Advanced International Journal for Research (AIJFR)
E-ISSN: 3048-7641 ● Website: www.aijfr.com ● Email: editor@aijfr.com

Design and Analysis of a Supercapacitor Based Hybrid Energy Storage System for Electric Vehicles

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Abstract

Electric vehicles (EVs) require both high energy density and high power density from their onboard energy storage systems. Lithium-ion batteries provide high energy density but experience degradation when exposed to repeated high current spikes during acceleration, regenerative braking, and hill climbing.

To address these challenges, this work proposes a hybrid energy storage system (HESS) combining lithium-ion batteries and supercapacitors. Supercapacitors offer extremely high power density, rapid charge–discharge capability, and long cycle life. The proposed architecture integrates a supercapacitor module with the battery pack using a bidirectional DC–DC converter to enable efficient energy sharing.

MATLAB Simulink simulations are used to analyze voltage, current, and power characteristics of the hybrid system. Results indicate improved transient response, enhanced regenerative braking energy capture, and reduced battery stress. The modular design provides a scalable architecture suitable for modern electric vehicle applications.

1. Introduction

The rapid growth of electric vehicles is driven by environmental concerns, rising fuel costs, and government regulations aimed at reducing greenhouse gas emissions. The energy storage system is the most critical subsystem of an EV as it determines vehicle range, acceleration capability, and overall efficiency.

Lithium-ion batteries dominate EV technology due to their high energy density and mature manufacturing processes. However, batteries alone cannot efficiently handle rapid power fluctuations. High peak currents during transient conditions accelerate battery degradation and increase thermal stress.

Supercapacitors, also known as ultracapacitors, are electrochemical capacitors capable of delivering extremely high power in short durations. Integrating supercapacitors with batteries creates a hybrid energy storage system capable of delivering both high energy and high power [1].

2. Literature Review

Several studies have investigated hybrid battery–supercapacitor systems for EV applications.

Nguyen et al. proposed an energy management strategy using Pontryagin's Minimum Principle to optimize power sharing between batteries and supercapacitors, significantly improving system efficiency [2].

Burke et al. discussed the role of ultracapacitors in electric and hybrid vehicles and demonstrated their advantages in handling transient loads and regenerative braking [3].

Tyagi et al. implemented a hybrid energy storage system combining batteries and ultracapacitors for EV systems and reported improved dynamic response and reduced battery current ripple [4].

Recent research focuses on intelligent energy management algorithms and optimized converter topologies to maximize energy efficiency in hybrid energy storage systems [5].

3. Supercapacitor Fundamentals

Supercapacitors store energy electrostatically at the electrode–electrolyte interface rather than through chemical reactions.

The energy stored in a capacitor is given by

$$E = 1/2\ C\ V^2$$

where C is capacitance and V is voltage.

The maximum power delivered by a supercapacitor can be approximated by

$$P = V^2 / (4R)$$

where R represents the equivalent series resistance (ESR).

Due to their extremely low ESR, supercapacitors can deliver high instantaneous power, making them ideal for peak load support in EV systems [3].

4. Supercapacitor Sizing Calculation

Assume peak power demand of the EV motor is 2 kW for a duration of 30 seconds.

Energy required:

$$E = P \times t$$
$$E = 2000 \times 30$$
$$E = 60000 \text{ Joules}$$

Required capacitance:

$$C = 2E / V^2$$

For a 48 V system,

$$C = (2 \times 60000) / (48^2)$$
$$C \approx 52\ F$$

Therefore, a supercapacitor bank with an equivalent capacitance of approximately 50 F is required to support the peak power demand.

5. Battery System Modeling

The lithium-ion battery pack considered in this project has the following specifications:

$$\text{Nominal voltage} = 48\ V$$
$$\text{Capacity} = 20\ Ah$$
$$\text{Energy} = 48 \times 20 = 960\ Wh \approx 1\ kWh$$

Battery models in MATLAB Simulink include internal resistance and state-of-charge dynamics to accurately represent real battery behavior.

6. Bidirectional DC–DC Converter

A bidirectional DC–DC converter is used to regulate power flow between the battery and supercapacitor modules.

The converter operates in two modes:

Buck mode – regenerative braking energy charges the supercapacitor.
Boost mode – supercapacitor provides energy support during acceleration.

Such converters enable efficient power sharing and improve system flexibility [6].

7. BLDC Motor Load Modeling

The traction system of the EV is represented by a BLDC motor model.

Advantages of BLDC motors include high efficiency, high torque-to-weight ratio, and precise speed control. The motor controller regulates phase currents and rotor position to produce smooth torque output.

8. MATLAB Simulink Simulation

The hybrid energy storage system is modeled using MATLAB Simulink.

Key blocks used in the model include:

Battery block
Supercapacitor block
Bidirectional DC–DC converter

BLDC motor model
Control logic

Simulation outputs analyzed include voltage response, current response, and power flow dynamics.

9. Results and Discussion

Simulation results show that the supercapacitor effectively handles transient power demand. The battery current profile becomes smoother, indicating reduced peak stress.

During regenerative braking, the supercapacitor absorbs energy quickly due to its high power capability. This improves overall energy efficiency of the vehicle.

10. Advantages of Hybrid Energy Storage

Improved acceleration performance

Higher regenerative braking efficiency

Reduced battery degradation

Improved power density

Longer battery lifespan

11. System Limitations

Thermal management requirements

Converter efficiency losses

Higher initial system cost

Complex control algorithms

12. Future Work

Future work includes hardware prototype development, advanced energy management algorithms, and integration with renewable charging infrastructure.

13. Conclusion

The proposed hybrid energy storage system effectively combines lithium-ion batteries and supercapacitors to improve EV performance. Simulation results demonstrate improved transient response and reduced battery stress. The modular architecture allows scalability for different EV platforms. A, Burke (2000),hheogje. (, 2009)uuuuuuuu

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