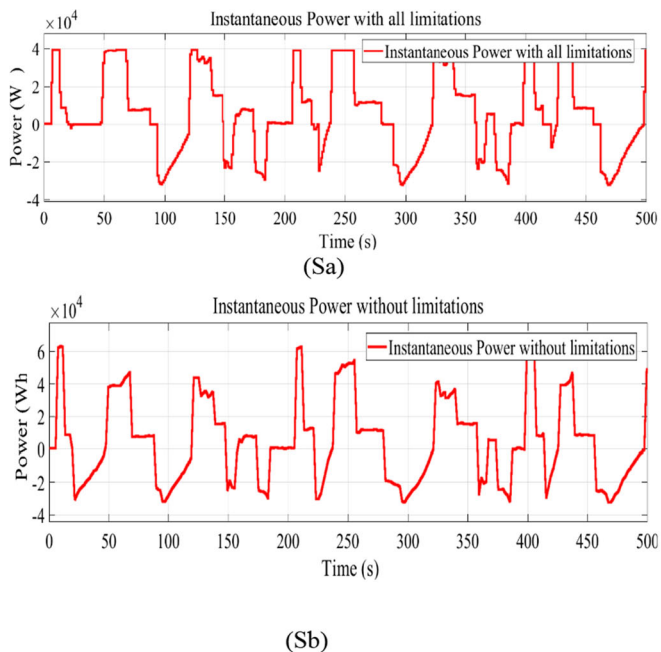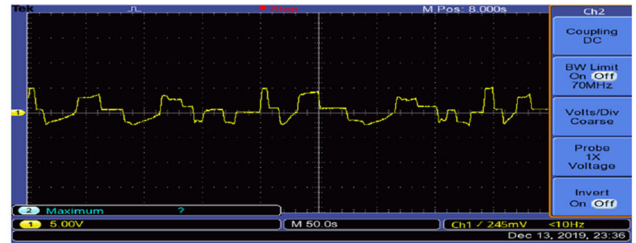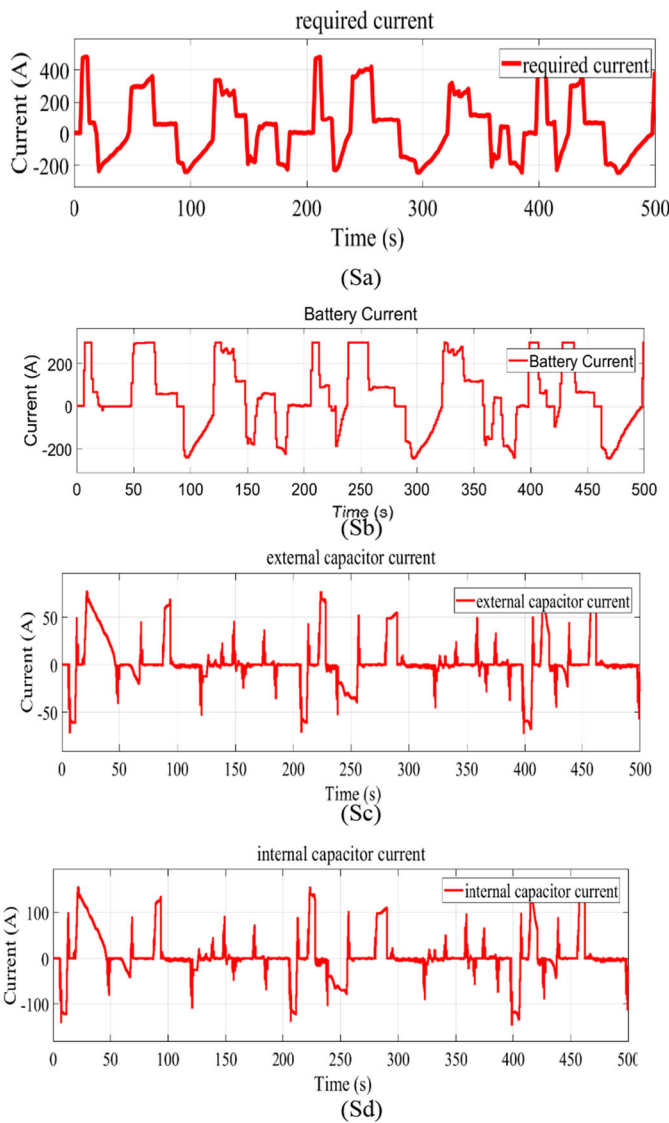

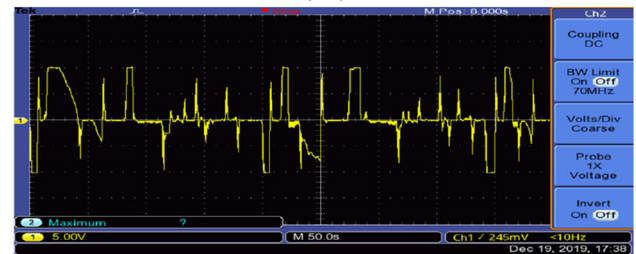**Fig. 12** Power levels of the battery modules
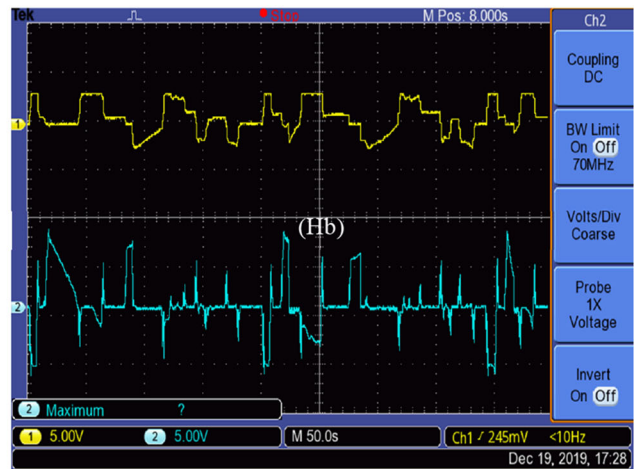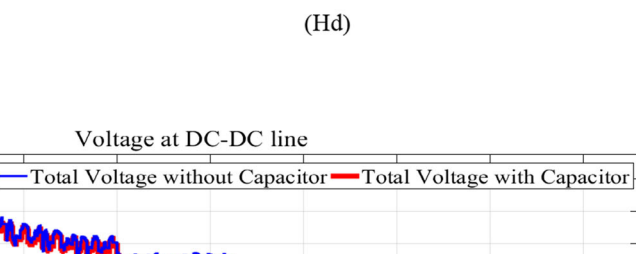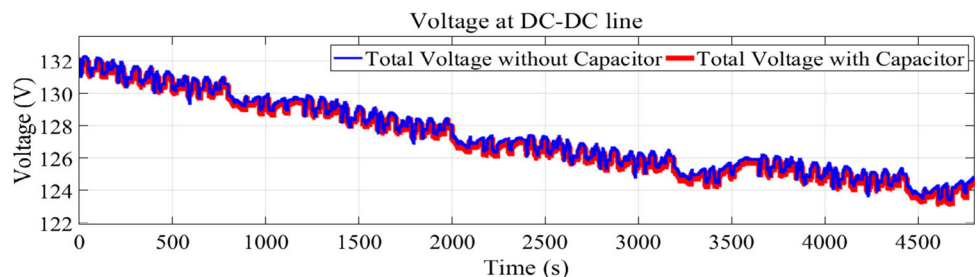
Fig. 13 Current through various components

Fig. 14 Voltage on DC-DC line during four continuous driving cycles

proposed method. With the removal of one converter from the proposed storage, the SoC decreases almost 500 s earlier. With no converters used, the battery gets overcharged during charging due to the capacitors and then discharges as soon as the load is applied. This proves the effectiveness of multiple smaller converters specific to each module. In the long run, retaining higher levels of battery SoH along with usage of multiple economic converters will save money by increasing the timespan between replacements of batteries. The cost of the storage due to use of multiple low rated converters is almost the same as of a single high rating converter used in BMS.
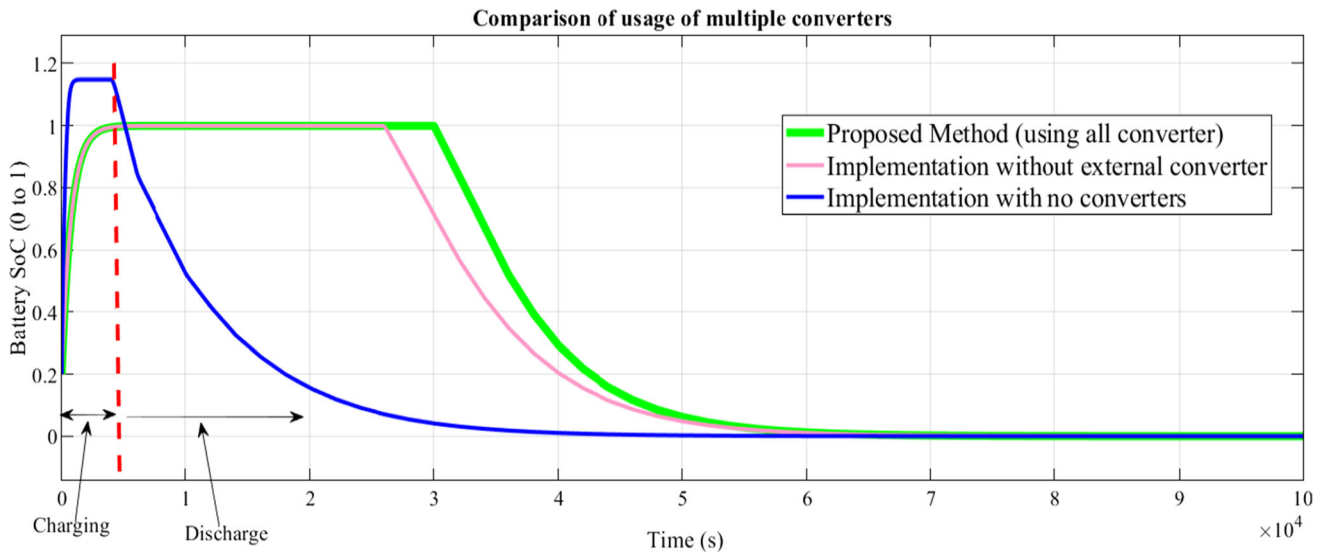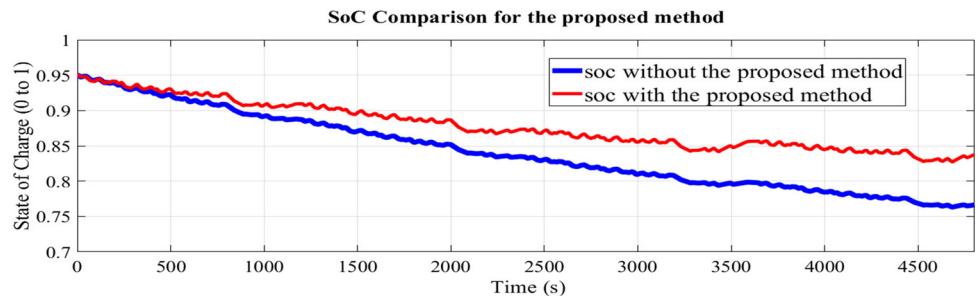
Comparison of usage of multiple converters

Fig. 15 Comparison of usage of multiple converters

Table 2 SoC comparison of proposed method and conventional method (Fig. 16)

Sr. no	Time (s)	No. of driving cycles	Conventional method(SoC)	Proposed method(SoC)
1	0 s	0	0.95	0.95
2	4800 s	4	0.766	0.838
Difference			0.184	0.113
Peak-to-peak fluctuation			0.1870	0.1229

Fig. 16 SoC Comparison

Though the EMS can become complicated, it provides better conditions for the battery modules.

In the implementation without the usage of converters, the SoC of the battery rises to 1.2 which means that the voltage of the battery is above 80% of nominal value ("Appendix"—1). This indicates that heavy fluctuations in battery voltages when it is charged without proper control.

3.5 Contributions of the Proposed Method

The major contributions of the proposed method can be seen from Table 2 and Fig. 16 where fluctuations in SoC and its corresponding peak-to-peak values have been decreased. The proposed method provides a boost of 38.6%

in SoH over the conventional method. This means that the chemical and physical composition are kept healthier with the help of the proposed method. Therefore, the proposed method makes the battery-less prone to the fluctuations in supplied and absorbed power, saving its health, and retaining high SoH which increases RUL of the battery for a given number of the charge/discharge cycles.

The proposed approach employs multiple low rated converters which maintain a constant voltage across the batteries and on the DC bus. Further, it enables controlled current discharge from the batteries as well as the capacitors, maintaining similar voltages and temperatures across the storage. Being low voltages and power ratings, their size, weight, cost, and losses are less.

4 Conclusion

This paper presents a circuit design wherein ultra-capacitors are used in conjunction with the Li-ion batteries. The rule-based energy management strategy provides quite satisfactory results. The current limiting strategy works to limit the voltage fluctuations and power drawn from the batteries. The batteries are used as a primary source of power, while ultra-capacitors are used to provide and absorb peak power requirements. The proposed method reduces frequent significant peaks in the current input and output from the battery, which has been quantitatively proven by higher SoC levels using this scheme than conventional methods. The proposed method also provides better health of battery over several charging and discharging cycles, giving a significant boost to the available mileage of batteries. Improvement of 38.6% in SoH is observed over conventional HESS methods.

The proposed method can also help in the development of sophisticated EMS and can be extended to any driving cycles.

Appendix 1

See Table 3

Table 3 Vehicle parameters

Components	Values
Tire radius	0.3 m
Wheel inertia	0.1
Vehicle glider mass	918 kg
Aerodynamic drag coefficient	0.26
Vehicle gear ratio	1.3
Final drive ratio	3.93
Distance from center of gravity to front axle	1.3500 m
Distance from center of gravity to front axle	1.3500 m
Frontal area	2.160 m2
Motor (PMSM)	50 kW @ 500 V DC volts
Generator (PMSM)	30 kW @ 500 V DC volts

The SoC of battery is defined as the normalized range between the 20% and 80% nominal voltage level of the battery. Let the nominal voltage of battery be V_{nom}.

Therefore, minimum voltage becomes:

$$V_{\min} = 0.2 \times V_{nom} \tag{15}$$

And the maximum voltage becomes:

$$V_{\max} = 0.8 \times V_{nom} \tag{16}$$

Hence, the SoC is formulated as:

$$SoC = \frac{V - V_{\min}}{V_{\max} - V_{\min}} \tag{17}$$

where V is real-time voltage of the battery.

Similarly, the SoC of UCs is defined as normalized range between 0 and 100% nominal voltage level of UCs.

List of symbols BEV: Battery electric vehicle; BMS: Battery management systems; C_{int}: Internal Capacitor; C_{ext}: External capacitor; $C_{residue}$: Residual charging capacity; $C_{Specified}$: Specified/designed charging capacity; E_{UC}: Energy requirements from capacitors; EMS: Energy management system; ESS: Energy storage system; EV: Electric vehicle; FPGA: Field-programmable gate array; H: Represents HIL results in figures; HEV: Hybrid electric vehicles; HESS: Hybrid energy storage systems; HIL: Hardware in loop; I_{BM}: Current rating of a battery module; I_{Li_cell}: Current rating of a LiFePO$_4$ cell; ICE: Internal combustion engine; I^2R: Loss of energy as heat due to resistance; LiFePO$_4$: Lithium iron phosphate; Li ion: Lithium ion; N: Number of UC cells per modules; N_{BP}: Number of LiFePO$_4$ cell in parallel; N_{BS}: Number of LiFePO$_4$ cell in series; N_{UCex}: Number of UC modules in external UC; N_{UCint}: Number of UC modules in internal UC; PHEV: Plug-in hybrid electric vehicle; R_{int}: Internal resistance of LiFePO$_4$ cell; RUL: Remaining useable life; s: Seconds; S: Represents MATLAB simulation results in figures; SC: Supercapacitors; SoC: State of charge; SoH: State of health; V_C: Voltage rating of a LiFePO$_4$ cell; V_{BM}: Nominal voltage of a battery module; V_{UCM}: Nominal voltage of a UC module; V_{Li_cell}: Nominal voltage of a LiFePO$_4$ cell; V_{UCext}: Nominal voltage of external UC module; V_{UCint}: Nominal voltage of internal UC module; UC: Ultracapacitors; XEV: Any type of electric vehicle—PHEV/HEV/BEV; W_{Li_cell}: Watt rating of a LiFePO$_4$ cell

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