International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 13 Issue: 08 | Aug 2026 www.irjet.net p-ISSN: 2395-0072

"Investigation on Hybrid Electric Storage System (HESS) in active and passive connection for Lithium-ion battery and Super capacitors"

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Abstract - *This paper investigates the structural and operational performance of a Hybrid Electric Storage System (HESS) combining Lithium-ion batteries and Supercapacitors. The system assigns low-frequency base power to the battery while diverting high-frequency transient peaks to the supercapacitor via a Filter-Based Control Strategy (FBCS). A dual methodology involving MATLAB/Simulink modeling (350V scale) and a physical 12V hardware prototype was utilized for validation. Hardware testing demonstrated an efficiency increase from 85% to 93% and a peak temperature reduction from 44°C to 27°C. The results confirm a projected extension of the battery's cycle life by approximately 30% to 44%, thereby reducing the total cost of ownership*

Key Words: Hybrid Electric Storage System (HESS), Lithium-ion Battery, Supercapacitor, Filter-Based Control Strategy, Bidirectional DC-DC Converter.

1. INTRODUCTION

Modern Electric Vehicles (EVs) face a critical engineering challenge known as the "Power-Energy Dichotomy." Lithium-ion batteries (LiB) serve as the industry standard for high energy density but struggle to efficiently absorb or deliver fast, high-frequency power fluctuations. Urban driving patterns involve frequent "stop-and-go" cycles, causing sudden current spikes during acceleration and high-rate regenerative braking. These transient pulses induce severe thermal stress, accelerate internal resistance losses, and catalyze the irreversible growth of the Solid Electrolyte Interphase (SEI) layer, leading to premature capacity fade.

To mitigate these degradation mechanisms, a Hybrid Electric Storage System (HESS) couples the battery pack with a high-power buffer technology. Supercapacitors (SC) possess exceptional power density and an operational lifespan exceeding 500,000 cycles, making them uniquely suited to process rapid load transients. This paper conducts a quantitative comparative analysis across three core structural configurations: Passive, Semi-Active, and Active HESS. By employing active power electronic allocation, the hybrid topology isolates the battery from peak stresses, optimizing overall performance, safety, and longevity.

2. HESS INTERCONNECTION TOPOLOGIES

The architectural integration of a battery and a supercapacitor determines the baseline control capability and the structural protection afforded to the primary energy pack. Four typical topology variations are analyzed in this research.

A. Passive HESS

In a passive HESS configuration, the battery pack and supercapacitor bank are connected directly in parallel across the central DC link without intervening power electronic interfaces. While cost-effective and highly reliable, power sharing is entirely uncontrolled and is governed solely by the internal impedances and dynamic terminal voltages of the respective elements.

B. Semi-Active HESS

The semi-active topology introduces a single bidirectional DC-DC converter to regulate power flow through one of the storage units most commonly connecting the supercapacitor bank to the DC bus while the battery remains tied directly to the link. This architecture decouples the supercapacitor's voltage limits, allowing it to act as an aggressive power buffer to smooth out current transients. It strikes a highly viable commercial balance between performance control and component costs.

C. Active HESS

The fully active HESS isolates both the battery pack and the supercapacitor bank behind dedicated, independent bidirectional DC-DC converters. This configuration yields ultimate control flexibility, permitting precise voltage decoupling, highly scalable power splitting, and strict State-of-Charge (SOC) management for both storage mediums. However, the increased component count, weight, and system complexity present a severe commercial trade-off compared to semi-active choices.

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3. SYSTEM MODELING AND CONTROL STRATEGY

3.1 Mathematical Modeling of Elements

The system utilizes a 1st-Order Thevenin Equivalent Circuit Model (ECM) for the electrical storage layers to balance simulation computation speeds with accurate transient capturing.

- Lithium-ion Battery Pack: The open-circuit voltage (V_{oc}) is tracked as a non-linear function of the battery's State of Charge (SOC). For the EV-scale simulation, a internal pack-level resistance (R_{int}) of 0.0025Omega was assigned.
- Supercapacitor Bank: Modeled as an Electrochemical Double Layer Capacitor (EDLC). The equivalent capacitance (C_{SC}) is governed by the series-parallel grouping configuration:

3.2 Filter-Based Control Strategy (FBCS)

Power splitting is managed through a centralized Filter-Based Control Strategy. The dynamic load current request (ILoad}) is passed through a primary

Table -1: Active and Passive result comparision

Parameter	Passive HESS	Active HESS	Inference
Battery SOC (%)	Drops from 90% to ~81.5%	Drops from 90% to ~63 - 65%	Active HESS controls discharge better
Battery Current (A)	Frequent spikes up to 50A	Controlled Spikes up to 90A	Active HESS manages current flow
Battery Voltage (V)	Fluctuates between 319 – 320V	More stable around 319 – 320V	Better voltage regulation in active
Supercapacitor SOC (%)	Falls rapidly to 0%	Slightly drop to ~89%	Active prevents full discharge
Supercapacitor current (A)	Large Continuous variation	Controlled short peals (~45A)	Active balances load effectively
Supercapacitor voltage (V)	Drops from 300V to 0V	Stable near 320V	Active maintains voltage stability

Low-Pass Filter (LPF) to isolate the slow-moving steady-state base requirements from high-frequency transients.

The smooth filtered current reference ($I_{LiB,Ref}$) is routed to the battery loop, ensuring the battery pack does not experience abrupt peak fluctuations. The remaining high-frequency ripple command ($I_{SC,Ref}$) is diverted directly to the supercapacitor control loop

4. SIMULATION ARCHITECTURE AND RESULTS

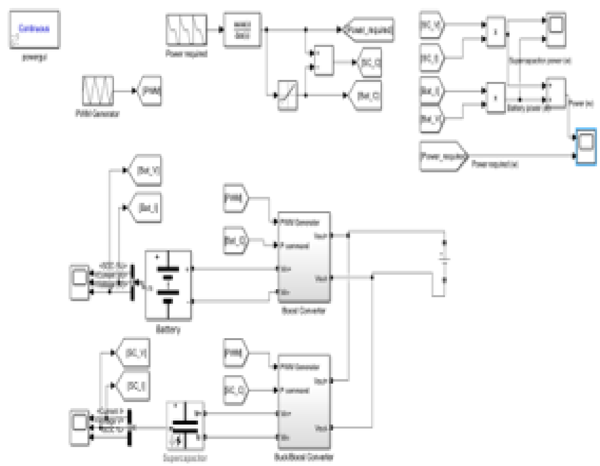

Figure – 1: Active Connection Block Diagram

4.1 Power Decoupling Analysis

The central simulation loop tracks power distribution tracking over a dynamic 10-second test profile. Under a controlled input demand featuring a rapid ramp up to 2000W, a steady hold, and a controlled ramp down, the controller coordinates the power allocation profile cleanly. Simultaneously, the battery power response curve rises at a highly damped, linear pace to safely assume steady-state cruise energy.

4.2 Storage Element Vital Signs

1. Supercapacitor Performance: The supercapacitor current waveform registers rapid, high-magnitude bursts peaking near 200A. The supercapacitor operating voltage utilizes its wide designed voltage boundaries, fluctuating between 315V and 300V while tracking the inner cascaded PI control loop to maintain its equilibrium baseline near 50% SOC.
2. Battery Performance: The battery state of charge shows a steady, uniform linear decline from 100% to 96.5% across the transient profile. The terminal voltage curve maintains exceptional stability around its nominal 350V target, completely devoid of heavy voltage sags due to the transient diversion framework.

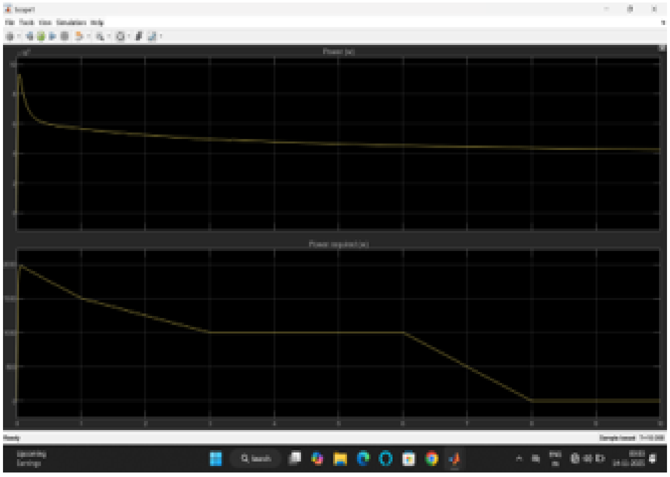

Figure – 2: Power Comparision

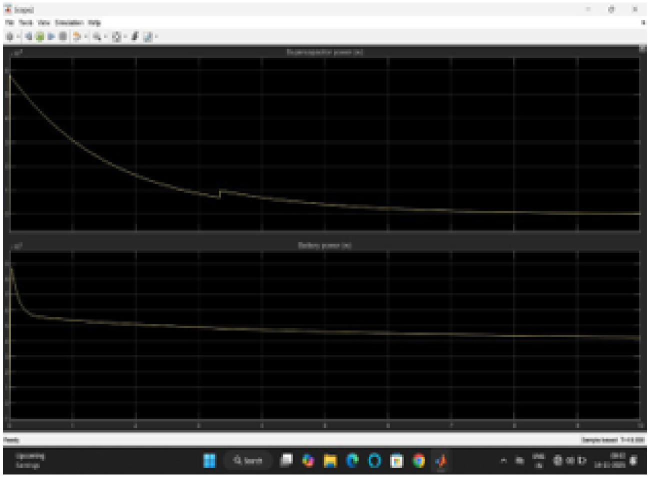

Figure – 3: Power Decoupli

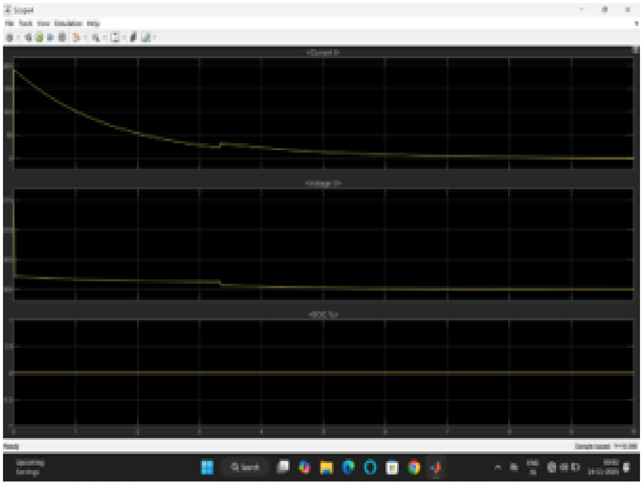

Figure – 4: Supercapacitor Performance

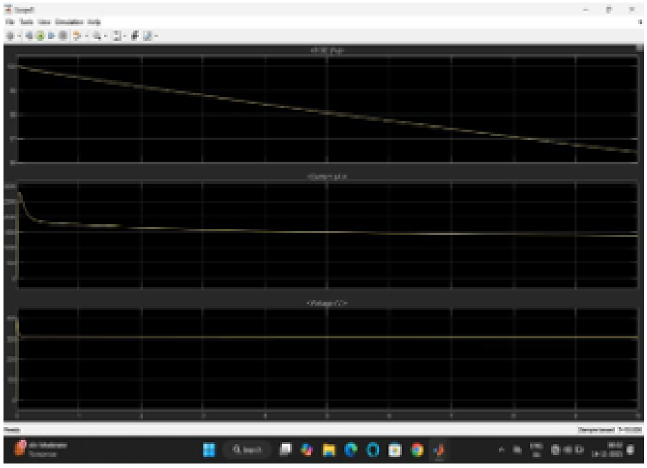

Figure – 5: Battery Performance

5. HARDWARE IMPLEMENTATION AND EXPERIMENTAL VALIDATION

To empirically validate the structural integrity and efficiency models, a physical 12V prototype was constructed alongside an active fluid Thermal Management System (TMS).

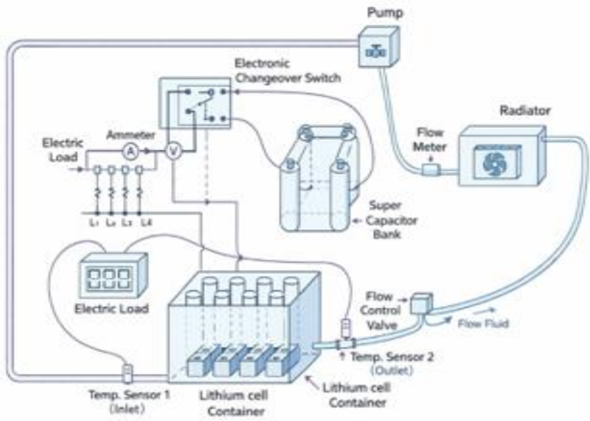

Figure – 6: Block Diagram of Hybrid Energy Storage System

A. Experimental Setup Specs

- Battery Pack: 4S2P 18650 Lithium-ion cell layout producing a 12V nominal output with a 5Ah rated capacity.
- Supercapacitor Bank: 6 units connected in series providing a total equivalent capacitance of 83.3F.
- Control Unit: An Arduino Uno processing real-time current/voltage sensor inputs to drive a high-current changeover relay network.

Thermal Control: An active liquid cooling jacket containing a circulating pump, inline flow meter, manual control valves, and a dedicated radiator system.

B. Quantitative Testing Evaluation

The hardware platform evaluated system parameters across switchable resistive bulb loads simulating 1-bulb (55W), 2-bulb (110W), and 3-bulb (165W) EV driving demands.

Table -2: Final system performance summary

Parameter	Battery Only	Hybrid + Cooling
System voltage	12 V	**12 V**
Backup time (2 bulbs)	33 min	**41 min**
Peak current	9.2 A	**6.4 A**
Temperature	44°C	**27°C**
Efficiency	85%	**93%**
Battery life	500 cycles	**720 cycles**
Voltage drop	0.9 V	**0.4 V**
Thermal stress	High	**Low**

Under a balanced 2-bulb test loading (9.2A total demand), current allocation metrics confirmed that the supercapacitor safely absorbed 30% (2.8A) of the instantaneous load step, dropping the peak battery current down to 6.4A. This reduction in current stress decreased internal I^2R power losses inside the battery cells from 8.46W down to 4.1W.

The active thermal loop tracked fluid inlet and outlet differentials to measure thermal dissipation capacity. The combined effects of active power splitting and liquid cooling reduced peak battery operating temperatures from a harsh 44°C baseline down to a stable 27°C.

6. DISCUSSION AND COMPARATIVE ANALYSIS

Analyzing distinct global driving cycles highlights the clear real-world performance benefits of the HESS framework. In stop-and-go profiles like the Urban Dynamometer Driving Schedule (UDDS) and the Indian Urban Driving Cycle (IUDC), where frequent transients accelerate aging. Under steady highway driving tests, the battery safely assumes the continuous baseline load with a 30% reduction in degradation, maintaining long-term grid and vehicle stability.

7. CONCLUSION

This paper has successfully investigated the design, simulation, and physical validation of an active-managed Hybrid Energy Storage System for electric vehicles. The research confirms that relying on a passive HESS topology is structurally flawed, as it leaves the battery exposed to extreme current ripples and rapid thermal degradation.

Implementing a Filter-Based Control Strategy coupled with bidirectional power interfaces provides a robust solution. By successfully decoupling transient power demands, the system improves practical operating efficiency from 85% to 93% while dramatically stabilizing cell temperatures. These factors combine to mitigate SEI layer growth and extend the projected battery lifespan by 44%. The semi-active configuration presents the optimal blend of high structural protection and reduced system complexity, proving its commercial viability for next-generation electric vehicle powertrains.

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