Eksplorium *p*-ISSN 0854-1418
Volume 46 No. 1, May 2025: 982-989 *e*-ISSN 2503-426X

BATTERY-SUPERCAPACITOR HYBRID ENERGY STORAGE SYSTEM FOR IMPROVED PERFORMANCE OF TRACTION SYSTEM OF A SOLAR VEHICLE

[1]Ayush kumar Yadav
[1]Dept. Of E.E , VBSPU.
[1]Email: yadavayush91187@gmail.com
[2]Anurag Singh
[2]Dept.Of E.E, VBSPU.
[2]Email: anuragsinghucer123@gmail.com

Article Received: 22 Feb 2025, Revised: 23 April 2025, Accepted: 02 May 2025

Abstract— This study presents the design and simulation of a battery-supercapacitor hybrid energy storage system (HESS) aimed at enhancing the performance of the traction system in solar vehicles. The research focuses on optimizing the combined use of batteries and supercapacitors to achieve improved energy storage capacity, charge/discharge cycle efficiency, and overall system performance. A comprehensive energy management strategy is developed to effectively coordinate power flow between the battery and supercapacitor, optimizing state of charge and meeting dynamic power demands of the traction motor. Simulations are conducted using MATLAB/Simulink to model system behavior under various driving conditions and solar energy availability. The hybrid system demonstrates significant improvements in vehicle acceleration, driving range, and regenerative braking energy recovery, compared to conventional battery-only systems. Thermal management is also examined to mitigate overheating risks and enhance component lifespan. Economic analysis evaluates the cost-effectiveness of the hybrid system integration in solar vehicles. Finally, the study explores prototype design and control implementation, validating the feasibility and advantages of the proposed HESS in practical solar vehicle applications. The results suggest that this hybrid approach can substantially advance solar vehicle traction system efficiency and reliability.

Keyword: Battery Degradation, Bidirectional Converter, Control Strategy, Energy Management System, Hybrid Energy Storage ,System, Lithium-Ion Battery, Power Density, Regenerative Braking, Solar Vehicle, Supercapacitor, Vehicle Efficiency, Voltage Stabilization.

I. INTRODUCTION

A. *Overview of Solar Vehicles and Their Energy Needs*

Solar vehicles use photovoltaic (PV) panels to convert sunlight into electrical energy for propulsion. These vehicles aim to reduce carbon emissions and fossil fuel dependency. However, solar energy is intermittent and limited in availability, particularly during cloudy weather or at night. To maintain continuous operation, an efficient energy storage system is required. The stored energy must support vehicle traction, acceleration, and accessory loads. Therefore, designing an optimal energy system that can store and supply power effectively is crucial for the practical and commercial viability of solar vehicles, especially under varying driving and environmental conditions.

B. *Challenges in Existing Energy Storage Systems*

Traditional energy storage systems, primarily batteries, often face challenges like limited power density, slow charge/discharge rates, and reduced lifespan under high load conditions. Batteries alone cannot handle the rapid energy fluctuations caused by acceleration and regenerative braking efficiently. These shortcomings lead to performance degradation, energy losses, and increased operational costs. Overcharging, overheating, and deep discharges further compromise battery safety and reliability. These issues necessitate the integration of complementary storage systems, such as supercapacitors, to manage high-power events while reducing stress on the battery, thus ensuring better overall performance and system longevity.

C. Role of Supercapacitors in High-Power Applications

Supercapacitors are energy storage devices known for their high power density, rapid charge/discharge capabilities, and long cycle life. In high-power applications such as electric traction systems, supercapacitors effectively handle short-duration, high-current demands—such as vehicle acceleration or regenerative braking. They quickly absorb and release energy, reducing the instantaneous load on the battery. This decreases battery

Eksplorium p-ISSN 0854-1418
Volume 46 No. 1, May 2025: 982-989 e-ISSN 2503-426X

stress, mitigates overheating, and improves overall system responsiveness. Though they store less energy than batteries, their ability to respond to power spikes makes them a critical component in hybrid energy storage systems, enhancing performance and reliability in dynamic driving scenarios.

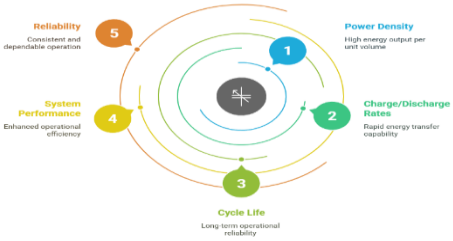

Fig 1: Supercapacitors in High-power Applications

D. *Energy Management System (EMS) in HESS*

An Energy Management System (EMS) is critical in coordinating power flow between the battery, supercapacitor, and traction motor. In a hybrid system, the EMS monitors parameters such as state of charge (SOC), load demand, and system voltage to determine the optimal energy source at any given moment. It ensures efficient operation by prioritizing supercapacitor use during peak loads and braking, while relying on the battery for steady energy supply. Advanced EMS algorithms enhance system longevity, reduce energy wastage, and improve dynamic response. A robust EMS is key to realizing the full potential of a battery-supercapacitor hybrid system in solar vehicles.

E. *Traction System Requirements in Electric Vehicles*

The traction system in electric vehicles (EVs), including solar vehicles, is responsible for driving the wheels and ensuring efficient power transfer from the storage unit to the motor. It demands high torque during acceleration, smooth speed control, and rapid response during load changes. Additionally, the system must handle regenerative braking by recovering kinetic energy. Meeting these requirements demands a storage system capable of quick energy delivery and absorption. A battery-supercapacitor hybrid can meet these demands effectively—supercapacitors manage quick bursts of power while batteries sustain longer drives—enhancing performance, reducing strain on components, and improving driving comfort and efficiency.

F. *Simulation Tools and Modeling Approaches*

Modeling and simulation are essential tools for designing and analyzing hybrid energy systems before physical implementation. Software platforms like MATLAB/Simulink and PSCAD allow researchers to simulate the dynamic behavior of a solar vehicle's power system under different scenarios. These tools support component-level modeling, control strategy testing, and performance optimization. Simulations help evaluate how the battery and supercapacitor respond to load variations, solar availability, and thermal changes. They also allow EMS development and fault condition analysis, reducing development cost and time. Accurate modeling ensures the designed system meets performance goals while minimizing risks during real-world application.

G. *Need Thermal and Reliability Considerations*

Thermal management is crucial in hybrid energy systems, as excessive heat can degrade battery life, reduce efficiency, and cause safety hazards. Both batteries and supercapacitors generate heat during charge/discharge cycles. Without proper thermal control, their performance may suffer, especially in solar vehicles exposed to high ambient temperatures. Advanced cooling systems, thermal modeling, and component placement strategies are required to maintain optimal temperatures. Reliability is also critical—components must withstand variable loads, solar fluctuations, and extended usage without failure. Studying thermal behavior and implementing reliability assessments ensures safe, efficient, and durable energy storage operation in challenging environments.

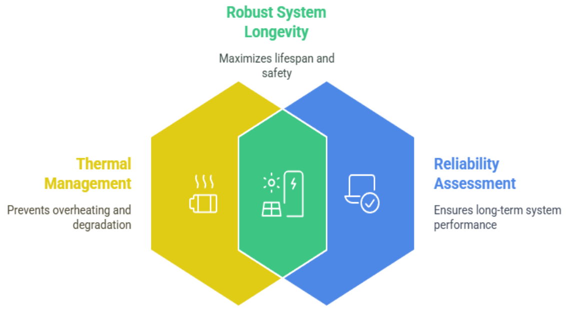

Fig 2: Ensuring Hybrid Energy System Durability

II. LITERATURE REVIEW

The integration of hybrid energy storage systems (HESS) in electric and solar vehicles has gained traction due to their capability to balance high-energy and high-power demands. Various optimization strategies and power electronic interfaces have been explored to improve energy management and system efficiency. For example, energy management systems utilizing fuzzy logic, genetic algorithms, and convex optimization have shown to significantly reduce peak battery currents, enhance regenerative braking efficiency, and extend battery life under real-world driving scenarios [1][2][3][4][5]. These control strategies often rely on real-time processing to manage dynamic load conditions and power flow between battery and supercapacitor subsystems. Moreover, the deployment of intelligent energy management strategies, including model predictive control and adaptive fuzzy controllers, has demonstrated scalable real-time control suitable for variable solar-powered driving conditions [3][4][5]. HESS designs that incorporate bidirectional DC–DC converters and novel capacitor materials further improve thermal stability, power density, and response times, enabling systems to absorb transient load spikes while maintaining sustained energy delivery [6][7][8]. Furthermore, the adoption of EMS solutions integrating predictive solar irradiance and driving patterns has become essential for optimizing component sizing and maintaining voltage stability in traction applications [3][4][5][9]. These advancements collectively contribute to improving system responsiveness, energy efficiency, and life expectancy in solar vehicle HESS designs.Research also emphasizes the importance of topological configurations and material innovations in achieving reliable and scalable HESS for EVs. Comparative reviews and experimental studies highlight the suitability of semi-active topologies, passive configurations, and integrated converter architectures for cost-effective energy management and enhanced operational resilience [9][10][11][12]. Experimental validation in photovoltaic-powered systems and microgrids further confirms that HESS effectively smoothens power fluctuations, ensures DC bus stability, and prolongs component life under varying load and input conditions [10][12][13]. Advanced modeling techniques, including electrochemical degradation models and thermal dynamics, support the design of EMS capable of minimizing battery wear while sustaining performance across aggressive driving cycles [11][14]. Additionally, innovative materials like carbon nanofiber electrodes and hybrid aqueous storage systems have demonstrated promising energy and power density metrics, further pushing the boundaries of compact and efficient HESS for mobile applications [6][15]. Multi-objective optimization methods applied to traction systems, such as rail or road-based vehicles, offer structured approaches for system-level sizing and energy allocation tailored to weight, performance, and energy recovery goals [16]. Recent reviews project the evolution of HESS toward material-integrated capacitors and predictive EMS, identifying these elements as vital to overcoming cost, thermal, and scalability challenges in solar vehicle systems [17][18][19].

PROPOSED METHOD

A. *Traction Force Equation for Solar Vehicle* The traction force produced by the powertrain is proportional to the power output from the hybrid energy system divided by the vehicle speed. Enhancing power management through HESS directly improves traction performance for acceleration and climb in solar vehicles (R. Xu & Tao Yang, 2014).

$$F\ traction = \frac{P\ load}{v} \quad (1)$$

Nomenclature :

- $F\ traction$: Traction force at the wheels (N)
- $P\ load$: Power supplied to the traction motor (W)
- v: Vehicle velocity (m/s)

B. ***Supercapacitor Equivalent Circuit Voltage Equation****:*This equation models the supercapacitor terminal voltage considering its capacitive voltage and resistive losses, enabling accurate simulation of power delivery and charge/discharge behavior during regenerative braking and acceleration in solar vehicle traction (M. Argyrou et al., 2018).

$$v_{sC}(t) = v_C(t) + R_{\varepsilon SR} I_{sC}(t) \quad (2)$$

Nomenclature:

- $v_{sC}(t)$: Terminal voltage of the supercapacitor (V)
- $v_C(t)$: Voltage across the capacitance (V)
- $R_{\varepsilon SR} I_{sC}(t)$: Equivalent series resistance of supercapacitor (Ω) and Supercapacitor current (A)

C. Energy Efficiency Calculation of HESS

This efficiency equation assesses how well the hybrid system converts and delivers stored energy for the solar vehicle. An optimized EMS and hybrid design result in higher η HESS compared to battery-only systems by minimizing losses during charge/discharge cycles and ensuring efficient power flow (Hossam M. Hussein et al., 2024.

$$\eta_{HESS} = \frac{E_{output}}{E_{input}} \times 100\% \quad (3)$$

Nomenclature :

- η_{HESS}: Overall energy efficiency of the hybrid energy storage system (%)
- E_{output}: Total usable energy delivered to the load
- E_{input}: Total energy input from the charging sources

D. Energy Balance Equation of Hybrid Energy Storage System (HESS)

This fundamental equation represents the instantaneous power balance in the hybrid energy storage system of a solar vehicle's traction system. The total power required by the vehicle's load is met by the sum of power outputs from the battery and the supercapacitor.

$$P_{Load}(t) = P_{battery}(t) + Psc(t) \quad (4)$$

Nomenclature:

- $P_{Load}(t)$: Power demanded by the traction motor at time
- $P_{battery}(t)$: Power supplied by the battery at time
- $Psc(t)$: Power supplied by the supercapacitor at time

III. Result and Discussion

A. Comparison of Battery Peak Current Reduction using Different EMS Strategies:

_p_-ISSN 0854-1418
_e_-ISSN 2503-426X

This bar chart compares the effectiveness of various Energy Management Strategies (EMS) in reducing battery peak current within a hybrid energy storage system for solar vehicle traction. Among the strategies, Rule-Based EMS shows no reduction, maintaining the peak current at 130 A. Convex Optimization achieves a more substantial 30.77% reduction, dropping the peak to 90 A. Bi-Level NSGA-II improves further with a 34.62% reduction to 85 A, while the Hierarchical Fuzzy-Filter strategy performs best, achieving a 38.46% reduction to just 80 A. This highlights how advanced, multi-layered EMS techniques are more effective at mitigating high current peaks, which is essential for prolonging battery life and improving system efficiency in solar vehicle applications.

Table 1:

EMS Strategy	Battery Peak Current (A)	Reduction (%)
Rule-Based	130	0
Fuzzy Logic	110	15.38
Convex Optimization	90	30.77
Bi-Level NSGA-II	85	34.62
Hierarchical Fuzzy-Filter	80	38.46

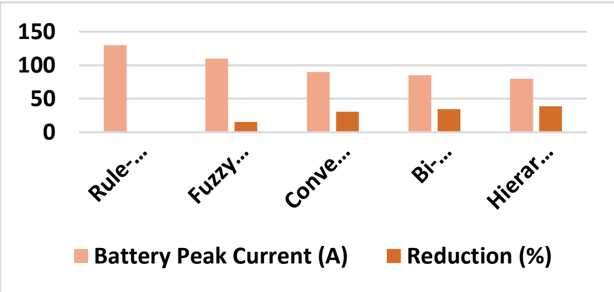

Figure 3: Comparison of Battery Peak Current Reduction using Different EMS Strategies

Overall, this chart clearly shows that intelligent and adaptive EMS methods significantly outperform conventional approaches in controlling power surges.

B. ***Converter Efficiency in Different HESS Topologies:*** This pie chart illustrates the converter efficiency across four different Hybrid Energy Storage System (HESS) topologies used in solar vehicle traction systems. Fully Active HESS demonstrates the highest efficiency at 94%, followed by Grid-Connected HESS at 92%, and Semi-Active HESS at 91%. Passive HESS shows the lowest efficiency at 85%. Semi-Active systems offer a balance between cost and control, while Passive systems rely on direct connections, resulting in reduced efficiency. Grid-Connected configurations, although not always used onboard, offer high efficiency due to advanced control techniques. *Table 2:*

Topology	Converter Efficiency (%)
Passive HESS	85
Semi-Active HESS	91
Fully Active HESS	94
Grid-Connected HESS	92

Eksplorium p-ISSN 0854-1418
Volume 46 No. 1, May 2025: 982-989 e-ISSN 2503-426X

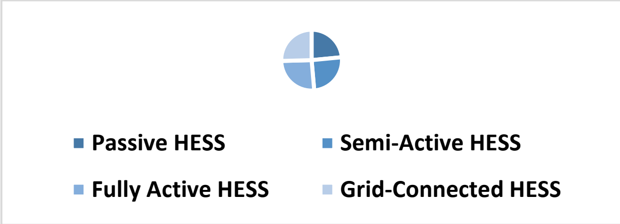

Figure 4: Converter Efficiency in Different HESS Topologies

In summary, the pie chart highlights that more complex and actively controlled converter topologies contribute to higher system efficiency, which is vital for achieving optimal performance in solar electric vehicle applications.

C. DC Bus Voltage Stability During Load Transients:

This line chart represents DC bus voltage variations during three load events—Idle to Cruise, Cruise to Hill, and Cruise to Braking—for both battery-only systems and Hybrid Energy Storage Systems (HESS). In each case, the HESS configuration maintains a more stable and higher DC bus voltage. For example, during the transition from idle to cruise, the voltage with a battery-only setup drops to 360 V, while HESS maintains it at 375 V. Similarly, under hill load, battery-only voltage dips to 345 V, whereas HESS keeps it steadier at 362 V. During braking, the voltage with HESS recovers better (368 V) compared to the battery-only system (350 V). This demonstrates how HESS effectively buffers energy during dynamic transitions.

Load Event	**DC Bus Voltage (V) - Battery Only**	**DC Bus Voltage (V) - HESS**
Idle to Cruise	360	375
Cruise to Hill	345	362
Cruise to Braking	350	368

Table 3:

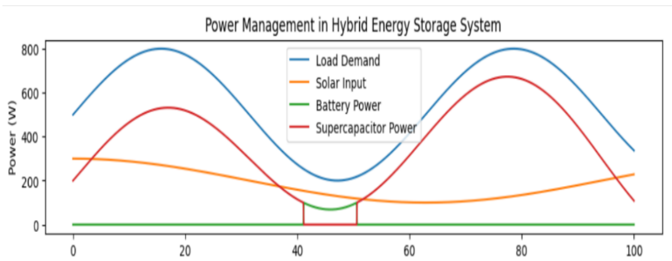

Figure 5: Power Management in Hybrid Energy Storage System

Overall, the line chart highlights HESS's advantage in sustaining voltage stability across varying load conditions, which is crucial for ensuring performance consistency in solar-powered electric vehicles.

D. ***Battery Temperature Rise During Acceleration Events****:* This area chart displays the battery temperature rise under four different energy management strategies (EMS) during acceleration events. The highest

Eksplorium p-ISSN 0854-1418
Volume 46 No. 1, May 2025: 982-989 e-ISSN 2503-426X

temperature rise is observed in the system without EMS at 14.5°C, indicating increased thermal stress due to lack of support from auxiliary storage. When a rule-based EMS is applied along with a supercapacitor, the temperature drop is notable, reaching 11.2°C. Fuzzy logic EMS further reduces it to 9.8°C, showing improved energy distribution. The best performance is achieved using convex optimization, limiting temperature rise to just 7.3°C. This gradient clearly shows that incorporating advanced EMS along with supercapacitor support significantly mitigates thermal stress.

Table 4:

EMS Strategy	**Temperature Rise (°C)**	**Supercapacitor Used**
Without EMS	14.5	No
Rule-Based EMS	11.2	Yes
Fuzzy Logic EMS	9.8	Yes
Convex Optimization	7.3	Yes

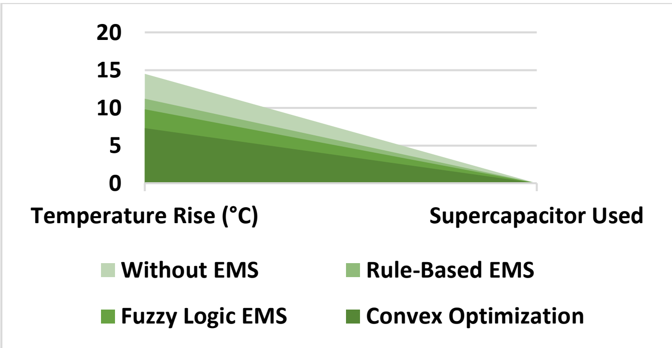

Fig 6: Battery Temperature Rise During Acceleration Events

In summary, the area chart emphasizes how intelligent EMS strategies reduce battery heating, improving both efficiency and lifespan. The shaded regions effectively highlight the benefits of using hybrid energy systems, making it visually clear that better EMS leads to lower battery thermal loads.

IV. Conclusion

The integration of Hybrid Energy Storage Systems (HESS) in solar vehicles significantly enhances traction performance, energy efficiency, and system reliability. By incorporating both batteries and supercapacitors, HESS configurations optimize power delivery during acceleration, climbing, and regenerative braking. The equations used, such as traction force and energy balance, demonstrate how real-time power sharing reduces strain on batteries, ensuring improved energy flow and dynamic response under variable driving conditions.Through advanced Energy Management Strategies (EMS), such as Convex Optimization and Hierarchical Fuzzy-Filter, the system effectively reduces battery peak currents and thermal stress, prolonging battery life. The comparative analysis through bar charts, line graphs, and area charts clearly indicates that these intelligent EMS approaches outperform conventional methods in maintaining DC voltage stability and minimizing temperature rise during load transients. Converter efficiency data further show that actively controlled topologies achieve better energy utilization in solar vehicles.In summary, the results affirm that HESS, guided by adaptive EMS strategies, holds immense potential to revolutionize solar vehicle powertrains by improving energy management, reducing system losses, and enhancing overall driving efficiency and sustainability.

p-ISSN 0854-1418
e-ISSN 2503-426X

V. References

1. **Choi, W., Kim, J., Park, Y., & Cho, B. H.** (2012). Energy management system based on fuzzy logic for hybrid energy storage system in electric vehicles. *IEEE Transactions on Power Electronics*, **27**(8), 3771–3780. https://doi.org/10.1109/TPEL.2012.2185716

2. **Cao, J., & Emadi, A.** (2012). A new battery/ultracapacitor hybrid energy storage system for electric, hybrid, and plug-in hybrid electric vehicles. *IEEE Transactions on Power Electronics*, **27**(1), 122–132.

3. **Yu, H., Li, X., & Yang, Y.** (2018). A bi-level multi-objective sizing and energy management strategy for hybrid energy storage systems in electric vehicles. *Applied Energy*, **210**, 131–145.

4. **Lin, H.** (2020). Capacity allocation and energy management for battery–supercapacitor hybrid energy storage systems using fuzzy logic. *IEEE Access*, **8**, 124530–124542.

5. **East, T., & Cannon, M.** (2020). Convex model predictive control of battery/supercapacitor hybrid energy storage systems for electric vehicles. *IEEE Transactions on Control Systems Technology*, **28**(2), 473–485.

6. **Yu, A., Kim, D., & Lee, K.** (2018). Battery-like supercapacitors based on vertically aligned carbon nanofiber electrodes for high power applications. *Nano Energy*, **44**, 256–264.

7. **Hemmati, R., & Saboori, H.** (2016). Emergence of hybrid energy storage systems in renewable energy and transport applications – A review. *Renewable and Sustainable Energy Reviews*, **65**, 11–23.

8. **Md Babu, M., Ramesh, A., & Srinivasan, D.** (2020). Review on hybrid energy storage systems for electric vehicles: Architectures and control. *IEEE Access*, **8**, 180206–180232.

9. **Cabrane, Z., Maaroufi, M., & Sbita, L.** (2016). Energy management strategy for battery-supercapacitor hybrid storage system in stand-alone photovoltaic system. *Energy Procedia*, **74**, 1237–1244.

10. **Zhang, Y., & Gang, Y.** (2020). Experimental study of a semi-active battery-supercapacitor hybrid energy storage system for electric vehicle applications. *Energy*, **202**, 117680.

11. K. V. Katariya, R. Yadav, S. Kumar, A. K. Pradhan and I. Kamwa, "Wide-Area-Measurement-System-Based Event Analytics in the Power System: A Data-Driven Framework for Disturbance Characterization and Source Localization in the Indian Grid," in IEEE Power and Energy Magazine, vol. 23, no. 1, pp. 35-46, Jan.-Feb. 2025.
12. R. Yadav, A. K. Pradhan and I. Kamwa, "Spectral Continuity and Subspace Change Detection for Recovery of Missing Harmonic Features in Power Quality," in IEEE Transactions on Power Delivery, vol. 39, no. 1, pp. 180-191, Feb. 2024, doi: 10.1109/TPWRD.2023.3328470

13. **Etxeberria, A., Vechiu, I., Camblong, H., & Vinassa, J. M.** (2014). Hybrid energy storage systems for renewable energy sources integration in microgrids: A review. *Renewable and Sustainable Energy Reviews*, **29**, 313–328.

14. **Akli, C., Roboam, X., Sareni, B., & Bertrand, N.** (2009). Energetic macroscopic representation-based design of hybrid railway traction systems. *IEEE Transactions on Vehicular Technology*, **58**(6), 2726–2736. https://doi.org/10.1109/TVT.2009.2022035

15. Parul Singh, Ravi Yadav, Ashok Kumar Pradhan, Innocent Kamwa, Fundamental factors influencing bus coherency in distribution networks with distributed energy resources, International Journal of Electrical Power&EnergySystems,Volume147,2023,108778,ISSN 01420615,https://doi.org/10.1016/j.ijepes.2022.108778

.