International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347 - 6435 (Online) Volume 15, Issue 1, January 2026)

A Hybrid Energy Storage System Integrating Batteries and Supercapacitors for Electric Vehicles

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Abstract: **Hybrid energy storage systems (HESS) integrating batteries and supercapacitors have emerged as an effective solution to meet the diverse power and energy demands of electric vehicles. This approach combines the high energy density of batteries with the high power density and fast charge–discharge capability of supercapacitors, enabling improved performance during acceleration, regenerative braking, and transient load conditions. This paper presents an overview of battery–supercapacitor hybrid energy storage architectures, power electronic interfaces, and energy management strategies designed to enhance efficiency, extend battery lifespan, and improve overall system reliability. The advantages of hybridization in reducing battery stress, improving thermal behavior, and supporting renewable energy integration are discussed, along with key challenges and future research directions for high-performance and sustainable electric vehicle applications.**

Keywords— Hybrid Energy Storage System, Electric Vehicles, Battery–Supercapacitor Integration, Energy Management, Power Electronics.

I. INTRODUCTION

The rapid growth of electric vehicles (EVs) has become a key component of global efforts to reduce greenhouse gas emissions, minimize air pollution, and decrease dependence on fossil fuels. As transportation systems transition toward electrification, the performance, reliability, and sustainability of onboard energy storage systems have emerged as critical factors influencing EV adoption[1]. Conventional single-source energy storage systems, particularly battery-only configurations, face limitations in meeting the simultaneous requirements of high energy density and high power density. These limitations have driven research interest toward hybrid energy storage systems (HESS) that integrate batteries and supercapacitors to achieve improved overall performance[2].

Batteries, especially lithium-ion batteries, are widely used in electric vehicles due to their high energy density and ability to store large amounts of energy for long driving ranges. However, batteries suffer from inherent drawbacks such as limited power density, slow charge–discharge response, thermal stress, and degradation under frequent high-current transients[3]. During rapid acceleration, hill climbing, and regenerative braking, batteries experience high current spikes that accelerate aging and reduce lifespan. These challenges restrict the efficiency and long-term reliability of battery-only EV energy storage systems[4].

Supercapacitors, also known as ultracapacitors, offer complementary characteristics that make them ideal partners for batteries in hybrid energy storage systems. They exhibit extremely high power density, rapid charge–discharge capability, long cycle life, and high efficiency. Supercapacitors are particularly effective in handling short-duration, high-power demands and capturing regenerative braking energy[5]. However, their low energy density limits their ability to support long driving ranges when used alone. This contrast in characteristics makes batteries and supercapacitors naturally suited for hybridization in EV applications[6].

A hybrid energy storage system integrating batteries and supercapacitors leverages the strengths of both technologies while mitigating their individual weaknesses. In such systems, batteries primarily supply the average energy demand required for cruising, while supercapacitors handle peak power demands and absorb sudden energy surges[7]. This coordinated operation significantly reduces stress on batteries, leading to improved efficiency, enhanced safety, and extended battery lifespan. As a result, HESS architectures contribute to improved vehicle performance and reduced maintenance costs[8].

The effectiveness of a battery–supercapacitor hybrid energy storage system heavily depends on its system architecture and power electronic interface. Various configurations such as passive, semi-active, and fully active topologies have been proposed in the literature. Among these, active configurations using bidirectional DC–DC converters provide better control over power flow and energy distribution. Power electronics play a vital role in ensuring efficient energy transfer, voltage regulation, and system protection under dynamic driving conditions[9].

Energy management strategies are another critical aspect of hybrid energy storage systems. Intelligent control

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algorithms are required to determine optimal power sharing between batteries and supercapacitors in real time. Rule-based methods, optimization techniques, fuzzy logic controllers, and artificial intelligence-based approaches have been widely explored to enhance system performance. Effective energy management not only improves efficiency but also minimizes battery degradation and enhances regenerative braking effectiveness[10].

Hybrid energy storage systems also support the integration of renewable energy sources and advanced EV functionalities. When combined with renewable-powered charging infrastructure, HESS can efficiently manage variable energy input and output. Additionally, hybrid systems enhance compatibility with vehicle-to-grid (V2G) technologies, allowing EVs to act as distributed energy storage units. This capability improves grid stability and promotes better utilization of renewable energy resources[11].

Despite their advantages, hybrid energy storage systems face challenges related to system complexity, cost, control implementation, and component sizing. The integration of additional components such as supercapacitors and converters increases system weight and design complexity. Therefore, ongoing research focuses on optimizing system design, reducing cost, and developing adaptive control strategies [12].

II. PROPOSED MODEL

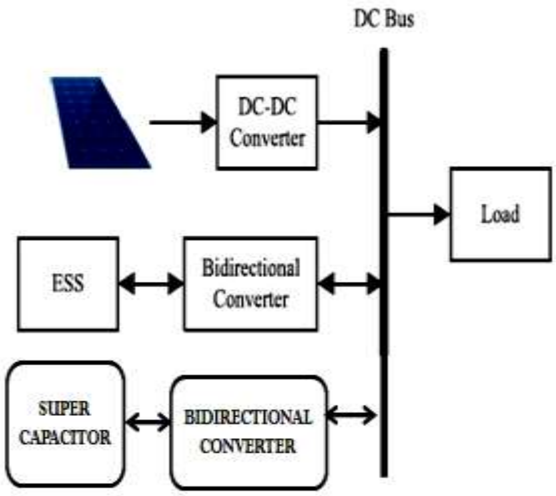

Figure 1: Model Flow Chart

Step 1: Solar Energy Generation

The system begins with a solar photovoltaic (PV) panel, which converts solar energy into electrical energy in the form of DC power. However, the voltage and current generated by the PV panel are variable and depend on sunlight intensity, temperature, and environmental conditions. Therefore, this raw DC power cannot be directly used by the electric vehicle or storage units.

Step 2: DC–DC Converter Operation

The output of the solar panel is fed into a DC–DC converter. This converter performs voltage regulation and power conditioning, ensuring that the PV output is converted into a stable and usable DC voltage level. The DC–DC converter may also include maximum power point tracking (MPPT) to extract maximum available power from the solar panel. The regulated output is then supplied to the DC bus.

Step 3: DC Bus as Central Power Link

The DC bus acts as a central energy distribution node in the system. It collects regulated DC power from the solar source and distributes it to different components. The DC bus ensures voltage stability and enables smooth power exchange between the energy sources, storage systems, and the load. All major power flows in the system are coordinated through this DC bus.

Step 4: Supplying Power to the Load

The load, representing the electric vehicle motor drive or auxiliary systems, is directly connected to the DC bus. When sufficient power is available from the solar source or storage units, the DC bus supplies energy to the load. This allows the EV to operate using renewable energy whenever available.

Step 5: Battery-Based Energy Storage System (ESS)

The Energy Storage System (ESS), typically a battery pack, is connected to the DC bus through a bidirectional DC–DC converter. This bidirectional converter allows two modes of operation:

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- **Charging mode**: Excess energy from the DC bus is stored in the battery.

- **Discharging mode**: Stored battery energy is supplied back to the DC bus when renewable generation is insufficient.

This helps in maintaining continuous power availability and supports longer driving range.

Step 6: Supercapacitor Integration

The supercapacitor is also connected to the DC bus via a separate bidirectional converter. Unlike batteries, supercapacitors handle high power and fast transient conditions. They absorb sudden energy during regenerative braking and supply quick bursts of power during acceleration. This reduces stress on the battery and improves overall system efficiency.

Step 7: Power Sharing via Bidirectional Converters

Both bidirectional converters play a crucial role in power flow management. They ensure controlled energy exchange between the DC bus, battery, and supercapacitor. The converters enable smooth transitions between charging and discharging modes based on system demand, energy availability, and load conditions.

Step 8: Hybrid Energy Management Operation

During normal operation:

- The battery supplies steady, long-duration energy.

- The supercapacitor handles short-duration, high-power demands.

- The DC bus balances power flow among all components.

This hybrid arrangement improves battery lifespan, enhances efficiency, and ensures stable EV operation under varying driving conditions.

IV. SIMULATION RESULTS

A. Steady State Simulation Results

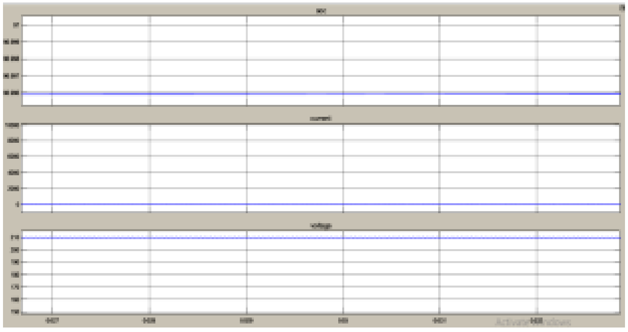

Figure 2: Battery (SOC, Current, Voltage)

Figure 2 is battery state of charge,voltage and current graph. Here X axis is denoting as a time scale and Y axis is denoting as a state of charge, value of current and voltage.

Here, the battery discharge to compensate the load power

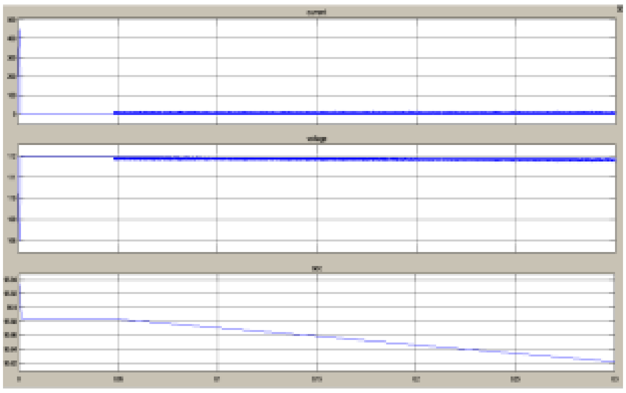

Figure 3: Super Capacitor (Current, Voltage, SOC)

Figure 3 is super capacitor state of charge, voltage and current graph. Here X axis is denoting as a time scale and Y axis is denoting as a value of current, voltage and state of charge. Here, the super capacitor is discharge to compensate the load power.

Table 1: Simulation parameters

Sr No.	Parameter	Value
1	DC Load Power	1782watts
2	Solar (PV) Power	1100watts

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3	Battery SOC	97
4	Battery Current	5A
5	Battery Voltage	210V
6	Super Capacitor SOC	95
7	Super Capacitor Current	Aprox 0
8	Super Capacitor Voltage	112V
9	DC Load Voltage	500V
10	Solar(PV) Voltage	450V

B. Dynamic Response Simulation Results

The dynamic performance of the system with the irradiance dropping from 1000 W/m2 to 500 W/m2 at t = 1 to 10 sec, the simulation results is presented in various operating modes. Other simulation conditions are as follows: Temperature = 25C and load power. The DC bus voltage *V*bus keeps stable during the transition. In this scenario the MPPT loop always takes charge of the control of the duty cycle *D*. There is a slight rise of the PV reference voltage *V*ref, due to the variation of the PV characteristic curve during the transition.

In this mode, the PV power is less than the load power and the battery SoC is within limits. Therefore, the battery discharges to regulate the DC link voltage.

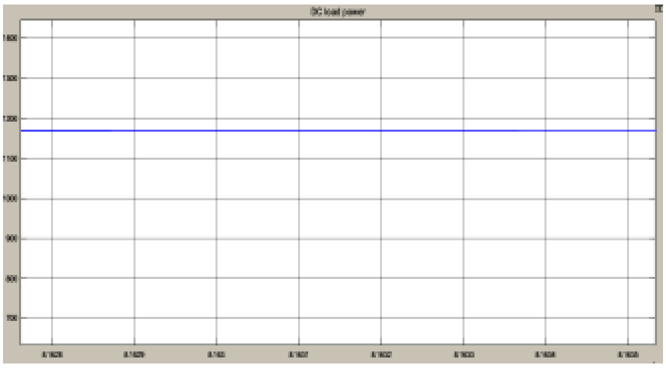

Figure 4: DC Load Power

Figure 4 is showing DC load power graph. Here X axis is denoting as a time scale and Y axis is denoting as a value of power. So load power value is 1170W.

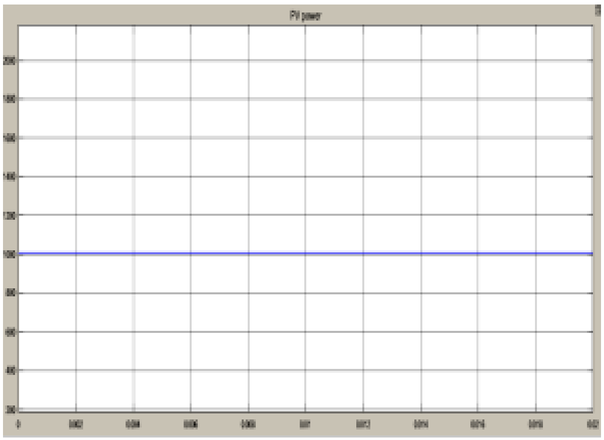

Figure 5: Solar (PV) Power

Figure 5 is showing Solar power graph. Here X axis is denoting as a time scale and Y axis is denoting as a value of PV power. So Solar (PV) power value is 1100W. PV characteristic curves with Irradiance =500 W/m2 (Temperature C= 25). Here, the solar power is 1000watts < load power is 1170watts

Table 2: Simulation parameters

Sr No.	Parameter	Value
1	DC Load Power	1170 watts
2	Solar (PV) Power	1000 watts
3	DC Load Voltage	500V
4	Solar(PV) Voltage	450V

Table 4: Result Comparison

Sr No.	Parameters	Previous Work	Proposed Work
1	PV Max Power	9.6KW	11KW
2	MPPT Voltage	435V	450V
3	Nominal DC Voltage	500V	500V
4	Battery Nominal	200V	200V

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	voltage		
5	Battery max charged voltage	208V	210V
6	State of Charge	NA	97%
7	Super capacitor	NA	Yes
8	Mode of operation	7	4
9	Sub-Module	PV, MPPT, Bi-directional converter,	PV, MPPT, Bi-directional converter,
10	Controller	Conventional incremental conductance MPPT technique and PI Controller	Energy Control Controller

Therefore proposed model simulation result for performance is better than previous model in terms battery, load, and super capacitor. Proposed model gives significant improved results.

V. CONCLUSION

The simulation studies conducted using the battery bank and supercapacitor bank models, along with their respective charge controllers, demonstrate that the battery bank is well suited for delivering energy over long durations. Its exponential voltage–discharge characteristic provides a wide operating region with relatively stable voltage, making it a reliable primary power source for DC loads. Under steady-state conditions, the battery efficiently supplies the required power. However, the battery alone is not capable of responding effectively to sudden or unexpectedly high power demands. Rapid load variations increase battery stress and negatively impact its lifespan. In such transient conditions, the supercapacitor bank plays a vital role by delivering high power within a very short time interval. Its fast charge–discharge capability allows it to handle peak power demands efficiently. The supercapacitor also absorbs sudden energy surges, thereby supporting system stability. By sharing peak power requirements, the supercapacitor significantly reduces the load on the battery. This coordinated operation improves voltage regulation at the DC bus. It also enhances overall system efficiency and dynamic performance. Additionally, thermal stress on the battery is minimized. The hybrid operation ensures smoother power flow under varying load conditions. As a result, energy utilization becomes more effective. Overall, the simulation results clearly indicate that the proposed hybrid energy storage system offers superior performance compared to conventional standalone battery-based systems.

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