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Battery Supercapacitor Hybrid Storage System

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ABSTRACT: A battery–supercapacitor hybrid energy storage system (HESS) integrates the high energy density of batteries with the high power density and rapid charge/discharge capabilities of supercapacitors. This synergy addresses the inherent limitations of each storage technology, resulting in a more efficient, durable, and high-performance energy storage solution. In such systems, supercapacitors manage transient power demands and absorb regenerative energy, thereby alleviating stress on the battery and extending its operational lifespan. Concurrently, the battery delivers sustained energy for longer-duration applications, creating a complementary dynamic that enhances overall system efficiency and responsiveness. HESS technologies find widespread application across diverse domains, including electric vehicles (EVs), renewable energy systems, uninterruptible power supplies (UPS), and portable electronics. In EVs, HESS facilitates rapid acceleration, efficient regenerative braking, and extended driving range. In renewable energy integration, it mitigates output fluctuations and improves grid stability. For UPS applications, HESS ensures rapid and reliable backup power delivery. To fully exploit the complementary characteristics of batteries and supercapacitors, the implementation of optimized control strategies and intelligent power management techniques is essential. Advanced algorithms play a critical role in real-time power distribution, enabling dynamic adaptability, performance optimization, and extended system longevity. This paper highlights the significance of such control frameworks in maximizing the potential of HESS across a range of modern energy applications.

KEYWORDS: Hybrid energy storage, Battery, Supercapacitor, Battery-supercapacitor HESS topologies, Power electronics components.

I. INTRODUCTION

The transition toward sustainable energy systems has become a global imperative in response to environmental concerns, energy security issues, and the increasing demand for clean, reliable power. Central to this transition is the development of advanced energy storage systems (ESSs) capable of managing the variability of renewable energy sources, enhancing grid stability, and supporting the electrification of transportation. Traditional single-source energy storage technologies—such as lithium-ion batteries and supercapacitors—have proven effective within their respective performance domains, but they face inherent limitations when used independently in dynamic and high-demand environments.

Lithium-ion batteries, known for their high energy density and relatively long discharge durations, are widely used in applications requiring sustained power delivery. However, they suffer from limitations including low power density, long charging times, and degradation under high current loads or rapid cycling. Supercapacitors, on the other hand, exhibit excellent power density, high cycle efficiency, and rapid charge/discharge capabilities, making them ideal for handling peak power demands and transient loads. Nevertheless, their low energy density restricts their use in applications that require continuous energy supply over extended periods.

To address these challenges, hybrid energy storage systems (HESSs) have emerged as a promising solution, particularly those that combine batteries and supercapacitors in a single architecture. A battery–supercapacitor hybrid energy storage system (BS-HESS) integrates the complementary characteristics of both technologies, leveraging supercapacitors to handle instantaneous power demands and regenerative energy spikes, while batteries provide a stable energy source for longer-term operation. This strategic energy partitioning not only enhances overall system efficiency and performance but also significantly improves the lifespan and reliability of the battery by mitigating stress from high-frequency power fluctuations.

The benefits of BS-HESS extend across a wide spectrum of applications. In electric vehicles (EVs), for instance, BS-HESS enables improved acceleration, efficient regenerative braking, and longer driving range, while also contributing to battery longevity and thermal management. In renewable energy systems, HESSs can smooth power output fluctuations from intermittent sources such as solar and wind, thereby enhancing grid integration and stability. Additionally, in microgrids and uninterruptible power supplies (UPS), BS-HESS facilitates rapid response to load changes and ensures continuous, high-quality power delivery. The versatility and adaptability of hybrid storage systems make them indispensable in the design of modern, intelligent, and decentralized energy infrastructures.

Despite the promising potential of BS-HESS, several technical and operational challenges must be addressed to achieve optimal performance. These include the selection of appropriate battery and supercapacitor technologies, system sizing and configuration, and the design of power electronic interfaces such as bidirectional DC-DC converters. Furthermore, the development of intelligent energy management systems (EMS) and battery management systems (BMS) is critical for ensuring safe, efficient, and adaptive operation. Control strategies must dynamically allocate power between the storage devices based on real-time operating conditions, load demands, and state-of-charge (SoC) levels. Advanced algorithms—such as model predictive control (MPC), fuzzy logic, neural networks, and machine learning techniques—are increasingly being explored for this purpose.

This paper aims to provide a comprehensive overview of battery–supercapacitor hybrid energy storage systems. It reviews the state-of-the-art in system architectures, power conversion systems (PCS), control strategies, and energy management techniques. The study also explores recent advancements in predictive control methods and discusses application-specific design considerations. In addition, economic and feasibility aspects are examined to evaluate the practicality of deploying BS-HESS in real-world scenarios. By synthesizing current research and identifying existing gaps, this work serves as a reference for scholars, engineers, and practitioners seeking to develop and implement robust hybrid energy storage solutions.

II. ENERGY STORAGE DEVICES

Energy storage devices can be broadly classified into two categories based on their primary performance characteristics: energy-based and power-based systems. Energy-based storage devices are designed to store large amounts of energy and release it over extended periods, making them suitable for applications that require continuous power delivery. This category includes technologies such as lead-acid batteries, lithium-ion (Li-ion) batteries, sodium-ion batteries, and redox flow batteries. Lead-acid batteries are widely used due to their low cost, though they suffer from limited cycle life and energy density. Li-ion batteries, on the other hand, offer high energy density and long cycle life, making them a popular choice for electric vehicles and renewable energy systems. Sodium-ion batteries are gaining attention as a more sustainable and cost-effective alternative to Li-ion, while redox flow batteries offer scalable energy capacity and are well-suited for large-scale grid storage.

In contrast, power-based storage devices are optimized for rapid energy delivery and absorption, making them ideal for handling transient power demands, frequent cycling, and high-power applications. This category includes supercapacitors, Li-ion capacitors, flywheel energy storage systems, and superconducting magnetic energy storage (SMES). Supercapacitors are known for their exceptional power density and fast charge/discharge capabilities, although they have relatively low energy capacity. Li-ion capacitors combine the benefits of batteries and capacitors, offering a balance between energy and power density. Flywheel systems store energy mechanically and are used for applications requiring short-term, high-power output. SMES systems, while still largely experimental due to their high cost and cooling requirements, offer ultra-fast

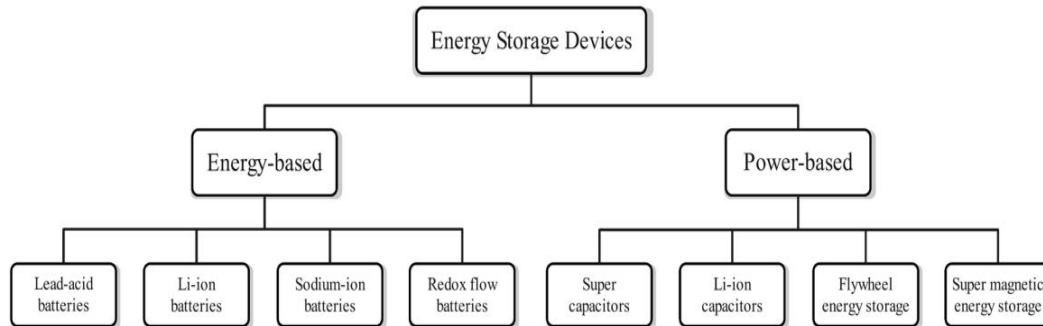


Fig.1: Classification of energy storage devices

response times and near-perfect efficiency. By combining both energy- and power-based devices, hybrid energy storage systems (HESS) can deliver both sustained energy and instantaneous power, thereby enhancing overall system performance and flexibility.

III. LITHIUM-ION BATTERY

Energy storage devices are generally categorized into two main types based on their operational focus: energy-based and power-based storage systems. Energy-based devices are designed to store substantial amounts of energy and discharge it over long periods, making them suitable for continuous or sustained power supply. Among these, lithium-ion (Li-ion) batteries are the most prominent and widely adopted due to their high energy density, long cycle life, and relatively compact size. They have become the preferred choice for a broad range of applications including electric vehicles (EVs), portable electronics, and renewable energy systems. Other energy-based technologies include lead-acid batteries, which are cost-effective but heavier and less efficient; sodium-ion batteries, which are gaining traction as a sustainable alternative to Li-ion; and redox flow batteries, which offer flexible scalability for large-scale energy storage, especially in grid-level applications.

A lithium-ion battery is a type of rechargeable electrochemical energy storage device that operates through the movement of lithium ions between two electrodes: the anode (negative electrode) and the cathode (positive electrode), separated by an electrolyte and a separator.

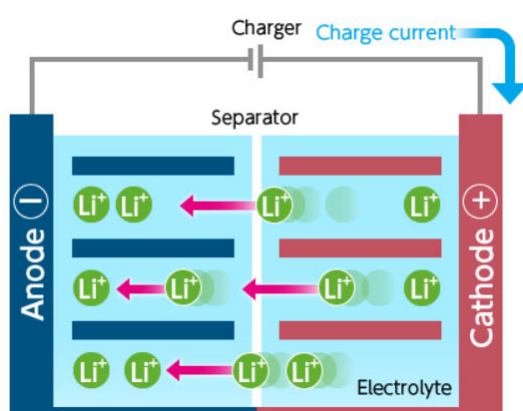


Fig.2: charging of lithium-ion battery

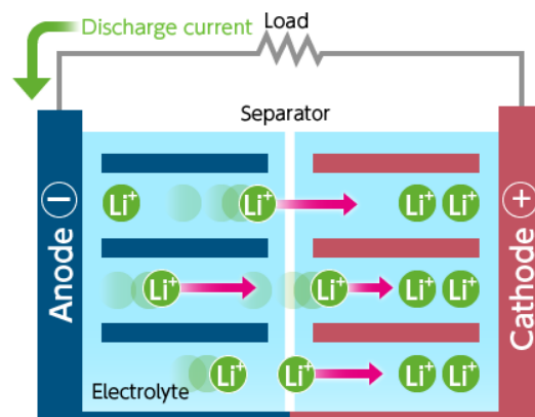


Fig.3: discharging of lithium-ion battery

The anode is typically made of graphite, while the cathode is composed of lithium metal oxides such as lithium cobalt oxide (LiCoO_2), lithium iron phosphate (LiFePO_4), or lithium nickel manganese cobalt oxide (NMC). The electrolyte is

usually a lithium salt (e.g., LiPF_6) dissolved in an organic solvent, allowing for the transport of lithium ions but not electrons.

During discharge, when the battery is supplying power to a load, lithium ions move from the anode to the cathode through the electrolyte, while electrons flow through the external circuit to power the device. At the same time, lithium ions intercalate (embed) into the cathode material. Conversely, during charging, an external power source applies a voltage greater than the battery's operating voltage, causing lithium ions to migrate from the cathode to the anode, where they are stored between the layers of graphite. Electrons travel in the opposite direction through the external circuit, completing the electrochemical cycle.

IV. SUPERCAPACITOR

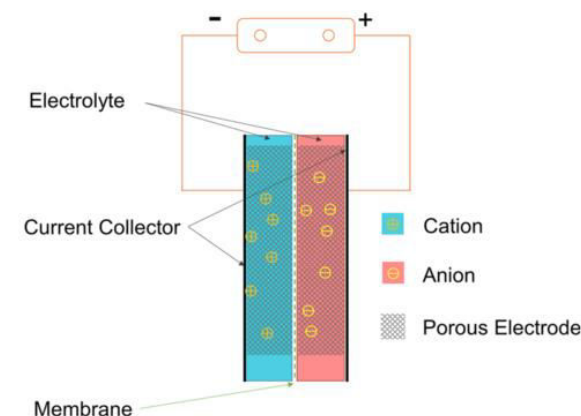


Fig.4 Schematic diagram of a Supercapacitor

A supercapacitor, also known as an ultracapacitor or electrochemical capacitor, is an energy storage device that bridges the gap between traditional capacitors and batteries. It stores energy through electrostatic charge separation rather than chemical reactions, which allows it to charge and discharge much faster than batteries. The main components of a supercapacitor include two porous electrodes (usually made of activated carbon), an electrolyte (liquid or solid), and a separator.

Supercapacitors store energy by forming an electric double layer at the interface between the electrode and the electrolyte. When a voltage is applied across the electrodes, positive and negative ions in the electrolyte move toward the respective electrodes, creating two layers of opposite charges—a phenomenon called the electric double-layer effect (EDLC). This process is non-faradaic, meaning there is no charge transfer through chemical reactions, allowing for high cycle life and rapid energy delivery.

A supercapacitor stores energy through the formation of electric double layers at the interface between its porous electrodes and the electrolyte, as shown in the diagram. When a voltage is applied, positively charged ions (cations) in the electrolyte migrate toward the negatively charged electrode, while negatively charged ions (anions) move toward the positively charged electrode. This creates a physical separation of charge without chemical reactions, allowing for rapid charging and discharging. The separator (membrane) between the electrodes permits ion flow but prevents electrical contact, ensuring safe operation. Electrons move through the external circuit during charging and discharging, enabling energy storage and release. This electrostatic process gives supercapacitors their high power density, long cycle life, and fast response, making them ideal for applications requiring quick bursts of energy and frequent cycling.

V. BATTERY-SUPERCAPACITOR HESS TOPOLOGIES

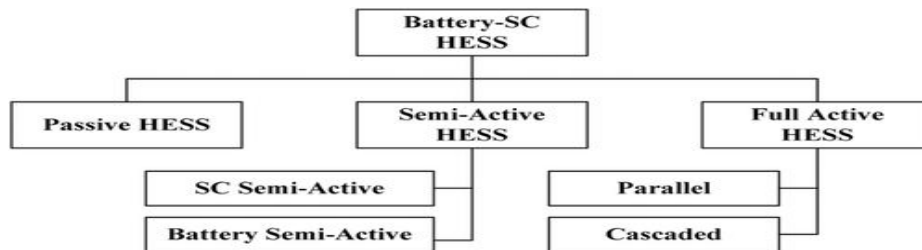


Fig.5: Classification of battery-Sc HESS topologies

In battery-supercapacitor HESS, the two ESS elements can be coupled to either a common DC or AC bus. For standalone micro-grid, common DC bus is the preferred choice due to various reasons. First, most ESS elements and renewable energy generators operate in DC voltage. Therefore, maintaining a DC bus minimises the needs of power converter. Second, DC bus does not require synchronisation which greatly reduces the complexity of the overall system. As a result, DC coupling is more efficient and lower cost than equivalent AC bus systems.

Passive HESS

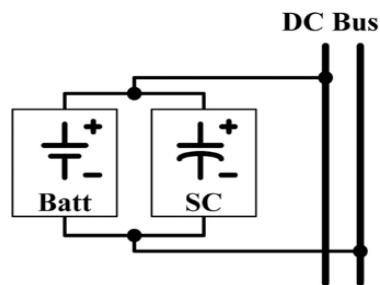


Fig.6: Passive HESS

Passive connection of battery and supercapacitor to the DC bus is the simplest and cheapest HESS topology. It has been shown to effectively suppress transient current under pulse load conditions, increase the peak power and reduce internal losses. The battery and supercapacitor are connected to the DC bus directly. They share the same terminal voltage that depends on the state-of-charge (SoC) and charge/discharge characteristic of battery. In some rural micro-grid applications, the battery capacity is sized up to five days as reserve without any external source of energy. Consequently, most of the time the battery will be cycled with relatively low depth-of-discharge (DoD) and charged/discharged in a relatively low C-rate. As a result, the fluctuation in DC bus voltage will be minimal, ensuring a relatively stable system voltage.

However, the system current will be drawn from or feed into the battery and supercapacitor based on their respective internal resistances. Therefore, the transient power handing capability of the supercapacitor is not optimally utilized. In addition, as the voltage variation of the battery terminal is small, the supercapacitor will not be operating at its full SoC range which results in poor volumetric efficiency.

Semi-active HESS

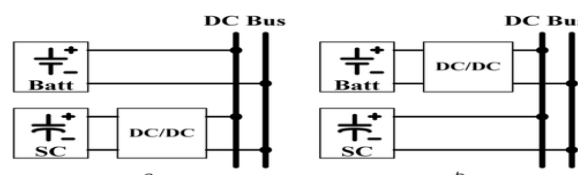


Fig.7: Semi-active HESS

To make better use of the ESS elements in passive HESS, power electronic converters are included between the ESS elements and DC bus. This allows the power flow to be actively controlled. In semi-active HESS topology, only one of the two ESS elements is actively controlled. Fig shows a semi-active HESS topology in which only the supercapacitor is interfaced to the DC bus via a bidirectional DC/DC converter, while the battery is directly connected to DC Bus. In this topology, the bidirectional DC/DC converter isolates the supercapacitor from the DC bus and battery terminal. In this setting, the supercapacitor can be operated within a wider range of voltages, which significantly improves the volumetric efficiency. The direct connection of battery also ensures stable DC bus voltage. However, the passive connection of battery unavoidably exposes the battery to fluctuating high current that has negative impact on battery's lifespan.

The other semi-active HESS configuration is shown in Fig. b. The battery is isolated by a bidirectional DC/DC converter, while the supercapacitor is passively connected to the DC bus. Unlike passive and supercapacitor semi-active HESS topologies, the battery current can be controlled at a relatively gentler manner regardless of the fluctuation in the power demand. The battery terminal voltage is not required to match the DC bus voltage, allowing flexible and efficient sizing and configuration of battery bank. However, the volumetric efficiency of the supercapacitor is low. The linear charge/discharge characteristic of the supercapacitor also causes large fluctuation in the DC bus, which may result in poor power quality and system stability. To maintain a relatively stable DC bus voltage, the capacity of supercapacitor must be extremely large, which leads to high cost.

Full active HESS

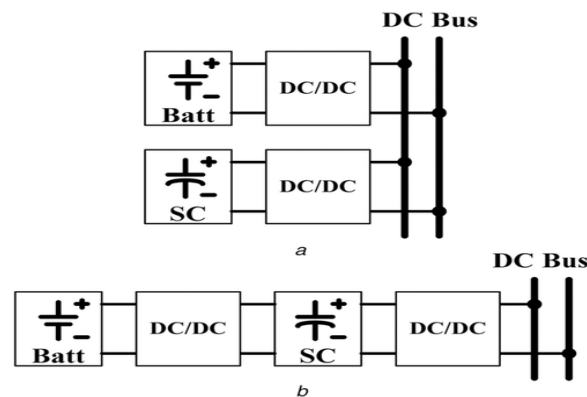


Fig.8: Full active HESS

In full active HESS topology, the power flow of battery and supercapacitor are both actively controlled via bidirectional DC/DC converters. This enhances the flexibility of the HESS and improves the overall system performance and cycle life. Two of the most common full active HESS topologies are shown in Fig., namely parallel active HESS and cascaded active HESS.

In parallel active HESS topology, both battery and supercapacitor are isolated from the DC bus by bidirectional DC/DC converters as shown in Fig. a. Parallel active HESS is one of the most common topologies for grid scaled storage applications which allows full control of both ESS elements. With this topology, the performance, battery life and DC bus stability can be improved through carefully designed control strategy. For instance the battery, as a high energy density ESS, can be programmed to meet the low-frequency power exchanges. The supercapacitor can be programmed to response to the high-frequency power surges and regulate the DC bus voltage. The decoupling of battery and supercapacitor allows both ESS elements to operate at a wider range of SoC that can greatly improve the volumetric efficiency of the HESS.

In cascaded topology, two bidirectional DC/DC converters are cascaded to isolate the battery and supercapacitor from the DC bus, as illustrated in Fig. b. The bidirectional DC/DC converter that isolates the battery is normally current controlled to provide smooth power exchange with the battery. This releases the battery from harsh charge/discharge process due to the intermittency of renewable power generation and load. The bidirectional DC/DC converter that

isolates the supercapacitor from the DC bus is normally voltage controlled to regulate the DC bus voltage while absorbing the high frequency power exchanges. Since the supercapacitor has wide operating voltage, a large voltage swing between the supercapacitor and DC bus is expected. As a result, the power losses in the DC/DC converter will be higher as it is difficult to maintain efficiency across wide range of operating voltages.

As the number of power converter increases, the overall coulombic efficiency of the HESS decreases due to losses in the power converters. The performance of full active HESS system is also extremely reliant on the reliability of the DC/DC converters and their control system.

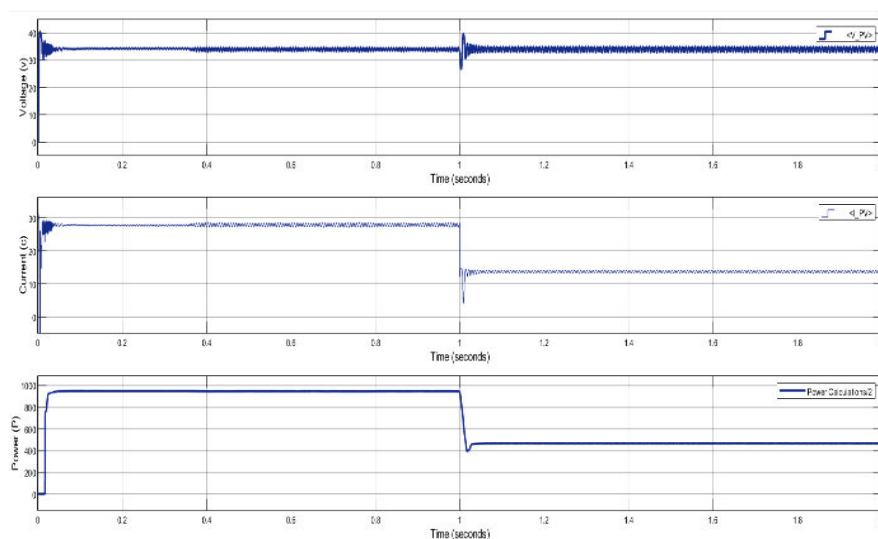
VI. POWER ELECTRONICS COMPONENTS

The hybrid energy storage system (HESS) integrates photovoltaic (PV) generation with a battery and supercapacitor, managed through a network of power electronic converters. The primary power electronics components include a DC-DC boost converter, two bidirectional DC-DC converters, and multiple power switches. The DC-DC boost converter is connected to the PV panel and is responsible for stepping up the low PV voltage to a higher, regulated DC-link voltage. It operates under the control of a Maximum Power Point Tracking (MPPT) algorithm, which ensures that the solar array operates at its optimal power point under varying conditions.

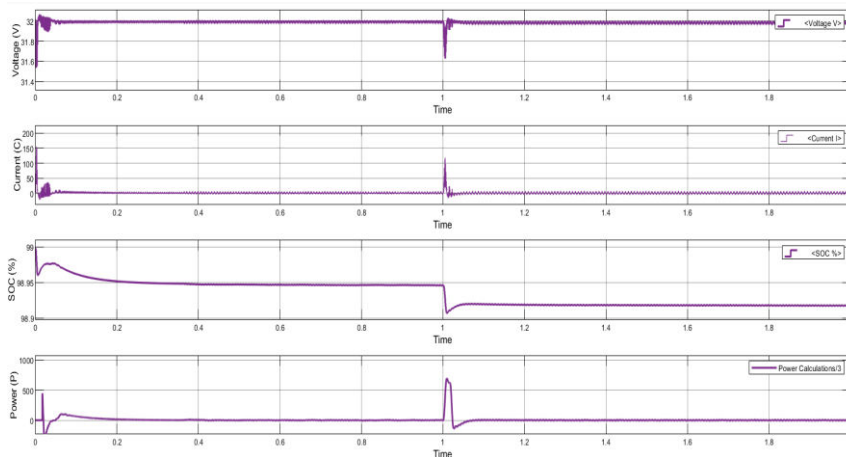
The battery and supercapacitor each have their own bidirectional DC-DC converters, enabling controlled energy exchange between the storage devices and the DC bus. The bidirectional converter for the supercapacitor allows it to rapidly charge and discharge, handling short-term power fluctuations and protecting the battery from high current spikes. Meanwhile, the bidirectional converter for the battery manages long-term energy supply, regulating battery charging and discharging based on load requirements and battery state-of-charge (SOC). These converters use power semiconductor switches (such as IGBTs or MOSFETs) driven by PWM (Pulse Width Modulation) control signals for efficient voltage and current regulation. Together, these power electronics components ensure stable operation, efficient power sharing, and prolonged battery life within the hybrid system.

VII. RESULTS AND DISCUSSION

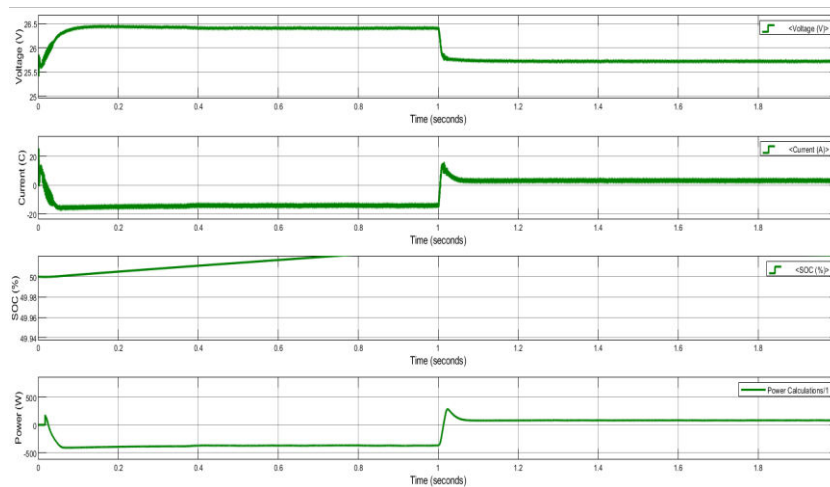
PV Scope:



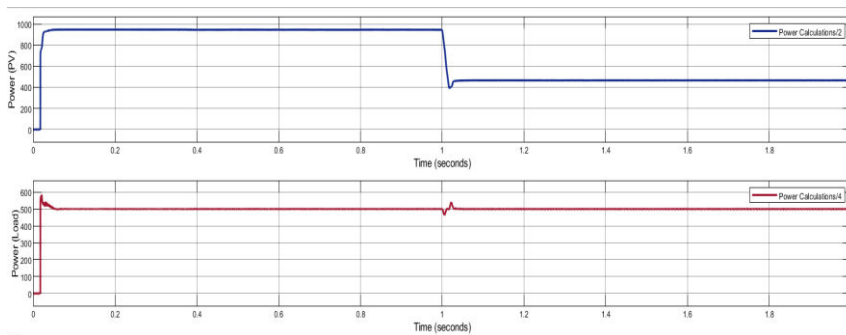
Supercapacitor Scope:

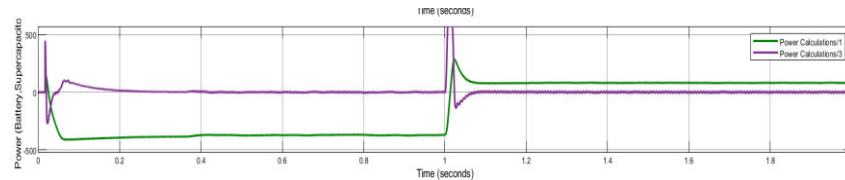


Battery Scope:



P Scope:





VDC Scope:

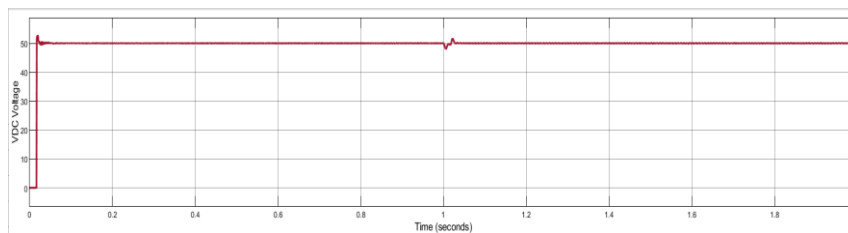


Fig. 9 Simulation Results of Battery-supercapacitor hybrid energy storage system.

The simulation results of the Battery–Supercapacitor Hybrid Energy Storage System (HESS) demonstrate how effectively the system manages dynamic power demands through coordinated operation of its components. Initially, the photovoltaic (PV) panel operates at its maximum power point, supplying energy to the load while simultaneously charging the battery. This is observed from the steady PV voltage and current, and a constant increase in battery state-of-charge (SOC). However, at around $t = 1$ second, a sudden drop in PV power occurs—likely simulating a decrease in solar irradiance or an increase in load. This triggers an immediate response from the supercapacitor, which discharges rapidly to fill the temporary power gap. The sharp spike in supercapacitor current and power confirms its high responsiveness, while its SOC drops only slightly, indicating it delivers a short, high-power burst to stabilize the system.

Simultaneously, the battery transitions from charging to discharging, showing a more gradual change in current and power. This controlled response helps sustain the energy flow after the supercapacitor compensates for the initial transient. Throughout this event, the DC-link voltage remains stable (as observed in the VDC scope), and the load receives uninterrupted power, confirming that the control strategy effectively balances supply and demand. Overall, the results highlight the complementary nature of batteries and supercapacitors in a hybrid system—where the supercapacitor handles fast transients, and the battery supports longer-duration demands—resulting in improved system stability, efficiency, and protection of individual components from excessive stress.

VIII. CONCLUSION

The simulation and analysis of the Battery–Supercapacitor Hybrid Energy Storage System (HESS) confirm the effectiveness of combining lithium-ion batteries with supercapacitors to manage power and energy demands in a dynamic environment. The system successfully demonstrates coordinated power sharing, where the supercapacitor handles rapid transients and sudden load fluctuations, while the battery delivers steady, long-term energy support. This synergy not only enhances overall system efficiency and stability but also extends the lifespan of the battery by reducing high current stress during sudden load changes.

The observed results validate the importance of proper control strategies and power electronic interfaces in maintaining a stable DC-link voltage and ensuring reliable load supply under varying conditions. The HESS proves to be a robust and efficient solution for applications such as electric vehicles, renewable energy integration, and smart grid systems. Ultimately, this project highlights the potential of hybrid storage systems to deliver high performance, improved energy management, and operational longevity in modern power systems.

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