AUIQ Technical Engineering Science

Volume 3 | Issue 1 Article 3

2026

Design and Analysis of a Hybrid Energy Storage System for a BLDC Motor in Lightweight Electric Vehicles

Mohammed Turki Baidar
Department of Electrical Engineering, University of Mosul, Iraq, Mohammed.23enp23@student.uomosul.edu.iq

Yasir M. Y. Ameen
Department of Electrical Engineering, University of Mosul, Iraq, Yasir_752000@uomosul.edu.iq

Recommended Citation

Baidar, Mohammed Turki and Ameen, Yasir M. Y. (2026) "Design and Analysis of a Hybrid Energy Storage System for a BLDC Motor in Lightweight Electric Vehicles," *AUIQ Technical Engineering Science*: Vol. 3: Iss. 1, Article 3.
DOI: https://doi.org/10.70645/3078-3437.1054

AUIQ TECHNICAL ENGINEERING SCIENCE 2026;3:46–55

ORIGINAL STUDY

Design and Analysis of a Hybrid Energy Storage System for a BLDC Motor in Lightweight Electric Vehicles

Mohammed Turki Baidar *, Yasir M. Y. Ameen

Department of Electrical Engineering, University of Mosul, Iraq

ABSTRACT

Internal Combustion Engine (ICE) vehicles are being replaced by electric vehicles to decrease fossil fuel depletion, pollution, and the effects of global warming. However, in electric vehicles, the primary concern is battery power consumption and lifespan, which affects the driving range. This study presents a hybrid energy storage system (HESS) comprising a lithium-ion battery and super capacitor array, designed and simulated in MATLAB/Simulink to enhance the range and performance of lightweight electric motorcycles powered by 2.5 kW BLDC motors. A 16-cell super capacitor module (3V, 3000F per cell) achieving 187F total capacitance was integrated with a 44.4V battery through a bidirectional DC-DC converter. Simulation results demonstrated that during startup acceleration, the super capacitor delivered peak currents up to 300A while battery current went to a steady value at 12A, reducing battery stress by 25 times. During variable torque transitions (half to full rated load), the super capacitor handled transient power peaks reaching 1700W, while battery power ramped gradually to 1150W. Most significantly, regenerative braking analysis revealed the super capacitor's state-of-charge increased by 0.85% (from 97.6% to 98.45%) within two seconds, compared to only 0.035% for battery-only systems under identical conditions, representing a 24-fold improvement in energy capture efficiency. These results confirm that the proposed HESS effectively isolates transient load fluctuations from the battery, including regenerative braking capability, and providing a practical pathway toward extended battery lifespan and improved vehicle range in lightweight electric vehicle applications.

Keywords: Electric vehicle (EV), Hybrid energy storage system (HESS), Super capacitor (SC), State of charge (SOC)

1. Introduction

Electric vehicles are becoming more popular due to their low cost and environmental benefits. Battery-only systems face performance issues under changing load demands. Hybrid systems using both batteries and super capacitors offer a better solution by combining energy storage and fast power delivery [1]. The integration of Hybrid Energy Storage System (HESS) helps solve key issues in electric vehicles such as handling peak power during acceleration, recovering energy from braking, and reducing battery stress to extend its lifespan [2]. Super capacitors provide high power density, fast charge and discharge, and long cycle life, making them well-suited for handling sudden power demands and capturing energy during braking [3]. HESS improves regenerative braking efficiency because super capacitors can handle high charging currents better than battery-only system [4]. Different HESS topologies have been proposed, mainly divided into passive parallel setups and active types that use DC-DC converters. Each type offers a trade-off between control complexity, cost, and performance [5]. Passive HESS setups are simpler and more cost-effective but have limited control over power flow. Semi-active and fully active systems offer better power management but come with added

Received 24 August 2025; revised 25 November 2025; accepted 27 November 2025.
Available online 19 January 2026

* Corresponding author.
E-mail addresses: mohammed.23enp23@student.uomosul.edu.iq (M. T. Baidar), Yasir_752000@uomosul.edu.iq (Y. M. Y. Ameen).

https://doi.org/10.70645/3078-3437.1054

complexity [6]. Choosing the right DC-DC converter topology is important in active HESS designs. Bidirectional converters allow better control but increase system complexity and cost [7]. The performance of a HESS largely depends on proper sizing of its components to balance energy, power, weight, volume, and cost, while also matching the vehicle's needs and driving conditions [8]. Advanced power and energy management strategies are key to managing power flow between storage units based on driving conditions. These strategies include rule-based methods, optimization approaches, and machine learning algorithms [9]. Understanding aging and degradation in batteries and super capacitors is important for predicting their lifetime and designing energy management strategies that consider long-term performance [10]. Recent improvements in lithium-ion batteries have increased their energy density and lifespan. However, issues like thermal management, safety risks, and long-term degradation still present challenges [11]. Standardized testing protocols and performance metrics are needed for HESS to allow fair comparison between different system designs and control methods [12]. Integrating HESS with electric motors and power electronics calls for a holistic design approach to ensure the entire system works efficiently and effectively [13]. While electric vehicles offer environmental benefits and lower operating costs, several technical and practical drawbacks limit their widespread adoption and performance. Battery-only EVs typically provide 150-400 km per charge, significantly less than ICE vehicles, causing 'range anxiety' among potential users. Complete battery recharging requires 30 minutes to several hours depending on charging infrastructure -, compared to minutes for refueling ICE vehicles. Lithium-ion batteries experience capacity fade of 2–3% per year, with high discharge rates during acceleration accelerating this degradation. The battery pack constitutes 30-40% of total EV cost. [14–17].

This research presents the design of HESS, first to choose the motor size for the e-Motorcycle, after that the sizing of super capacitor is done. The focus of research will be on sizing of super capacitor, the sizing of battery and bidirectional converter will be passed. The simulation was done by MATLAB / Simulink. The first section is introduced here in introduction. The second section will have the HESS and its components. The third section will have the methodology. Fourth section will have the motor selection and super capacitor sizing. The fifth section will have the results and discussion. Finally, section six will give the conclusion and future works. The motivation for this research stems from three critical gaps identified in existing literature, where most HESS studies focus on full-size electric cars, limited research addresses lightweight vehicles (motorcycles, scooters, tricycles) despite their growing market share in developing countries. Also, existing studies often propose complex control algorithms (fuzzy logic, neural networks, model predictive control) that increase computational requirements and cost, limiting practical implementation. Lastly, quantitative comparative data between battery-only and HESS configurations under identical operating conditions remains limited in the literature.

A simplified hysteresis-based control strategy and optimized HESS sizing are developed for a 2.5kW electric motorcycle, enabling practical implementation without high-cost algorithms. Results demonstrate 24× improvement in regenerative braking energy recovery, reduced battery current stress with 25 times (12A vs. 300 A), and superior performance compared with battery-only configurations under various driving conditions.

2. Hybrid energy storage system

HESS integrates multiple energy storage technologies to enhance performance, efficiency, and reliability in energy management. These systems typically combine energy-type storage, such as batteries, with power-type storage, like super capacitors, to optimize energy delivery and stability across various applications [18].

2.1. Super capacitor

Super capacitors are a promising alternative to lithium-ion batteries or at least a complement source at the moment, offering a balance between traditional capacitors and batteries. They combine fast charge-discharge rates, high power density, moderate energy density, and extended life cycles [19, 20]. In this study, they are used to reduce battery degradation caused by load fluctuations during frequent acceleration and braking [21]. Compared to batteries, super capacitors are lighter, charge faster, and support far more charge-discharge cycles [22].

3. Methodology

Fig. 1 presents a block diagram of the proposed system to drive a BLDC motor. The system begins with a battery that supplies energy to a bidirectional converter, enabling power flow in both directions, either from the battery to the super capacitor and load, or back to the battery for energy recovery. The converter is connected to a super capacitor, which responds

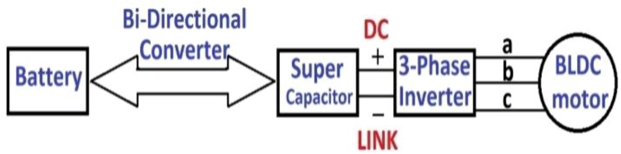

Fig. 1. Block diagram of a HESS feeding a BLDC motor via three phase inverter.

to sudden power demands and voltage surges. The super capacitor is linked to a three-phase inverter via a DC-link. This inverter converts the DC voltage into a three-phase AC signal, which drives the BLDC motor through phases(a, b, c).

3.1. Comparison of energy storage approaches

There is Battery-Only Systems, where it has advantages of simple architecture, lower initial cost, mature technology, no additional converters required. And its disadvantages are limited peak power capability, slow charge acceptance during regenerative braking (0.035% SOC gain in 2 seconds as shown in this study), accelerated degradation under high C-rate operation, reduced lifespan under frequent acceleration/deceleration cycles.

In Passive HESS (Direct Parallel Connection), it has advantages of simple implementation, no active control required, cost-effective. It has disadvantage of uncontrolled power distribution, inability to optimize charge/discharge profiles, limited performance improvement, super capacitor underutilization.

In Semi-Active HESS (One Bidirectional Converter), it has advantages of controlled power management for one storage element, moderate complexity, better performance than passive systems. It has disadvantages of limited control flexibility, suboptimal power sharing, one storage element still directly exposed to load variations. Lastly, for Fully Active HESS (Two Bidirectional Converters), it has advantages of complete control over both storage elements, optimal power distribution, maximum performance. Its disadvantages include highest complexity, increased cost and weight, higher control system requirements, reduced overall efficiency due to multiple conversion stages [23].

For the proposed Semi-Active HESS with battery-side control, this study implements a semi-active topology with the battery connected through a bidirectional buck-boost converter and the super capacitor. This configuration offers advantages of controlled battery charging/discharging prevents stress, super capacitor handles all DC-link voltage fluctuations naturally, moderate complexity suitable for lightweight vehicles, cost-effective implementation, fast super capacitor response without converter delay. Unlike previous studies focusing on complex optimization algorithms, this work demonstrates that simple hysteresis-based control achieves effective power management for lightweight EVs, making implementation more practical for commercial adoption.

Fig. 2. A hub BLDC motor.

Table 1. BLDC motor specifications.

Parameter	Value	Unit
Rated Power	2500	W
Rated Speed	888	RPM
Rated Voltage	48	V
Rated Torque	26.8	N.m
Rated Current	48.71	A
Phase-Phase Resistance	19.1	$m\Omega$
Phase-Phase Inductance	0.096	mH
Rated Torque Constant	0.47	N.m/A

3.2. Motor selection

Fig. 2 shows a hub-type BLDC motor. With a rated power of 2.5 kW and nominal voltage of 48V selected for this study, The specifications of this motor are listed in Table 1.

3.3. Super capacitor sizing

The sizing of the super capacitor system follows a methodology aimed at ensuring adequate dynamic power support during transient events, such as sudden accelerating, sudden hill climbing and regenerative braking.

The selected single-cell super capacitor has a typical voltage of ($V_{sc-cell} = 3$ V) and a capacitance of ($C_{sc-cell} = 3000$ F). To achieve the required DC-link voltage, multiple cells must be connected in series. However, series connection reduces the overall capacitance, which necessitates a combination of series and parallel arrangements to meet both voltage and capacitance requirements [24].

Number of cells of series super capacitor required to fulfill system voltage is calculated by the Eq. (1)

Table 2. Calculated variables for super capacitor.

Output quantity	Unit	Value
Series cells, N_s	—	16
Parallel strings, N_p	—	1
Total cells, N_{SC}	—	16
Achieved capacitance, C_{SC}	F	187.5
String voltage	V	48

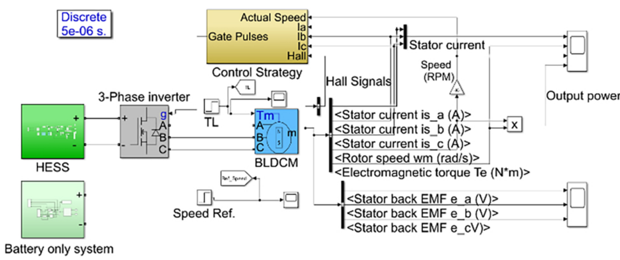

Fig. 3. Simulink diagram for the system.

[26]:

$$N_{SC series} = \frac{V_{DC-link}}{V_{sc-cell}}. \quad (1)$$

Assuming identical capacitors in series, the multiplication of number of series capacitors by the series capacitance string results in single cell capacitance (Cs-cell), or [26]:

$$C_{series} = \frac{C_{sc-cell}}{N_{SC series}} \quad (2)$$

It's known that to increase the voltage of super capacitor, cells are connected in series and to increase capacitance, cells are connected in parallel, so the resulting capacitance will be the product of capacitance of one string which its capacitors are connected in series by number of parallel connected strings, or [26]:

$$C_{sc} = C_{series} \times N_{SC parallel}. \quad (3)$$

The calculations of the super capacitor sizing are done based on Eqs. (1) to (3). The single cell capacitor has 3000F, 3V each. Desired dc-link voltage is 48V. Table 2 shows the obtained output variables.

For lithium-ion battery, the voltage was taken as 44.4V.

4. Simulation and results

Fig. 3 shows system using MATLAB / SIMULINK.

It consists of a hybrid energy storage system, three phase inverter, BLDC motor and control strategy. HESS is shown in Fig. 4.

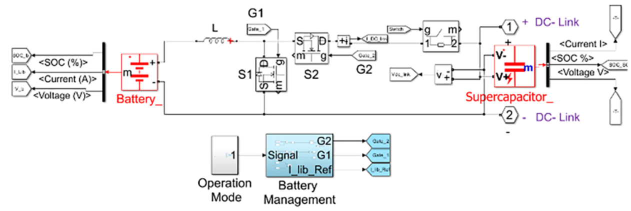

Fig. 4. HESS components.

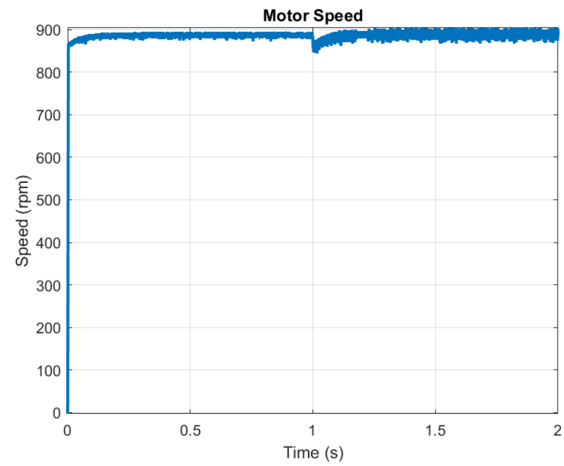

Fig. 5. BLDC motor speed during up-hill climbing scenario (battery-only system).

4.1. Hybrid energy storage system

It consists of a bi-directional converter which has a battery as source from left and super capacitor as second source at the DC-link. There are two MOSFET switches (S1, S2) in the BDC that switch on and off to act in boost or buck mode relying on battery management system.

4.2. Scenarios of simulation for the system

The cases will be taken first based on battery as the only energy source and second based on HESS (battery with super capacitor) as the energy source. Last but not least, the third case will be taken based on a comparison between battery and super capacitor in capturing SOC in regenerative mode.

4.2.1. Scenarios of system with battery-only

The Up-Hill climbing road simulation case was taken under half rated torque then a transition to full rated torque happens at second Eq. (1). Also, the system was subjected to rated load speed. Figs. 5 and 6 show the response of torque and speed of BLDC motor.

The BLDC motor starts with half rated torque and maintains a stable speed. At one second, the load

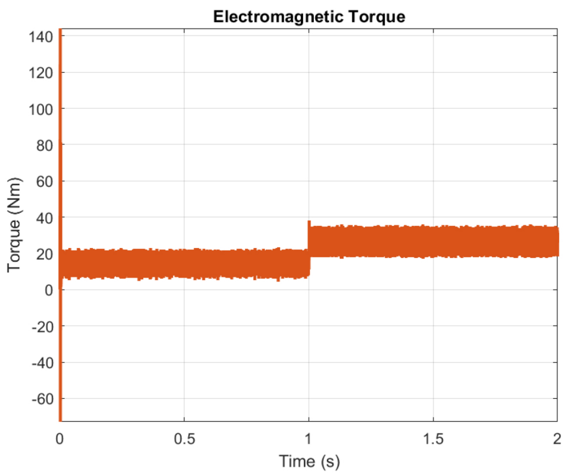

Fig. 6. Electromagnetic torque response in up-hill climbing scenario (battery-only system).

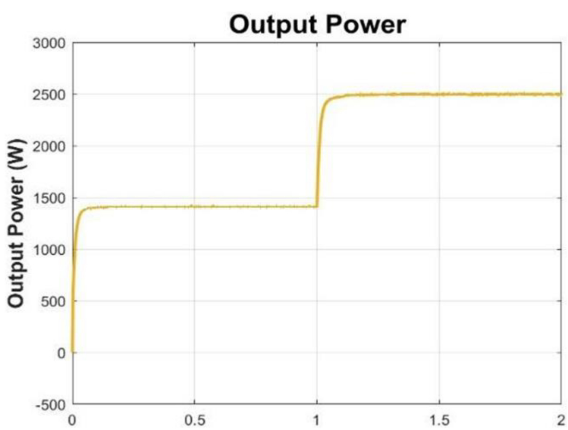

Fig. 7. Output power of the BLDC motor during variable torque (battery-only case).

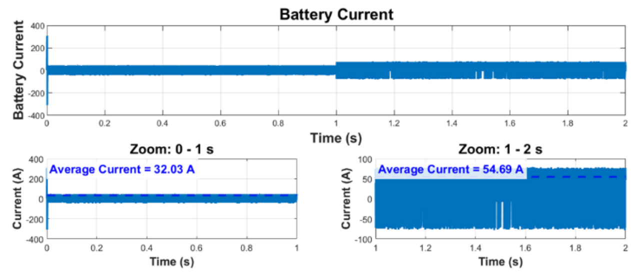

Fig. 8. Battery current during up-hill climbing scenario (battery-only system).

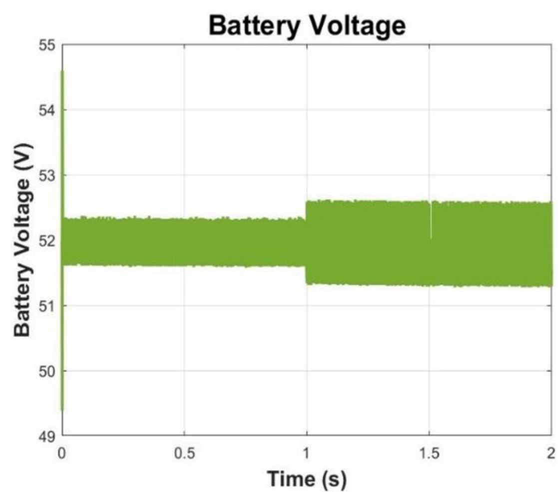

Fig. 9. Battery voltage during up-hill climbing scenario using battery-only system.

torque suddenly reaches its full rated value. The motor reacts instantly, shown by a sudden rise in electromagnetic torque. Despite the load change, speed remains nearly constant with minimal fluctuation at second one. This reflects effective control, ensuring smooth operation under varying loads.

Fig. 7 shows the output power. The output power rises at 1 second due to a torque increase. Initially, the motor delivers about 1400W at half-rated torque. When torque doubles, power increases to nearly 2500W at constant speed. This jump aligns with the power formula ($P = T \times \omega$). It confirms the motor's efficient response to sudden load changes.

Fig. 8 shows the battery's current. The main waveform is shown above, with zoomed average values below for 1–2 seconds At one second, battery current spikes due to a jump in torque demand. This reflects the need for more power to maintain speed under full load. After the spike, the current gradually decreases and stabilizes at a higher level. This shows the battery adapting to support the increased torque consistently.

Fig. 9 shows the battery voltage. The battery voltage stays relatively stable around 52V with minor fluctuations. This indicates minimal voltage sag despite sudden load changes. The voltage behavior mirrors the high current demand pattern. It gradually declines, showing potential stress on battery capacity. This reflects the impact of sustained load under six-step hysteresis control.

Fig. 10 shows the stator current phase A. The stator current starts at 27.1A under half-rated torque. At one second, it increases to 47.4A as full torque is applied. Phase A current shows high-frequency switching from hysteresis control. Brief fluctuations occur during the torque shift but quickly stabilize. This ensures efficient operation of rated speed under increased load.

4.2.2. Scenario of system with HESS

The Up-Hill climbing road in HESS will be taken for speed and torque based on variable load torque with constant speed. Or half rated torque, and full rated speed. ($T_L = 23.35/2$, 23.35 N.m, speed 888 rpm).

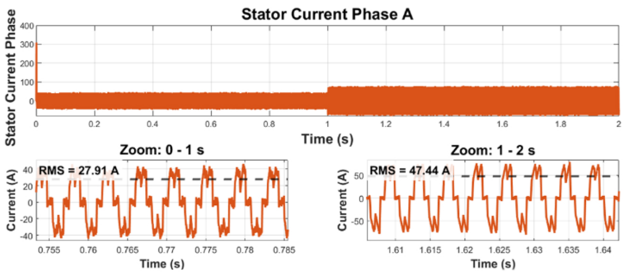

Fig. 10. Stator phase A current response during torque transition (battery-only system).

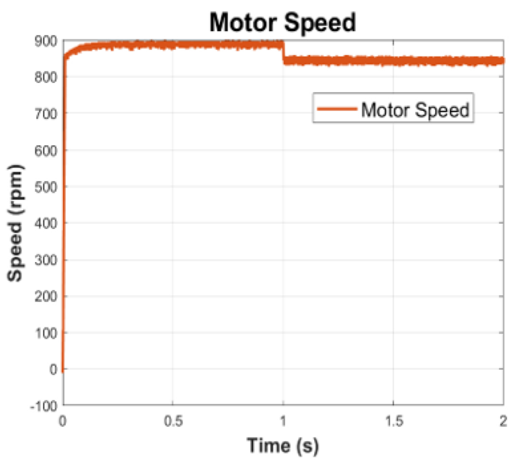

Fig. 11. BLDC motor speed in up-hill climbing scenario using proposed HESS.

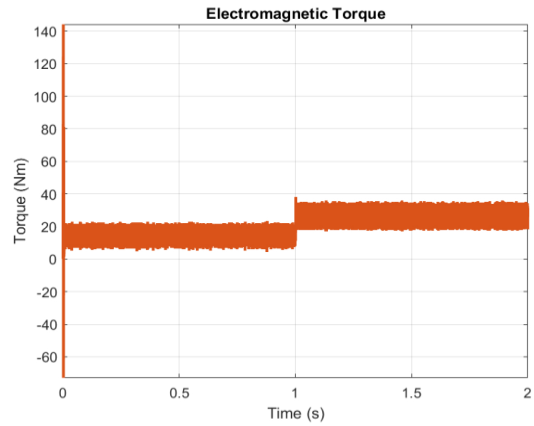

Fig. 12. Electromagnetic torque response in up-hill climbing scenario using proposed HESS.

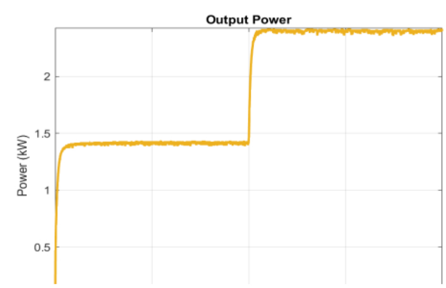

Fig. 13. Output power of the BLDC motor during torque transition (proposed HESS).

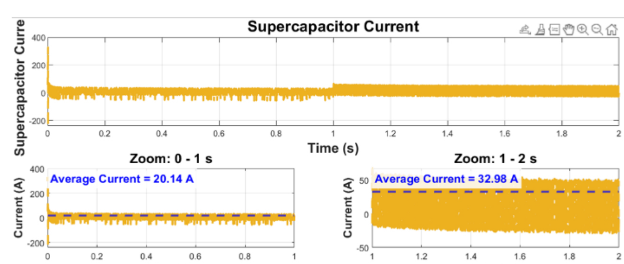

Fig. 14. Super capacitor current profile in up-hill climbing scenario (proposed HESS).

Figs. 11 and 12 show the motor speed and electromagnetic torque. The motor maintains a steady speed around 888rpm throughout the torque transition. Initially operating at half torque, it shows stable performance under light load. At one second, torque demand doubles, causing a sharp rise in electromagnetic torque. The HESS smoothly supports this shift, keeping the motor speed stable. After this transition, torque stabilizes at a higher level.

Fig. 13 shows the output power. The output power of the BLDC motor starts from 0 W and rapidly rises to approximately 1400 W, where it stabilizes. Until the 1-second mark. At exactly 1 second, a transition occurs as the power jumps from around 1400 W to rated power, reflecting the shift from half to full rated torque. Following this change, the output power settles, indicating the system's ability to sustain the higher load demand efficiently.

Figs. 14 and 15 show the super capacitor current and battery current, respectively. The super capacitor current starts high, supplying transient energy during half-rated load operation. At the one-second mark, it increases from about 20A to 33A to meet the surge in power demand. After this peak, the current steadily decreases as the system reaches full load steady-state. This decline shows reduced energy contribution, indicating less demand on the super capacitor. Its dynamic role buffers power transients and minimizes stress on the battery.

The battery current gradually rises from 0A to around 14A during half-load operation. When torque shifts to full load at one second, it increases to nearly 24A. This pattern reflects the battery's role in providing continuous power to the motor. Unlike the super capacitor, it supports steady-state operation rather than short bursts. Together, they ensure balanced, stable power delivery under varying load conditions.

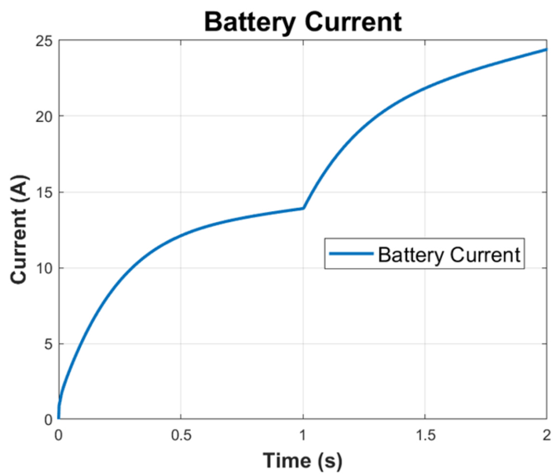

Fig. 15. Battery current profile in up-hill climbing scenario (proposed HESS).

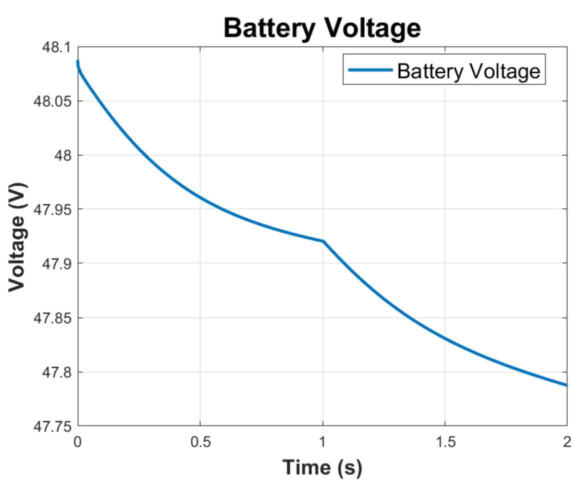

Fig. 16. Battery voltage profile during up-hill climbing scenario (proposed HESS).

This work handled a stress starting current of about 300A which exceeded the 250A in [25].

Figs. 16 and 17 show the battery voltage and super capacitor voltage. The system's battery voltage decreases gradually from approximately 48.1V to about 47.78V over 2 seconds, reflecting discharging under load, while the super capacitor voltage fluctuates around 48V due to the switching control and energy exchange dynamics between the battery and super capacitor. The battery's voltage drop indicates energy being supplied to the BLDC motor at full-rated speed, with the half-rated torque initially, before adjusting to full torque. Meanwhile, the super capacitor voltage shows rapid transient fluctuations owing to the six-step HCC, ensuring efficient energy delivery while the battery provides a stable supply voltage for the motor operation at high speed.

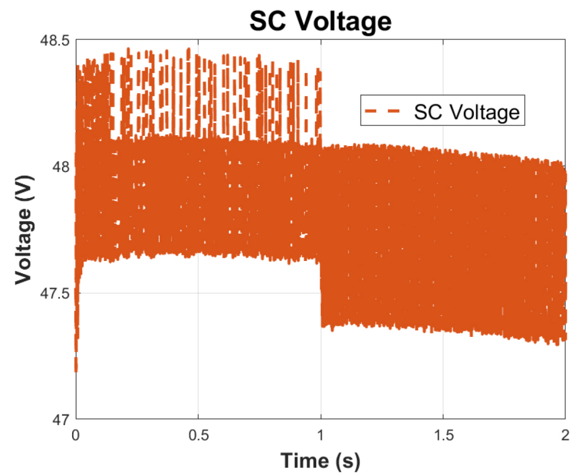

Fig. 17. Super capacitor voltage variations during up-hill climbing scenario (proposed HESS).

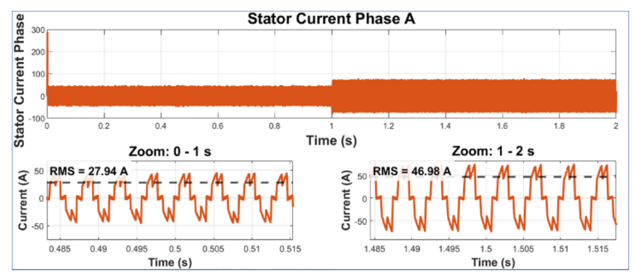

Fig. 18. Stator phase A current in up-hill climbing scenario (proposed HESS).

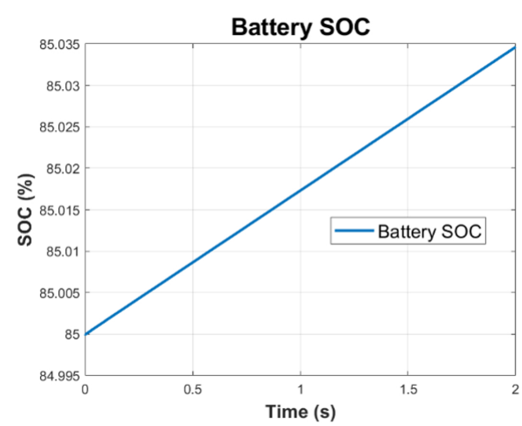

Fig. 19. Battery state-of-charge during regenerative braking on down-hill slope scenario (battery-only system).

Fig. 18 shows the stator current phase A The stator phase A current stays relatively steady with minor fluctuations, showing the controller's effort to maintain torque and speed under varying load. As torque demand rises, the current increases from around 28A to 47A, reflecting the surge from the HESS, battery and super capacitor combined. This response supports

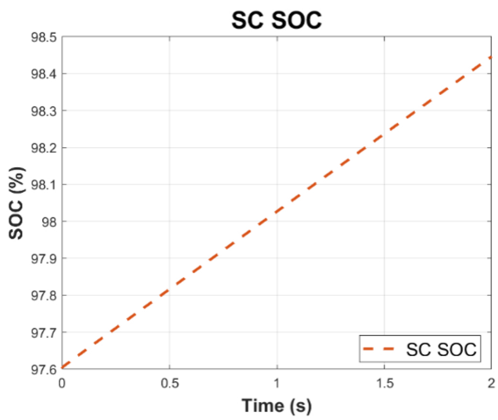

Fig. 20. Super capacitor state-of-charge during regenerative braking on down-hill slope scenario (proposed HESS).

acceleration and increased torque before the current stabilizes with the new load. The coordination between energy sources ensures smooth operation at rated speed. Overall, the current draw briefly amplifies during transition and returns to a steady level for stable performance.

4.2.3. Comparison scenario between super capacitor and battery based on SOC in down-hill slope road

The comparison will be based on simulation of the battery only system, and the HESS, both under the same condition which is down-hill slope road (regenerative braking). It will be taken for speed and torque based on constant negative load torque with constant speed at the rated values. (T_L = –23.35 N.m, speed 888 rpm).

Figs. 19 and 20 show battery SOC in battery only system and super capacitor SOC in HESS.

In a battery-only system powering a BLDC motor, the battery SOC shows a slight rise from 85% to 85.035%, due to regenerative braking. This gradual increase reflects the battery's inherent slow energy receiving in storage.

When using a HESS with both battery and super capacitor (where the super capacitor only gets the regenerative energy by the energy management sharing system, the super capacitor SOC rises sharply from 97.6% to 98.45%. This indicates its primary role in capturing short-term energy surges during dynamic phases. The high SOC gain allows the super capacitor to quickly absorb regenerative energy during deceleration. Meanwhile, the battery SOC stays mostly stable, supporting fair energy delivery over time. This work got measured 24-fold improvement in SOC recovery rate (0.85% vs. 0.035% in 2 seconds) substantially exceeds 8× improvement in [4].

Fig. 21 shows up-hill climbing road–battery power and super capacitor power.

During full-speed operation and a variable torque from half rated to full rated value at second 1, battery power rises from 0 to about 650 W at second 1 and then rises to 1150W as torque transitions to full-rated value, while the super capacitor initially peaks to 1600W to handle transient loads before stabilizing around 1200W. The HCC effectively coordinates these rapid power exchanges, optimizing energy delivery, easing battery stress, and sustaining BLDC motor performance.

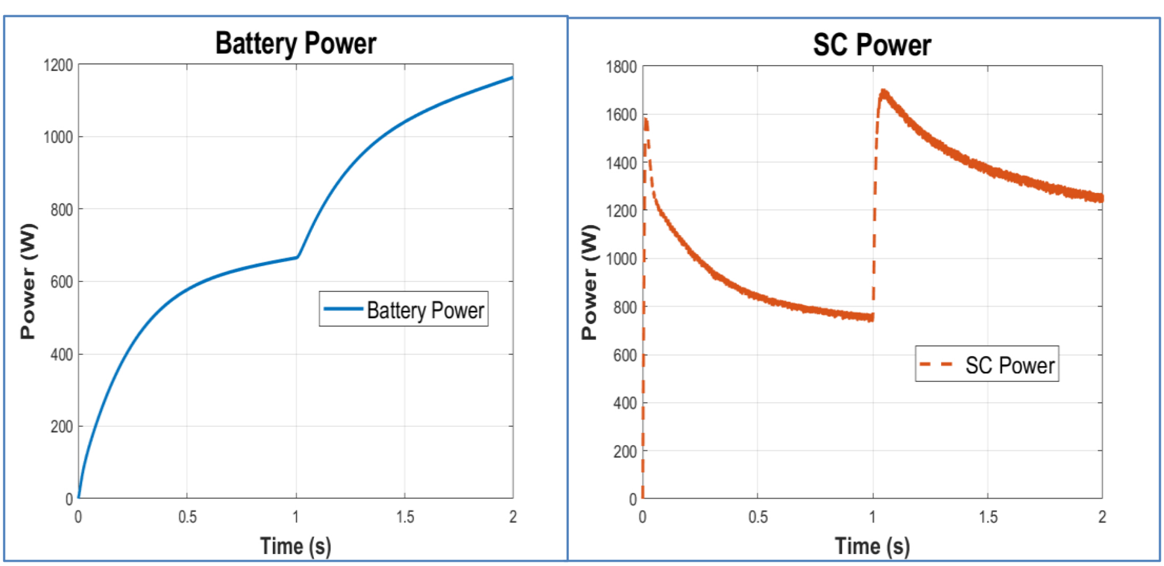

Fig. 21. Battery and super capacitor power contributions during up-hill climbing scenario (proposed HESS).

5. Conclusion

This paper proposed a HESS for a lightweight EV (e-Motorcycle) feeding a BLDC motor via three phase inverter. A 2.5KW motor with a voltage of 48V is selected. A super capacitor comprised of 16 series connected cells each of 3000F and 3V is added to the storage system along with the bi-directional converter. The sizing calculations were done and capacitance of the constructed super capacitor was 187 F. The simulation showed good results in shielding the battery by super capacitor where the last absorbed transient currents efficiently. The super capacitor was used to capture the regenerative energy instead of battery. The hybrid storage system achieved a balanced power distribution. The super capacitor handled startup demands and sudden load variations efficiently, protecting the battery from stress, while the battery ensured stable energy supply during steady operation. During regenerative braking, the super capacitor captured energy quickly and effectively, whereas the battery showed slower and less significant recovery. This work got measured 24-fold improvement in SOC recovery rate (0.85% vs. 0.035% in 2 seconds), and provides quantitative validation. It also handles stress starting current of about 300 A. This performance makes the configuration a strong candidate for lightweight electric vehicles, especially in handing stresses in circumstances where battery only system may not work well in it, and in protecting battery from surges and heavy loads. Future research should extend this work with detailed thermal analysis and more advanced control strategies to further enhance reliability and lifespan.

Conflict of interest

The authors declare that they have no conflict of interest regarding the publication of this paper.

Funding information

This research received no external funding.

Acknowledgement

The authors would like to express their sincere gratitude to all friends and colleagues who placed their trust in this work and provided continuous encouragement and support throughout the course of this research.

References

1. C. T. Tshiani and P. Umenne, “The impact of the electric double-layer capacitor (EDLC) in reducing stress and improving battery lifespan in a hybrid energy storage system (HESS) system,” *Energies*, vol. 15, no. 22, p. 8680, 2022. https://doi.org/10.3390/en15228680.
2. E. M. Szumska, “Regenerative braking systems in electric vehicles: A comprehensive review of design, control strategies, and efficiency challenges,” *Energies*, vol. 18, no. 10, p. 2422, 2025. https://doi.org/10.3390/en18102422.
3. R. Raghavendra Rao, B. N. Sharath, P. Madhusudan, and S. Pradeep, “Energy Storage Applications of Mechanically Alloyed Materials Super capacitors, Battery Applications,” In: S. Rajendrachari, (ed.) *Mechanically Alloyed Novel Materials: Processing, Applications, and Properties*, Springer Singapore, 2024, pp. 407–436. ISBN 978-981-97-6503-4. https://doi.org/10.1007/978-981-97-6504-1_17.
4. D. Lemian and F. Bode, “Battery-Super capacitor Energy Storage Systems for Electrical Vehicles: A Review,” *Energies*, vol. 15, no. 15, p. 5683, 2022. https://doi.org/10.3390/en15155683.
5. T. S. Babu, K. R. Vasudevan, V. K. Ramachandaramurthy, S. B. Sani, S. Chemud, and R. M. Lajim, “A comprehensive review of hybrid energy storage systems: Converter topologies, control strategies and future prospects,” *IEEE Access*, vol. 8, pp. 148702–148721, 2020. https://doi.org/10.1109/ACCESS.2020.3015919.
6. R. S. Sankarkumar and R. Natarajan, “Energy management techniques and topologies suitable for hybrid energy storage system powered electric vehicles: An overview,” *International Transactions on Electrical Energy Systems*, vol. 31, no. 4, p. e12819, 2021. https://doi.org/10.1002/2050-7038.12819.
7. Y. Tong, I. Salhi, Q. Wang, G. Lu, and S. Wu, “Bidirectional DC-DC converter topologies for hybrid energy storage systems in electric vehicles: A comprehensive review,” *Energies*, vol. 18, no. 9, p. 2312, 2025. https://doi.org/10.3390/en18092312.
8. Y. Huang, H. Wang, A. Khajepour, B. Li, J. Ji, K. Zhao, and C. Hu, “A review of power management strategies and component sizing methods for hybrid vehicles,” *Renewable and Sustainable Energy Reviews*, vol. 96, pp. 132–144, 2018. https://doi.org/10.1016/j.rser.2018.07.020.
9. A. Recalde, R. Cajo, W. Velasquez, and M. S. Alvarez-Alvarado, “Machine learning and optimization in energy management systems for plug-in hybrid electric vehicles: A comprehensive review,” *Energies*, vol. 17, no. 13, p. 3059, 2024. https://doi.org/10.3390/en17133059.
10. M. López-Pérez, J. Domínguez-Zenteno, G. Valencia-Palomo, F. R. López-Estrada, S. Gómez-Peñate, and I. Santos-Ruiz, “Performance-driven battery pack sizing for light-duty electric vehicles,” *IEEE Access*, 2025. https://doi.org/10.1109/ACCESS.2025.3585754.
11. Y. Ortiz, P. Arévalo, D. Peña, and F. Jurado, “Recent advances in thermal management strategies for lithium-ion batteries: A comprehensive review,” *Batteries*, vol. 10, no. 3, p. 83, 2024. https://doi.org/10.3390/batteries10030083.
12. I. E. Atawi, A. Q. Al-Shetwi, A. M. Magableh, and O. H. Albalawi, “Recent advances in hybrid energy storage system integrated renewable power generation: Configuration, control, applications, and future directions,” *Batteries*, vol. 9, no. 1, p. 29, 2022. https://doi.org/10.3390/batteries9010029.
13. J. G. Hayes and G. A. Goodarzi, *Electric Powertrain: Energy Systems, Power Electronics and Drives for Hybrid, Electric*

and Fuel Cell Vehicles. Wiley, 2018. https://doi.org/10.1002/9781119063681.
14. X. Ma, R. Xie, L. Guo, S. Niu, L. Cheng, and R. Hu, "Range anxiety of battery electric vehicles: Quantification and determinants using real-world data," *Transp. Res. D, Transp. Environ.*, vol. 146, 2025, Art. no. 104837.
15. U.S. Department of Transportation, "Charger Types and Speeds," U.S. Department of Transportation Rural EV Toolkit. https://www.transportation.gov/rural/ev/toolkit/ev-basics/charging-speeds (accessed Oct. 26, 2025).
16. N. Kirkaldy, M. A. Samieian, G. J. Offer, M. Marinescu, and Y. Patel, "Lithium-ion battery degradation: Comprehensive cycle ageing data and analysis for commercial 21700 cells," *J. Power Sources*, vol. 603, 2024, Art. no. 234185, doi: 10.1016/j.jpowsour.2024.234185.
17. P. Walsh, R. Isaac, R. Vijayagopal, A. Rousseau, J. Seo, and N. Kim, "Impact of cold ambient temperature and extreme conditions on electric vehicles," U.S. Department of Energy, Vehicle Technologies Office, Washington, DC, USA, Sep. 2024. [Online]. Available: https://www.energy.gov/sites/default/files/202410/Impact_of_Cold_Ambient_Temperature_on_BEV_Performance_v15_TechEditFinal_12Sep2024__0.pdf.
18. A. M. Adeyinka, O. C. Esan, A. O. Ijaola, and P. K. Farayibi, "Advancements in hybrid energy storage systems for enhancing renewable energy-to-grid integration," *Sustainable Energy Research*, vol. 11, no. 1, pp. 2–6, 2024. https://doi.org/10.1186/s40807-024-00120-4.
19. H. Xu and M. Shen, "The control of lithium-ion batteries and super capacitors in hybrid energy storage systems for electric vehicles: A review," *International Journal of Energy Research*, vol. 45, no. 15, pp. 20524–20544, 2021. https://doi.org/10.1002/er.7150.
20. A. G. Olabi, Q. Abbas, A. Al Makky, and M. A. Abdelkareem, "Super capacitors as next generation energy storage devices: Properties and applications," *Energy*, vol. 248, p. 123617, 2022. https://doi.org/10.1016/j.energy.2022.123617.
21. M. F. Hsieh, P. H. Chen, F. S. Pai, and R. Y. Weng, "Development of super capacitor-aided hybrid energy storage system to enhance battery life cycle of electric vehicles," *Sustainability*, vol. 13, no. 14, p. 7682, 2021. https://doi.org/10.3390/su13147682.
22. M. G. Bakker, R. M. Frazier, S. Burkett, J. E. Bara, N. Chopra, S. Spear, *et al.*, "Perspectives on super capacitors, pseudocapacitors and batteries," *Nanomaterials and Energy*, vol. 1, no. 3, pp. 136–158, 2012. https://doi.org/10.1680/nme.11.00007.
23. M. B. F. Ahsan, S. Mekhilef, T. K. Soon, M. B. Mubin, P. Shrivastava, and M. Seyedmahmoudian, "Lithium-ion battery and SCbased hybrid energy storage system for electric vehicle applications: A review," *Int. J. Energy Res.*, vol. 46, no. 14, pp. 19826–19854, 2022, doi: 10.1002/er.8439.
24. T. Horiba, "Lithium-Ion Battery Systems," *Proceedings of the IEEE*, vol. 102, no. 6, pp. 939–950, Jun. 2014. https://doi.org/10.1109/JPROC.2014.2319832.
25. B. Saied, "Pioneering battery-super capacitor hybrid energy storage system for electric scooters," *Przegląd Elektrotechniczny*, no. 4, pp. 100–104, 2024.
26. S. G. Krishnan, H. D. Pham, and D. P. Dubal, Eds., *Supercapacitors: Materials, Design, and Commercialization*. Elsevier, 2024, ISBN 978-0-443-15478-2.