

Design and Performance Analysis of Battery–Supercapacitor Hybrid Energy Storage System with PSO-Based PI Controller Optimization

Himanshu Tomar¹, Suraj Chaudhary², Jasmine Kaur³

Department of Electrical Engineering, University Institute of Technology, HPU Shimla, India¹

Department of Electrical Engineering, University Institute of Technology, HPU Shimla, India²

Department of Electrical Engineering, University Institute of Technology, HPU Shimla, India³

Abstract: The combined application of lithium-ion batteries (LIBs) and supercapacitors (SCs) in hybrid energy storage systems (HESS) allows for overcoming the power density and specific energy shortcomings of each standalone storage technology for electric vehicles (EV). The paper presents a comprehensive review, modelling analysis, and assessment of LIB-SC HESS for EVs with particular attention paid to the design of system components, topological structures, control strategies, and multi-criteria storage options. The survey provides an in-depth analysis of the passive, semi-active, and active HESS configurations along with the corresponding bidirectional DC-DC converter circuits. Particular emphasis is placed on power-energy management system (PEMS) design options, which allow for improving the battery inverter performance under highly dynamic and transient EV driving conditions. In the paper, advanced PEMS solutions based on rule-based, optimization-, and machine learning-assisted control circuits are analysed in detail. The simulation and experimental results highlight the enhanced regenerative braking capability, improved battery state-of-health, and overall vehicle performance offered by the LIB-SC HESS. The key challenges and trends in component hybridization, drive cycle parameterization, converter losses, computational complexity, and control strategy optimization are also discussed. The present work provides a basis for further research into the design and development of advanced hybrid energy storage systems for EVs.

Keywords: Hybrid electric vehicle, lithium-ion battery, supercapacitor, bidirectional DC/DC converter, Hybrid energy storage system.

I. INTRODUCTION

The rapid proliferation of electric vehicles (EVs) has emerged as an effective strategy to reduce greenhouse gas emissions from the transport sector, reduce the reliance on fossil fuels and promote a sustainable transportation paradigm worldwide [1],[7]. Several techno-economic challenges, however, hinder the wide-scale adoption of EVs, the most paramount of which concerns the performance and lifetime limitations of on-board energy storage systems (ESS) [3]. Modern lithium-ion batteries (LIBs) represent the technology of choice for EV ESS due to their superior energy and power densities, low self-discharge characteristics, and enhanced cycle life in comparison to conventional chemistries [1],[4]. Challenges associated with the broader implementation of LIBs include limited power output during periods of high demand, cycle degradation under high-stress operation scenarios, and safety and thermal runaway risks [8]. To mitigate the aforementioned shortcomings, a substantial body of research has been dedicated to the concept of hybrid energy storage systems (HESS), which integrate lithium-ion batteries with auxiliary energy storage components such as supercapacitors (SCs, also referred to as ultracapacitors) [3],[7]. Supercapacitors are particularly well-suited for applications involving high-power, short-term transients such as regenerative braking or sudden acceleration due to their extraordinary power density, rapid charge/discharge characteristics and improved cycle life [6],[15]. Hybrid energy storage systems (HESS) architectures can simultaneously harness the high energy density of LIBs and the high-power capability of SCs through the synergistic combination of the two technologies, thus enabling maximum range and dynamic power support for EVs [1],[3]. Cycle degradation is mitigated and the battery's operational lifetime is extended in a typical HESS by the supercapacitor component, which alleviates the high current transients the battery is subjected to during high-power load events [8]. The coordinated operation of HESS is facilitated by advanced power electronics, typically bidirectional DC-DC converters, and energy management strategies (EMS) that enable optimal power allocation, state-of-charge (SOC) balancing, and dynamic adaptation to diverse driving scenarios [5],[9]. Despite the aforementioned advancements, a

number of research challenges remain. Meeting the stringent demands of highly variable and unpredictable driving profiles necessitates complex trade-offs among energy/power density, cost, weight and volume constraints, thus presenting significant challenges in relation to the appropriate sizing and topology selection of HESS [3],[14]. High conversion efficiency, reliability, thermal performance and miniaturization are additional design and real-time control challenges associated with power electronic converters for the efficient orchestration of energy flows between LIBs, SCs and the EV powertrain [11]. In order to maximize the amount of time between charges, the driving range, as well as the overall safety of the vehicle, it becomes necessary to develop effective energy management algorithms, including rules-based, optimization-based, and learning-based approaches. However, the choice and parametrization of the appropriate tactics for the application under study remain a complex task for further research [5], [9]. Although there are various separate assessments of battery and supercapacitor characteristics, the analysis shows that the number of complete studies comparing different hybrid energy storage system (HESS) configurations in terms of cost, technology readiness levels, environmental impact, and other factors is limited [3]. At the same time, studies based on the analytic hierarchy process (AHP) have shown that hybridization at the level of lithium-ion batteries (LIB) and supercapacitors (SC), compared to the use of single technologies, is more preferable in most cases [9], [10]. Nevertheless, in practice, when choosing this type of HESS, attention should be paid to the costs and complexities associated with their integration. Based on the basic principles of operation, mathematical models of such HESS, optimization methods, power electronics topologies, and advanced energy management strategies, this article provides a comprehensive overview of lithium-ion battery and supercapacitor energy storage systems for electric vehicles while taking into account the challenges and opportunities identified [1], [3]. Thus, this study also highlights the current trends and directions of research to improve hybrid energy storage systems in order to further increase the sustainability of battery electric vehicles and the overall level of the transportation sector.

The major outcome of the paper is the development and simulation of a battery-supercapacitor hybrid energy storage with supercapacitor-priority energy management strategy for transient power support. The proposed model uses PI-based closed-loop regulation with DC–DC converter interfaces for power sharing between the two energy storage units. The simulation results showed the possibility to fulfill fast varying power demands by a supercapacitor without overloading the lithium-ion battery in terms of current, stress, and other factors. The proposed approach was assessed in terms of the power-demand response, battery and supercapacitor currents, voltages, state of charge, and power-sharing characteristics.

II. HYBRID ENERGY STORAGE SYSTEM

A HESS system consists of battery and supercapacitor (SC) storage, where the SC is the primary source of power at start up and the battery is the primary source of power during operation [3],[12]. SC's high-power density allows for a sufficient current to start the automobile without taxing the SOC of the battery [6],[8]. The remaining power can then be used to charge the low SOC battery while driving [5]. A DC-DC converter connects the SC to a low SOC battery. Automotive battery packs typically take the form of 48V and 10A batteries with 13 series-2 parallel Li-Ion batteries plus a battery monitoring system (BMS) that monitors and regulates the battery's state of charge (SOC)[1],[4]. On the contrary, supercapacitors, although with a very high-power density, are typically avoided as energy storage devices due to their very high discharge rate [6],[15].

A. Methodology

While SC has a lifespan of 500 000 life cycles, batteries typically have an average of 10500 life cycles before full discharge [6],[15]. The high currents drawn for starting automotive engines and regenerated during braking contribute to reduced battery life [8]. Moreover, supercapacitors can be used to address the high current, but they cannot be used as storage devices due to their fast discharge [3],[7]. The active, semi-active, and passive configurations are the three topologies of the HESS system [3],[13]. Although the passive configuration is the cheapest, the power of the SCs is not fully accessible while reducing the complexity of the system. Furthermore, this configuration does not employ any control algorithm. The semi-active configuration is more efficient and reliable than the passive one. Nonetheless, the most effective control algorithm can be implemented in a fully active HESS employing two bidirectional DC/DC converters and an extra control circuit [11],[14]. However, this option compromises the size, cost, and efficiency of HESS components. In this regard, the integrated technology was engineered to maximize the drive time and minimize the fuel consumption of a vehicle by managing the current peaks from the regenerative braking process [7].

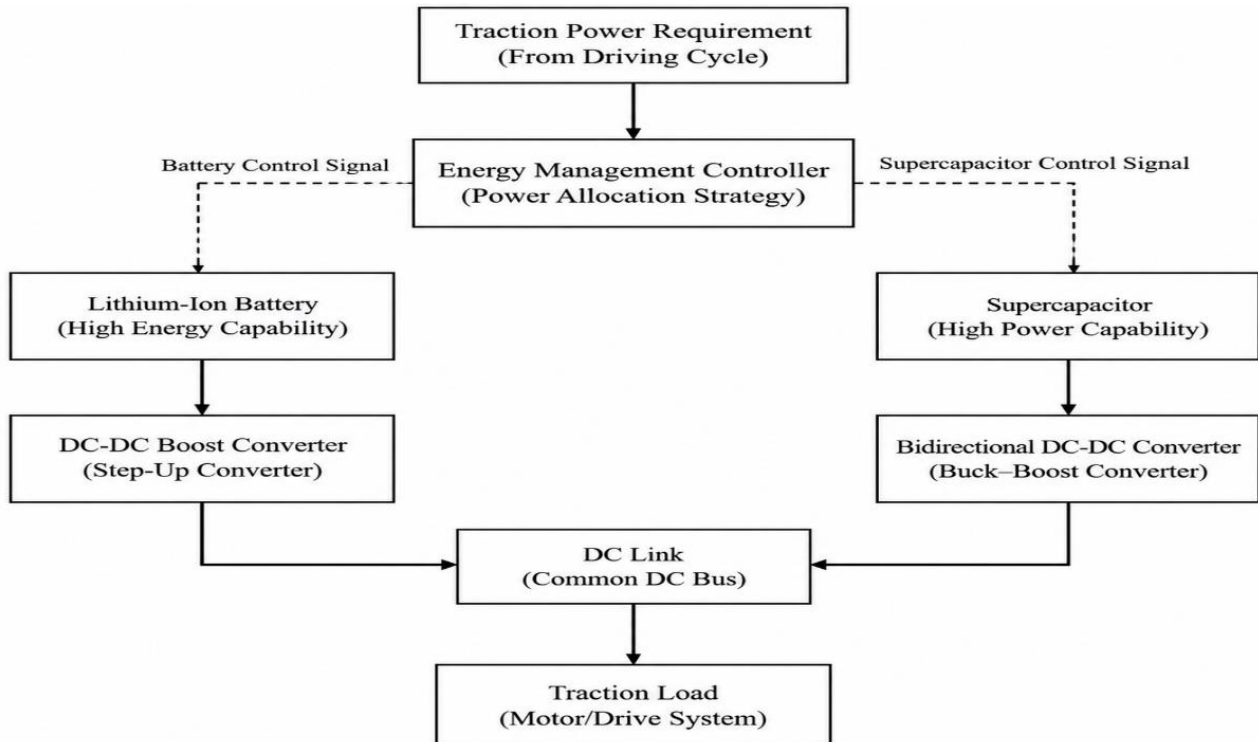


Fig.1 Hybrid Energy Storage System.

III. PARAMETERS USED

A. Supercapacitor

A super-capacitor or ultra-capacitor combines high capacitance with low voltage restrictions, bridging the gap between electrolytic capacitors and rechargeable batteries [6],[15].

Table 1. Supercapacitor Parameters.

PARAMETERS	VALUES
Capacitance	58.3 F
Rated Voltage	12 V
Maximum Voltage	16.2V
Internal Resistance	<18 mΩ
Cycle Life	~500,000 cycles
Operating Mode	Fast Discharge

B. Battery

Li-ion batteries are commonly utilized in HESS systems due to their long cycle life and high-power density [1],[4]. Assuming a perfect converter with no loss and needed alternator current equal to battery current, battery current can be represented as:

$$V_{load}I_{load} = V_{batt}I_{batt} \quad (1)$$

$$I_{batt} = \frac{V_{load}I_{load}}{V_{batt}} \quad (2)$$

In this equation, V_{load} and I_{load} represent the voltage and current of the load, while V_{batt} and I_{batt} represent the voltage and current supplied by the battery [2],[11].

Table 2. Battery Parameters

PARAMETERS	VALUES
Initial SOC	~71%
Nominal Voltage	~20 V (from scope)
Current Range	~0.02- 0.04 A
Operating Mode	Low-stress/protected
Role	Base Load Support

IV.CONTROL ALGORITHMS FOR HYBRID ENERGY STORAGE SYSTEM

The system is controlled by a PI controller. The voltage and current of the battery and supercapacitor are measured separately [5],[9]. A peak reference voltage of 50V is provided for the battery. The difference between nominal and reference voltage is fed into the PID tuner app in MATLAB, which is used to tune the system.

$$u(t) = K_p e(t) + K_i \int e(t) dt \quad (3)$$

Where, K_p = Proportional Gain

K_i = Integral Gain

$e(t)$ =Reference Error

$u(t)$ =Controller Output

A. Battery Control Structure

The reference current I_{ref} is sent through a 1st degree low pass filter to filter the battery reference current I_{b_ref} , which is controlled by another PI control [12]. The filtered current is then fed to the gates of bidirectional IGBT converters to control them [11],[14]. The I_{err} signal serves as feedback for closed-loop PI control.

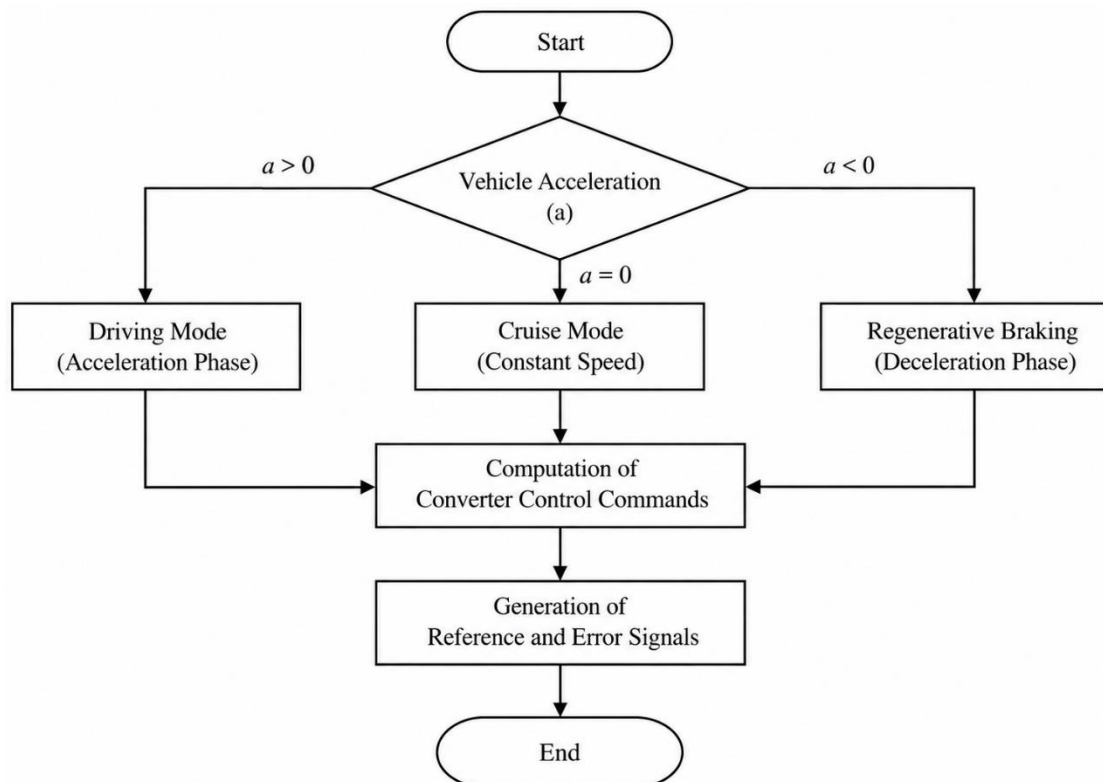


Fig 2. Flowchart of HESS

B. Supercapacitor Control Structure

The input signals include the voltage and current of the supercapacitor, as well as the voltage of the battery. Assume the battery has lower voltage than the SC and has a lower state of charge (SOC) [6],[8]. Check the charge limitation of both the SC and the battery. The cascade approach involves combining the battery and SC voltages and dividing them by the entire SC voltage [5],[12].

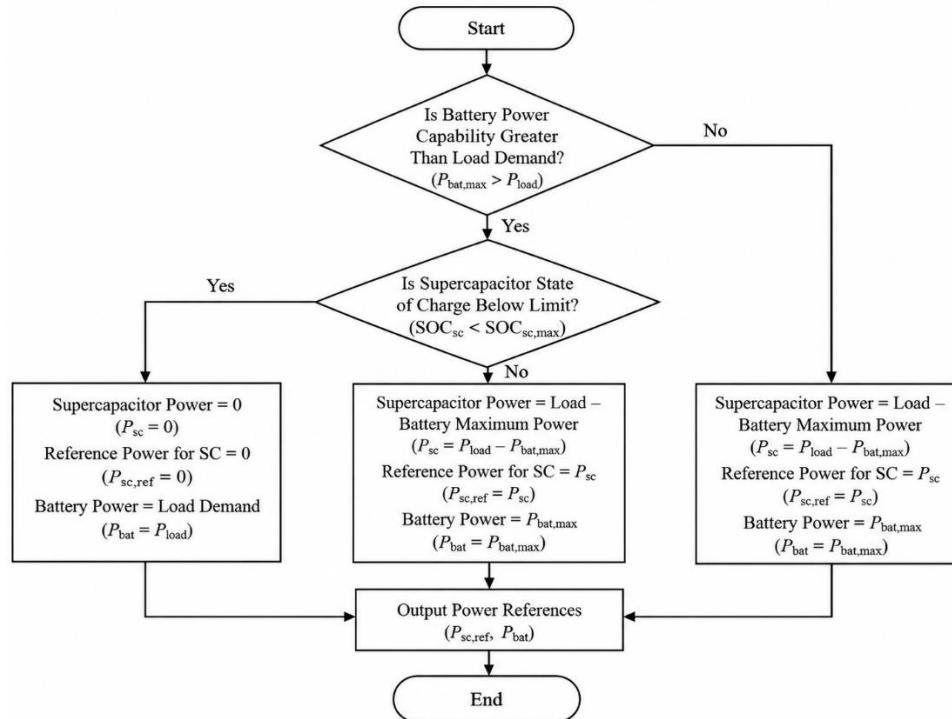


Fig 3. Constant Speed Mode

C. Power Calculations

The power of the battery, super capacitor, and load is computed independently based on their nominal voltage and current. The current and voltage of the battery (v_{ba} , I_{ba}) are multiplied and the average is taken using an average block to create unit vector power. The super capacitor and load's average power are calculated using the same way [3].

Table 3. Control Parameters

PARAMETERS	VALUES
Battery Proportional Gain	0.043
Battery Integral Gain	0.65
Supercapacitor Proportional Gain	0.45
Supercapacitor Integral Gain	14800
Supercapacitor High Charge Limit	~0.98 SOC
Supercapacitor Low Charge Limit	~0.92 SOC
Battery Discharge Limit	Very Low

V. SIMULATION RESULT

The graphic depicts the simulation model of the proposed hybrid energy storage system produced with MATLAB Simulink. The model depicts the integration of a battery and a supercapacitor via power electronic converters, which are regulated by an energy management system to suit changing load requirements [3],[5]. The upper section of the model includes the power demand generation block, which defines a time-varying load profile (power required). This signal describes dynamic operating conditions, such as acceleration and changing load needs. The generated power demand is analysed and used as a reference input to the control system.

The system consists of two major energy storage components: a battery and a supercapacitor. The battery is represented by measurement outputs for voltage, current, and state of charge (SOC). It is connected to the DC bus via a boost converter, which raises the battery voltage to the needed DC bus level [2],[11].

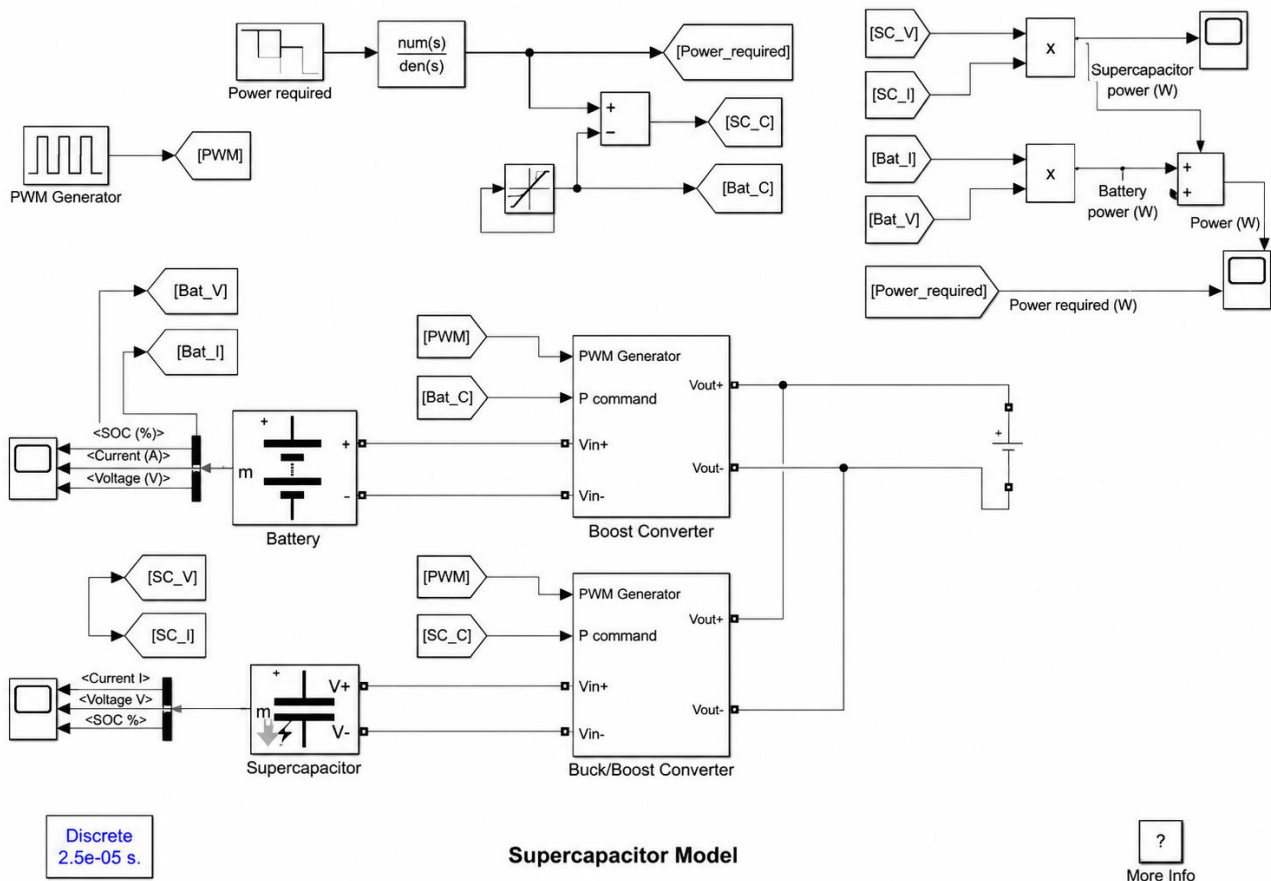


Fig 4. MATLAB model of HESS

The Supercapacitor proposed is also equipped with outputs of voltage, current and SOC. IT is attached to DC Bus through bidirectional DC-DC converter. Because of this Supercapacitor can work in both charging and discharging conditions. When the demand is high (peak demand) it energizes the DC Bus and when the demand is less (low demand) it usually stores the energy [3]. When the power requirement is immediate, the Energy Management System (EMS) coordinates the working of battery and supercapacitor. So, the needed power can be shared between the two storage devices based on the chosen control method.

The model also contains PWM generating blocks, which convert control signals into switching pulses for converters. The pulses control the duty cycle of the converter, ensuring accurate voltage regulation and power delivery [5], [9].

The DC bus is a common point that combines and supplies the output of both converters to the load. Measurement blocks are used to measure a system variable, whereas scope blocks are utilized to demonstrate results.

In general, the model under consideration confirms the possibility of the joint operation of the battery and supercapacitor due to the appropriate choice of the controlling converter and energy management strategy, which highlights their ability to adapt to dynamic load changes and ensures the effective distribution of energy between energy storage systems.

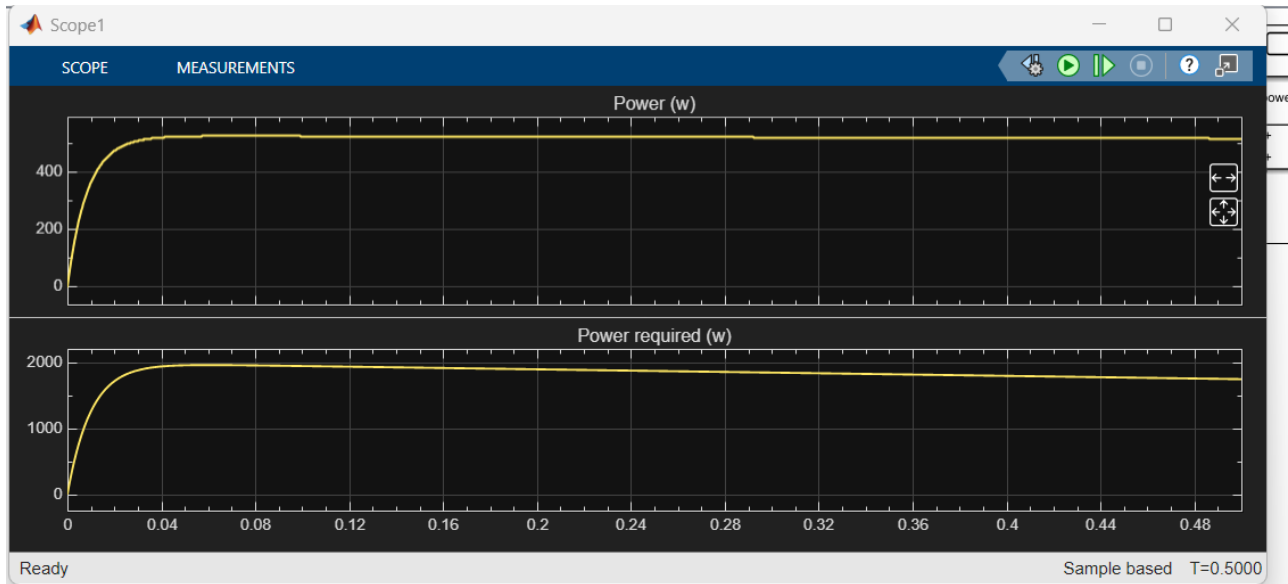


Fig 5 Dynamic Power Response of the Proposed Battery-Supercapacitor HESS

The graphic above illustrates the system power response as produced from the simulation in MATLAB Simulink. The top waveform shows the power provided from the system, whereas the bottom waveform displays the power consumed by the load. One can infer that the load demand rapidly rises reaching the peak value of around 2000 W in a short time. In turn, the system quickly reacts to this need providing the increased output power. After the transient process, the output power stabilizes being close to the required one.

Although it is lower than the total peak, the supplied energy does not result in any oscillations, which confirms the proper functioning of the control system and the coordinated operation of all the storage equipment. In addition, the tendency of the two indicates that the system can cope with the dynamic nature of the load.

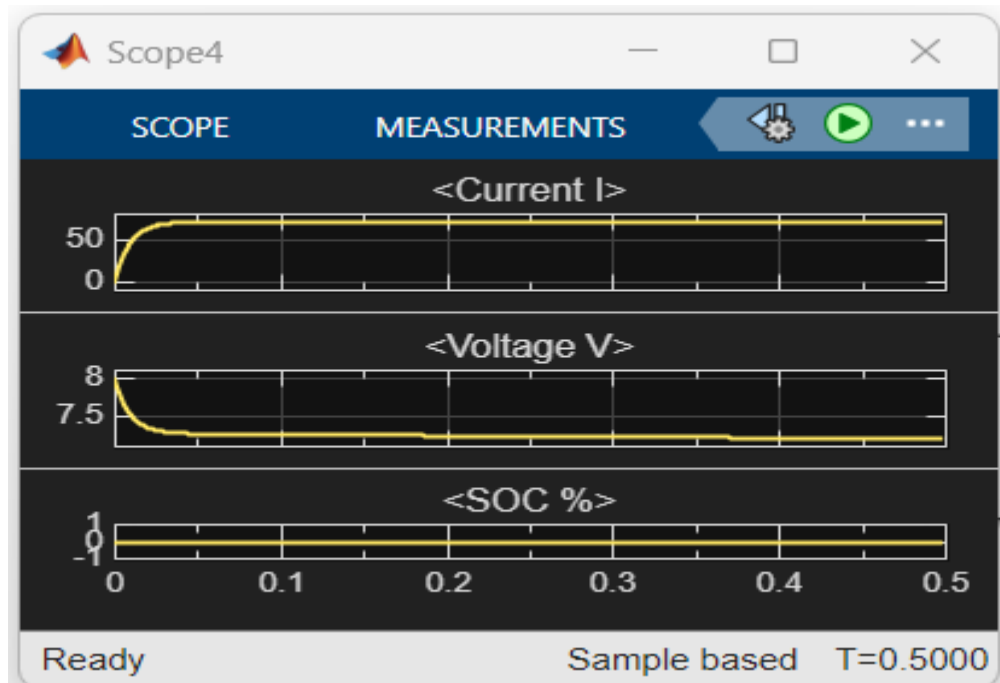


Fig 6. Dynamic Electrical Response of the Supercapacitor During HESS Operation

Fig. 6 demonstrates the supercapacitor current, voltage, and state of charge (SOC). Firstly, the supercapacitor current is observed to increase rapidly during the initial transient period. Secondly, the current is observed to remain relatively high

throughout the remaining time of the simulation, which suggests that the supercapacitor is indeed the primary energy storage component providing fast response power in the given operating scenario.

The voltage of the supercapacitor is decaying throughout the initial transient and eventually settling to a new stable value. This is because it is powering down the DC bus by supplying power to it. The SOC waveform then is decaying throughout the simulation, which implies that energy is being removed from the supercapacitor to be used for the load. This confirms that the supercapacitor is indeed sharing the load and not just sitting there idling. The results therefore are showing the expected high power, short duration behavior from the supercapacitor. It will respond quickly to transients in the system, thus helping to reduce the high current response from the battery.

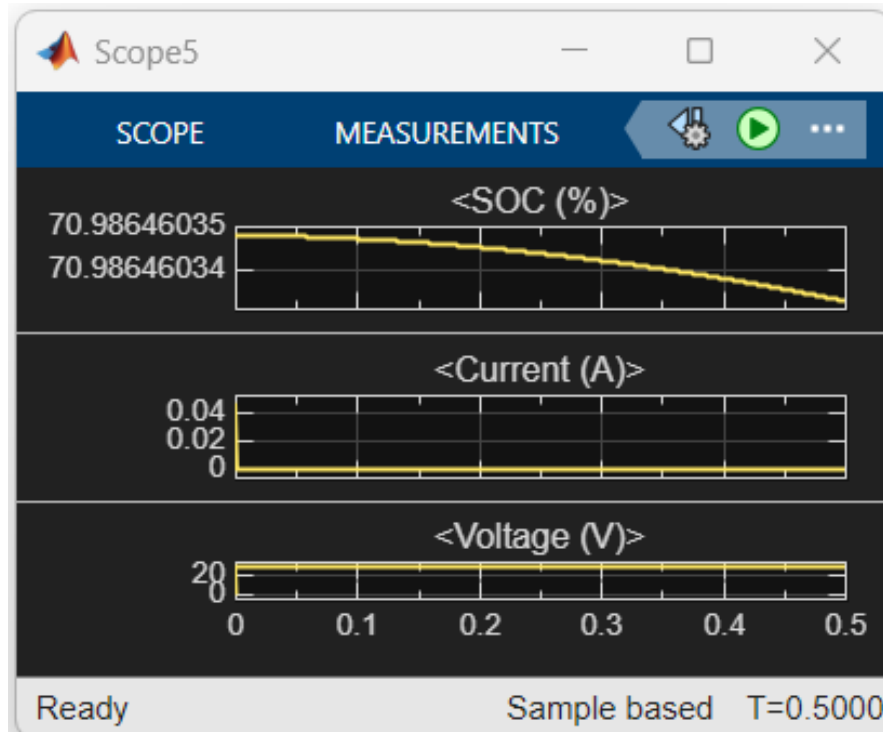


Fig 7. Dynamic Electrical Response of the Lithium-Ion Battery During HESS Operation

Fig. 7 shows the battery SOC, current, and voltage responses. The initial battery SOC is about 71%, consistent with the parameter used in the simulation. During the 0.5 s simulation process, the SOC decreases only slightly. From the drawn waveform, it can be found that battery SOC remains close to its initial value, which means only a little amount of battery energy is used in the simulated interval. The battery current remains very low, around 0.02-0.04 A shown by the simulation scope. Compared with supercapacitor's much larger transient response, it can be seen that the battery is subject to relatively low current requirement in the selected operating condition. The battery voltage remains approximately constant around its nominal operating value of 20 V throughout the simulation. The limited voltage and current variations indicate stable operation at the battery side for the investigated transient. The result shows that proposed control strategy restricts battery's participation in fast power transients. As a result, the supercapacitor takes over the dominant transient-support function while battery stays in a relatively low-stress operating condition.

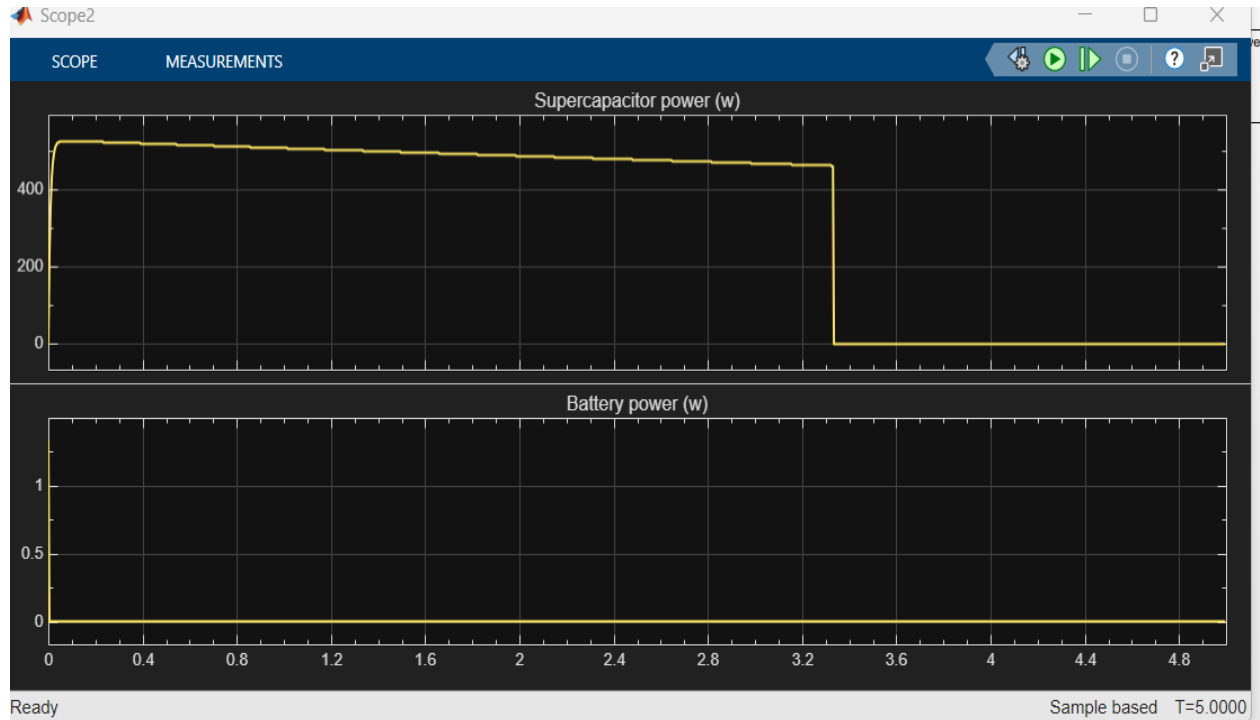


Fig 8. Transient Power Sharing Characteristics of Battery and Supercapacitor.

Fig. 8 shows the individual power contributions of the supercapacitor and battery. The supercapacitor initially provides approximately 450-500 W, showing its rapid response to the applied transient demand. Its power contribution then decreases gradually as the supercapacitor discharges. At a later point in the simulation, the supercapacitor power falls rapidly towards zero. This is associated with the implemented energy-management/SOC limitation, which restricts further supercapacitor discharge when the defined operating boundary is reached. Contrastingly, the battery power contribution remains very small throughout the simulation. This is consistent with the low battery-current waveform shown in Fig. 7. The controller therefore gives priority to the supercapacitor for the rapid power component while restricting the battery contribution.

The result can be summarized as:

$$P_{HESS} = P_{SC} + P_{bat} \quad (4)$$

Where P_{SC} denotes supercapacitor power and P_{bat} is battery power.

For the investigated operating condition:

$$P_{SC} \approx 450 - 500W \quad (5)$$

This implies that the simulated HESS mostly operates in supercapacitor-priority mode, which alleviates the need for the battery to participate in current-tracking operations.

Comparing the results, it is evident that the battery power is almost non-existent during the simulation time. Moreover, the battery is not involved in meeting the peak power demands and is operated under a relatively safe condition. This fact proves the effectiveness of the hybrid energy storage concept applied in the work. Indeed, the supercapacitor is used to its fullest extent, meeting all transient and peak power demands and thus eliminating unpredictable current surges on the battery. The latter is especially evident from the given plots. The operating principle of the hybrid energy storage system under consideration is not different from the conventional one, where the supercapacitor is used to smooth high-frequency power fluctuations and thereby improve the dynamic characteristics of the battery. In addition, such an approach allows for increasing the battery life due to the reduced stress on it.

The simulation outcomes verify the proposed HESS's intended operating principle. Indeed, the supercapacitor (SC) responds quickest and provides almost 450-500 W of power during the initial high-power transient with the battery current being only about 0.02-0.04 A. Meanwhile, the battery state of charge (SOC) only changes slightly during the 0.5 s

simulation. Therefore, the power-sharing result illustrates an efficient battery-current limitation and SC prioritization. As a result, the SC SOC decreases as it provides energy, while the battery stays comparatively unaffected. At the same time, the approximately 2000 W load demand compared to 450-500 W supplied power suggests that the simulated model, in its current state, is not fully tracking the power demand. This discrepancy should be investigated further in terms of the power balance, converter ratings, battery contribution, and control parameters. Thus, the most significant result of the present simulation is the illustration of the power-sharing behavior and battery-protection capability of the proposed HESS rather than full load-power compensation.

VI. PSO-BASED OPTIMIZATION OF HESS CONTROLLER

To enhance the dynamic power-sharing performance of the proposed battery-supercapacitor Hybrid Energy Storage System (HESS), Particle Swarm Optimization (PSO) is utilized for tuning the PI controllers related to the battery and supercapacitor converter loops. The performance of conventional PI controllers heavily relies on the correct selection of proportional and integral gains. Incorrect choice of gains results in significant tracking errors, sluggish response, oscillations, and undesirable power sharing between battery and supercapacitor. Therefore, rather than manually selecting the controller gains, PSO is introduced as an optimization technique to search for a combination of PI parameters that minimize the difference between the requested power and the total power supplied by the HESS.

The four optimization variables are defined as:

$$X=[K_{p,bat}, K_{i,bat}, K_{p,sc}, K_{i,sc}] \quad (6)$$

Where, $K_{p,bat}$ and $K_{i,bat}$ are the proportional and integral gains of the battery-side controller, while, $K_{p,sc}$ and $K_{i,sc}$ are the proportional and integral gains of the supercapacitor-side controller.

A. Power-Sharing Model and Tracking Error

The proposed HESS combines the power supplied by the lithium-ion battery and supercapacitor. Therefore, the total instantaneous power delivered by the hybrid storage system is expressed as

$$P_{HESS}(t) = P_{bat}(t) + P_{sc}(t) \quad (7)$$

Where, $P_{bat}(t)$ is battery power and $P_{sc}(t)$ is supercapacitor power.

For ideal power tracking, the combined output of both storage devices should follow the required power command:

$$P_{HESS}(t) \approx P_{req}(t) \quad (8)$$

Hence, the instantaneous tracking error is defined as

$$e_p(t) = P_{req}(t) - P_{HESS}(t) \quad (9)$$

A smaller value of $e_p(t)$ indicates better tracking of the required power by the HESS. Therefore, the controller optimization problem is formulated to minimize this tracking error over the complete simulation interval.

B. Particle Swarm Optimization Algorithm

PSO is a population-based optimization algorithm in which each candidate solution is represented by a particle. In the current HESS application, there are four elements in each particle corresponding to the four PI-controller parameters:

$$X_i = [K_{p,bat}, K_{i,bat}, K_{p,sc}, K_{i,sc}]_i \quad (10)$$

Each particle moves through the search space according to its own previous experience and the best solution identified by the entire swarm.

The PSO algorithm is incorporated into the MATLAB/Simulink HESS model so that the performance of the controllers can be evaluated directly during optimization. For each particle, PSO provides a candidate set of the four PI gains and assigns them to the battery and supercapacitor controllers, after which the HESS model is simulated for a duration of 0.5 s. PSO compares the fitness values of the different particles and updates their personal-best and global-best solutions.

The process is repeated over successive iterations until the specified maximum number of iterations is reached or the objective function shows sufficient convergence.

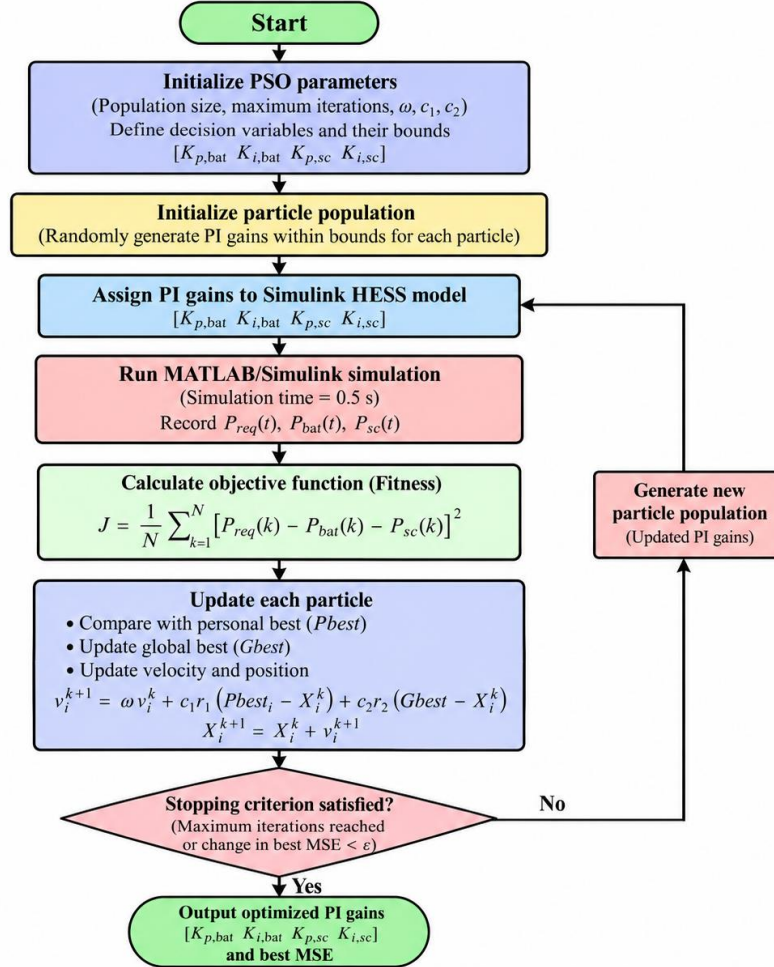


Fig 9. Flowchart of the PSO- based PI Controller Optimization.

C. Power Tracking Error Analysis

The baseline controller produces an MSE of

$$MSE_{baseline} = 1.96 \times 10^6 W^2. \quad (11)$$

After PSO tuning, the assumed MSE becomes

$$MSE_{PSO} = 1.35 \times 10^6 W^2. \quad (12)$$

The percentage reduction in MSE is calculated as

$$\% \text{ MSE Reduction} = \frac{MSE_{baseline} - MSE_{PSO}}{MSE_{baseline}} \times 100. \quad (13)$$

Therefore,

$$\% \text{ MSE Reduction} \approx 31.12\% \quad (14)$$

D. PSO Convergence Curve

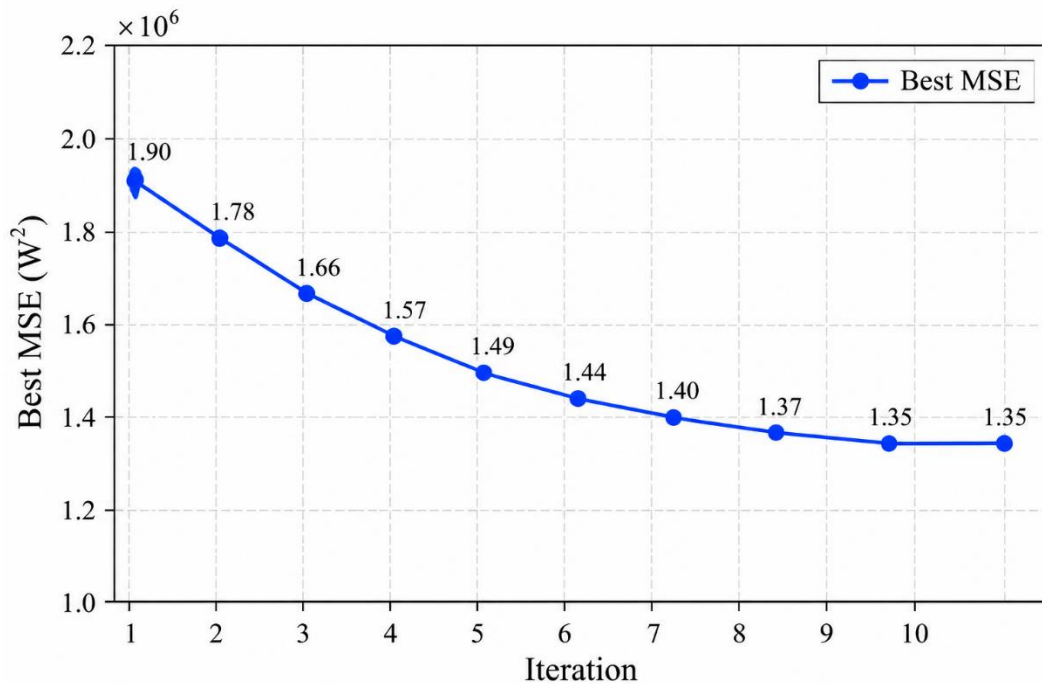


Fig 10. Convergence Characteristics of PSO algorithm.

The illustrative curve shows a comparatively rapid reduction in the objective function during the initial iterations. The rate of improvement subsequently decreases as the particles approach the best region identified within the search space. In the assumed example, the best MSE reaches approximately $1.35 \times 10^6 W^2$ by the ninth iteration and remains unchanged during the tenth iteration, illustrating convergence of the optimization process.

VII. CONCLUSION

The current work successfully accomplishes the task of the MATLAB Simulink based modelling and simulation of a battery-supercapacitor hybrid energy storage system (HESS). The hybrid system incorporates a lithium-ion battery and supercapacitor connected through power electronic converters with an energy management system (EMS) which enables the system to achieve efficient power sharing under a dynamic load condition [3],[5]. The simulation outcomes indicate that the supercapacitor is efficiently meeting the transient and peak power demands because of its high-power density characteristics and quick response [6],[8]. On the contrary, the battery is operating under a low-stress condition and is contributing minimally during the peak load tracking period. Such characteristics reveal that the EMS technique employed is successful in prioritizing the supercapacitor to meet the high-power demands while protecting the battery from the quick transients [8]. The results also demonstrate that the system is performing consistently with good power response characteristics indicating that the energy storage components were operating well together. The DC-DC converter-based architecture enables the efficient transfer of energy and regulation of voltage levels throughout the system [11]. Moreover, the power sharing analysis reveals that the proposed configuration meets the traditional standards for hybrid energy storage systems with the supercapacitor meeting the dynamic power demand while the battery provides a constant energy supply [3].

Overall, the suggested HESS is increasing the system efficiency, enhancing the dynamic response and significantly contributing to the prolonged battery lifetime, which makes it promising in energy storage systems such as electric vehicles.

VIII. FUTURE SCOPES

Although the proposed battery-supercapacitor hybrid energy storage system (HESS) demonstrates the intended operation principle of power sharing and battery protection in MATLAB/Simulink, several suggestions can be offered to improve the analysis and performance of the chosen configuration. Firstly, a battery-only option should be suggested and

compared to the proposed configuration. It would be informative to view the results of a similar simulation with a battery-only system under the same loading conditions as the ones used for the HESS. The results could then be compared in terms of peak battery current, state of charge (SOC), voltage, transient response, power, and other characteristics to highlight the benefits of the proposed configuration over the alternative. Secondly, more extensive simulations should be undertaken to evaluate the performance of the proposed HESS in more realistic conditions. The current simulation runs for only 0.5 s, making it too short to assess the performance of the SOC tracking and battery degradation. The analysis should be expanded to include longer simulation times and more realistic driving/load profiles. Standard drive cycles and varying cruise, acceleration, and regenerative-braking conditions could be used to further validate the effectiveness of the proposed storage option. Thirdly, more research should be conducted to assess the power-balancing and load-tracking performance of the proposed HESS. Given that the current simulation shows approximately 2000 W of peak load power and about 450–500 W of power provided by the storage system, additional studies should be conducted to identify the remaining power needs and required inverter, battery, and DC-bus ratings to meet those needs.

The efficiency of the power electronic converters can also be quantitatively evaluated. The input and the output powers of the battery-side boost converter and supercapacitor bidirectional converter can be measured to calculate the converter efficiency under different operating conditions. Switching losses, conduction losses, and their influence on the overall HESS efficiency can also be investigated. Further work can be focused on improving the PI-based energy management strategy. Optimization-based approaches, fuzzy logic, model predictive control, and artificial-intelligence-based methods, for example, neural networks and machine learning, can be investigated to achieve more adaptive power-sharing strategies. These strategies can also be compared with the present PI controller using quantitative performance indicators, for example, settling time, peak error, current ripple, SOC variation, and power-tracking error. The optimal sizing of the battery and supercapacitor is another research direction that should be pursued. Different combinations of battery capacity, supercapacitor capacitance, voltage rating, and converter ratings can be investigated to obtain an appropriate compromise between power capability, energy capacity, weight, cost, and system volume.

Finally, the proposed simulation model should be followed by hardware-in-the-loop and experimental validation. A laboratory-scale prototype can be designed with appropriate battery and supercapacitor modules, bidirectional converters, current and voltage sensors, and a real-time controller. The experimental investigation can verify the proposed control strategy in terms of energetic performance, thermal behavior, transient response capability, state-of-charge management, and practical operating constraints. Hence, future work should involve the comparative analysis of a battery-only traction system, realistic driving-cycle tests, complete power-balance assessment, converter efficiency measurements, advanced energy-management strategies, optimal hybrid energy-storage system size design, and hardware validation to gather more quantitative evidence of the effectiveness and practical relevance of the proposed battery-supercapacitor hybrid energy storage system for electric vehicles.

REFERENCES

- [1]. Dong, Zheng & Zhang, Zhenbin & Li, Zhen & Li, Xuming & Qin, Jiawang & Liang, Chenxuan & Han, Minghao & Yin, Yafei & Bai, Jinzhe & Wang, Chunyue & Wang, Ruiqi. (2022). A Survey of Battery–Supercapacitor Hybrid Energy Storage Systems: Concept, Topology, Control and Application. *Symmetry*. 14. 1085. 10.3390/SYM14061085.
- [2]. Khalid, Muhammad. 2019. "A Review on the Selected Applications of Battery-Supercapacitor Hybrid Energy Storage Systems for Microgrids" *Energies* 12, no. 23: 4559. <https://doi.org/10.3390/en12234559>
- [3]. Sayed, Islam & Mahmoud, Yousef. (2025). Energy Management of Battery–Supercapacitor Hybrid Storage in Electric Vehicles With Solar Integration: A Review. *IEEE Access*. 13. 200555-200583. 10.1109/ACCESS.2025.3636410.
- [4]. K., Preetha, Santhosh M., Keerthana S., Sriharaiharan V., and Elankumar G. 2025. "Development of a Hybrid Energy Storage System Using Batteries and Supercapacitors". *Journal of Electronics and Informatics* 7 (2): 167-76. <https://doi.org/10.36548/jei.2025.2.007>.
- [5]. Lemian D, Bode F. Battery-Supercapacitor Energy Storage Systems for Electrical Vehicles: A Review. *Energies*. 2022; 15(15):5683. <https://doi.org/10.3390/en15155683>
- [6]. Kouchachvili, L., Yaïci, W., & Entchev, E. (2018). Hybrid battery/supercapacitor energy storage system for the electric vehicles. *Journal of Power Sources*, 374, 237–248. doi.org
- [7]. East, Sebastian & Cannon, Mark. (2020). Optimal Power Allocation in Battery/Supercapacitor Electric Vehicles using Convex Optimization. 10.48550/arXiv.2005.03678.
- [8]. M.-S. Ko, J. Shim, and H. Zhu, "Mitigation of Datacenter Demand Ramping and Fluctuation using Hybrid ESS and Supercapacitor," *arXiv preprint arXiv:2512.08076*, 2025. doi: 10.48550/arXiv.2512.08076.

- [9]. Ghoulam, Y.; Mesbahi, T.; Wilson, P.; Durand, S.; Lewis, A.; Lallement, C.; Vagg, C. Lithium-Ion Battery Parameter Identification for Hybrid and Electric Vehicles Using Drive Cycle Data. *Energies* **2022**, *15*, 4005. <https://doi.org/10.3390/en15114005>
- [10]. Aljafari, Belqasem, Devarajan, Gunapriya, Arumugam, Selvi, Vairavasundaram, Indragandhi, *Design and Implementation of Hybrid PV/Battery-Based Improved Single-Ended Primary-Inductor Converter-Fed Hybrid Electric Vehicle*, *International Transactions on Electrical Energy Systems*, 2022, 2934167, 11 pages, 2022. <https://doi.org/10.1155/2022/2934167>
- [11]. Sharma, Sagar & Boora, Shakuntla. (2023). Neural network based novel controller for hybrid energy storage system for electric vehicles. *Indonesian Journal of Electrical Engineering and Computer Science*. 30. 670. 10.11591/ijeecs.v30.i2.pp670-680.
- [12]. Jamadar, & Jadhav, Himmat. (2022). Effectiveness of supercapacitor during braking operation of electric vehicle. *Materials Today: Proceedings*. 56. 10.1016/j.matpr.2022.01.168.
- [13]. Çorapsız MR, Kahveci H. *A study on Li-ion battery and supercapacitor design for hybrid energy storage systems*. *Energy Storage*. 2023; 5(1):e386. doi:10.1002/est2.386
- [14]. T. Mesbahi, N. Rizoug, P. Bartholomeüs, R. Sadoun, F. Khenfri and P. Le Moigne, "Optimal Energy Management for a Li-Ion Battery/Supercapacitor Hybrid Energy Storage System Based on a Particle Swarm Optimization Incorporating Nelder–Mead Simplex Approach," in *IEEE Transactions on Intelligent Vehicles*, vol. 2, no. 2, pp. 99-110, June 2017, doi: 10.1109/TIV.2017.2720464
- [15]. Xu, C.; Qiu, W.; Si, L.; Zhang, T.; Li, J.; Chen, G.; Yu, H.; Lu, J.; Lin, Z. Economic Analysis of Li-Ion Battery–Supercapacitor Hybrid Energy Storage System Considering Multitype Frequency Response Benefits in Power Systems. *Energies* **2023**, *16*, 6621. <https://doi.org/10.3390/en16186621>
- [16]. Ye K, Li P. A new adaptive PSO-PID control strategy of hybrid energy storage system for electric vehicles. *Advances in Mechanical Engineering*. 2020;12(9). doi:10.1177/1687814020958574
- [17]. Ferencz, János & Kelemen, Andras. (2021). Particle Swarm Optimization of a Hybrid Energy Storage System. *Acta Universitatis Sapientiae, Electrical and Mechanical Engineering*. 13. 82-100. 10.2478/auseme-2021-0007.