

Battery-Based HESS with Ultracapacitor Assistance for Electric Vehicles Considering Ageing Batteries

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Abstract - Improved battery life, system efficiency, and dynamic power delivery in response to changing driving circumstances are all goals of modern energy management strategies for electric cars (EVs). This study presents a smart hybrid energy storage system (HESS) composed of lithium-ion (LI) battery and ultracapacitor (UC) based on an adaptive predictive energy management technique. The suggested controller maintains the battery operating within a safer and lower stress area, while dynamically sharing the transient high-power demand to the UC. The suggested method adopts the real-time variable C-rate aging model to accurately calculate battery capacity loss under different driving modes, compared with the traditional model that assumes the battery charging rate is fixed.

The suggested method continuously checks changes in load, changes in state of charge as well as regenerative braking energy to ensure optimal sharing of power between storage devices. The proposed system's integration of battery health information with the control system offers several advantages, such as decreased degradation effects, thermal stress, and peak current usage. The simulation results and hardware validation demonstrate that the adaptive strategy extends battery lifetime, helps to use energy optimally and maintains vehicle performance at a constant level even under dynamic conditions. The findings of the experimental analysis, revealed that the proposed system is suitable for future sustainable electric mobility applications as a smart alternative to the conventional fixed C-rate based energy management method which considers the real-time properties of the battery aging and operating condition.

Key Words: Ampere-hour (Ah), bidirectional dc-dc converter (BDDC), charging rate (C-rate), depth of discharge (DoD), electric vehicle (EV), energy management strategy (EMS), Indian drive cycle (IDC), state of charge (SoC), ultracapacitor (UC), vehicle to grid (V2G).

1.INTRODUCTION

Considering that sustainable energy use and reducing carbon emissions are important issues in the modern society in the new era of green transportation, energy efficiency and carbon reduction are emerging as key concerns. The huge development of electric mobility has spurred the automotive industry to build more efficient and environmentally friendly hybrid electric vehicles

(HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (EVs). The effectiveness of the on-board energy storage system is the key factor that determines the operational performance of EVs. In electric vehicles, lithium-ion batteries (LIBs) are widely used because of their high performance in terms of energy density, number of cycles, high operational efficiency, etc. Moreover, LIB technology is crucial for integration of renewable energy and smart grid applications. But battery ageing is still a big challenge as the continuous electrochemical reactions cause continuous decline in capacity and power. Thermal effects, overcharging, high discharge rates and voltage stress intensify the degradation process resulting in significant energy fading after long operation, such as by the processes of electrolyte decomposition, degradation of the active material, and loss of conductivity [1]. To overcome these limitations, ultracapacitors (UCs) are used along with Batteries in hybrid energy storage systems (HESSs) due to its high-power density, fast charging property and long-life characteristics [2].

To improve the performance of electric vehicles based on HESS, some advanced converter topologies and intelligent energy management methods have been developed. The proposed configuration for the UC-assisted HESS is that the battery supplies a relatively constant average power, whereas the ultracapacitor is used for the transient and high frequency power requirements when accelerating and when braking regeneratively. The architectures of HESS can be divided into passive, semi-active, and active HESS in the sense of its application requirements.

An optimized energy management strategy (EMS) can balance the power flow under dynamic driving conditions, which is vital for efficient coordination between the battery and UC. Offline optimization methods and online adaptive techniques are the two main types of existing EMS approaches. Offline techniques are dynamic programming and rule-based algorithms, while online techniques are predictive control, artificial intelligence, and machine learning-based optimization schemes. Predictive velocity estimation, driving pattern recognition by support vector machine, current estimation by neural network and model predictive control are some of the recent studies focused on the improvement of power distribution and

vehicle efficiency. These techniques improve system performance, but most current approaches determine battery degradation based on charging and discharging currents that are held constant, which is not representative of real-world conditions for EVs. This work proposes an adaptive degradation-aware energy management (AEME) framework that can predict current battery degradation characteristics under different C-rate changes during the driving cycle to address these drawbacks. The strategy continuously monitors the actual profiles, depth of discharge, thermal conditions and regenerative braking energy to optimise the allocation of power between the battery and the ultracapacitor. Battery current stress and thermal rise is greatly reduced as the UC provides a buffer against sudden load changes, increasing battery's overall durability.

In addition, the developed control architecture includes a dynamic battery ageing model which is capable of estimating the real battery capacity more accurately than the traditional fixed C-rate method. Analytical and experimental tests show that the suggested intelligent HESS can effectively prolong the battery life, improve energy utilization efficiency, reduce the peak power stress and improve the reliability of the vehicle under real-world driving conditions. The results obtained show that adaptive predictive control along with real-time degradation monitoring is an efficient and sustainable solution for future-generation electric transportation systems.

2. System Description

The applications of EVs have attempted different combinations of Hybrid Energy Storage Systems (HESS) to improve energy efficiency, battery protection and power utilization. Common topologies for the integration of lithium-ion batteries and ultracapacitors are semi-active, fully active, cascaded and passive. Semi active systems employ a bidirectional DC-DC converter to control one energy source for limited power regulation, but passive systems are just connected between both energy storage elements and the DC bus without any control capability. Fully active topologies have separate bidirectional buck-boost DC-DC converters for the battery and ultracapacitor in order to accurately control the voltage and power sharing during various driving conditions.

This research utilizes a fully active HESS design by providing a separate converter to connect the two sources to the common DC-link and then a voltage source inverter to provide the regulated DC-link voltage to the electric traction motor. The high-power density of the ultracapacitor and its quick reaction make it possible to supply large amounts of power when accelerating and when the load suddenly changes, while the average power demand could be kept steady by the battery.

Based on their charge states and operational circumstances, the recovered energy is effectively transferred between the battery and ultracapacitor during regenerative braking. This setup reduces thermal stress and enhances the reliability of the system, while also optimizing its energy usage. Also removes battery current fluctuations.

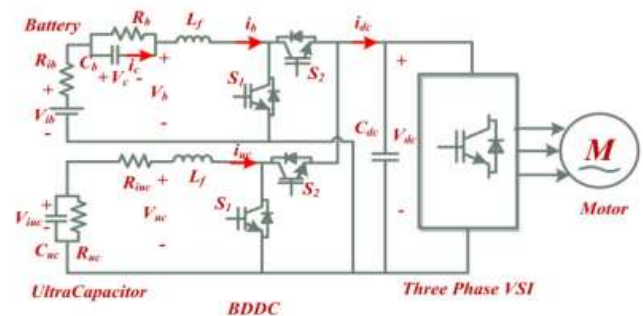


Fig. 2. System configuration for the battery- and UC-based HESS.

3. Energy Management Strategy

Model Predictive Control (MPC) is used as the Energy Management Strategy (EMS) to assess the proposed Hybrid Energy Storage System (HESS). MPC is very effective in prediction and optimization even under varying operating conditions. MPC is based on the system state-space mathematical model and will predict the future behaviour of the system over a given prediction horizon. The controller continually minimizes an objective function subject to operational constraints to ensure system performance is accurate and consistent. This research aims to estimate and control the ultracapacitor's State of Charge (SoC) using MPC, while reducing current variations in the battery.

The optimization strategy will reduce the stress on the battery and maximize battery life because the ultracapacitor can easily handle short-term power spikes and deliver a high peak current during acceleration and regenerative braking operations. The goal function is restricted to operate within the safe working limits of the system such as the voltage of the ultracapacitor, the current through the battery, and the range of the system on a chip. The MPC controller can be employed to define variables such as measured output, unmeasured disturbances, controlled input, and control constraint of a system in MATLAB/Simulink. A continuously-time state-space model of the HESS is derived and linearized for the purpose of implementing predictive control, and simplified mathematical models of the lithium-ion battery and ultracapacitor are created. This intelligent control technique provides the electric car with greater reliability, improving energy

consumption efficiency, voltage stability, reducing thermal stress, etc., in various driving conditions.

4. EMS Evaluation Using Battery Aging

An energy management strategy is used based on model predictive control (MPC) to maintain the average power consumption of the electric vehicle reasonably steady when a high-power demand occurs at an unpredictable time, drawing power from the battery and the ultracapacitor. To reduce overcharging and overdischarging of the battery, the controller's goal function gives more weight to controlling the current flowing through the battery, which in turn reduces the frequency and magnitude of current variations. The C-rate values vary during the driving cycle due to the fact that the required power demand and battery current constantly change during the vehicle's operation throughout the driving cycle. Single set C-rate results in a wrong evaluation of the battery deterioration and capacity loss. Therefore, the actual battery current profile is constantly sampled throughout the driving cycle using numerical calculation methods to provide the real-time C-rate data.

This study considers an IDC driving cycle consisting of 108 sec of total driving time and the battery current is sampled every 1 sec for system evaluation in order to calculate the instantaneous C-rate. The measured C-rate values under real-world operating conditions can be fed into the battery aging model, and the pre-exponential degradation factor B calculated to provide a more accurate estimate of the gradual reduction in battery capacity under real-world operating conditions. This adaptive approach not only reduces thermal and electrical stresses but also enhances the reliability and efficiency of the Hybrid Energy Storage System over time, leading to improved battery health prediction accuracy.

5. Simulation Results

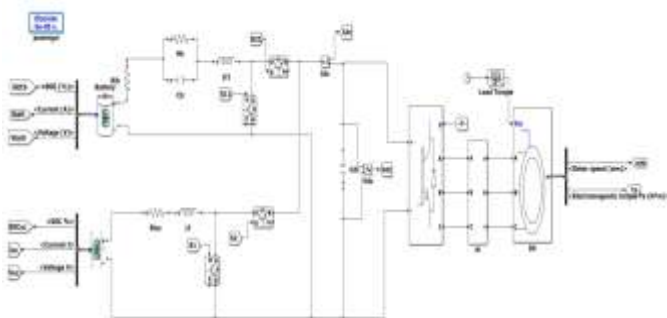
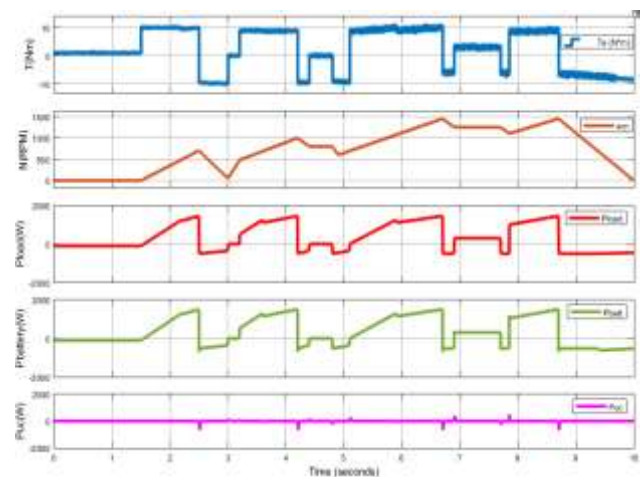


Fig. 3. MATLAB/SIMULINK circuit of the system

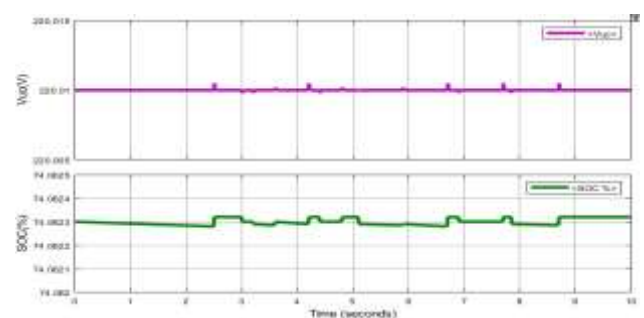
Figure 1 shows the whole MATLAB/Simulink model that was created for the electric car application's proposed HESS, which uses ultracapacitors. The electric traction motor, three-phase voltage source inverter, DC-link capacitor, bidirectional DC-DC converters, lithium-

ion battery, and ultracapacitor are the main parts of the simulation model. The battery provides average power continuously while the ultracapacitor provides transient power to assist in fast acceleration and power recovery during regenerative braking in normal operating conditions. The bidirectional converters regulate the energy flow between the storage devices and DC-link and keep the voltage level constant.

The inverter needs to convert DC current to AC current to be able to operate the motor. The model also includes energy management based on Model Predictive Control (MPC) to intelligently distribute the power between battery and ultracapacitor. The extensive modeling platform can be used to study variations in driving conditions, power sharing, voltage stability and battery current fluctuations. As for the application fields of electric vehicles, it is suitable for evaluating system reliability, heat performance and battery life characteristics.



(a)



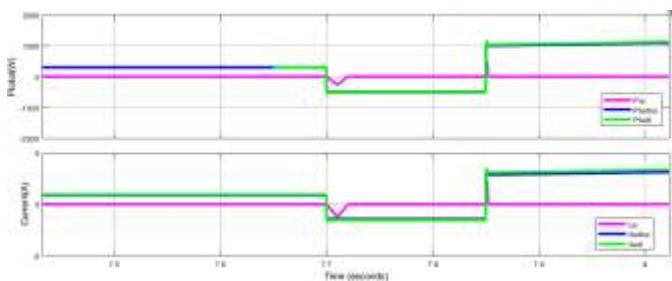
(b)

Fig. 4. Results for the complete drive cycle showing: (a) torque, speed, load power, battery power, and UC power; (b) voltage of UC and SoC; and (c) load power and battery power with and without UC.

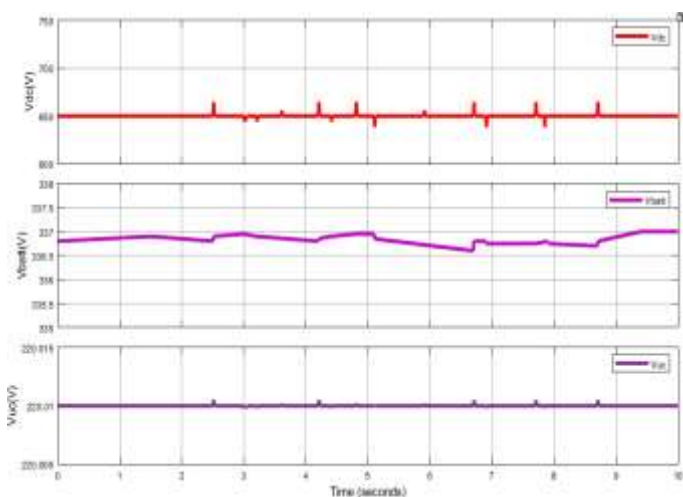
The simulation results for the whole driving cycle of the proposed Hybrid Energy Storage System are shown in Figure 3. The graphic displays KPIs that vary during operation, including motor speed, torque, load power, battery power, ultracapacitor power, voltage and state-of-charge. The results confirm that the ultracapacitor can

effectively meet the transient power requirements of the vehicle's acceleration and regeneration.

The ultracapacitor's ability to absorb rapid currents variations keeps battery power smooth and steady. Also plotted on the graph is the voltage and state-of-charge of the ultracapacitors, which do not exceed safe operating limits throughout the driving cycle. When the power value is negative when regenerative braking, it means that the power is being recovered and stored in the energy storage devices. As shown in the comparisons, the HESS significantly improves the efficiency of power distribution and reduces battery stress, compared to battery-only operation. The results demonstrate that the Model Predictive Control method performs well to maintain the system's performance level in various driving cases. Overall, the figure shows that the electric car system is more reliable, requires less energy and has less battery degradation.



(a)



(b)

Fig. 5. Results showing(a) zoomed view of battery and UC power and current and (b) dc bus voltage, battery voltage, and UC voltage for the complete drive cycle.

The voltage and current of the battery and ultracapacitor throughout the entire driving cycle are shown in figure 4. The figure depicts a battery and an ultracapacitor, along with the variation in their power, DC bus voltage, battery voltage, and ultracapacitor voltage under dynamic operating conditions, with a zoomed-in depiction of these values. The results indicate that the ultracapacitor quickly responds to current transients and

sudden changes in load, which helps to minimize battery current surges. The bidirectional (DC-DC) converter and model predictive (MP) control method are working well as the DC bus voltage is quite steady despite load demand changes.

The deviation in battery pack voltage is very low, which shows that the battery pack has been subjected to very little electrical and thermal stress. A drive cycle is also within acceptable ranges throughout the ultracapacitor's voltage. The graph also shows the battery and ultracapacitor can handle energy sharing and sharing efficiently during acceleration and regenerative braking activities. The results indicate that the proposed HESS is suitable for electric vehicle applications, where it enhances the voltage control, stability of the system and energy economy and operational reliability, while minimizing the effects of battery ageing.

6. CONCLUSIONS

The suggested Hybrid Energy Storage System (HESS) greatly extends the life of electric car batteries by enabling the ultracapacitor to manage abrupt surges in power demand caused by acceleration and changes in dynamic load. The Energy Management Strategy, based on Model Predictive Control (MPC), is able to efficiently optimize the distribution of energy between the ultracapacitor and lithium-ion battery in various driving conditions.

We analyze the aging of batteries in this study under both constant and variable C-rate operation, both in battery-only and battery-with-ultracapacitor operation. Since the current flow through the battery changes continuously depending on the load conditions, it is seen that the results indicate that the value of the C-rate is misleadingly assumed constant during the entire driving cycle, which is why the calculation of battery degradation is incorrect. To get accurate capacity fade estimate, the actual battery current profile is continuously recorded during driving cycle to compute C-rate values in real-time. The results demonstrate that the HESS arrangement slows down battery ageing. This is because the ultracapacitor absorbs the transients of electrical current and peak power from the battery, thereby lowering the electrical and thermal stress on the battery. Furthermore, the current changing C-rate provides more accurate and realistic results compared to the usual C-rate assumption for battery aging. Intelligent power sharing with MPC improves electric vehicle energy storage systems' long-term performance and reliability, decreases battery deterioration, boosts voltage stability, and improves energy consumption efficiency, according to the research.

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