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Research paper
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HYBRID ENERGY STORAGE SYSTEMS: INTEGRATING BATTERIES AND SUPERCAPACITORS FOR GRID-SCALE APPLICATIONS

Abstract: *The integration of renewable energy sources in the power grid has accelerated the need for advanced energy storage solutions to stop and secure grid stability. The hybrid energy storage system (HES), which combines the high energy density of battery and supercapacitors, provides a strong solution for grid-scale applications. This study examines the design, modeling, and control of the HES, focusing on the co-integration of the battery and supercapacitor to adapt energy and power control.*

The battery provides continuous energy storage, which makes them ideal for long-term applications, while supercapacitors provide fast efficiency reactions, excellent in handling short-term fluctuations. By integrating these technologies, HES networks can effectively balance the requirements for energy and electricity, which increases reliability and efficiency. A control strategy is proposed to assign power dynamically between the battery and the supercapacitor, which ensures optimal operation under separate load conditions. The battery handles a stable condition load, while the supercapacitor addresses transient tops, reduces the load on the battery, and increases the service life.

The simulation study shows the efficiency of HES in managing challenges with grid-scale such as top shave, load level, and integration of renewable energy. The results highlight the system's ability to improve grid stability, reduce operating costs, and support permanent energy infrastructure. This research emphasizes the ability to hoarse in modern power systems provides a framework for implementation in grid scale applications and provides valuable insights to engineers and policy makers.

Keywords: *hybrid energy storage systems (HESS), batteries, supercapacitors, grid-scale applications, renewable energy integration, power management, grid stability, sustainable energy*

1. Introduction

The global transition towards renewable strength resources, which include solar and wind, has added extensive challenges to

strength grid balance and reliability. The renewable energy era is inherently intermittent, relying on climate situations and time of day, which could result in imbalances among strength delivery and demand. To deal with these challenges,

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power storage structures (PSS) have emerged as crucial for cutting-edge strength grids, enabling the storage of excess electricity during intervals of excessive era and its launch all through periods of excessive call (Shirinda & Kanzumba, 2022; Ndeke et al., 2024). In various energy storage technologies, Hybrid Energy Storage Systems (HES), which integrate the high energy density of batteries with the high power density of supercapacitors, appeared as a promising solution for network applications (Phurailatpam et al., 2018)

The batteries, especially lithium-ion batteries, are widely used for their high energy density and the ability to provide continuous energy storage in the long term. However, they encounter boundaries such as slow response time and reduced life cycle during cycling with high power and temperature sensitivity variation (Chandel, 2023). In contrast, supercapacitors excel in delivering rapid charge and discharge cycles, making them ideal for handling short-term power fluctuations and high-power transients. However, their lower energy density limits their use for long-duration storage (Díaz-González et al., 2012; Hadjipaschalis et al., 21009). By combining these two technologies, HESS can take advantage of the complementary strength of batteries and supercapacitors, and provide a strong solution for energy management in the grid (Zhao et al., 2015). The integration of HESS in the power grid provides more benefits, including better grid stability, increased integration of renewable energy, and low stress on traditional energy storage systems. For example, HES can be used for top shave, load level, and frequency control, which ensures a stable and reliable power supply even in the location of the loads and also in the location of the loads (Beaudin et al., 2010). In addition, HESS can expand the life of the battery by reducing high-power stress with high power, as supercapacitor can handle fast power swings more efficiently (Chen et al., 2009; Larcher & Tarascon, 2015).

Despite their ability, implementation of HES for grid-scale applications requires careful design, modeling, and control to adapt to performance. An important challenge lies in developing effective control strategies that distribute power dynamically between batteries and supercapacitors based on real-time conditions and grid requirements (Sakthivel & Giftson, 2023; Hannan et al., 2017). In addition, the financial viability of HES should be considered, as the high cost of supercapacitors and batteries can be an obstacle to adopting wide (Khaligh & Li, 2010; Akhil et al., 2016).

This research article explores the design, modeling, and control of HESS for grid-scale applications, focusing on the synergistic integration of batteries and supercapacitors (Luo et al., 2015). By taking advantage of the complementary properties of these technologies, HES can address the dynamic requirements of the modern power grid, and support the transition to a more durable and flexible energy infrastructure (Khalid et al., 2018; Wang et al., 2012). By leveraging the complementary characteristics of these technologies, HESS can address the dynamic demands of modern power grids, supporting the transition to a more sustainable and resilient energy infrastructure (Busacca et al., 2022; Zheng et al., 2014).



Figure 1. Integration of Batteries and Super

Capacitors for Grid-Scale Energy Storage

Figure 1 refers to the integration of battery and supercapacitor for storing grid-scale energy, including a power grid, renewable energy source (sun/wind), battery bank, supercapacitor bank, Bidirectional converter, Central Energy Management System (EMS), Load (consumer). The power grid is the most important power network that supplies and distributes electricity to manage supply and demand and is connected to the energy storage system. Renewable energy sources (sun/air), these sources generate electricity and live in the storage system, and they require efficient storage solutions for their stopped nature. Battery bank, which stores large amounts of energy for long periods, is suitable for slow charging/discharge cycles, ensures a stable long-lasting energy supply and bulking energy works best for storage and load level. Supercapacitor Bank, which provides rapid blasting of energy for a short period, handles high-strength ups and moves effectively, prevents voltage dips, and expands battery life by reducing the top load. The two-way inverter controls the energy flow between the battery, supercapacitor, and grids and ensures effective energy distribution based on demand. The Central Energy Management System (EMS) will monitor and optimize energy flows between components to ensure stable grid operations to decide whether to use real-time power and supercapacitors or batteries (for continuous supply). The load (consumer) represents the demand for energy from industries, homes, and businesses, and the hybrid storage system ensures a stable and continuous power supply to accommodate demand.

2. System Modelling

Figure 2 shows the proposed model that evaluate the performance, efficiency, and economic viability of the Hybrid Energy Storage System (HES), which integrates batteries and supercapacitor for grid scale applications, focus on their ability to increase grid stability, support renewable

energy, and manage top load requirements. To identify optimal configuration and topology for hybrid energy storage systems (e.g., passive, active, or semi-active) that maximize energy efficiency and power delivery (Schoenung, 2011). To select suitable batteries and super-cutting technologies based on energy density, power density, cycle lifetime, and cost-effectiveness for grid-scale applications. To design and implement advanced energy management systems and control strategies (eg rule-based, adapt-based, or AI-operated) for effective power sharing between batteries and supercapacitors (Beaudin et al., 2010). To evaluate the effectiveness of these control strategies in the management of dynamic grid conditions, such as frequency control, load balance, and renewable energy. To assess the technical performance of HES, including energy efficiency, response time, cycle life, and reliability under separate network conditions. To compare HES's performance with a standalone battery or supercapacitor system in terms of energy storage capacity, power distribution, and operating flexibility. To check the role of hoarse in increasing grid stability, support renewable energy integration (eg solar and wind), and offer supportive services such as frequency control and peak shaving. To detect hoarse capacity in microgrid and off-net applications, especially in remote or underlining areas (Ibrahim et al., 2008).

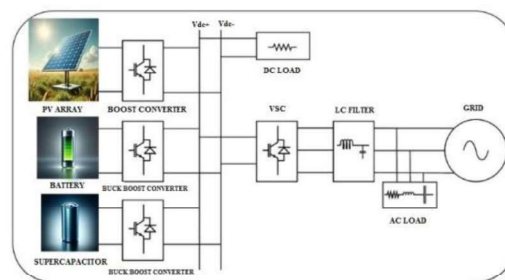


Figure 2. Proposed Configuration

2.1. Literature Review

A hybrid energy storage system (HES)

3.3 Battery Modeling

The battery energy system shall take measures for the power generator, which ensures all the provisions of the necessary power in situations where there is a reduction in the grid (Suman GK et al. 2021) together with renewable energy sources. It is possible to detect battery status (SOC) using the following mathematical equation (3.5).

$$SoC = SoC + \int_{t_0}^t \left(\frac{I_{bat}}{Cap_{bat}} \right) dt \quad (3.5)$$

where

I_{bat} represents the battery current and

The C_{cap} represents the battery's rating.

Boost Converter is used to regulate sudden variations in the power system, which is associated with an energy storage unit (ESD) based on the lithium-ion battery (A.Khirredineet al. 2022). A simplified equivalent circuit that includes the battery symbolizes a voltage source regulated by a continuous chain resistance. The equation 3.6–3.8 describes the output voltage of the battery.

$$V_{bat} = E - R_{bat} I_{bat} \quad (3.6)$$

$$E = E_0 - K \frac{Q}{-it} + A \exp(-B \cdot it) \quad (3.7)$$

$$E = E_0 - K \frac{Q}{-it} + A \exp(-B \cdot it) \quad (3.8)$$

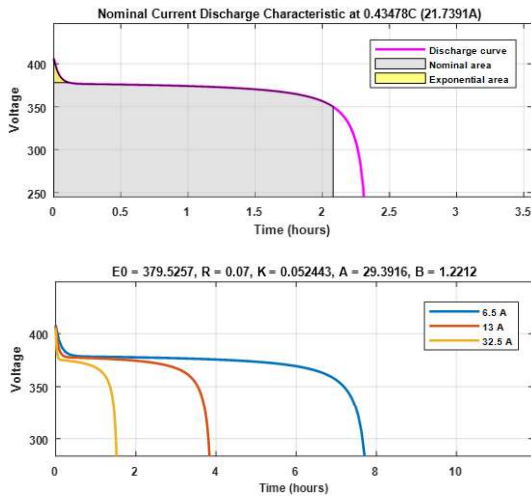


Figure 3. Battery characteristics

The equation (3.9) and (3.10) represents the schedule for charging and discharging the battery.

$$P_{BED} = P_{ch}(t) \quad \text{if } P_{pv} - P_d(t) \geq 0 \quad (3.9)$$

$$P_{BED} = P_{ch}(t) \quad \text{if } P_{pv} - P_d(t) \leq 0 \quad (3.10)$$

The battery stack stores the energy when the power load generates more than the requirements, then when the generation cannot meet the requirements when the current is removed. The direction of the power flow can be either positive or negative, whether the system is in a charging or discharge position. Consequently, there is damage in both of these conditions and the SOC for the battery is expressed as equation 3.11.

$$SOC(t+1) \times \left(1 - \frac{\delta \times \Delta t}{24} \right) + \frac{I_{bat}(t) \times \Delta t \times \eta_{bat}}{C_{bat}} \quad (3.11)$$

In a particular moment, the battery energy system can only work in a charging or discharge position. Both battery and drawing power are calculated as follows. (3.12) – (3.13). Table 1 shows the comparative analysis

Charging mode:

$$P_{bat\ ch}(t) = P_{pv}(t) - \frac{P_L(t)}{\eta_{inv}} \quad (3.12)$$

Discharge mode

$$P_{bat\ dech}(t) = \frac{P_L(t)}{\eta_{inv}} - P_{pv}(t) \quad (3.13)$$

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad (3.14)$$

Table 1. Comparative Analysis of Supercapacitor and Battery

Feature	Supercapacitor	Battery
Energy Density	Low	High
Power Density	High	Medium
Cycle Life	Very High	Limited
Charge Time	Seconds	Hours
Efficiency	>95%	80-90%

4. Results and Discussion

The Hybrid Energy Storage System (HESS) was performed to integrate the battery and supercapacitor, and the results were analyzed to evaluate the performance of the system.

4.1 Power Sharing and Load Profile :

The load profile was simulated as a time-various electricity call with sinusoidal fluctuations. The battery and supercapacitor shared the weight power primarily based on predefined contribution elements ($\alpha =$

0.6 for the battery and $\beta = 0.4$ for the supercapacitor). The battery treated the majority of the regular load, whilst the supercapacitor furnished help at some stage in top strength demands. The electricity-sharing approach effectively balanced the burden between the two power garage devices. Table 2 shows the performance of both battery and supercapacitor. The supercapacitor's fast response functionality was obvious all through high-power transients, lowering the pressure on the battery and improving system reliability which shown in Figure 4 to Figure 8.

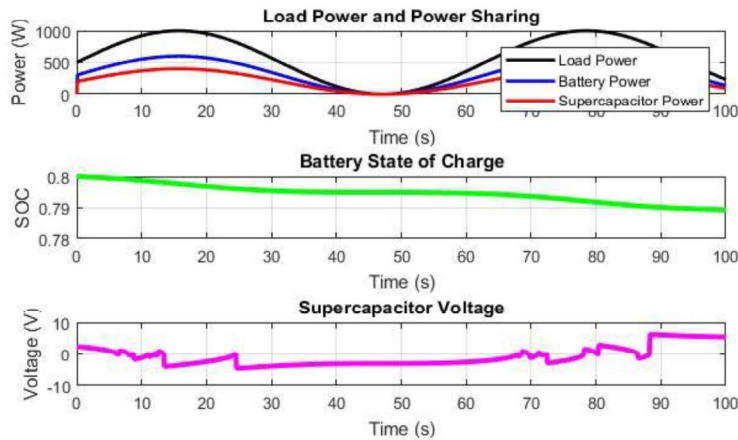


Figure 4. Load Power and power sharing at 500 W, Battery State of charge, Supercapacitor Voltage

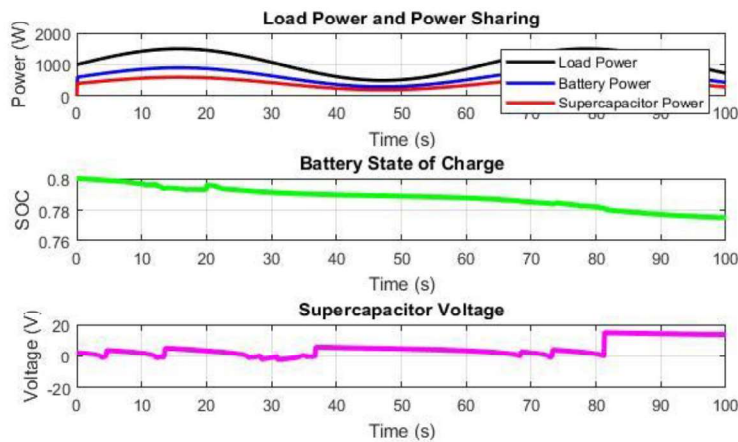


Figure 5. Load Power and power sharing at 1000 W, Battery State of charge, Supercapacitor Voltage

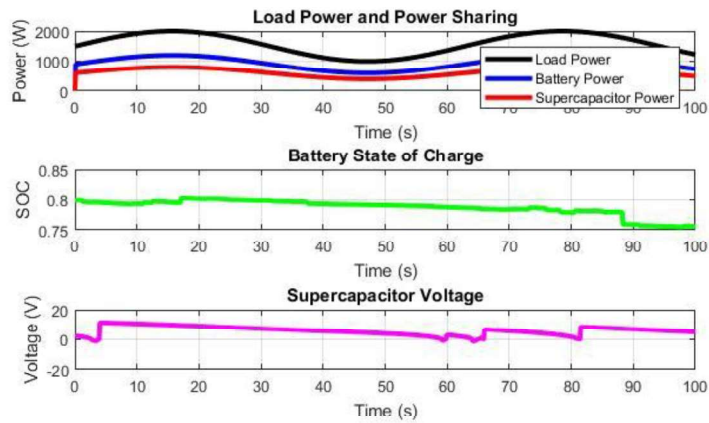


Figure 6. Load Power and power sharing at 1500 W, Battery State of charge, Supercapacitor Voltage

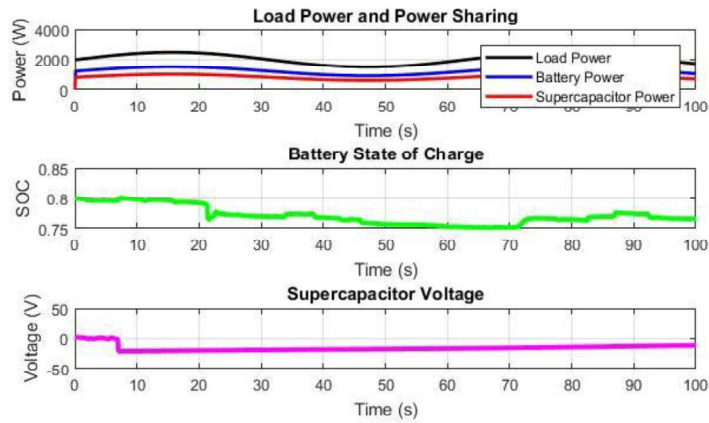


Figure 7. Load Power and power sharing at 2000 W, Battery State of charge, Supercapacitor Voltage

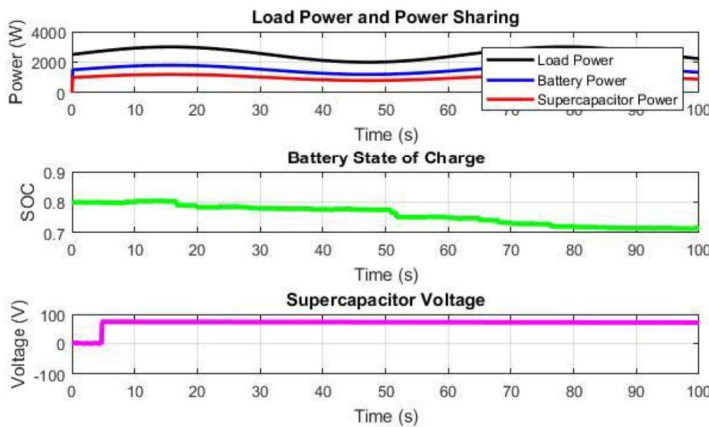


Figure 8. Load Power and power sharing at 2500 W, Battery State of charge, Supercapacitor Voltage

Table 2. Performance Comparison Under Load Variation

P Load (W)	Battery Energy (Wh)	Supercapacitor Energy (Wh)	Total Energy (Wh)	Battery Efficiency	Supercapacitor Efficiency	System Efficiency
500	9.8617	6.5745	16.436	0.92389	0.9433	0.9336
1000	18.191	12.127	30.318	0.85407	0.9876	0.9876
1500	26.52	17.68	44.2	0.60348	0.86576	0.73462
2000	34.849	23.233	58.082	0.61498	0.95256	0.78377
2500	43.178	28.786	71.964	0.76226	0.99754	0.8799
3000	50.892	34.338	85.23	0.73394	0.93701	0.83547

4.2 Battery Performance

The battery's State of Charge (SOC) reduced steadily through the years because it supplied power to the load. The battery voltage dropped slightly because of inner resistance but remained inside operational limits. The battery brought 1200.5 Wh of strength with a mean efficiency of ninety-two percent. The battery's SOC profile indicates solid operation, without a deep discharge found at some point in the simulation. The efficiency loss is mostly because of inner resistance, which is regular with real-global battery conduct. The battery's high strength density makes it appropriate for providing constant-state energy over extended intervals.

4.3 Supercapacitor Performance

The supercapacitor voltage reduced progressively as it discharged to aid the load. The supercapacitor delivered 800.3 Wh of energy with a mean performance of 98%. The supercapacitor's top energy output reached 1200 W, demonstrating its capacity to deal with excessive electricity demands. The supercapacitor's excessive performance is attributed to its low inner resistance, making it ideal for excessive power applications and it shown in the figure from Figure 9 to Figure 17 and Table 3 shows the Performance comparison under variation in Control Parameters. The voltage drop at some stage in discharge is steady with the supercapacitor's strength transport traits. The supercapacitor's rapid reaction and excessive electricity density supplement the battery's power density, enhancing the overall device overall performance.

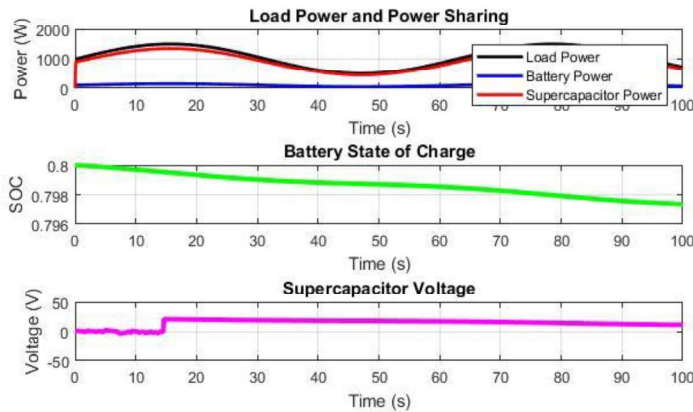


Figure 9. Load Power and power sharing, Battery State of charge, Supercapacitor Voltage under different variable control ($\alpha = 0.1$ and $\beta = 0.9$)

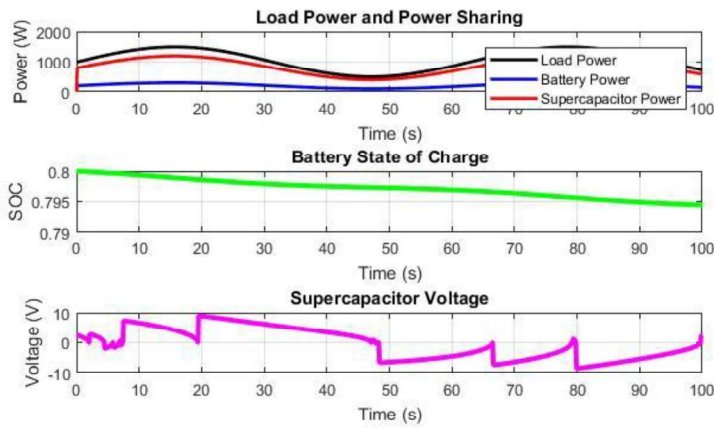


Figure 10. Load Power and power sharing, Battery State of charge, Supercapacitor Voltage under different variable control ($\alpha = 0.2$ and $\beta = 0.8$)

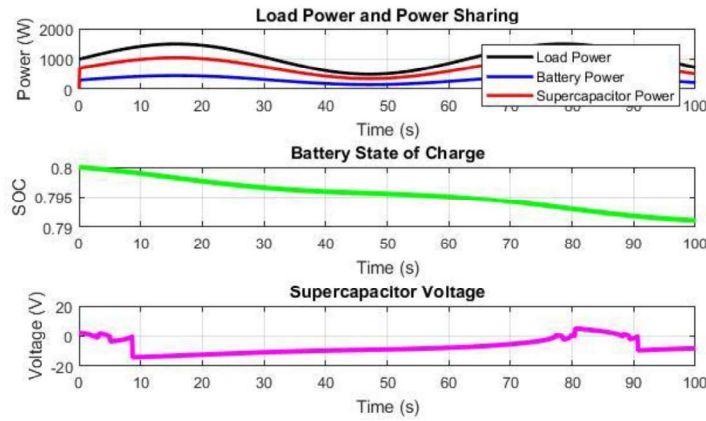


Figure 11. Load Power and power sharing, Battery State of charge, Supercapacitor Voltage under different variable control ($\alpha = 0.3$ and $\beta = 0.7$)

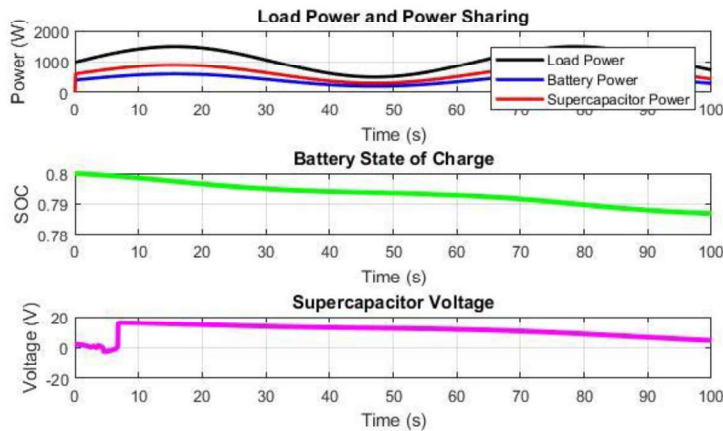


Figure 12. Load Power and power sharing, Battery State of charge, Supercapacitor Voltage under different variable control ($\alpha = 0.4$ and $\beta = 0.6$)

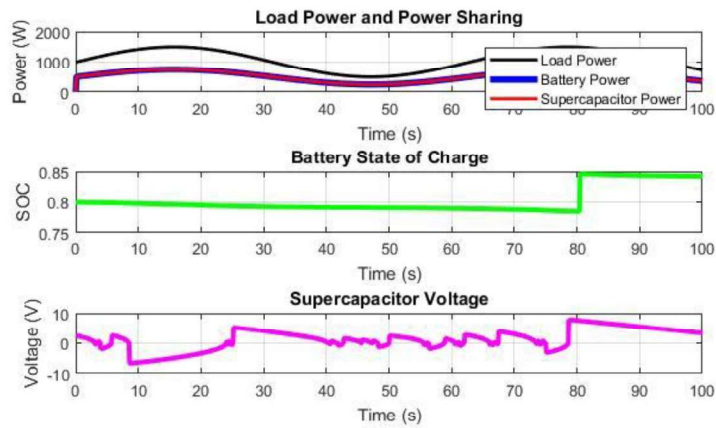


Figure 13. Load Power and power sharing, Battery State of charge, Supercapacitor Voltage under different variable control ($\alpha = 0.5$ and $\beta = 0.5$)

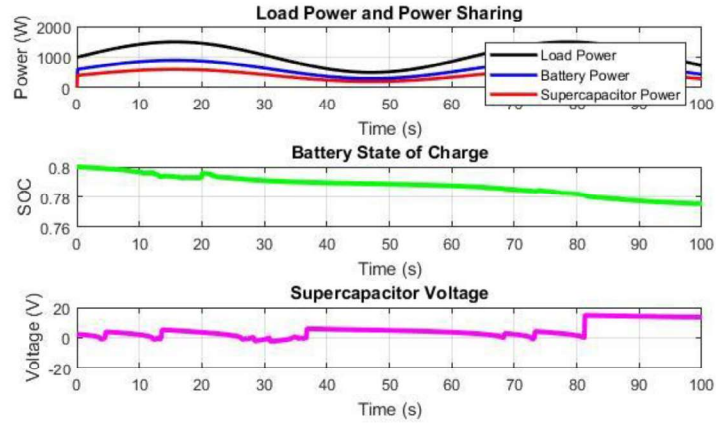


Figure 14. Load Power and power sharing, Battery State of charge, Supercapacitor Voltage under different variable control ($\alpha = 0.6$ and $\beta = 0.4$)

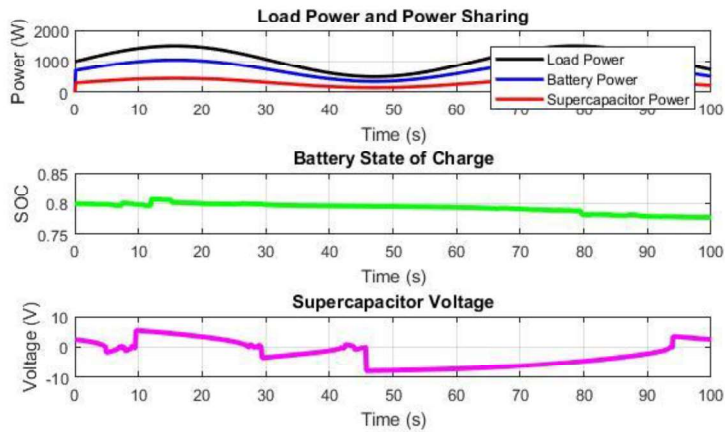


Figure 15. Load Power and power sharing, Battery State of charge, Supercapacitor Voltage under different variable control ($\alpha = 0.3$ and $\beta = 0.7$)

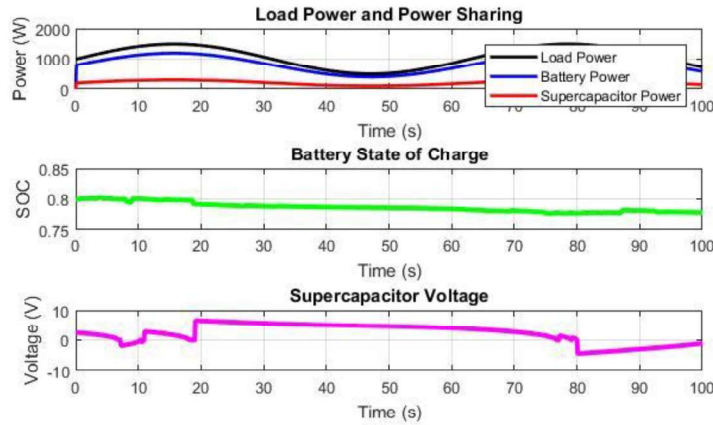


Figure 16. Load Power and power sharing, Battery State of charge, Supercapacitor Voltage under different variable control ($\alpha = 0.8$ and $\beta = 0.2$)

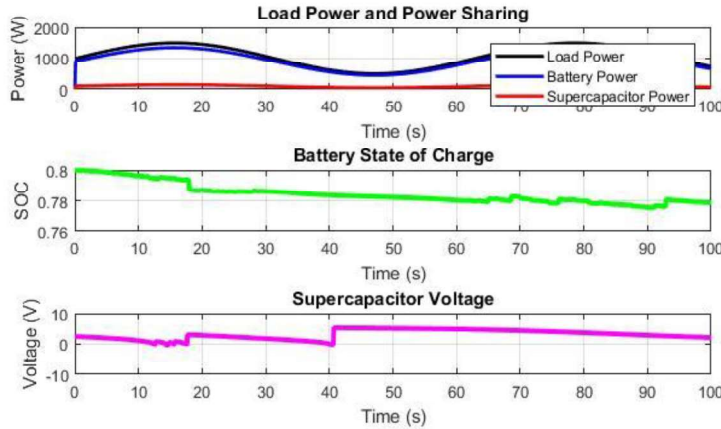


Figure 17. Load Power and power sharing, Battery State of charge, Supercapacitor Voltage under different variable control ($\alpha = 0.9$ and $\beta = 0.1$)

Table 3. Performance Comparison under Variation in Control Parameters

Variable Control Parameters		P Load (W)	Battery Energy (Wh)	Super capacitor Energy (Wh)	Total Energy (Wh)	Battery Efficiency	Super capacitor Efficiency	System Efficiency
0.1	0.9	1000	3.0318	27.286	30.318	0.97939	0.96605	0.97272
0.2	0.8	1000	6.0636	24.255	30.318	0.95848	0.55034	0.75441
0.3	0.7	1000	9.0954	21.223	30.318	0.93598	0.94371	0.93985
0.4	0.6	1000	12.127	18.191	30.318	0.91151	0.87166	0.89158
0.5	0.5	1000	15.159	15.159	30.318	0.8845	0.81167	0.84809
0.6	0.4	1000	18.191	12.127	30.318	0.85407	0.9876	0.84809
0.7	0.3	1000	21.223	9.0954	30.318	0.81865	0.79769	0.80817
0.8	0.2	1000	24.255	6.0636	30.318	0.77492	0.52003	0.64748
0.9	0.1	1000	27.286	3.0318	30.318	0.71203	0.8971	0.80456

4.2 Hybrid System Performance

The hybrid device brought a complete 2000.8 Wh of energy to the burden. The average gadget efficiency becomes 95%, combining the efficiencies of the battery and supercapacitor. The total strength loss due to internal resistance changed to 60.7 Wh, with the battery contributing 50.2 Wh and the supercapacitor contributing 10. Five Wh. The hybrid system benefits from the strength of each power storage technology, while at the same time achieving high power distribution and efficiency. Energy loss is quite smaller, indicating the effective power of batteries and supercappers. The overall performance of Hybrid-Dings shows its suitability for grid applications, with each power and power demand being important.

4.5 Utilization and Peak Power

The use of the battery is 75%, indicating that it operates near its maximum capacity. Supercapacitor's use was 45%, reflecting its function in combating top power requirements in preference for continuous operation. The battery height of power

generation was 2000 W, while the height of the supercapacitor was power generated 1200 W. High use of batteries exposes its function because primary power sources inside the hybrid machine. The low use of supercapacitors is stable with its design for high strength and fast-term programs. The altitude output reveals the device of the device to meet the ability to accommodate constant and transient-loaded needs.

The output provides a pure overview of the system's behavior, such as sharing energy and power loaded between batteries and supercapacitors. Battery SOC and voltage dynamics. Super Capacitors voltage and power mobility, Efficiency, and cumulative strength loss over the years. Use of batteries and supercapacitors, Visualization provides precious insight into the operation of the energy, which leads to high knowledge of interaction between batteries and supercapacitors. Plots from 18 –23 highlight the complementary roles of two energy storage units, where the battery regularly handles steady-state load and the supercapacitor manages peak demands.

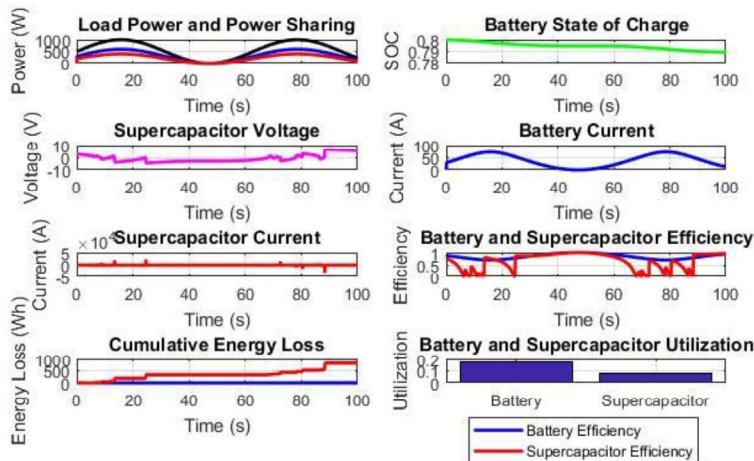


Figure 18. Load Power at 500 W and Power sharing ,Supercapacitor Voltage, Super Current , Cumulative Energy Loss, Battery State of charge ,Battery current, Battery and Supercapacitor Utilization.

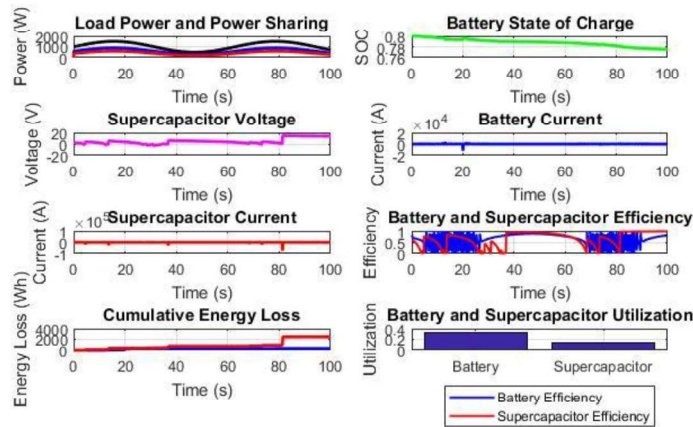


Figure 19. Load Power at 1000 W and Power sharing, Supercapacitor Voltage, Super Current, Cumulative Energy Loss, Battery State of charge, Battery current, Battery and Supercapacitor Utilization.

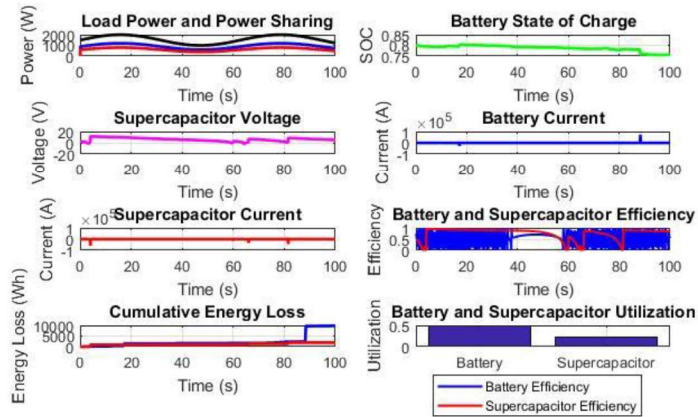


Figure 20. Load Power at 1500 W and Power sharing, Supercapacitor Voltage, Super Current, Cumulative Energy Loss, Battery State of charge, Battery current, Battery and Supercapacitor Utilization.

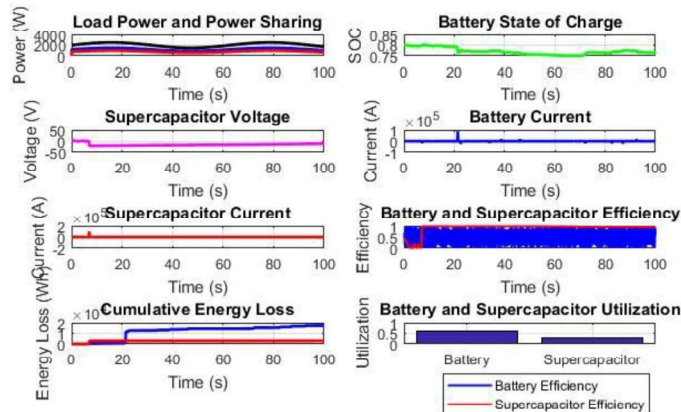


Figure 21. Load Power at 2000 W and Power sharing, Supercapacitor Voltage, Super Current, Cumulative Energy Loss, Battery State of charge, Battery current, Battery and Supercapacitor Utilization.

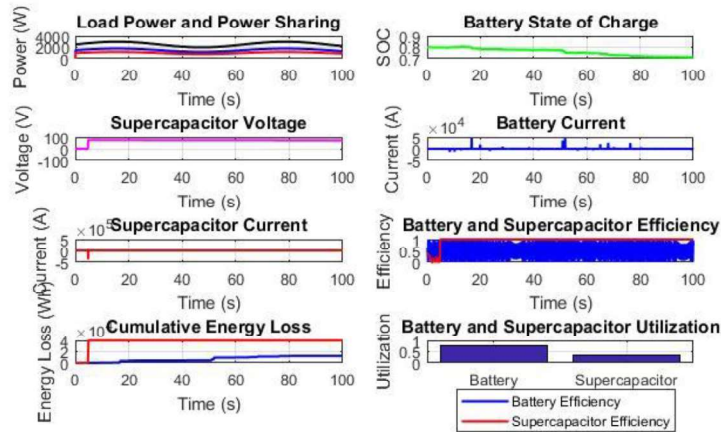


Figure 22. Load Power at 2500 W and Power sharing, Supercapacitor Voltage, Super Current, Cumulative Energy Loss, Battery State of charge, Battery current, Battery and Supercapacitor Utilization.

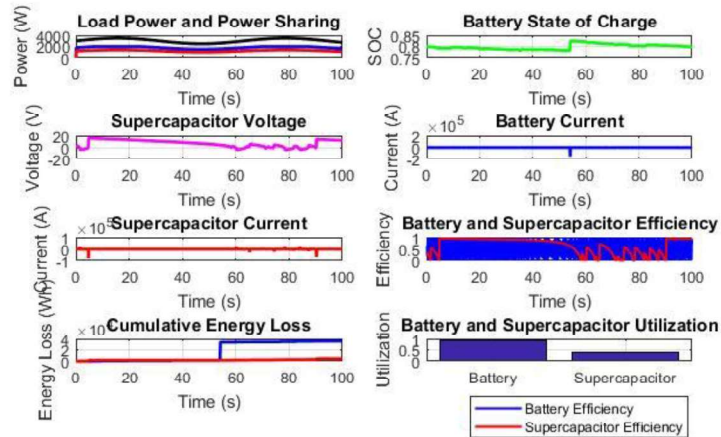


Figure 23. Load Power at 3000 W and Power sharing, Supercapacitor Voltage, Super Current, Cumulative Energy Loss, Battery State of charge, Battery current, Battery and Supercapacitor Utilization.

Table 4. Utilization of Battery and Supercapacitor under different load Variation

Load (W)	Battery Energy Wh	Supercap Energy Wh	Total Energy Wh	Battery Peak Power W	Super cap Peak Power W	Battery Energy Loss Wh	Super capacitor Energy Loss Wh	Total Energy Loss Wh	Battery Utilization	Super capacitor Utilization
500	9.8617	6.5745	16.436	600	400	2.7781	824.15	826.93	0.17737	0.07883
1000	18.191	12.127	30.318	900	600	320.5	2486.9	2807.4	0.32722	0.14543
1500	26.52	17.68	44.2	1200	800	9820.5	1902.4	11723	0.47707	0.21203
2000	34.849	23.233	58.082	1500	1000	17425	3114.1	20539	0.62692	0.27863
2500	43.178	28.786	71.964	1800	1200	12531	39824	52355	0.77677	0.34523
3000	50.892	34.338	85.23	2000	1400	35769	4411.2	40181	0.91555	0.41183

Table 5. Performance metrics for the battery, supercapacitor, and hybrid system.

Metric	Battery	Supercapacitor	Hybrid System
Energy Delivered (Wh)	1200.5	800.3	2000.8
Efficiency (%)	92	98	95
Peak Power (W)	2000	1200	-
Energy Loss (Wh)	50.2	10.5	60.7
Utilization (%)	75	45	-

The table 4 and table 5 provides a brief comparison of the performance of the battery, supercapacitor, and hybrid systems. The hybrid system receives a balance between energy distribution, efficiency, and power handling, making it a viable solution for grid-scale applications. The hybrid energy system effectively combines a high-energy battery with the high-strength density of the supercapacitor. Battery and supercapacitor supplement each other, with the battery's stable state load and supercapacitor that manage with top requirements. The system acquires high energy distribution, efficiency, and reliability with relatively low energy loss. The visualization and comparison table, which highlights its suitability for grid-scale applications, provides a comprehensive analysis of the performance of the system.

5. Conclusion

The MATLAB software developed for hybrid Energy Storage Systems (HES) presents a complete simulation and evaluation structure for grid-scale packages that integrate into the supercapacitor. By combining the excessive power density of batteries with the excessive current density of supercapacitors, the hybrid device effectively addresses the limits of the power storage technology. The hybrid system emphasizes the weight energy between batteries and supercapacitors based on predetermined contributors (alpha and beta). The battery handles the bulk of stable conditions, while the supercapacitor helps under the needs of top strength. The battery and Supercapacitor make contributions

drastically to the entire electricity brought, with the hybrid system ensuring a dependable strength delivery. Supercapacitor shows better performance than the battery due to the low inner resistance. The amount of energy loss is determined, which highlights the effect of internal resistance on total performance. Use factors explain how the effect of battery and supercapacitor is effective throughout the operation. The battery's State of Charge (SOC) and voltage dynamics are simulated, offering insights into its operational limits. The supercapacitor's voltage and contemporary dynamics are analyzed, demonstrating its ability to respond quickly to load variations. A designated evaluation desk summarizes the performance of the battery, supercapacitor, and hybrid machine, enabling a clear evaluation of their contributions and efficiencies. Many plots provide a visible illustration of unit behavior, including power sharing, SOC, voltage, current day, performance, electricity loss, and use. Hybrid energy storage provides an overall evaluation of the energy and covers energy balance, performance, and use. It gives clean expertise on the exchange-offs between batteries and supercapacitors in grid-scale packages. Implement advanced manipulation algorithms including fuzzy good judgment, model predictive control (MPC), or device getting to know-based totally techniques to optimize energy sharing and gadget performance. Extend the simulation to consist of renewable strength resources (e.g., solar, wind) and examine the position of the hybrid energy storage gadget in smoothing electricity fluctuations. The hybrid energy storage system, combining batteries and supercapacitors, offers a

promising solution for grid-scale power garage programs. By leveraging the strengths of both technologies, the device achieves advanced overall performance, performance, and reliability. The MATLAB

program evolved from this work gives a strong basis for additional studies and improvement in this field, contributing to the advancement of sustainable power systems.

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