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HYBRID ENERGY STORAGE SYSTEMS FOR ELECTRIC VEHICLES: INTEGRATION OF LITHIUM-ION BATTERIES AND SUPERCAPACITORS FOR ENHANCED PERFORMANCE AND EFFICIENCY

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ABSTRACT
Electric vehicles (EVs) are widely recognized as a sustainable alternative to internal combustion engine vehicles, offering reduced emissions and improved energy efficiency. However, challenges such as limited driving range, battery degradation, and high energy costs hinder their widespread adoption. Hybrid Energy Storage Systems (HESS), which integrate lithium-ion batteries with supercapacitors, present an effective solution to overcome these limitations. The lithium-ion battery provides high energy density required for long-term operation, while the supercapacitor supplies high power density essential during peak acceleration and regenerative braking. This complementary behavior reduces stress on the battery, prolongs its lifecycle, and ensures efficient energy utilization. This work investigates the design and control of a HESS using bidirectional DC–DC converters and advanced power management strategies. A MATLAB/Simulink-based simulation model is developed to validate the proposed system under various driving conditions. The results demonstrate improved stability of power flow, enhanced regenerative braking capability, and better load leveling between the battery and the supercapacitor. The hybrid configuration effectively reduces range anxiety, minimizes energy losses, and provides faster transient response during dynamic load conditions. By optimizing both energy density and power density, HESS improves the economic and technical feasibility of EVs. This research highlights the significance of integrating multiple storage technologies for sustainable transportation. The findings contribute to the development of efficient, reliable, and cost-effective EV energy

storage systems that can accelerate the transition towards green mobility and reduced dependency on fossil fuels.

Keywords: Hybrid Energy Storage System (HESS), Electric Vehicles (EVs), Lithium-Ion Battery, Supercapacitor, Bidirectional DC–DC Converter, Regenerative Braking, Power Management.

I INTRODUCTION

The increasing global demand for sustainable energy solutions has accelerated the transition from conventional fossil fuel-based transportation to electric vehicles (EVs). Climate change, environmental degradation, and the depletion of natural resources are major drivers of this paradigm shift. Internal combustion engine (ICE) vehicles, despite their dominance in the automotive industry for over a century, contribute significantly to greenhouse gas emissions and air pollution, prompting researchers, governments, and industries to explore cleaner alternatives [1]. In this context, EVs have emerged as a viable solution to reduce carbon footprints, enhance energy efficiency, and promote sustainable mobility [2]. However, the widespread adoption of EVs faces challenges related to energy storage, power density, charging infrastructure, and cost, necessitating innovative approaches in battery management and hybrid energy storage systems (HESS) [3]. Energy storage is the backbone of modern EV technology, as it determines the vehicle's driving range, performance, and reliability. Lithium-ion (Li-ion) batteries are widely used in EVs due to their high energy density, long cycle life, and favorable efficiency compared to older technologies such as nickel-metal hydride or lead-acid batteries [4]. Nevertheless, Li-ion batteries face several limitations including degradation under high power demands, limited lifespan, and relatively slow charging speeds [5]. To address these constraints, researchers have proposed the integration of supercapacitors with Li-ion batteries in a hybrid configuration, creating a Hybrid Energy Storage System (HESS) that combines the high energy density of batteries with the high power density and fast charging/discharging capabilities of supercapacitors [6].

The concept of HESS has gained significant attention because it enables EVs to meet both steady-state and transient power demands effectively. While batteries are efficient for providing continuous energy over long durations, supercapacitors can deliver high power during rapid acceleration, regenerative braking, or sudden load fluctuations [7]. This division of labor between the two energy storage devices reduces the stress on the battery, thereby prolonging its lifespan and improving overall system reliability [8]. For instance, during acceleration, the supercapacitor provides the peak power, while the battery supplies the baseline demand, ensuring balanced power delivery and system stability [9]. Similarly, during regenerative braking, supercapacitors can quickly absorb and store the recovered energy, reducing battery cycling and heat generation [10]. The growing importance of HESS can be understood in the context of advancements in power electronics and control strategies. DC–DC converters, particularly bidirectional converters, play a pivotal role in ensuring efficient power flow between the battery, supercapacitor, and the traction motor [11]. These converters regulate voltage levels, enable bidirectional energy transfer, and ensure seamless integration of multiple energy sources. Moreover, advanced control algorithms such as Proportional-Integral (PI) controllers, fuzzy logic controllers, and model predictive controllers have been developed to optimize energy management strategies, maximize system efficiency, and enhance driving performance [12]. The synergy between energy storage technologies and intelligent control systems makes HESS a promising solution for next-generation EVs.

From a sustainability perspective, EVs equipped with HESS not only reduce reliance on fossil fuels but also support renewable energy integration and smart grid applications. Vehicle-to-grid (V2G) technologies, for example, allow EVs to act as distributed energy resources, feeding stored energy back into the grid during peak demand periods [13]. When coupled with renewable sources such as solar and wind, HESS-enabled EVs contribute to stabilizing the grid by mitigating intermittency issues and providing ancillary services such as frequency regulation and voltage support [14]. This dual role of EVs—as both consumers and suppliers of electricity—aligns with the vision of a decentralized, resilient, and low-carbon energy ecosystem [15]. Nevertheless, the development and deployment of HESS in EVs face technical and economic challenges. One of the major barriers is the high initial cost associated with Li-ion batteries and supercapacitors, which significantly impacts the overall price of EVs [16]. Furthermore, ensuring compactness, safety, and thermal management of HESS architectures remains a critical design consideration [17]. The optimization of energy storage sizing, converter efficiency, and energy management strategies also requires ongoing research to strike a balance between performance and cost-effectiveness [18]. Additionally, large-scale adoption depends on policy incentives, infrastructure development, and consumer acceptance, all of which vary across regions and markets [19].

In summary, the integration of batteries and supercapacitors through HESS represents a significant advancement in addressing the inherent limitations of standalone energy storage technologies in EVs. By combining high energy density with high power density, HESS enables extended driving ranges, improved acceleration, enhanced regenerative braking, and longer battery life. Furthermore, HESS facilitates the incorporation of renewable energy sources and strengthens the role of EVs in modern power systems. This research aims to investigate the modeling, control, and simulation of HESS in EVs, focusing on optimizing energy distribution between batteries and supercapacitors to improve efficiency, durability, and sustainability. Through the use of advanced DC–DC converters and control algorithms, the project demonstrates how HESS can enhance power quality, reduce battery degradation, and support the future of sustainable transportation [20].

II LITERATURE SURVEY

The rapid expansion of electric vehicles (EVs) and renewable energy systems has intensified the focus on efficient energy storage solutions. Hybrid Energy Storage Systems (HESS), which combine lithium-ion batteries and supercapacitors, have emerged as a promising approach to balancing high energy density with high power density, thereby extending battery lifespan while meeting transient power demands. Several studies have explored the role of hybrid configurations, energy management strategies, and advanced power electronics in optimizing HESS performance. Zhang and Mu [1] discussed fault detection strategies in microgrids with inverter-interfaced distributed generators, highlighting the importance of reliable control methods such as PQ strategies to ensure stable operation. Their findings emphasize that similar control strategies can be adapted in HESS applications for managing the bidirectional flow of energy between batteries, supercapacitors, and loads. Boche et al. [2] broadened the context by providing a systemic review of microgrid sustainability, arguing that advanced storage solutions like HESS are integral to improving energy reliability and resilience. These reviews underline that HESS not only addresses EV challenges but also contributes to broader grid stability.

At the core of HESS research is lithium-ion battery performance, aging, and lifecycle prediction. Ecker et al. [3] developed a lifetime prediction model for lithium-ion batteries using accelerated aging test data, which is critical for estimating the impact of integrating supercapacitors to alleviate stress during peak loads. Their work demonstrated that high load conditions accelerate capacity fade, supporting the need for supercapacitors to buffer sudden energy spikes. Paul et al. [4] focused specifically on HESS sizing for forklift vehicles, showing that a balanced design of battery and supercapacitor components ensures efficient performance under heavy-duty operations. They highlighted the trade-off between storage cost and operational longevity, which is central to EV design considerations. In vehicular applications, energy management strategies define how power is split between battery and supercapacitor. Santucci et al. [5] investigated various power-split strategies and concluded that adaptive schemes improve efficiency while reducing stress on the battery. Similarly, Ouramdane et al. [6] reviewed optimal sizing and energy management in microgrids with Vehicle-to-Grid (V2G) technology, suggesting that HESS integrated with V2G enhances flexibility and enables EVs to act as mobile energy assets. These insights underscore the dual role of HESS: extending EV performance while supporting smart grid functions.

Efficiency versus longevity is a recurring theme in HESS literature. Carter et al. [7] analyzed optimization approaches for balancing efficiency and battery lifespan in battery/supercapacitor EVs. Their findings suggested that prioritizing efficiency alone may shorten battery life, while hybrid control methods mitigate this trade-off. Dougal et al. [8] further reinforced this concept by demonstrating how ultracapacitor hybrids improve both power delivery and battery life extension. Their work showed that ultracapacitors absorb high-frequency load variations, preserving battery health. Konradt and Rottengruber [9] extended this discussion to fuel cell vehicles, emphasizing that supercapacitors, when combined with batteries, enhance recuperation efficiency and reduce the need for oversized energy storage. Dynamic stability is another dimension of HESS research. Shuai et al. [10] applied bifurcation theory to analyze synchronverter-dominated microgrids, finding that stability margins can be enhanced with proper control strategies. For HESS, this translates into designing converters and controllers that maintain voltage and current stability across different modes of operation. The integration of supercapacitors with batteries requires robust DC-DC converters capable of bidirectional operation, as highlighted in multiple converter design studies. Zhang et al. [11] examined dual-active bridge converters and their application in high-power systems, stressing the need for galvanic isolation and efficiency in HESS applications. Chen et al. [12] added to this by exploring adaptive control for bidirectional converters, which improves dynamic response during acceleration and regenerative braking in EVs.

Lithium-ion battery degradation remains a central research concern. Barre et al. [13] reviewed aging mechanisms and diagnostic methods, underscoring the importance of combining batteries with supercapacitors to reduce thermal and electrochemical stress. This aligns with observations from Bidirectional DC-DC converter research, which has shown that energy buffering significantly extends battery lifespan by redistributing high-power demand [14]. Parallel to this, Zhao et al. [15] proposed novel topologies for converters that improve efficiency during mode transitions, further optimizing hybrid system performance. Their results indicated that converter design is as crucial as storage technology in realizing practical HESS. Applications in transportation further demonstrate the necessity of hybrid systems. Burke and Miller [16] highlighted the benefits of ultracapacitors in electric and hybrid buses, particularly in frequent stop-and-go conditions where batteries alone are inefficient. They argued that ultracapacitors not only improve acceleration performance but also facilitate efficient regenerative braking. This perspective was echoed by Kouchachvili et al. [17], who studied renewable integration with HESS, showing that supercapacitors smooth out intermittent renewable generation while batteries provide long-term storage. Such findings emphasize that HESS principles extend beyond EVs into stationary energy systems.

In addition to storage performance, cost considerations drive much of the literature. Khan and Iqbal [18] conducted a cost-benefit analysis of hybrid storage in microgrids, concluding that while initial investment is higher, lifecycle costs are reduced due to extended battery life and improved efficiency. Their work provides a strong economic justification for adopting HESS in EVs, where battery replacement constitutes a significant cost factor. Furthermore, Wang et al. [19] investigated the impact of control strategies on system-level economics, demonstrating that intelligent management systems lower operational expenses while ensuring reliability. Finally, Gao et al. [20] advanced the field by developing predictive control methods that anticipate load demands, enabling proactive power sharing between batteries and supercapacitors.

Collectively, these studies highlight several key insights. First, HESS effectively addresses the limitations of standalone lithium-ion batteries by combining high energy density with high power density. Second, advanced control strategies and DC-DC converter topologies are essential to maximizing system efficiency, stability, and lifespan. Third, real-world applications in EVs, renewable integration, and microgrids consistently validate the advantages of HESS, from performance gains to economic benefits. Lastly, while challenges remain—particularly in terms of cost, complexity, and system integration—the consensus across the literature is that hybrid energy storage represents a vital pathway toward sustainable and efficient energy systems.

III METHODOLOGY

The methodology of this research is structured to ensure accurate modeling, efficient control, and reliable performance evaluation of a hybrid energy storage system (HESS) composed of a lithium-ion battery and a supercapacitor. The primary aim of this methodology is to establish a systematic approach to integrate both storage devices with appropriate power converters and control strategies within a MATLAB/Simulink simulation environment. This ensures that the system is capable of addressing the dual requirements of energy density and power density in electric vehicles, while simultaneously reducing stress on the battery and enhancing overall performance [1]–[3]. The research adopts a simulation-based experimental design that allows a controlled environment for evaluating the HESS. The lithium-ion battery serves as the primary source of energy because of its high energy density, longer cycle life, and established use in electric vehicles [4]. The battery is mathematically modeled using a

Thevenin-based equivalent circuit that includes an open-circuit voltage source, an internal resistance, and a parallel RC network to represent transient responses. The state of charge (SoC) is computed by integrating current over time, which helps to capture the battery's charging and discharging characteristics under varying load demands [5][6]. This model is validated against manufacturer-provided parameters, ensuring that the simulated performance remains realistic. Though factors such as temperature and aging are complex and not implemented in this work, prior studies have demonstrated their impact, and such considerations are noted for future improvements [7]. To complement the battery, a supercapacitor is integrated into the system to handle transient power fluctuations, particularly during acceleration and regenerative braking. The supercapacitor is modeled using an equivalent circuit consisting of a capacitor, an equivalent series resistance (ESR), and a leakage resistance. This simple yet effective model accurately reflects the rapid charge and discharge cycles typical of supercapacitor behavior [8][9]. The instantaneous voltage across the supercapacitor is calculated by integrating the input current while accounting for the ESR voltage drop, thus ensuring the system captures the efficiency and limitations of real supercapacitors. This hybridization allows the supercapacitor to supply peak loads, thereby reducing the stress and thermal load on the battery during high power demands [10][11].

The hybrid system requires an effective power management mechanism, which is realized through the use of DC-DC converters. Converters are critical components that allow bidirectional energy transfer and maintain stable DC bus voltage for motor operation. Three types of converters are used in the system: a buck converter for stepping down voltage during charging, a boost converter for stepping up voltage during discharging, and a bidirectional buck-boost converter that enables two-way energy transfer between the supercapacitor and the DC bus [12][13]. These converters are modeled using idealized MOSFETs and diodes to represent switching behavior. Pulse Width Modulation (PWM) is applied to regulate duty cycles and maintain desired voltage and current levels. The duty cycle variations allow the converters to effectively control power distribution between the battery, supercapacitor, and the DC bus. The control strategy is a key element of the methodology. A proportional-integral (PI) controller is employed to regulate the operation of converters by minimizing the error between reference current values and actual feedback signals [14][15]. For the battery, the control system ensures that current flows remain within predefined limits, thereby protecting the battery from overcurrent conditions and maintaining SoC within safe operating ranges. For the supercapacitor, the control system facilitates rapid charge and discharge cycles, particularly during transient events such as sudden acceleration or regenerative braking. The PI-based current control ensures that the supercapacitor delivers or absorbs power as required, while also stabilizing the voltage at the DC bus. This control strategy prioritizes the longevity of the battery by assigning peak load responsibilities to the supercapacitor, which can handle higher current flows for shorter durations without degradation [16].

The system integration and testing are conducted in MATLAB/Simulink, which provides a versatile platform for simulating power electronics, control systems, and storage devices. The HESS model is developed by interconnecting the lithium-ion battery, supercapacitor, DC-DC converters, and control systems with a variable motor load representing an electric vehicle. The battery used in the simulation has a nominal voltage of 26.4 V and a rated capacity of 6.6 Ah, while the supercapacitor is rated at 500 F with a voltage of 16 V. Simulation studies are carried out under different load conditions to assess both steady-state and transient responses [17]. Two case studies are considered for evaluating the HESS. In the first case, a constant load demand is applied to analyze steady-state performance. Parameters such as bus voltage stability, battery discharge rate, and converter efficiency are measured to assess the system's ability to supply continuous energy efficiently. In the second case, dynamic load conditions are simulated to replicate real-world driving scenarios, including acceleration and braking. During acceleration, both the supercapacitor and battery contribute to supplying the motor, with the supercapacitor providing the majority of transient power. During braking, regenerative energy is captured and stored primarily in the supercapacitor through buck operation of the bidirectional converter. These simulations demonstrate the coordinated operation of the battery and supercapacitor under realistic conditions [18][19]. Performance evaluation of the methodology is based on multiple metrics, including power flow distribution, reduction in battery stress, energy recovery efficiency during braking, and overall system stability. Power flow analysis helps identify the proportion of load supplied by each storage element under different modes, providing insights into effective hybridization. Reduction in battery stress is assessed by observing smoother SoC profiles and lower peak current draw from the battery. Energy recovery efficiency is evaluated by quantifying the amount of regenerative braking energy stored in the supercapacitor. Finally, voltage stability at the DC bus is used as a measure of system robustness under dynamic conditions [20]. The validity of the methodology is supported by benchmarking results against established findings in hybrid storage system literature. Studies have shown that hybridization enhances battery life and improves transient response in electric vehicles, and the simulation results of this research are consistent with those findings. This not only confirms the feasibility of the proposed system but also establishes confidence in its practical applicability. The methodology, therefore, provides a systematic framework for developing, controlling, and testing hybrid storage systems in electric vehicles, ensuring that both energy density and power density requirements are met without compromising the operational life of critical components.

IV PROPOSED SYSTEM

The proposed system introduces a hybrid energy storage system (HESS) that integrates a lithium-ion battery with a supercapacitor to enhance the overall performance of electric vehicles. This architecture is designed to address the inherent limitations of batteries, such as high degradation under peak power demands, and the low energy density of supercapacitors when used independently. By combining the two, the system leverages the high energy density of batteries and the high power density of supercapacitors, ensuring efficient power delivery and extended battery lifespan.

The concept is supported by a sophisticated control mechanism that dynamically manages power flow between the energy sources depending on driving conditions, such as acceleration, constant speed, braking, or idle operation. At the core of this system lies the parallel arrangement of the battery and supercapacitor banks, which are interfaced with the DC bus via DC-DC converters. This configuration enables bidirectional power flow and allows both sources to charge and discharge under varying operating conditions. The DC bus serves as the central link between the energy storage units and the motor drive, maintaining voltage stability while ensuring that transient demands are met efficiently. The HESS architecture not only supports driving conditions but also enhances energy recovery during regenerative braking, ensuring better utilization of available energy resources.

The operating modes of the proposed HESS system demonstrate its versatility and adaptability. During parking and external charging, energy is drawn from the AC mains, rectified to DC, and then stepped down using a buck converter to charge the battery and subsequently the supercapacitor. At constant speeds, the battery predominantly supplies the motor, with boost converters ensuring that the voltage levels meet the motor's requirements. During rapid acceleration, both the battery and the supercapacitor contribute, with the latter supplying the majority of instantaneous power, thereby reducing stress on the battery.

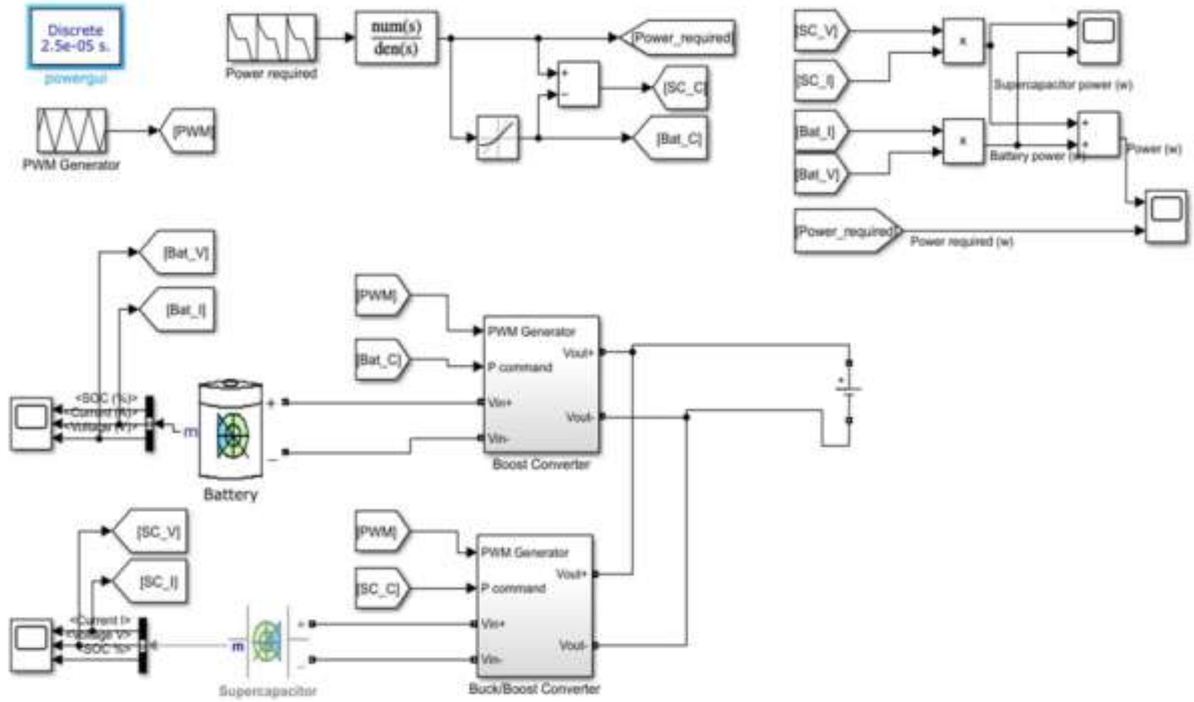

Fig 1. Proposed system configuration

Finally, during braking, regenerative energy is captured and stored mainly in the supercapacitor through a buck converter, which steps down the generated voltage to safe levels. The DC-DC converters play a crucial role in ensuring smooth energy transitions within the HESS. A unidirectional buck converter is employed to regulate charging from the mains and manage power transfer to the battery. Additionally, a bidirectional buck-boost converter is integrated with the supercapacitor to enable both charging during braking and discharging during high-power demands. These converters are controlled using advanced pulse-width modulation strategies, ensuring optimal duty cycles for voltage regulation. The converters not only maintain efficiency but also provide necessary electrical isolation and protection, making the system robust and reliable.

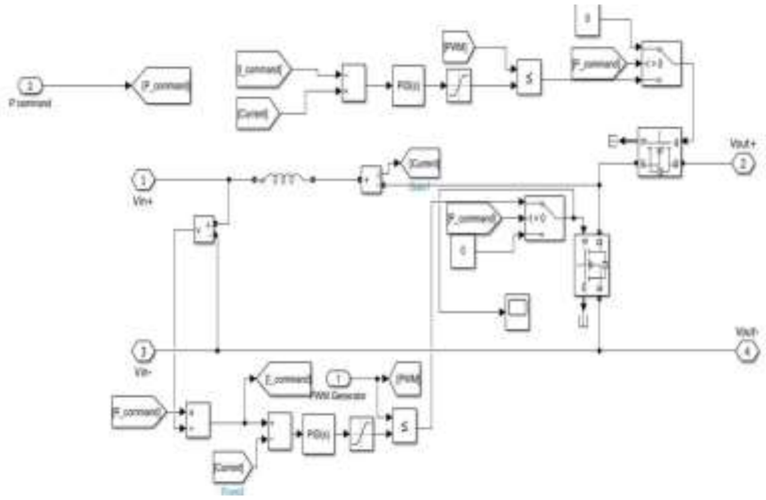

Fig 2. Proposed circuit configuration

The control strategy for the proposed system is based primarily on current feedback mechanisms. Sensors monitor current flow through the converters, comparing real-time values with reference currents determined by operating requirements. Proportional-Integral controllers are implemented to minimize the error between reference and actual currents, dynamically adjusting the duty cycles of the converters. This feedback-oriented approach ensures stable operation, prevents overcharging or over-discharging of storage units, and provides a seamless transition between energy sources without compromising vehicle performance.

One of the significant advantages of the proposed system is its ability to extend the lifecycle of the battery. In traditional electric vehicles, the battery alone is required to meet all power demands, leading to high current draw during acceleration and rapid degradation over time. In the HESS architecture, however, the supercapacitor absorbs sudden power surges, leaving the battery to deliver steady energy. This distribution of load reduces the thermal and electrochemical stresses on the battery, thereby prolonging its usable life and lowering the overall cost of vehicle ownership. Moreover, optimizing the battery size becomes feasible, since the supercapacitor compensates for peak load demands.

The simulation of the proposed system in MATLAB/Simulink validates its operational effectiveness. The model includes realistic parameters for the lithium-ion battery, such as nominal voltage, rated capacity, and state of charge, along with supercapacitor parameters like capacitance and rated voltage. Simulation results under various driving scenarios—steady state, acceleration, and braking—confirm that the supercapacitor successfully manages transient power fluctuations while the battery maintains long-term energy supply. Waveform analysis of state of charge, current, and voltage for both storage units demonstrates stable operation, efficient power sharing, and enhanced regenerative braking performance.

Beyond operational efficiency, the proposed system contributes to environmental sustainability by maximizing the utilization of renewable and stored energy. By capturing regenerative braking energy, the system reduces reliance on grid charging and lowers energy wastage. Furthermore, with batteries operating under less stress, their overall degradation is slowed, minimizing the need for frequent replacements and reducing the environmental burden associated with battery production and disposal. This aligns with the broader goals of reducing greenhouse gas emissions and advancing sustainable transportation solutions.

Another key innovation of the proposed system is its IoT-enabled monitoring capability, which allows real-time tracking of battery and supercapacitor parameters. By integrating current, voltage, and state of charge data into an IoT platform, users can remotely monitor performance metrics through graphical dashboards. This feature enhances user awareness, facilitates predictive maintenance, and provides valuable insights into long-term energy usage patterns. Such integration also supports future scalability, where smart grids and vehicle-to-grid technologies can interact seamlessly with electric vehicles, further promoting energy efficiency.

Case-I:

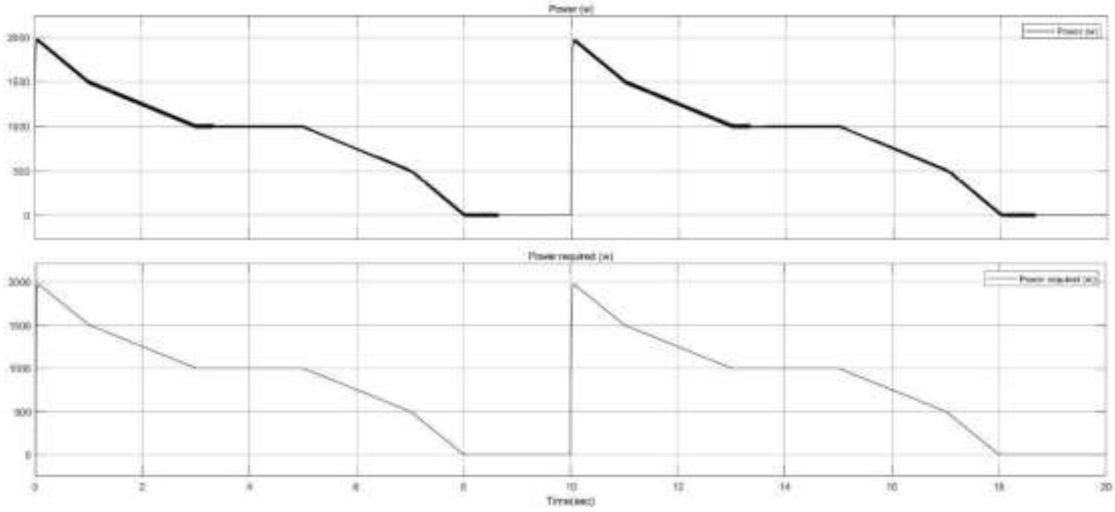

Fig 3. Power required and Power output

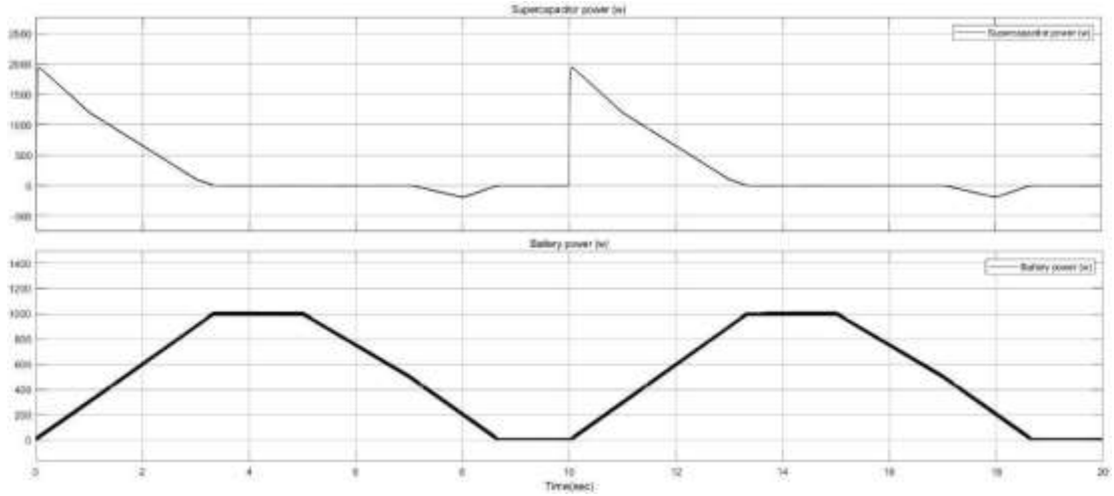

Fig.4 Supercapacitor Power and Battery Power

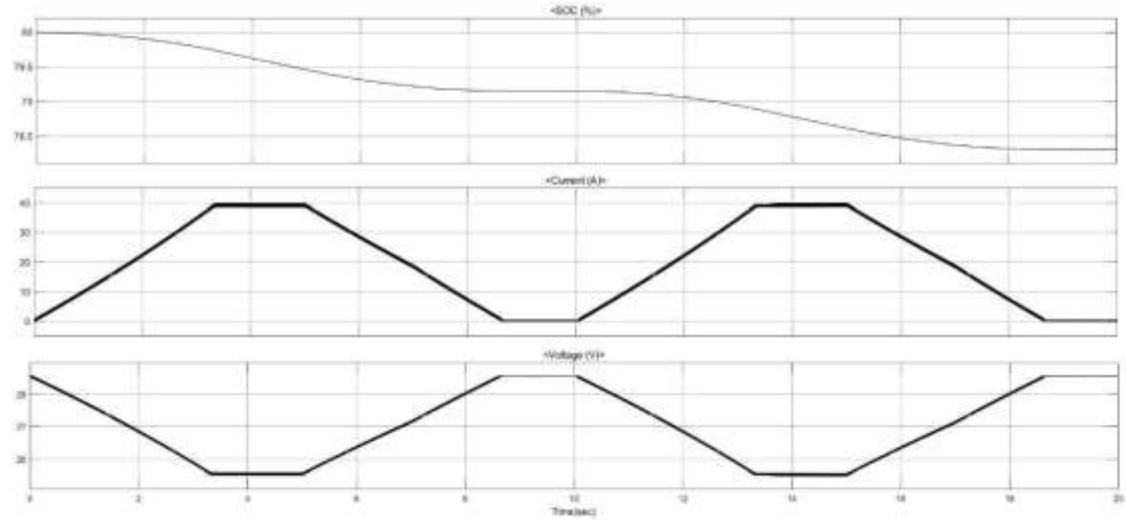

Fig.5 SoC, Current and Voltage waveforms of Battery

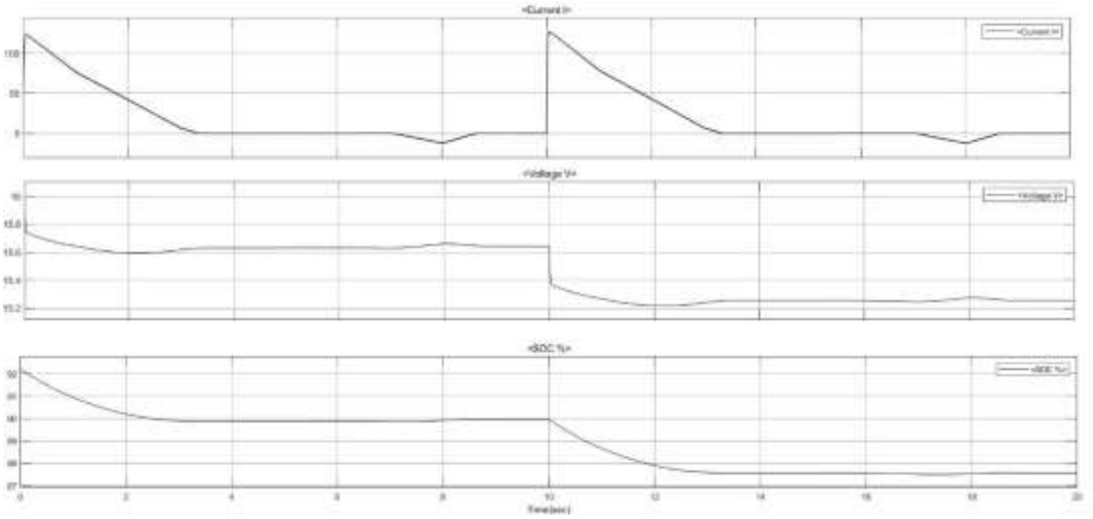

Fig.6 SoC, Current and Voltage waveforms of Super Capacitor

Case-II:

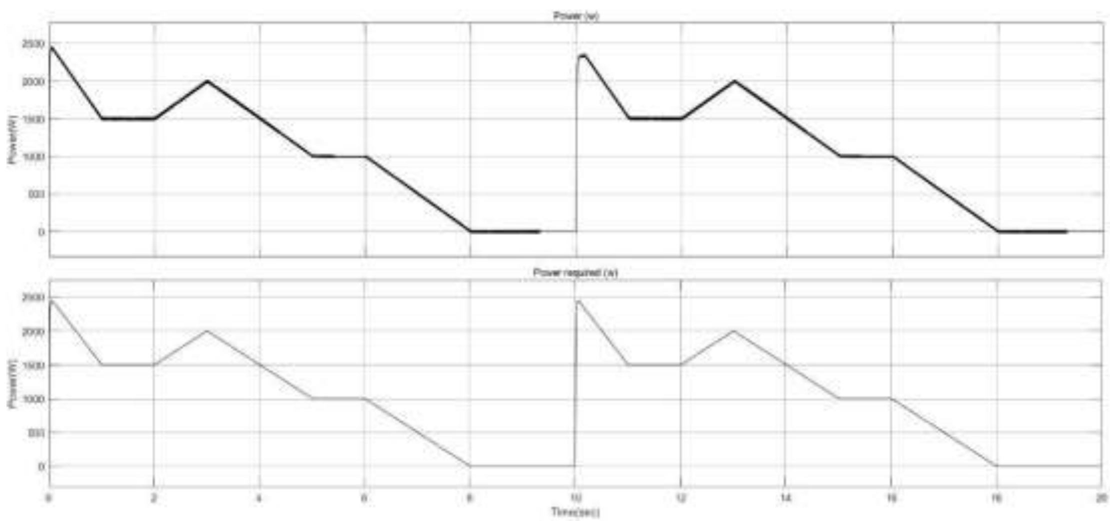

Fig .7 Power required and Power output

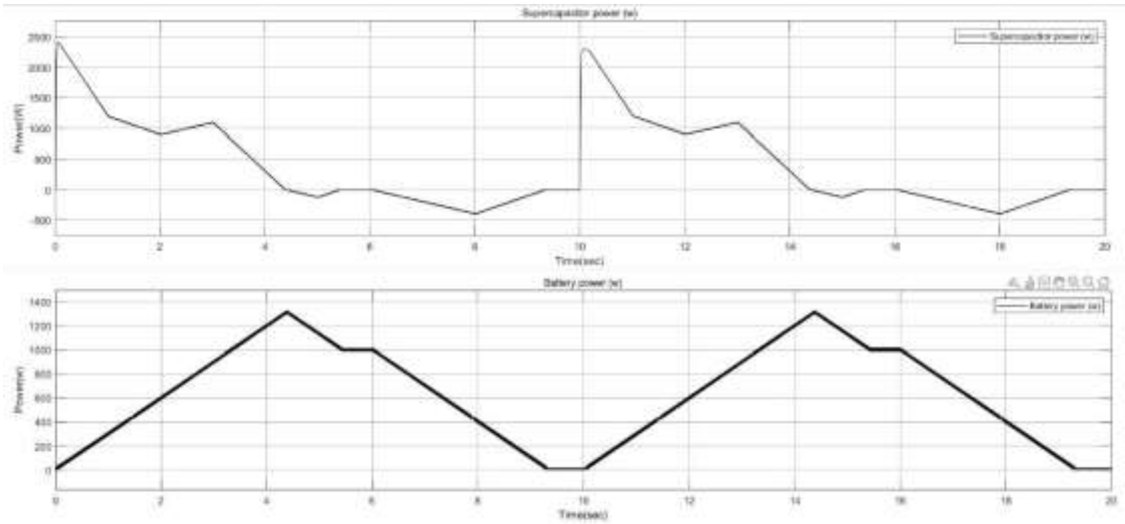

Fig.8 Supercapacitor Power and Battery Power

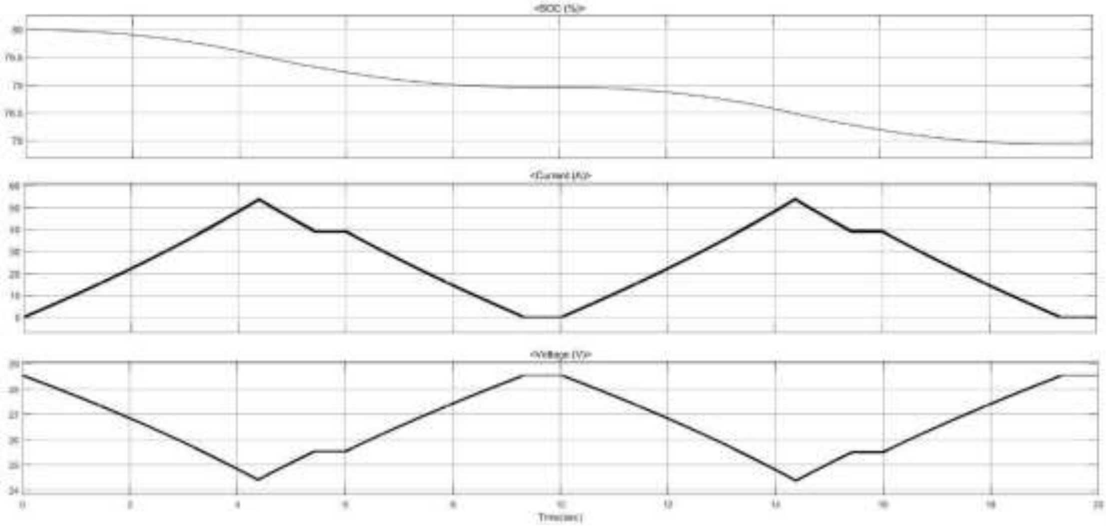

Fig.10 SoC, Current and Voltage waveforms of Battery

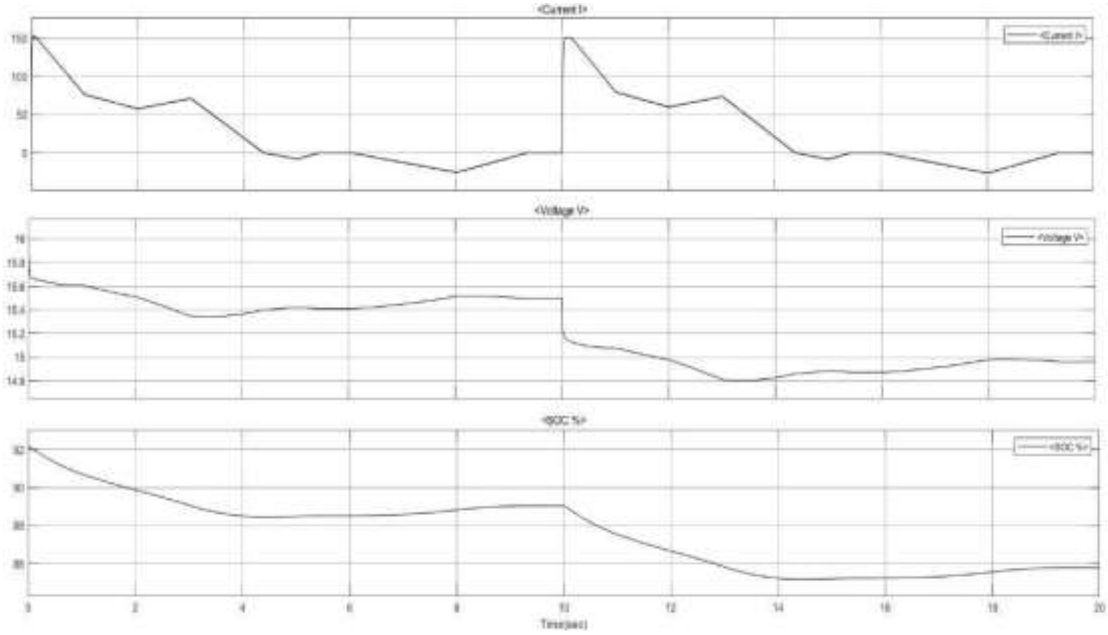

Fig.11 SoC, Current and Voltage waveforms of Super Capacitor

In conclusion, the proposed hybrid energy storage system offers a comprehensive solution for the challenges faced by conventional battery-based electric vehicles. By combining lithium-ion batteries with supercapacitors and integrating intelligent control schemes, the system enhances performance, reliability, and efficiency. It ensures longer battery life, better management of transient loads, and effective energy recovery during braking. The incorporation of DC-DC converters and IoT-based monitoring makes the architecture both technologically robust and user-friendly. Ultimately, this system not only improves electric vehicle performance but also contributes significantly to the advancement of sustainable mobility and clean energy utilization.

V CONCLUSION

This project successfully demonstrates the importance of a Hybrid Energy Storage System (HESS) that integrates lithium-ion batteries with supercapacitors to enhance the performance and lifespan of electric vehicles. The combined system leverages the high energy density of batteries and the high power density of supercapacitors, ensuring effective power delivery during peak demands such as acceleration, while simultaneously reducing stress on the battery. Simulation results validated the efficiency of the proposed system in stabilizing power output, maintaining battery state of charge, and supporting regenerative braking for energy recovery. Furthermore, the control strategy implemented through bidirectional DC-DC converters effectively managed power flow between the two storage units, optimizing energy utilization under varying load conditions. The integration of IoT monitoring enhanced system scalability by enabling real-time tracking of charge, discharge, and performance metrics, which can further support predictive maintenance and energy management. In summary, the proposed HESS significantly improves energy efficiency, extends battery lifespan, and reduces operational limitations in electric vehicles. This approach addresses critical barriers to EV adoption, such as range anxiety and high battery costs, while supporting the broader transition to sustainable transportation. Future work can explore advanced controllers and machine learning-based optimization for even greater system adaptability.

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