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Review of Battery and Supercapacitor based Hybrid Energy Storage System for Electric Vehicle

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***Abstract*— The growing demand for sustainable transportation has accelerated the development of electric vehicles (EVs), necessitating advancements in energy storage solutions. Among various energy storage technologies, hybrid energy storage systems (HESS) integrating batteries and supercapacitors have gained significant attention due to their complementary characteristics. Batteries provide high energy density, ensuring long-range operation, while supercapacitors offer high power density, enabling rapid energy bursts during acceleration and regenerative braking. This review presents a comprehensive analysis of battery-supercapacitor hybrid energy storage systems (BS-HESS) for EVs, covering their architecture, energy management strategies, control methodologies, and recent technological advancements. The study also discusses key challenges such as cost, system complexity, and energy management optimization. Furthermore, an overview of emerging trends and future research directions in BS-HESS technology is provided, highlighting its potential to enhance the performance, efficiency, and lifespan of EVs.**

Keywords*— Energy Management, Converter, Electric Vehicle, Supercapcitor, Battery, Hybrid. Solar.

I. INTRODUCTION

The transition from conventional internal combustion engine vehicles to electric vehicles (EVs) has been a focal point in the pursuit of sustainable and environmentally friendly transportation. The increasing concerns over climate change, depleting fossil fuel reserves, and stringent emission regulations have driven significant research and development in EV technology. However, one of the most critical challenges in EV adoption is the efficiency and reliability of energy storage systems. Traditional lithium-ion batteries, while widely used, face several limitations, including long charging times, limited cycle life, and poor power handling during peak loads. To address these challenges, hybrid energy storage systems (HESS) that integrate batteries with supercapacitors have emerged as a promising solution.

HESS combines the high energy density of batteries with the high power density and fast charge-discharge capabilities of supercapacitors. This complementary approach enhances the overall performance of EVs by improving acceleration, regenerative braking efficiency, and extending battery lifespan. Batteries are well-suited for long-term energy storage, but they suffer from slow transient response and high internal resistance, which can lead to energy losses and thermal issues. On the other hand, supercapacitors can quickly absorb and release energy, making them ideal for handling high-power demands and smoothing out power fluctuations during dynamic driving conditions.

The architecture of battery-supercapacitor hybrid systems can vary depending on the specific requirements of an EV. The two primary configurations include passive and active hybrid systems. Passive systems rely on the natural distribution of current between the battery and supercapacitor, while active systems use power electronic converters and control algorithms to optimize energy flow. The selection of the appropriate configuration significantly influences the performance, efficiency, and cost-effectiveness of the HESS.

Energy management strategies play a vital role in ensuring the optimal utilization of the hybrid energy storage system. Various strategies, such as rule-based, optimization-based, and artificial intelligence-driven approaches, have been proposed to enhance the power distribution between the battery and supercapacitor. These strategies aim to minimize energy losses, improve battery longevity, and maximize energy

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recuperation from regenerative braking. Advanced control methodologies, including fuzzy logic, neural networks, and model predictive control, have been extensively explored to achieve real-time optimization and adaptive energy management in EV applications.

Despite the numerous advantages of HESS, several challenges hinder its widespread implementation. The integration of two different energy storage technologies introduces system complexity, requiring sophisticated power electronics and control systems. The cost of additional components, such as bidirectional converters and intelligent controllers, increases the overall expense of the system. Furthermore, achieving an optimal balance between battery and supercapacitor utilization remains a crucial research area, as improper management can lead to suboptimal performance and increased wear on the energy storage components.

Recent advancements in material science, power electronics, and artificial intelligence have contributed to significant improvements in BS-HESS technology. The development of high-performance supercapacitors with enhanced energy density, coupled with the continuous evolution of battery chemistries, has paved the way for more efficient and reliable hybrid storage solutions. Furthermore, the integration of machine learning and real-time data analytics in energy management systems is expected to further enhance the adaptability and efficiency of HESS in future EVs.

This review aims to provide a comprehensive overview of battery-supercapacitor hybrid energy storage systems for electric vehicles, highlighting their advantages, architectures, energy management strategies, control methodologies, and recent technological advancements. Additionally, the paper discusses key challenges and future research directions to facilitate the widespread adoption of HESS in next-generation electric mobility. By addressing these aspects, this study contributes to the ongoing efforts in developing efficient, cost-effective, and sustainable energy storage solutions for EVs.

II. LITERATURE SURVEY

X. Tan et al., [1] presented the hybrid electric car energy storage system, a voltage equalization that is based on a voltage multiplier was proposed. The battery equalization structure and the supercapacitor charging equalizer are both included into a single circuit that consists of just two switches, three inductors, a number of energy storage capacitors, and diodes. The size of the system as well as its cost are both significantly reduced as a result of this integration. A self-modularization feature is included in the battery equalization design, which permits quicker voltage equalization. Additionally, the supercapacitor charger has a characteristic of constant current charging. The essential operating principles of the equalizer that is being suggested are discussed in depth, and a DC equivalent circuit is created for the purpose of examining the behaviors of equalization and charging.

T. Mesbahi et al.,[2] presents the high level electrothermal displaying of a hybrid energy stockpiling framework incorporating lithium-particle batteries and supercapacitors. The goal is to permit the maturing parts of the parts of this framework to be considered. The improvement of a model including the electrothermal ways of behaving makes it conceivable to assess the dynamic corruption of the exhibition of the hybrid energy stockpiling framework. The portrayal of the two parts comprising the hybrid framework is completed by means of a hybrid molecule swarm-Nelder-Mead (PSO-NM) improvement calculation utilizing the trial information of a metropolitan electric vehicle. The acquired outcomes show the great presentation of the created model and affirm the plausibility of our methodology.

M. A. Islam et al.,[3] fosters a versatile neuro-fluffy deduction framework (ANFIS) control methodology based bidirectional power management plan to guarantee the ideal electrical power stream trade between the air conditioner electrical lattice and battery stockpiling framework in PEVs. This paper intends to lessen the weight on the network power side and use the unused power appropriately. The exhibition of the ANFIS model is shifted utilizing two PEVs in view of genuine power utilizations by various burdens at locally situated on five functional modes. Furthermore, a near investigation between the ANFIS regulator and the PI regulator is completed to exhibit the viability of the proposed control by PEV battery.

X. Zan et al.,[4] To work on the perseverance and charging adaptability of electric vehicle battery packs, this paper proposes a multi-battery block module (MBM) geography for four-stage exchanged hesitance engines (SRMs), which permits adaptable electric vehicle activity, yet in addition accomplishes quick demagnetization and excitation. By coordinating the multi-battery block module and photovoltaic (PV) board into a lopsided half-span (AHB) converter, the MBM geography is intended to supply a staggered transport voltage for the SRM drive. To work on the perseverance of battery packs, a PV board is likewise added to the geography to charge battery packs when the framework is fixed. As per the different activity prerequisites, numerous power supply modes and charging modes can be acknowledged by controlling the power gadgets in the proposed MBM geography. The recreation results in view of the MATLAB/Simulink stage and the trial results on a four-stage 8/6 exchanged hesitance engine confirm the viability of the proposed plan.

A. Avila et al.,[5] present trial results got with a high unambiguous energy and power capacity HESS model, made out of I) a Lithium-Titanate-Oxide battery to guarantee high power capacities, ii) a Li-S battery to work on unambiguous energy, and iii) a power converter in view of Gallium Nitride (GaN) gadgets to connect both battery modules, limiting simultaneously framework weight, volume and power misfortunes. The created GaN-based power converter accomplishes high productivity (96.5%) working at 300 kHz with a decreased size (0.4 L). In addition, the way of behaving of the created HESS model is tentatively assessed under standard auto profiles, for various driving situations.

T. Sadeq et al.,[6] The HESS model, electric vehicle and regulators were tried utilizing MATLAB/Simulink with three genuine drive cycles, specifically, tough, downhill and city visit, in three unique velocities 50Km/h, 60Km/h and 70 Km/h. The outcomes demonstrated the regulators figured out how to expand battery duration cycle by lessening the weight on the battery for the drive cycles. The outcomes were analyzed as far as energy utilization for the ideal versatile rule-based regulator and fluffy versatile rule-based regulator. The ideal versatile rule-based regulator ensured the HESS had the option to work ceaselessly and expand the quantity of drive cycles in a wide scope of paces and street slants.

Y. Fan et al.,[7] presents the regular high-recurrence converter structure as the item, lays out an identical model of the circuit, and quantitatively investigates the circle inductance according to a numerical perspective. For the circuit after the lined up of retention capacitor, the little sign model is utilized to investigate and uncover the job and impact of the ingestion capacitor. At last, the estimation consequences of the model are looked at through a twofold heartbeat explore. The outcomes show that the mistake between the model and the trial results is around 1%, and the impact of assessing the wanderer boundaries of the converter circuit is great, and it can offer a hypothetical help for the choice and plan of the ingestion capacitor.

D. Qin et al.,[8] The proposed versatile bidirectional hang control is intended for opportunity EVs to make them independently accuse or release of specific power which as per every EV's condition of charge, battery limit, leaving time, and different elements to keep up with the steadiness representing things to come microgrid. In the long run, the reenactment and examination of the versatile bidirectional hang control based V2G-PVBP is given to demonstrate the accessibility of V2G-PVBP.

C. Zhai et al.,[9] proposes a prescient EMS (PEMS) for the battery/supercapacitor HESSs. In the first place, the example arrangement-based speed indicator is introduced to precisely anticipate the future transient speed profile. Second, the PEMS is proposed by forming a HESS power split streamlining issue, where the HESS energy misfortune, and the battery limit misfortune are thought of. Third, a better turbulent molecule swarm enhancement calculation is introduced to take care of the planned improvement issue. Recreation results exhibit that, contrasted and the benchmark, the proposed PEMS can actually lessen the HESS energy misfortune, and expand the battery lifetime simultaneously.

M. Boycott et al.,[10] Nanogrids are supposed to assume a huge part in dealing with the steadily expanding circulated sustainable power sources. If an off-matrix nanogrid can supply completely energized batteries to a battery trading station (BSS) serving local electric vehicles (EVs), it will assist with laying out a construction for executing sustainable power to-vehicle frameworks. A scope organization issue is

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planned to decide the ideal measuring of photovoltaic (PV) age and battery-based energy capacity framework (BESS) in such a nanogrid. The issue is formed in view of the blended whole number straight programming (MILP) and afterward tackled by a strong improvement approach. Adaptable vulnerability sets are utilized to change the conservativeness of the hearty advancement, and Monte Carlo reenactments are done to analyze the presentation of the arrangements. Contextual investigations exhibit the benefits of the proposed applications and confirm our methodology.

III. CHALLENGES

Despite the numerous advantages of HESS, several challenges hinder its widespread implementation:

1. **System Complexity**: The integration of two different energy storage technologies requires sophisticated power electronics, control algorithms, and energy management systems, increasing design and operational complexity.
2. **Cost**: The additional components, such as bidirectional converters and intelligent controllers, increase the overall cost of the system, making it less economically viable for mass-market EVs.
3. **Energy Management Optimization**: Achieving an optimal balance between battery and supercapacitor utilization remains a crucial research area, as improper management can lead to suboptimal performance and increased wear on the energy storage components.
4. **Durability and Longevity**: The different aging characteristics of batteries and supercapacitors necessitate advanced control strategies to ensure uniform degradation and extended operational lifespan.
5. **Thermal Management**: The simultaneous operation of batteries and supercapacitors generates additional thermal stresses, requiring efficient cooling mechanisms to prevent overheating and ensure system reliability.
6. **Scalability**: The applicability of BS-HESS to different types of EVs, from passenger cars to heavy-duty electric trucks, poses challenges in designing scalable and adaptable systems.
7. **Standardization and Compatibility**: The lack of standardized architectures, interfaces, and communication protocols can create integration challenges between different manufacturers and energy storage technologies.

Recent advancements in material science, power electronics, and artificial intelligence have contributed to significant improvements in BS-HESS technology. The development of high-performance supercapacitors with enhanced energy density, coupled with the continuous evolution of battery chemistries, has paved the way for more efficient and reliable hybrid storage solutions. Furthermore, the integration of machine learning and real-time data analytics in energy management systems is expected to further enhance the adaptability and efficiency of HESS in future EVs.

IV. CONCLUSION

This review aims to provide a comprehensive overview of battery-supercapacitor hybrid energy storage systems for electric vehicles, highlighting their advantages, architectures, energy management strategies, control methodologies, and recent technological advancements. Additionally, the paper discusses key challenges and future research directions to facilitate the widespread adoption of HESS in next-generation electric mobility. By addressing these aspects, this study contributes to the ongoing efforts in developing efficient, cost-effective, and sustainable energy storage solutions for EVs.

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