

PERFORMANCE ENHANCEMENT OF ELECTRIC VEHICLE HYBRID ENERGY STORAGE SYSTEMS USING ULTRACAPACITORS AND BATTERY AGING ANALYSIS

DOOSA NAVEEN¹, MRS.CH.RAJA SRI²

¹Mtech Student, Dept of EEE, Holy Mary Institue of Technology & Science, Keesara, Bogaram, Telangana, India.

²Assistant Professor, Dept of EEE, Holy Mary Institute of Technology & Science, Keesara, Bogaram, Telangana, India. Mailed: rajasri045@gmail.com

ABSTRACT:

With the proliferation of Electric Vehicles (EVs) and the need for efficient, reliable, and sustainable energy storage solutions that enhance vehicle performance and battery life, the market is experiencing a surge in demand for such solutions. Lithium-ion batteries are popular in EVs due to their high-energy density and durability, but they are sensitive to degradation from repeated charging and discharging cycles, heat effects, heavy current surges and aging. This can lead to reduced battery capacity, high battery internal resistance, and a negative impact on the vehicle's performance. This project aims to address these constraints by developing an Ultracapacitor-Assisted Battery-Based Hybrid Energy Storage System (HESS) for Electric Vehicles (EVs) in the presence of battery ageing. The proposed system incorporates a Model Predictive Control (MPC) based Energy Management Strategy to optimize the power distribution, bidirectional DC-DC conversion, lithium ion battery and an Ultracapacitor. The battery provides the average energy demand and the ultracapacitor provides high power demand when accelerating and for regenerative braking. This synchronized operation helps to reduce the fluctuation of battery current, reduces thermal stress, and improves battery energy utilization. The proposed methodology is different from the traditional ones that assume a constant C-rate during the battery charging process because it takes into account a real-time battery aging model that takes into account the variable C-rate conditions which makes the estimation of battery degradation more accurate. The system is designed and tested in MATLAB/Simulink under similar driving conditions. The simulation results show better power sharing, voltage stability, regenerative energy recovery, less battery degradation and extended battery life. This proposed HESS is a smart, cost-effective and energy efficient solution for next generation EVs and supports sustainable transportation and advanced energy management applications.

Keywords: Electric Vehicle (EV), Hybrid Energy Storage System (HESS), Lithium-Ion Battery, Ultracapacitor, Battery Aging, Model Predictive Control (MPC), Energy Management Strategy, Regenerative Braking, Battery Life Extension, Bidirectional DC-DC Converter, State of Charge (SOC), Sustainable Transportation.

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I.INTRODUCTION

In recent years, the proliferation of electric vehicles (EVs) has revolutionized the modern transportation industry by offering a cleaner and more sustainable mode of transportation compared to traditional internal

combustion engine vehicles. The increasing environmental concerns, greenhouse gases and falling fossil fuel resources have pushed the EV technology to gain traction globally. The energy storage system is one of the vital parts of an electric vehicle, which affect the performance, driving range, efficiency, and

reliability of the vehicle. The advantages of lithium-ion batteries for EVs are their high energy density, long cycle life, low self discharge and excellent charging performance. Though the benefits are far, Lithium ion batteries face performance reduction on repeated charging and discharging cycles, thermal stress, overcurrent, and ageing effects. Naturally, the battery losing capacity reduces the amount of charge available, and increases the battery's internal resistance, thus negatively impacting the vehicle's operating life. Hence, the life extension of batteries and efficient energy utilization in an electric vehicle system has become a significant research challenge today. The researcher is continuing to investigate the development of new energy storage concepts and intelligent control systems to address these issues and improve vehicle performance [1, 2].

In order to overcome the drawback of stand-alone battery systems, Hybrid Energy Storage Systems (HESS) have been developed as an effective solution for electric vehicle applications. A HESS is a combination of two or more energy storage devices that take advantage of the benefits of each. Lithium-ion batteries with ultracapacitors have been among several configurations that have attracted considerable interest, in part because they offer excellent performance attributes. Batteries have high energy density and can supply energy for a long period of time, while ultracapacitors have extremely high power density, can be charged and discharged rapidly, and have excellent cycle life. In sudden acceleration, hill climbing and regenerative braking, ultracapacitors can provide or remove significant amounts of power in a very short period of time, thus decreasing the strain on the battery. This simultaneous power sharing reduces battery current fluctuations, thermal loading and increases energy efficiency. Besides, ultracapacitors can efficiently store regenerative braking energy, which is wasted on other vehicles, thus improving the vehicle's energy utilization. Therefore, battery-

ultracapacitor hybrid energy storage devices are a potential technology for next generation EVs which demand high performances, reliability and long battery life [3], [4].

This project proposes an Ultracapacitor-Assisted Battery Based Hybrid Energy Storage System for Electric Vehicles Considering Battery Aging to enhance battery health, energy efficiency and vehicle reliability under dynamic driving conditions. The proposed system consists of a Lithium-ion battery, ultracapacitor bank, bidirectional DC-DC converters and a Model Predictive Control (MPC) based Energy Management Strategy. The proposed methodology is different to the traditional methods based on the assumption of the charging rate fixed for the entire battery life, but it takes into account a real-time modelling of the battery ageing, which assesses battery degradation under variable C-rate conditions as experienced during real car usage. MPC controller is continuously measuring battery SoC, ultracapacitor SoC, load demand and regenerative braking energy to decide optimal power allocation. The system is able to reduce battery degradation, which in turn improves overall system efficiency, by using the ultracapacitor for transient power requirements and keeping the battery operating at a steady level. MATLAB/Simulink simulation results show improved power sharing, voltage stability, reduction in thermal stress and battery life. Thus, the proposed HESS is a smart and sustainable solution for future of electric vehicle energy management applications [5, 6].

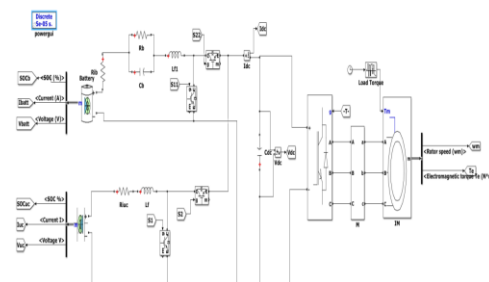


Fig. 1. MATLAB/SIMULINK circuit of the system

The complete MATLAB/Simulink model created for the proposed HESS of the electric car application (which uses ultracapacitors) is shown in Figure 1. The simulation model consists primarily of an electric traction motor, three-phase voltage source inverter, DC-link capacitor, bidirectional DC-DC converter, lithium-ion battery and ultracapacitor. During the normal operating conditions, the battery supplies the average power continuously, and the ultracapacitor supplies the power to help the car accelerate quickly and recovers energy during regenerative braking. The bidirectional converters regulate the energy flow between the storage devices and DC-link and keep the voltage level constant. The inverter should be able to transform the DC current into AC current, so as to drive the motor. The model also incorporates energy management derived using Model Predictive Control (MPC) in an intelligent manner to control the power distribution between battery and ultracapacitor. This rich modeling environment is available to explore variations in driving, power sharing, voltage stability and battery current variations. In terms of application fields of electric vehicle, it can be used for system reliability evaluation, heat performance and battery life characteristic evaluation.

II SURVEY OF RESEARCH

1. Vermeer et al. discussed and presented a detailed overview of Lithium-ion battery ageing mechanisms and modelling of degradation in Electric Vehicle applications. The researchers studied the lifespan of the batteries under varying charging current, temperature, depth of discharge, and cycling conditions. They found that operating conditions have a significant impact on battery degradation and that it could not be reliably predicted assuming a fixed charging rate. The study included highly sophisticated aging models that could forecast the capacity fade and internal resistance increase under actual operating conditions. The results of

experiments proved that the high charging and discharging currents have a great influence on the deterioration of the battery and decrease the amount of energy it can store. The authors highlighted the need for consideration of battery health in energy management systems to enhance reliability and battery service life. Their results offer a good foundation for developing adaptive energy management strategies of hybrid energy storage systems, taking into account the characteristics of battery ageing. This study underscores the need for real-time battery health monitoring methods to be combined with power management algorithms for future EV applications.

2. Cao and Emadi presented a new concept of battery-ultracapacitor hybrid energy storage system for electric and hybrid electric vehicles. They have been working on integrating the high power density of ultracapacitors with the high energy density of lithium-ion batteries. The proposed architecture allowed the ultracapacitor to meet the transient power requirements and the battery to meet the average ones. Experimental results showed that power usage management, battery protection, and energy use efficiency were improved significantly. The researchers discovered that the energy generated during regenerative braking could be efficiently absorbed by the ultracapacitor, and that the current fluctuation in the battery could be decreased during acceleration. This led to reduced thermal stress, increased battery life and better vehicle performance. The study found that hybrid energy storage systems are a promising option to address the drawbacks of battery systems. The results of their work have had an impact on the current energy storage architectures of electric vehicles and are used today as a reference for advanced HESS designs.

3. Hredzak, Agelidis and Jang designed an energy management strategy for battery-ultracapacitor hybrid energy storage systems

based on Model Predictive Control (MPC). The objective of this study was to maximize the utilization of the power provided by each of the storage devices without imposing significant stress on the batteries and to maximize the performance of the system. The MPC controller was able to predict future load conditions and dynamically adjust energy distribution based on system needs. The simulation and experimental results demonstrated that the proposed control method could minimize battery current fluctuations, stabilize the battery voltage, and enhance the battery energy efficiency. The researchers found that the use of predictive control was effective in controlling regenerative braking energy while minimizing the losses in the system under dynamic operating conditions. Moreover, due to the smart control the lifespan of the battery was also extended by avoiding overcharging or over-discharging currents. The study found that MPC can be used as a powerful technique for energy management in ESSs, which can enhance their reliability and efficiency.

4. Nguyen, Yoon and Lee presented the concept of an adaptive energy management system for battery-supercapacitor hybrid energy storage system in EVs. Their study used Model Predictive Control to control the energy distribution according to a variety of driving conditions. The controller was continuously monitoring the battery SoC, supercapacitor SoC, load demand and vehicle operating parameters, to decide the optimal power sharing strategy. The simulations showed better voltage regulation, minimized battery stress and better recovery of energy under regenerative braking. The adaptive control system was key to extending the battery life by minimizing high current operating conditions and minimizing degradation effects caused by the heat. The study also emphasized the need for the algorithms of intelligent decision making for efficient operation of HESS. The idea presented is particularly useful for knowledge about how to develop battery aging aware energy

management strategies for modern electric vehicles.

5. Mesbahi et al. have presented a state-of-the-art hybrid energy storage system model consisting of lithium-ion batteries and supercapacitors for electric vehicles. The study examined dynamic capabilities of both energy storage devices with different driving scenarios. Detailed mathematical models were developed to assess the performance in terms of power sharing, energy efficiency, voltage stability, and battery ageing. The experimental results showed that the hybrid system can effectively reduce the peak current of the battery and increase the efficiency of energy regeneration during regenerative braking. Supercapacitors helped mitigate thermal stress to the battery and improve system reliability. The converter topologies and control algorithms for the effective coordination between the storage devices were also studied. The results have also shown that hybrid energy storage systems achieve better performance than battery-only systems, especially for applications that involve high frequency acceleration and braking.

6. Song et. al. made a comparative study of different energy management strategies of electric vehicles which use hybrid energy storage systems. The study compares rule based control, fuzzy logic control, optimization and predictive control method with various driving cycles. For each control method the researchers compared energy consumption, battery deterioration, system efficiency and vehicle performance. Results showed that the improvement in energy utilization and decrease in battery stress when using the predictive and optimization-based methods over the traditional rule-based methods. The study has proved that intelligent use of energy allows for a noticeable increase in the share of energy supplied by batteries and ultracapacitors, and lengthens the battery life. In addition, advanced control strategies improved the efficiency of the

regenerative braking and ensured stable operation of the system under conditions of rapidly changing loads. The results highlight the need for smart control algorithms to fully leverage the advantages that hybrid energy storage systems can offer in EVs.

III. WORKING METHODOLOGY

The proposed Ultra Capacitor assisted Battery based Hybrid Energy Storage System (HESS) for Electric Vehicles with consideration on Battery Aging will enhance the energy usage, minimize battery degradation and enhance the performance of the EV during dynamic driving conditions. The system includes a Lithium-Ion Battery (LIB), an Ultracapacitor (UC), Bidirectional DC-DC Converter, Three-Phase Voltage Source Inverter (VSI), and Energy Management Strategy (EMS) based on Model Predictive Control (MPC). The battery supplies average power for the EV system and the ultracapacitor is used for high transient power requirements like sudden accelerations and regenerative braking. This coordinated operation results in batteries with reduced fluctuations in current, reduced thermal stress and increased battery life.

The configuration of hybrid energy storage system is shown in Figure 3-1. The structure of HESS is shown in Figure 3-1.

The proposed HESS is composed of two components: a lithium-ion battery pack and an ultracapacitor bank which are connected to a common DC-link via bidirectional DC-DC converters. The battery delivers high energy density and long duration power supply, while the ultracapacitor delivers high power density and fast charge/discharge power. The DC-DC converters handle power flow between the battery, ultracapacitor and DC-link during vehicle operation. The three-phase inverter, which is connected to the electric traction motor, receives a stable voltage from the DC-link.

The total power requirement is given by:

$$[P_d = \eta_{bat} P_{bat} + \eta_{uc} P_{uc}]$$

Where:

Vehicle Power Demand (P_d) (W)

(P_{bat}) = Battery Power (W)

The Ultracapacitor Power (P_{uc})(W) represents the electrical power generated by the ultracapacitor.

(η_{bat}) = Battery Efficiency

(η_{uc}) = Ultracapacitor Efficiency

This equation shows that the storage devices complement each other to fulfil the vehicle load demand.

Battery Power Management

The lithium-ion battery is the main energy supply and provides the vehicle with an average load power. The proposed system aims to reduce rapid power fluctuations by intelligently sharing power among various vehicles, thereby extending battery life by preventing frequent and excessive charging and discharging. The battery current is constantly checked and controlled to ensure safe operation.

The power of a battery is computed as:

$$[P_{bat} = V_{bat} I_{bat}]$$

Where:

(P_{bat}) = Battery Power (W)

(V_{bat}) = Battery Voltage (V)

(I_{bat}) = Battery Current (Ampere)

Ultracapacitor Power Assistance

The ultracapacitor is a secondary energy storage device that can complement battery during transient operating condition. The ultracapacitor provides power when accelerating and stores energy when regeneratively braking, thanks to its high power density and quick response to demand. This can greatly lower the stress on batteries and enhance overall system reliability.=

The energy stored in the ultracapacitor is given by:

$$[E_{uc}] = \frac{1}{2} CV_{uc}^2$$

Where:

(E_{uc}) = Stored Energy (J)

M = Mass of the object (kg)

(V_{uc}) = Ultracapacitor Voltage (V)

A Model Predictive Controller (MPC) is used to control power distribution between the battery and ultracapacitor for optimisation. The controller anticipates the future demand for vehicle power, based on the state variables in the system, and optimizes its power-sharing strategy. The MPC continually measures battery SOC, ultracapacitor SOC, load current, and vehicle operating conditions.

The goal of the MPC may be expressed as:

$$[J = \sum_{k=1}^N \left[(SOC_{ref} - SOC)^2 + \lambda I_{bat}^2 \right]]$$

Where:

(J) = Cost Function

(SOC_{ref}) = Reference State of Charge

The actual state of charge of the battery for the first time.

(I_{bat}) = Battery Current

(λ) = Weighting Factor

The controller reduces the amount of current stress on the battery and keeps the desired SOC level while providing stable operation.

Battery Aging Estimation

The proposed work will make one of the major contributions by considering battery aging with variable C-rate model. A method different from the conventional method which assumes constant charging rate is provided, which continuously assesses the actual charging

current of the battery during operation of the vehicle.

The C-rate of the battery (C-rate) is:

$$[C_{rate}] = \frac{I_{bat}}{Q_{rated}}$$

Where:

(C_{rate}) = Charging/Discharging Rate

(I_{bat}) = Battery Current (Ampere)

During braking operations, the electric motor operates as a generator and converts kinetic energy into electrical energy. Bidirectional converter system recovers the energy and stores it in the ultracapacitor and battery. The ultracapacitor can be charged quickly with high current levels, making it a candidate that is used for regenerative energy storage.

The power supplied by the regenerative braking is given by:

$$[P_{regen}] = T_m \omega_m$$

Where:

(P_{regen}) = Regenerative Power (W)

(T_m) = Motor Torque (Nm)

System Efficiency Evaluation

The Hybrid Energy Storage System is judged based on the power output to the motor and input to the storage devices.

$$[\eta] = \frac{P_{out}}{P_{in}} \times 100$$

Where:

(η) = System Efficiency (%)

(P_{out}) = Output Power (W)

(P_{in}) = Input Power (W)

The MATLAB/Simulink simulation results show that the proposed HESS can successfully alleviate the current fluctuation in the battery, reduce battery degradation, improve

regenerative braking performance, stabilize voltage, and boost the efficiency of the overall system. This coupling of ultracapacitors and intelligent predictive control is a reliable and sustainable solution for future energy management systems of EVs.

IV RESULTS EXPLANATIONS

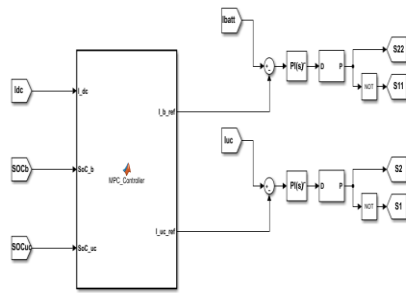
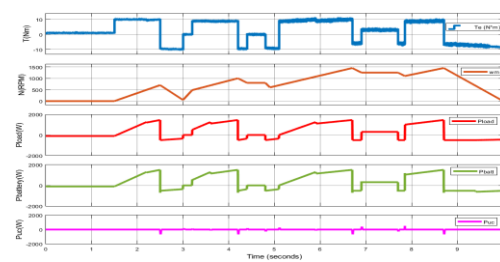


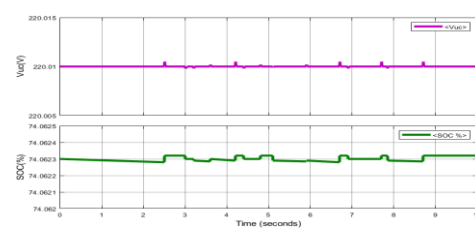
Fig.2 Control system for HESS

The control architecture of the Hybrid Energy Storage System that uses the Model Predictive Controller (MPC) is shown in Figure 2. In order to find the best way to distribute power between the battery and the ultracapacitor, the control system keeps a close eye on critical factors such load current, ultracapacitor state-of-charge (SoC), battery conditions, and system voltage. The MPC controller makes predictions of the system behavior over a prediction horizon to control the bidirectional DC-DC converters. Based on the operating condition, the controller decides whether the battery or the ultracapacitor should be used to supply the greater amount of power. This high power density and rapid response time makes the ultracapacitor useful to supply the load with maximum current when accelerated and an unexpected load increase occurs. The battery on the other hand, supplies the average power demand so that stresses are minimised, as is the increase in temperature. The storage units effectively distribute the collected energy during regenerative braking. The control system ensures the stability of the voltage at the DC-link, as well as reduces unnecessary changes in the current of the battery. An MPC-based controller is able to improve electric vehicle reliability, driving

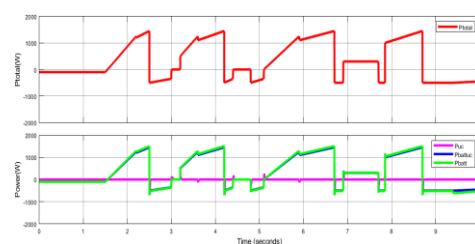
safety, battery life and energy efficiency in dynamic driving environments.



(a)



(b)

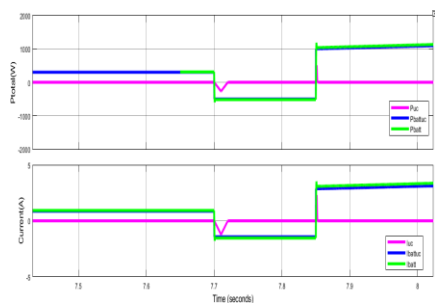


(c)

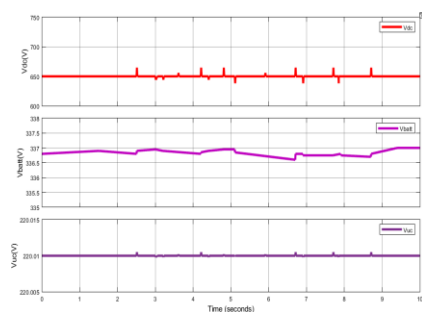
Fig. 3. Results for the complete drive cycle showing: (a) torque, speed, load power, battery power, and UC power; (b) voltage of UC and SoC; and (c) load power and battery power with and without UC.

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. 4. 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.

V.CONCLUSION

The proposed Hybrid Energy Storage System (HESS) significantly increases the durability of the electric car battery by allowing the ultracapacitor to control sudden power fluctuations (acceleration and dynamic loads). The Energy Management Strategy, based on Model Predictive Control (MPC), is able to efficiently optimise the distribution of energy between the ultracapacitor and lithium-ion battery in various driving conditions. In this study, the aging of batteries is analyzed in constant and variable-rate operation both with battery only operation and battery-ultracapacitor operation. The value of C-rate is not constant throughout the driving cycle, as its value changes with the load, so the calculation of battery degradation is not accurate, as seen in the results. 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 outcomes show that the HESS arrangement

decreases the ageing of the batteries. The reason for this is that the ultracapacitor absorbs the transients of electrical current and peak power on the battery, thereby reducing the electrical and thermal stress on the battery. In addition, the current changing C-rate delivers more realistic and accurate results rather than the typical C-rate used 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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