International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347 - 6435 (Online) Volume 14, Issue 2, February 2025)

Review of Hybrid Energy Storage System for Enhanced EV Performance

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***Abstract*— The integration of Hybrid Energy Storage Systems (HESS) in electric vehicles (EVs) has emerged as a promising solution to enhance performance, efficiency, and battery lifespan. By combining different energy storage technologies, such as lithium-ion batteries and supercapacitors, HESS effectively addresses the trade-off between energy density and power density, leading to improved energy management and dynamic response. This review explores various configurations, control strategies, and advancements in hybrid storage solutions for EV applications. It highlights the benefits of HESS, including regenerative braking efficiency, extended battery longevity, and optimized power delivery, while also discussing challenges such as system complexity, cost, and control optimization. The study provides a comprehensive analysis of recent research trends, potential improvements, and future directions to enhance the feasibility and adoption of HESS in modern EVs.**

Keywords*—*EV, HESS, Power, Energy.

I. INTRODUCTION

Electric vehicles (EVs) have gained significant attention in recent years as a sustainable alternative to conventional internal combustion engine (ICE) vehicles, driven by the need to reduce carbon emissions and reliance on fossil fuels. However, the performance and efficiency of EVs are largely dependent on their energy storage systems, which play a critical role in determining vehicle range, power output, and battery lifespan. Traditional battery technologies, such as lithium-ion (Li-ion) batteries, offer high energy density but suffer from limitations in terms of power delivery, charging time, and degradation over prolonged usage. These challenges have led to the exploration of Hybrid Energy Storage Systems (HESS), which integrate multiple energy storage components to balance energy and power demands effectively.

HESS typically consists of a combination of high-energy-density batteries and high-power-density storage devices, such as supercapacitors or flywheels. The synergy between these components enables efficient energy management, allowing batteries to handle sustained energy supply while supercapacitors provide rapid power bursts during acceleration and regenerative braking. This hybrid approach not only enhances vehicle performance but also extends battery life by reducing deep discharge cycles and high current loads. Moreover, HESS contributes to the overall efficiency of EVs by improving charge recovery during braking, reducing energy losses, and optimizing power flow based on driving conditions.

Several hybrid energy storage topologies have been proposed, each with unique benefits and trade-offs. The most common configurations include passive, semi-active, and fully active systems, each differing in the level of control and power-sharing strategies. Passive systems rely on natural power distribution between the storage components, while semi-active and fully active architectures use power converters to optimize energy flow dynamically. The selection of a suitable HESS configuration depends on factors such as vehicle requirements, cost constraints, and control system complexity.

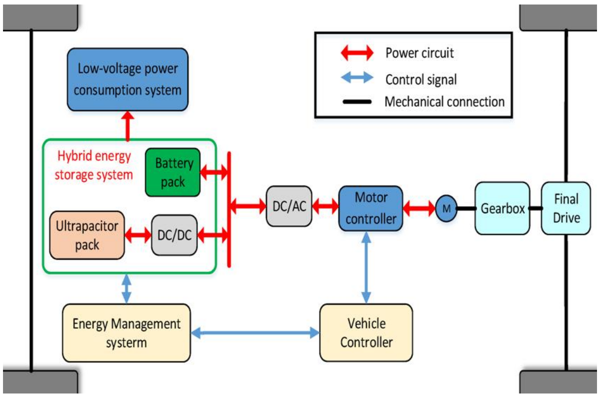

Figure 1: HESS

Despite its numerous advantages, the widespread adoption of HESS in EVs faces several challenges. These include increased system cost due to additional power electronics, the need for sophisticated energy management algorithms, and potential integration complexities. Advances in artificial intelligence and machine learning have facilitated the development of smart control strategies, enhancing the adaptability and efficiency of HESS in real-time applications. Additionally, research efforts continue to focus on improving component reliability, reducing weight, and minimizing costs to make HESS a viable solution for mass-market EV adoption.

This review aims to provide an in-depth analysis of the current state of hybrid energy storage systems for EV applications. It covers the key components, configurations, control strategies, and recent advancements in the field. Furthermore, the study discusses the challenges and potential future developments that can drive the large-scale implementation of HESS, contributing to the evolution of next-generation electric mobility.

II. LITERATURE SURVEY

Y. Zhao et al.,[1] investigates the problem of robust tracking control for a fully active hybrid energy storage system (HESS) in electric vehicles (EVs) consisting of battery and supercapacitor (SC) modules. A modified low-pass filter (MLPF)-based power split strategy is employed to divide the total power demand and generate the reference current for the battery while considering its power limit and the SC's state of charge (SoC). The SC handles the remaining power and compensates for unknown power losses caused by uncertainties such as modeling inaccuracy and perturbation of model parameters. Additionally, a multiple input-multiple output (MIMO) model-based robust controller design method is proposed to achieve the objectives of accurately tracking time-varying reference current, tightly maintaining the dc bus voltage constant, and automatically compensating for the power deficiency under the disturbance of the ever-changing load.

H. Maghfiroh et al.,[2] The global promotion of electric vehicle (EV) usage is a response to the challenges of energy crises and climate change. However, significant drawbacks remain, particularly related to the high costs and limitations of onboard energy storage. To mitigate these issues, the concept of Hybrid Energy Storage Systems (HESS), which integrate batteries with complementary energy storage solutions, has gained attention. This study focuses on the optimal sizing and energy management strategy of HESS, which are critical for enhancing the performance and viability of these systems in EVs. An Improved Low-Pass Filter (ILPF) is introduced to address limitations of conventional low-pass filters (LPF), including phase shift effects and state of charge limitations while optimizing the cut-off frequency and ensuring adaptability to varying driving conditions.

M. Al Takrouri et al.,[3] presents a comprehensive comparison of battery-only, passive, and semi-active hybrid energy storage system (HESS) topologies for electric vehicle (EV) applications. Despite numerous studies on HESS topologies for EVs, there remains a lack of consensus regarding the optimal topology, with limited attempts to address this gap through comprehensive comparisons. Previous research has focused on comparing different semi-active topologies through simulations, neglecting passive approaches and employing best-case scenarios for the energy management system (EMS), disregarding widely used rule-based power follower strategies. The present study aims to address the research gap by conducting a comprehensive comparison of battery-only, passive, and semi-active topologies for a realistic EV application case, focusing on their ability to enhance DC bus voltage stability, RMS battery current, and maximum battery current.

F. Noor et al.,[4] Conventional vehicles emit many pollutants and natural gases, such as carbon dioxide and nitrogen oxides, which reduce air quality and global warming. Due to their extensive consumption, another driving force behind the search for alternatives is the fast depletion of fossil fuels, oil, and natural gas. Consequently, Hybrid Electric Vehicles (HEVs) have recently been the subject of substantial research to tackle the dual problems of harmful emissions and resource depletion. This research attempts to develop a novel barrier function-based adaptive sliding mode controller (BFASMC) for a hybrid energy storage system (HESS) of electric Vehicle (EV). The HESS comprises a fuel cell (FC), battery, supercapacitor (SC), and photovoltaic (PV). The FC serves as a primary source, while the others are auxiliary sources. DC converters are employed to couple these sources to a DC bus. The proposed BFASMC stabilizes and regulates the DC bus voltage.

S. Mehdi Rakhtala et al.,[5] introduces an innovative fuzzy control system that employs teaching–learning-based optimisation (TLBO) in the energy management strategy domain of a HESS in EVs. This intelligent control mechanism aims to optimise various performance metrics – such as energy consumption, lithium battery output current, and peak power. The optimisation focuses on fine-tuning the parameters constituting the fuzzy rule base and membership functions. Simulation results substantiate the adaptability of the TLBO-based fuzzy energy management system in efficiently allocating power across various driving conditions. Comparative analyses are conducted with respect to the power-sharing capabilities of the proposed TLBO-fuzzy (TLBO-F), particle swarm optimisation-fuzzy (PSO-F), and non-optimisation-fuzzy (NO-F) strategies under two distinct driving conditions: the urban dynamometer driving schedule and the European extra-urban driving cycle.

H. Maghfiroh et al.,[6] explores the diverse applications of FLC as an EMS in both HEVs and HESS EVs, providing a comparative analysis with other EMS methods and delving into the advantages and challenges associated with each approach. A detailed examination of various FLC types employed as EMS has been conducted, drawing insights from a multitude of references. Each class of FLC EMS is scrutinized, presenting a broad overview of proposed methodologies within each category. By providing this comprehensive information, the article equips readers with foundational knowledge and insights for the continued development of FLC EMS in hybrid electric and hybrid energy storage system electric vehicles.

B. Wang et al.,[7] an integral sliding mode observer (ISMO) is designed for the disturbance term in ULM, and ULM generates the overall HESS current demand faster and more precisely than the conventional methods, which is then split into the transient and average components for driving the battery and supercapacitor (SC). Moreover, BVS generates extra current demand for SC during the transient process, realizing rapid recovery of bus voltage and decreasing the bus voltage spike. BVS will leave no degradation in steady-state performance with magnifying coefficients greater than one. Series simulations have been conducted to verify the dynamic performance and the effect of different curve functions on BVS. Consequently, a hardware-based experiment is conducted and the experimental results demonstrate the effectiveness of the proposed method with the 65%–69% faster dynamic performance and the 36%–41% lower voltage spike than the conventional PI methods.

X. Chen et al.,[8] presented a two-phase decision-making algorithm (TPDM), where the first phase uses a spatiotemporal cost-effectiveness aggregation method to determine the optimal SESS location; the second phase shapes a low-complexity solution space by arc destroying and repairing. The results show that HESS achieves significant arbitrage benefit improvement in 86.3% of the operating periods through a year compared with SESS and PESS alone. Compared with commercial solver, the proposed TPDM, on average, can reduce the computational time by 95.5% with an optimality of 1.04%. Note to Practitioners—Battery storage and electric vehicles (EVs) play a crucial role in renewable energy integration and in shaping a low-carbon and sustainable energy and transportation systems.

A. Mehraban et al.,[9] Exempting batteries from supplying power transients in electric vehicles (EVs) is beneficial to extend their useful lifespan. The adaptive capacity of high-power-density energy storage systems (HPESSs), such as ultracapacitors (UCs) or high-speed flywheel energy storage systems (FESSs), could fulfill the targets in this context. This article proposes a sizing/control methodology and real-time artificial intelligence (AI)-based control of the storage capacity (SC) for the adaptive capacity HPESSs, used in EVs. The sizing approach consists of an optimal energy management strategy and a sizing algorithm applied to a variable-step HPESS (VS-HPESS). This methodology derives the battery/VS-HPESS power split and sizes of SCs. In addition, a nonlinear autoregressive neural network with eXogenous inputs (NARX-NN) is trained offline to switch the desirable capacity of the VS-HPESS in real-time operation.

F. Jiang et al.,[10] a novel nonisolated bidirectional dc–dc converter (BDC) consisting of a quadratic voltage cell, a switched-capacitor (SC) cell, and a zero current ripple cell has been proposed for hybrid energy storage system (HESS) in electric vehicles (EVs). The converter presented combines the advantages of high voltage gain, wide voltage gain range, low voltage stress across power switches, zero current ripple, and common ground between both sides. Besides, synchronous rectification technology is applied to achieve higher efficiency of the converter. The comprehensive analysis of the operation principle, the characteristics analysis, and the efficiency analysis of the converter in a continuous conduction mode (CCM) are presented in detail.

B. Wang et al.,[11] The hybrid energy storage system (HESS) in solar-assisted electric vehicles (EVs) uses a novel bidirectional three-level cascaded (BTLC) converter, and this research proposes a deadbeat-based approach for operating the HESS. Additionally, photovoltaic (PV) panels are taken into account as part of the system, since the suggested approach is made for solar-assisted EV applications to get a greater range. To help solar-assisted EVs deal with power imbalances between their PV generators and their loads, the authors suggest a BTLC converter that can combine the two to form a hybrid energy storage system. When compared to traditional parallel-connected bidirectional battery/supercapacitor converters, the BTLC converter offers advantages in terms of both component size reduction and control flexibility. Deadbeat-based regulation is suggested for the BTLC converter to provide stable bus voltage and optimal battery and supercapacitor power management. The suggested deadbeat-based approach, including its design and execution, is critically examined.

H. Moradisizkoohi et al.,[12] When accelerating, a fuel cell (FC)-powered electric vehicle's double-input converter sends power from the battery and FC to an ultracapacitor (UC), and when braking, it sends power from the UC back to the battery. Given the unregulated nature of the battery and FC's low voltage, the converter must be capable of

International Journal of Recent Development in Engineering and Technology
Website: www.ijrdet.com (ISSN 2347 - 6435 (Online) Volume 14, Issue 2, February 2025)

producing a significant voltage gain while also converting power efficiently. This article proposes a buck-boost-half-bridge module-based double-input three-level converter for use in vehicles. Even without an FC or battery, the suggested converter can still power the load. For the sake of lowering voltage stress across switches and enhancing soft-switching performance, the converter makes use of an active clamp arrangement.

Q. Xu et al., [13] A revolutionary electromechanical energy converter, electrical variable transmission (EVT) finds use in hybrid electrical vehicles (HEV). The work investigates the EVT-based hybrid electric vehicle (EVT-HEV) and the efficiency optimization technique of the RBS. This firstly does an analysis of the EVT-dynamic HEV's coupling mode and develops an equation for the connection between the EVT and the engine's dynamic coupling. After then, there are four distinct types of braking, two of which are completely new. The next step is the proposal of a hierarchical controller, wherein a rule-based control approach is used for switching between braking modes and a neural network algorithm is utilised for optimum efficiency control of the system.

M. Asensio et al., [14] provides a comparison of two semi-active battery and ultracapacitor designs used in Hybrid Energy Storage Systems for electric cars. First, we provide an analysis of how to properly size the vehicle's battery and ultracapacitor bank to meet the vehicle's power needs. In addition, we present a strategy for choosing the frequency at which the power-dividing low-pass filter will shut out. All of the constituents in the system, including their associated losses, are modelled. A load power separation-based control approach is designed and a scaled NEDC driving cycle is simulated for both setups. Next, we do a loss and performance study to establish the optimal setup for this task.

A. Aldik et al. [15] This work presents a planning model for investors interested in supplying ancillary services (AS) to the energy market. The suggested model aids the investor in deciding between two alternatives: the use of an aggregated network of electric vehicle (EV) batteries or a stand-alone energy storage system (ESS). Planning for EV aggregations in AS markets requires careful consideration of the planned EV fleet size, which is a direct result of the energy pricing paid by the EV aggregator. The physical size of an ESS is the primary factor in its design. The suggested model compares and contrasts the long-term benefits of two investing strategies with the same starting capital.

III. CHALLENGES

Despite the significant advantages of Hybrid Energy Storage Systems (HESS) in improving the performance and efficiency of electric vehicles (EVs), several challenges hinder their widespread adoption and practical implementation. These challenges stem from technical, economic, and operational aspects, requiring further research and development to optimize HESS for real-world applications.

1. Increased System Complexity

One of the primary challenges in HESS integration is the complexity of the system architecture. Unlike conventional single-energy storage systems, HESS requires sophisticated coordination between different energy storage devices, such as batteries and supercapacitors. The integration of power converters, control algorithms, and energy management strategies adds to the overall complexity, making system design, implementation, and maintenance more challenging.

2. High Initial and Maintenance Costs

The inclusion of multiple storage devices and additional power electronic components significantly increases the cost of HESS compared to conventional battery-only systems. Advanced power converters, sensors, and energy management units contribute to higher upfront costs. Additionally, maintaining and replacing multiple energy storage components over time further adds to the total cost of ownership, which can be a barrier to large-scale adoption.

3. Control and Energy Management Optimization

Achieving an optimal balance between power and energy distribution in a hybrid system is a major challenge. Effective energy management strategies are required to ensure efficient power sharing between the battery and supercapacitor while minimizing losses. Developing real-time control algorithms that can adapt to varying driving conditions, state-of-charge levels, and power demands remains an area of active research.

4. Weight and Space Constraints

EVs are designed to be lightweight and compact to maximize energy efficiency and driving range. However, integrating multiple energy storage components, along with power converters and cooling systems, increases the overall weight and space requirements of the vehicle.

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Finding an optimal trade-off between storage capacity and weight remains a challenge in designing practical HESS configurations.

5. Power Converter Losses and Efficiency

The use of power converters to regulate energy flow between different storage elements introduces conversion losses, which can impact overall efficiency. High-frequency switching and power conditioning lead to heat dissipation, requiring additional cooling mechanisms that further increase energy consumption. Enhancing the efficiency of power converters and reducing energy losses remains a critical research area.

6. Thermal Management Issues

HESS components, particularly lithium-ion batteries and supercapacitors, generate heat during charging and discharging cycles. Effective thermal management is essential to prevent overheating, which can degrade performance, reduce lifespan, and pose safety risks. Developing efficient cooling techniques without adding excessive weight or power consumption is a significant challenge.

7. Compatibility and Standardization

Currently, there is no universal standard for HESS integration in EVs, leading to compatibility issues among different components, manufacturers, and vehicle architectures. The lack of standardization in battery-supercapacitor interfaces, control protocols, and communication systems makes it difficult to achieve seamless integration. Establishing industry-wide standards will be crucial for accelerating HESS adoption.

8. Durability and Lifecycle Management

Although HESS can extend the lifespan of individual storage components by reducing stress on batteries, long-term durability and performance degradation remain concerns. Batteries and supercapacitors have different aging characteristics, requiring adaptive lifecycle management techniques to ensure consistent performance. Developing predictive maintenance strategies and degradation models is necessary to improve the reliability of HESS in real-world applications.

IV. Strategy Plan

To overcome the challenges associated with Hybrid Energy Storage Systems (HESS) and ensure their efficient integration into electric vehicles (EVs), a well-defined strategy is essential. The following step strategy plan outlines key measures to optimize HESS performance, reduce costs, and enhance large-scale adoption.

1. Optimal System Design and Configuration

- Select the best combination of energy storage technologies (e.g., lithium-ion batteries and supercapacitors) based on energy and power requirements.
- Optimize system topology (passive, semi-active, or fully active) to balance cost, complexity, and efficiency.
- Develop lightweight, compact designs to minimize space constraints in EVs.

2. Advanced Energy Management Algorithms

- Implement real-time energy management strategies to optimize power distribution between batteries and supercapacitors.
- Utilize AI and machine learning-based algorithms for predictive energy control and adaptive decision-making.
- Develop intelligent power-sharing mechanisms to enhance battery life and efficiency.

3. High-Efficiency Power Converters

- Design next-generation power converters with minimal switching losses and improved thermal performance.
- Optimize power electronics for seamless energy transfer between different storage elements.
- Implement multi-stage converters to enhance voltage stability and efficiency.

Hybrid Energy Storage Systems can be optimized for high performance, cost-efficiency, and long-term sustainability in electric vehicles.

V. Conclusion

Hybrid Energy Storage Systems (HESS) offer a transformative solution for enhancing the performance, efficiency, and longevity of electric vehicles by combining the advantages of high-energy batteries and high-power supercapacitors. Despite challenges such as system complexity, cost, and control optimization, strategic advancements in system design, energy management, power electronics, and thermal regulation can drive widespread adoption.

Standardization, cost reduction, and predictive maintenance will further ensure sustainability and market feasibility. With continuous innovation and real-world implementation, HESS has the potential to revolutionize the EV industry, making electric mobility more efficient, reliable, and accessible for future generations.

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