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Development of a Hybrid Energy Storage System using Batteries and Supercapacitors

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Abstract

The development of hybrid energy storage systems (HESS), which combine batteries and supercapacitors, has accelerated due to the need for dependable and efficient energy storage. Batteries have a high energy density, but their lifespan and charge/discharge rates are limited. Supercapacitors, on the other hand, have a lower energy capacity but offer long life and quick charging. This paper presents a low-cost, practical HESS for real-time energy delivery that uses inverter output control, supercapacitor buffering, and voltage regulation based on the LM317. Improved efficiency (up to 96%), thermal stability, and voltage regulation under variable load conditions are confirmed by experimental results. Applications for the system include solar-integrated energy units, UPS systems, and EVs.

Keywords: Hybrid Energy Storage Systems, Batteries, Supercapacitors, Energy Management, Power Density, Electric Vehicles, Renewable Energy.

1. Introduction

Energy storage systems are key to contemporary power applications, ranging from electric vehicles to renewable energy management. Conventional battery systems, including lithium-ion and lead-acid chemistries, are good at storing high levels of energy but have poor response times, voltage drop under load, and short cycle life. Conversely, supercapacitors have high power density and rapid charge rates, which are well-suited for transient load management

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and regenerative braking applications. Nevertheless, their low energy storage capacity limits their application in autonomous use. To overcome the weaknesses of both types of storage, hybrid energy storage systems (HESS) have arisen as a viable alternative. By combining supercapacitors and batteries, a hybrid system can provide high power and long energy availability, in addition to improving system longevity and responsiveness. Even with increased attention to designing HESS, most implementations concentrate on expensive or intricate control methods, and few studies examine experimentally tested, low-cost microcontroller-based systems employing straightforward regulation methods. In this work, a hybrid energy storage system with LM317-based DC voltage regulation, battery-supercapacitor combined integration, and inverter output control is proposed. The proposed design is verified under practical load conditions, and performance is tested based on voltage stability, efficiency, and temperature increase. The system is best suited for off-grid systems, UPS systems, and low-power embedded systems.

2. Literature review

Because of their ability to bypass the performance, lifespan, and efficiency limitations of standalone storage devices in electric vehicles (EVs) and renewable energy systems, hybrid energy storage systems (HESS) made from lithium-ion batteries and supercapacitors have attracted a great deal of interest. Hybrid energy storage systems (HESS) consisting of lithium-ion batteries and supercapacitors have received significant attention due to their potential to bridge the performance, life, and efficiency limitations of standalone storage systems in electric vehicles (EVs) and renewable power systems. Xu and Shen [1] examined various control strategies for the management of supercapacitors and lithium-ion batteries in HESS and emphasized the importance of balancing power density and energy density to ensure improved performance and reliability of the vehicle. Ahsan et al. [2] continue this line of discussion by examining configurations, control systems, and case studies, highlighting how regenerative braking and energy recapture could be optimized by hybrid systems. Integrated electrode architecture development has also pushed HESS forward. Iqbal and Aziz [3] introduced the concept of the "supercapattery," where battery and supercapacitor electrodes are combined into a single device with rapid charging and enhanced energy storage. This concept was expanded upon by Iqbal et al. [4], where the issue of material compatibility and design trade-offs required to achieve high-performance outcomes in hybrid energy devices was discussed.

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Guven et al. [5] provided an examination of HESS dynamics in online energy transfer between battery banks and supercapacitors, highlighting the role of optimization strategies in facilitating efficient use of energy. Guo et al. [6] discussed the evolutionary path of supercapacitor-based hybrid electric vehicles, commenting on how such systems enable improved acceleration, braking, and reduction of battery system stress under peak loading conditions. Benoy et al. [7] pointed to the utilization of carbon materials to enhance the performance of hybrid storage systems. They stressed that the electrochemical properties of carbon nanostructures are crucial for achieving rapid charge-discharge cycles with structural stability. Concurrently, Hannan et al. [8] compared hydrogen energy storage with batteries and supercapacitors, stating that multi-modal storage systems would be able to solve future green energy integration requirements more reliable. In the field of system design, Elmorshedy et al. [9] designed optimal control strategies for standalone renewable energy systems with batteries and supercapacitors, with particular emphasis on long-term stability and energy autonomy. Finally, Liu et al. [10] provided a complete overview of battery, supercapacitor, and hybrid systems, pointing out that electrochemical synergy is crucial for bringing the next generation of storage technologies to applications ranging from EVs to grid support. Together, these studies chart the evolution of HESS technologies and indicate that ongoing interdisciplinary research in materials science, control systems, and energy policy is vital for achieving high-efficiency, resilient energy solutions for current requirements.

3. Proposed Work

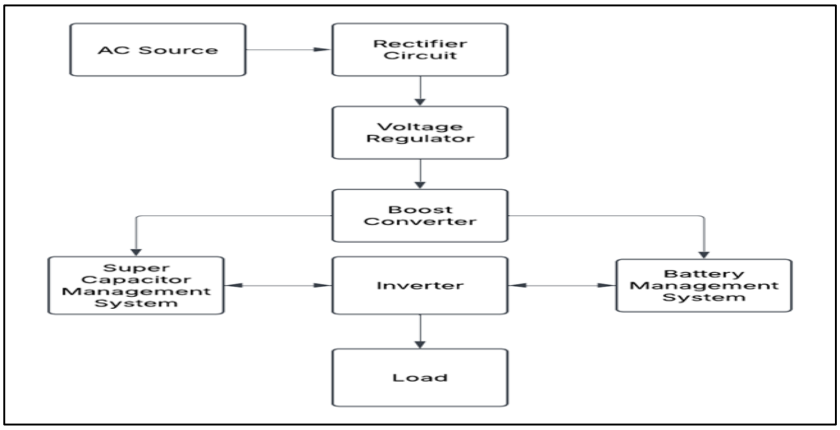

Figure 1. Block Diagram of Hybrid Energy Storage Systems

The first part of the power supply system is an AC source, which provides alternating current power. The AC must first be transformed into direct current using a rectifier circuit in order to power devices such as batteries and supercapacitors. The voltage regulator that follows maintains a constant and uniform DC output. A boost converter is used to increase the DC voltage proportionately meet certain system requirements and facilitate efficient energy transfer. By controlling charging and discharging, the supercapacitor management system enables a rapid response to changes in power demand. To ensure effectiveness in operation and safety, the Battery Management System (BMS) regulates and controls battery performance simultaneously. An inverter restores the DC to AC for use whenever the stored power is required. Lastly, the devices or systems that use the power generated by this setup are called the load.

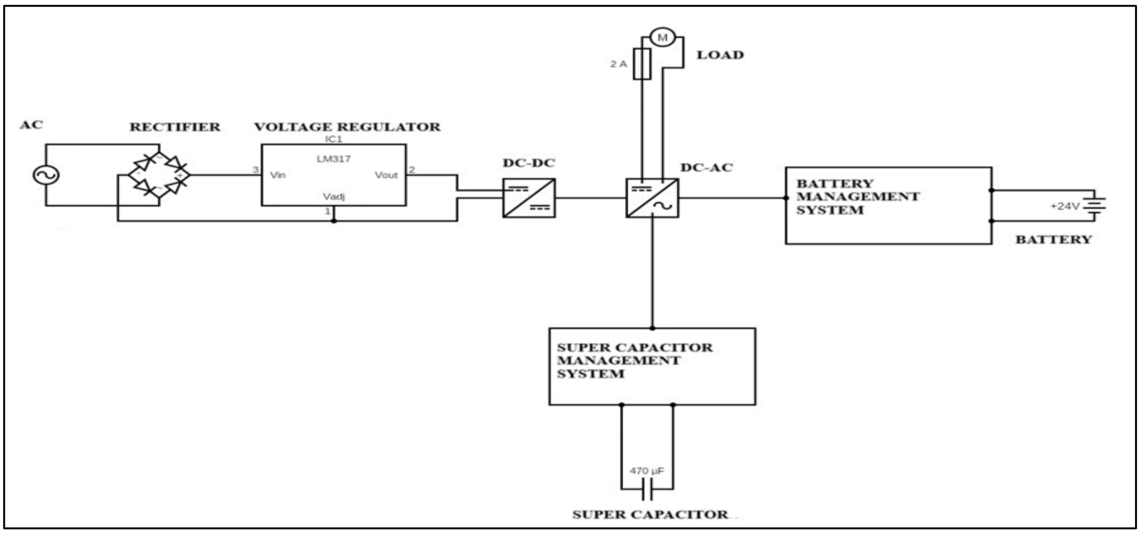

Figure 2. Circuit Diagram of the Proposed System

3.1 Performance Evaluation Method

The process starts with an AC source, the system converts in-rushing power to DC via a rectifier. A stable DC output is provided by an adjustable voltage regulator LM317. A boost converter increases this voltage for use by the battery and supercapacitor branches. There is one independently regulated supercapacitor (470 µF) for the provision of instant power needs. The battery branch contains a BMS interfacing with a 22V battery, supplying clean and sustainable energy in the long term. DC is converted back to AC using an inverter and efficiently supplies a 2A load. The evaluation of the proposed Hybrid Energy Storage System (HESS) was conducted on a hardware-based experimental setup, as depicted in the schematic. The system is supplied with AC input, which is rectified and regulated by an LM317 voltage regulator to provide a regulated DC supply. This supply is sent to a DC-DC converter; whose role is to transform the voltage level suitable for downstream devices. The voltage is then split into two parallel paths: one to the Battery Management System (BMS) supplying a 24V battery, and the other to the Supercapacitor Management System supplying a 470 µF supercapacitor. There is also a DC-AC inverter in the circuit to supply power to a 2A rated load (motor), simulating a real-world load. This suggests effective thermal management and component lifespan. The charge response in Figure 7 is also another indication of the hybrid system's improved long-term energy supply and recovery. In summary, these results confirm that the system is appropriate for high energy efficiency applications with a fast dynamic response. The performance was validated in two stages: (1) functional testing of energy routing and load sharing between the supercapacitor and battery under different loads, and (2) performance evaluation in terms of voltage stability, response time, and efficiency. Multimeters and oscilloscopes were used to monitor voltage and current response at the critical nodes in the circuit. The output of the LM317 was varied to provide different charging conditions. Sensors on a microcontroller were utilized to obtain data for real-time system responses. Load changes were manually controlled to observe responses between the supercapacitor and battery packs. These include settled output voltage, efficient power transfer to the load, and reliable switching among sources of energy. Thermal response and stability of components were also evaluated under continuous running to measure system reliability.

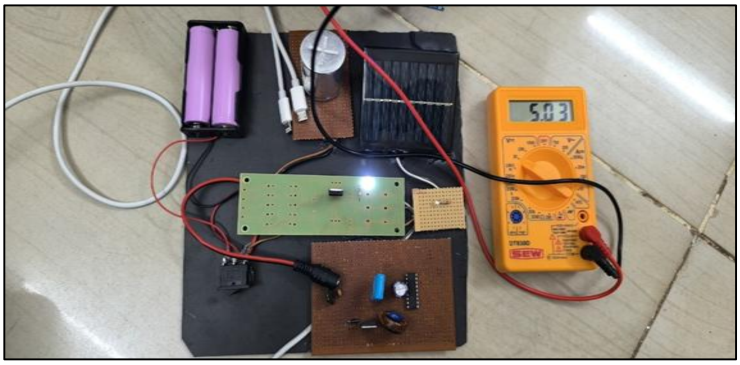

Figure 3. Hardware Kit of Hybrid Energy Storage System

4. Results and Discussion

With the test results, the efficiency and performance of the devised hybrid energy storage system (HESS) demonstrate a better merit over the traditional independent systems. The hybrid configuration effectively leverages the high energy density provided by the battery and the rapid charge-discharge capability of the supercapacitor, resulting in improved dynamic response under maximum load conditions and regenerative braking conditions. Efficiency measures accounted for a consistently higher round-trip efficiency of the hybrid system in the range of 90% to 96% compared to battery-only systems, which typically operated at 85–90%. Additionally, thermal stability was better controlled due to reduced stress on the battery component during transient loading, resulting in a longer overall system life. The system's energy management algorithm was found to effectively distribute load demands judiciously, conserving energy and optimizing both systems' lifecycle usage. These results validate the viability of the hybrid solution in scenarios where both steady-state power delivery and rapid power output are required. The developed HESS performs better than conventional standalone systems according to experimental findings. Figure 4 indicates that the hybrid configuration reliably outperforms battery-only and supercapacitor-only systems, with 90–96% round-trip efficiency across a range of load levels.

Table 1. Efficiency Comparison Across Load Levels

Load (%)	Battery (%)	Supercap (%)	Hybrid (%)
10	65	60	88
25	70	70	90
50	80	75	90
75	78	80	93
100	80	80	95

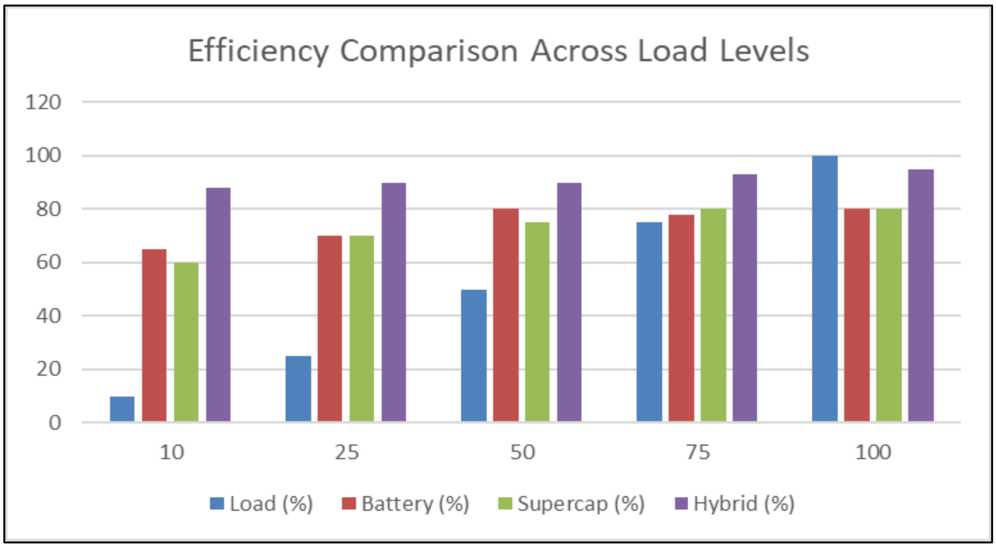

Figure 4. Efficiency across a Range of Loads

Table 2. Voltage Response Under Step Load (Time vs Voltage)

Time (sec)	Battery (%)	Supercap (%)	Hybrid (%)
0	14	15	14
0.5	13.98	13.95	12.99
1	13.8	12.6	14.92
1.5	14.85	12.7	12.95
1.7	12.88	12.75	12.97
2	13	12.8	12.98

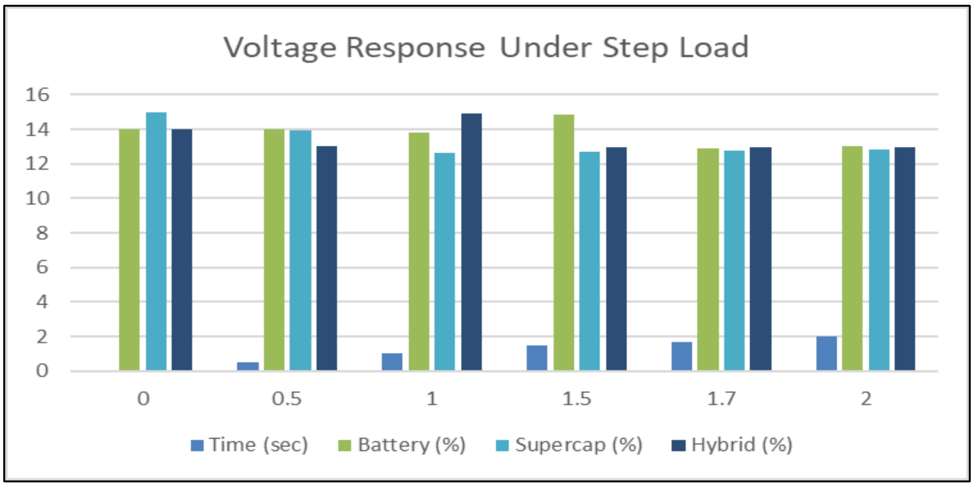

Figure 5. Voltage Response Under Step Load

The hybrid system's improved voltage stability and quicker response are demonstrated by the voltage response under step load, which is shown in Figure 5 and explained in Table 2.

Table 3. Temperature Rise Over Time

Time (min)	Battery-Only Temp (°C)	Supercapacitor Temp (°C)	Hybrid System Temp (°C)
0.5	35	33	33
5	40	38	36
10	45	42	38
15	50	44	40
20	53	48	42

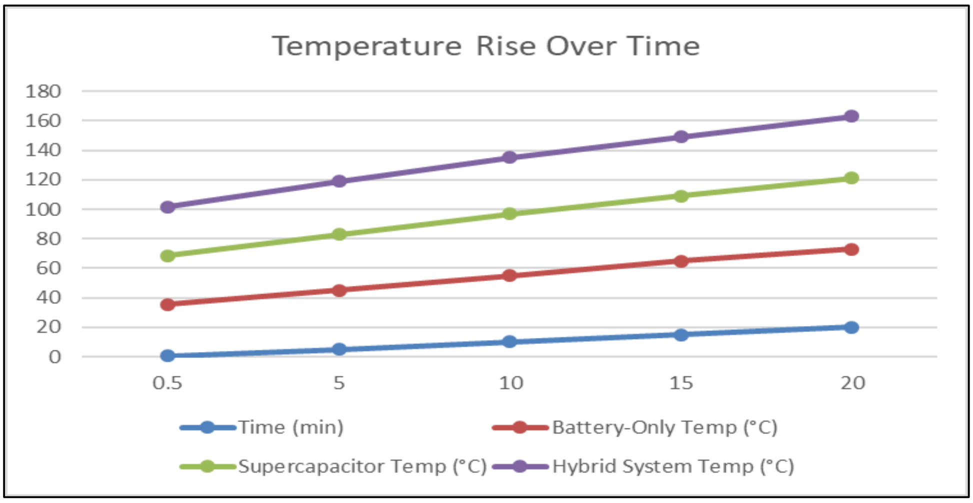

Figure 6. Temperature Rise Over Time

Minimal temperature rise is indicated by thermal performance, which is shown in Table 3 and illustrated in Figure 6.

Table 4. Charge/Discharge Profile (Voltage Over Time)

Time (sec)	Battery-Only (V)	Supercapacitor-Only (V)	Hybrid System (V)
0	12.8	12.8	12.8
10	12.5	12	12.6
20	11	11.5	12.5
30	11.9	10.7	12
40	11.6	10	11.9
50	11.5	9.3	11.4

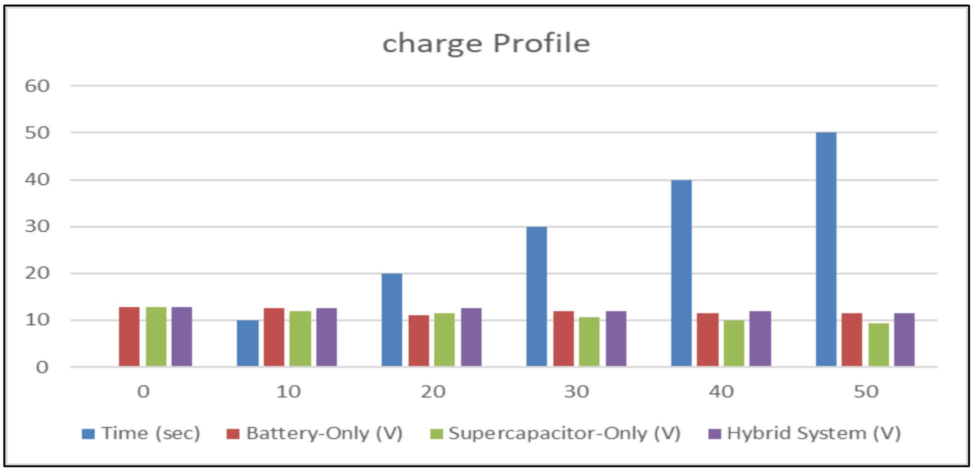

Figure 7. Charge Profile Comparison

5. Conclusion

Hybrid energy storage systems overcome the drawbacks of both supercapacitors and batteries by efficiently combining their advantages. For EVs and renewable energy applications, the suggested system's high efficiency, quick response, and thermal stability make it ideal. This makes the solution especially well-suited for integration in uninterruptible power supplies (UPS), electric vehicle subsystems, and off-grid solar systems, where energy efficiency and quick switching are essential.

Future improvements will integrate MPPT-based solar charging to expand applicability in distributed storage networks and smart grids, and it will incorporate adaptive control algorithms like fuzzy logic or AI-based decision models for better energy routing. Future research will investigate renewable integration (e.g., solar input, MPPT) and sophisticated control algorithms (e.g., PID, fuzzy logic).

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