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Enhance the Efficiency of the Regenerative Braking System in Electric Vehicles using a Hybrid Energy Storage System

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Battery, Supercapacitor, Hybrid Energy Storage System, HESS, MATLAB/Simulink, Electric vehicles, Regenerative braking, Standard drive cycle.

Abstract

Electric vehicles (EVs) are poised to revolutionise urban transportation by offering reduced emissions, enhanced energy efficiency, and sustainable transportation solutions compared to conventional internal combustion engine vehicles. A key factor in their efficiency is regenerative braking systems, which capture and convert kinetic energy into electrical energy during deceleration. However, challenges such as limited energy recovery efficiency and battery lifespan remain significant barriers. This paper proposes a novel approach to address these challenges through the development and simulation of a Battery-Supercapacitor Hybrid Energy Storage System (HESS) tailored for EVs. The study uses MATLAB/Simulink simulations and evaluates the system's performance under various standard drive cycles (Urban Dynamometer Driving Schedule - UDDS, New York City Cycle - NYCC, and New European Driving Cycle - NEDC). By integrating supercapacitors alongside batteries, the HESS aims to enhance regenerative braking efficiency, prolong battery life, and optimize energy utilization. The findings highlight that the integration of supercapacitors with batteries in the HESS significantly improves energy recovery during braking events, especially in urban stop-and-go driving conditions represented by the selected drive cycles. This enhancement not only increases overall vehicle efficiency but also reduces stress on the battery, thereby extending its operational lifespan. In conclusion, the study suggests that strategic energy management through HESS offers promising avenues for advancing EV technology and contributing to sustainable mobility solutions in urban environments.

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1. Introduction

Electric vehicles more commonly known as EVs, rely on electric propulsion systems instead of internal combustion engines (ICEs), heavily relying on batteries for energy. This focus highlights the significance of electrical power quality, especially during energy conversion processes. EVs are set to decrease greenhouse gas emissions, air pollution, and fossil fuel consumption significantly, making them more efficient, eco-friendly, quieter, and safer than traditional ICE vehicles [1-4]. Despite these advantages, EVs encounter challenges such as longer charging hours and limited driving ranges, with a full charge cycle taking approximately 1-2 hours [5]. Regenerative braking systems convert kinetic energy into electrical energy and are pivotal in enhancing EV efficiency, particularly in urban driving conditions with frequent braking. Nevertheless, conventional regenerative braking systems fail to recover maximum energy due to their sole reliance on batteries [6-7].

The objective of this study is to address current limitations by developing a Battery-Supercapacitor Hybrid Energy Storage System (HESS) aimed at improving the efficiency of regenerative braking. By introducing HESS, the study aims to achieve enhanced energy recovery during braking, prolonged battery life, and improved dynamic performance [8]. The approach involves utilizing MATLAB/Simulink for simulating and modeling the HESS, followed by evaluating its performance using standard drive cycles.

The research seeks to compare and analyze the effectiveness of regenerative braking systems with and without HESS, showcasing the practical advantages and efficiency improvements of this hybrid system in electric vehicles [9-10]. This highlights the potential for advancing EV technology by addressing significant challenges related to energy storage and efficiency. Fig 1 depicts the system architecture of HESS in EVs.

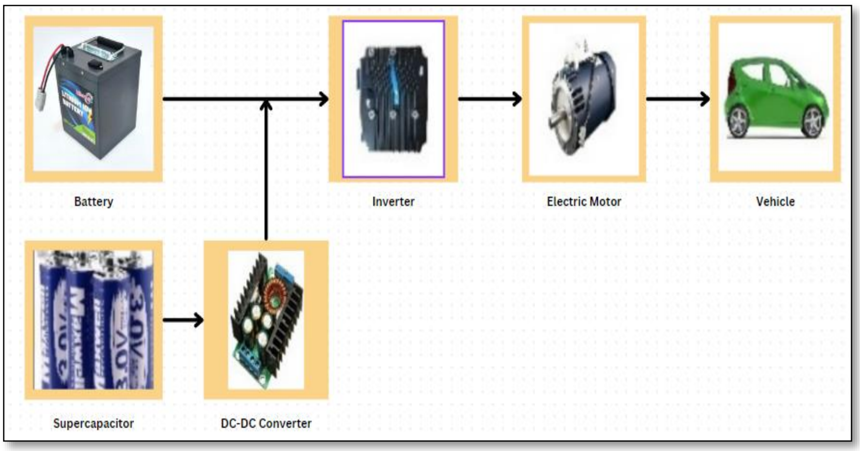

Fig. 1 *Architecture of HESS in Electric Vehicles*

2. Literature Review

The literature review begins by exploring hybrid energy storage systems (HESS) in electric vehicles (EVs), focusing on integrating batteries and supercapacitors to enhance the performance and efficiency of the vehicle. The review highlights the importance of HESS in optimizing regenerative braking, where the supercapacitors efficiently capture and store energy during braking events, simultaneously enhancing battery lifespan and overall system reliability [11-12]. The discussion highlights the practical applications and benefits of HESS across various EV platforms, such as electric railway vehicles, proving its role in improving energy conservation and system efficiency [13]. Moreover, case studies show how HESS is implemented, including the ones utilizing vibration-powered energy, contributing to safer braking and effective mechanical energy harvesting, which is crucial for sustainable mobility [14]. Overall, the literature underscores HESS as a pivotal technology advancing the capabilities of regenerative braking systems in EVs, enhancing efficiency, performance, and sustainability across different operational contexts [15-17]. Another important aspect examined is the wider scope of EV technologies, including battery-electric vehicles (BEVs) and hybrid electric vehicles (HEVs). BEVs are highlighted for their potential to reduce carbon emissions and advance sustainable transportation, driven by advancements in battery technology, particularly lithium-ion batteries [18-19]. The evolving infrastructure supporting EV adoption, such as bidirectional chargers and wireless electric vehicle charging systems, which are crucial for overcoming challenges like range anxiety and high initial costs [20-21].

Furthermore, the fundamentals of regenerative braking systems in EVs showcase their role in improving energy efficiency by converting kinetic energy into electrical energy during braking, thereby extending the driving range and enhancing overall vehicle performance [22-25]. Ultimately, the literature review provides a comprehensive overview of EV technologies and their components. It emphasises their collective contribution to sustainable transportation solutions and the ongoing evolution towards more efficient and environmentally friendly mobility options.

3. Methodology

The study utilizes a simulation-based approach with MATLAB/Simulink and standard drive cycles like UDDS, NYDC, and NEDC. This methodology is chosen for its precision, affordability, and safety, allowing for controlled experimentation and detailed analysis in a simulated environment. It streamlines developing and validating a model for an electric vehicle's regenerative braking system, integrating a battery-supercapacitor HESS, and evaluating its effectiveness under various circumstances. The use of simulations for testing and optimisation reduces risks and expenses while enabling thorough testing, making it an ideal methodology for this groundbreaking research.

3.1 Electric Vehicle Dynamic Model

Electric vehicles equipped with regenerative braking technology have the ability to capture and convert energy typically lost during braking into electrical energy. This enhances energy efficiency and extends the driving range. The system consists of various components, including an electric motor, power electronics, and control systems. When creating a realistic model of a regenerative braking system using MATLAB/Simulink, it's essential to identify and simulate key components such as the motor, battery, power electronics, and control algorithms. The integration of these components should accurately represent their individual functions, focusing on motor performance and battery charge dynamics. The ultimate goal is to develop an efficient simulation of the regenerative braking system.

Factors such as mass, aerodynamic drag coefficient, and rolling resistance exert influence on the performance and energy efficiency of electric vehicles (EVs). These factors affect acceleration, aerodynamic efficiency, and energy consumption. Expert researchers utilise computer simulations to precisely evaluate electric vehicle model battery systems, drivetrain, power electronics, and vehicle dynamics. This aids in determining energy consumption, estimating range, and evaluating performance.

The total force affecting the vehicle movement, as shown in Fig 2 and Equation 1, is the summation of acceleration force (Equation 2), grading force (Equation 3), rolling force (Equation 4), and aerodynamic force (Equation 5). Table 1 displays the main coefficients of the EV model.

$$\sum F_{total} = F_{accel} + F_{grad} + F_{roll} + F_{aero} \tag{1}$$

$$F_{accel} = M_v + \frac{\partial v}{\partial t} \tag{2}$$

$$F_{grad} = M_v \times g \times \sin\theta \tag{3}$$

$$F_{roll} = \mu_{rr} \times M_v \times g \times \cos\theta \tag{4}$$

$$F_{aero} = 0.5 \times \rho \times A_f \times C_d \times V^2 \tag{5}$$

Table 1 *Parameters of Electric Vehicle Model*

Parameter	Value
M_v = Vehicle Mass [kg]	1325
C_d = Drag coefficient	0.26
A_f = Frontal area [m^2]	2.57
r = Wheel radius [m]	0.3
μ_{rr} = *rolling* resistance	0.0048
g = Gravity acceleration (g) [ms^{-2}]	9.8
ρ = Air density [kgm^{-3}]	1.29
θ = Road angle [radian]	Variable
V = Vehicle Speed [Km/h]	Variable

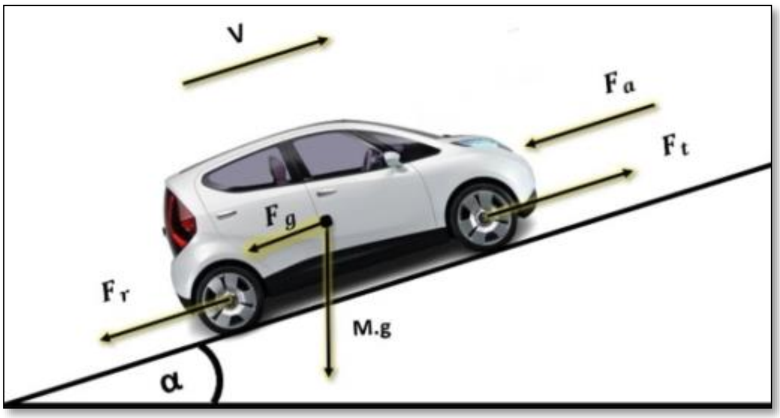

Fig. 2 *Forces affecting the vehicle during movement*

3.2 Battery Model

Electric batteries can be effectively simulated with electrical equivalent circuit models: Thevenin, impedance, and runtime-based. Charging and discharging present nonlinear behaviour influenced by state-of-charge (SOC) and electrolyte temperature, necessitating a dynamic model for accuracy. System identification helps estimate the parameters for these models, considering thermal effects. MATLAB/Simulink's library includes a relevant battery model showcasing an equivalent model with a control voltage source and internal resistance. Accurately modelling electric vehicle (EV) batteries requires parameter determination based on real data, as parameters vary with SOC, temperature, and current amplitudes. Traditional batteries display complex behaviour, leading to the creation of dynamic models. Parameter estimation has been achieved by testing or combining lab and manufacturer data [26-28].

The battery model can be found in the MATLAB/Simulink library. This equivalent model contains a control voltage source and an internal resistance, as shown in Fig 3. The relationship between the time-varying parameters in the battery model is shown in Equation 6. Table 2 shows the main parameters of the battery model used in this study.

$$\begin{cases} V_b(t) = E_b(t) - r_b . i_b(t) \\ \mathrm{SOC(t)} = 100\left(SOC\ (0) - \dfrac{1}{Q}\displaystyle\int_0^t i(t)dt\right) \end{cases} \qquad (6)$$

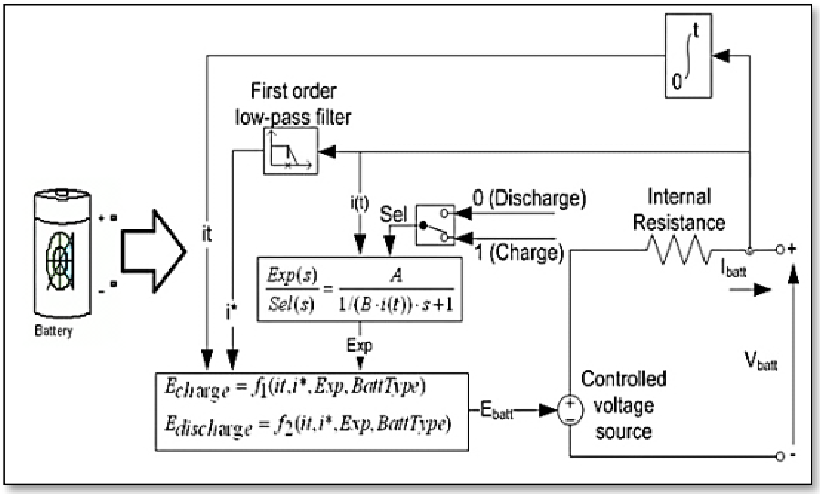

Fig. 3 *Equivalent model of the battery in MATLAB/Simulink library*

Table 2 *Parameters of battery model*

Parameters	Value
Rated Capacity (Ah)	100
Internal Resistance (Ohms)	0.125
Nominal Voltage (V)	500
Stored Energy (kWh)	50
Initial $\boldsymbol{SoC_b(0)}(\%)$	85

3.3 Supercapacitor Model

Supercapacitors have widespread use in academic and the automotive industry due to their characteristics, which are high efficiency, low internal resistance, high power density, long cycle life, fast charging, and wide operational temperature range. A model that can emulate supercapacitor dynamics with high precision and robustness is of utmost importance for energy management design. The model should also avoid complexity to be easily incorporated into real-time controllers. Therefore, it is vital to strike a balance between the model's accuracy, robustness, and model complexity. This research will rely on the equivalent circuit model for the supercapacitor in the MATLAB/Simulink library. Table 3 lists the parameters of the supercapacitor module used in this study whereas, the self-discharge phenomenon is represented in Equation 7.

$$i_{selfdis=}\begin{cases}\dfrac{C_{T\alpha 1}}{1+sR_{SC}C_T} \\ \dfrac{C_{T\alpha 2}}{1+sR_{SC}C_T} & if\ t-t_{oc}\leq t_3 \\ \dfrac{C_{T\alpha 3}}{1+sR_{SC}C_T}\end{cases} \tag{7}$$

Table 3 *Parameters of the supercapacitor model*

Parameter	Value
Rated Voltage (V)	500
Rated Capacitance (F)	60
Resistance (Ω)	2
Initial $\mathbf{SoC_{sc}(0)}$ (%)	80

3.4 Battery-Supercapacitor Hybrid Energy Storage System (HESS) Model

The Battery-Supercapacitor Hybrid Energy Storage System (HESS) integrates a high-energy-density battery with a high-power-density supercapacitor to optimize energy efficiency and performance. The HESS configuration is determined by connecting the battery and supercapacitor to optimize energy flow and utilization. The semi-active topology is the chosen topology of HESS used in this research.

Integrating the HESS with the regenerative braking model in MATLAB/Simulink maximises the braking system's potential through efficient management of energy generated during braking, rapid absorption of high-power bursts, and storage of excess energy for prolonged use. The charge-discharge efficiency increases the HESS's overall energy recovery and utilization capabilities and the efficiency of the regenerative braking system by assessing how effectively energy is transferred between HESS components.

4. Results and Discussion

This section presents the simulation findings and analyses conducted to evaluate the performance of regenerative braking systems in electric vehicles (EVs) using a Battery-Supercapacitor Hybrid Energy Storage System (HESS). The performance analysis of the battery-only and the battery-supercapacitor HESS under different driving cycles was presented. The driving cycles considered in this study include the Urban Dynamometer Driving Schedule (UDDS), New York City Cycle (NYCC), and New European Drive Cycle (NEDC). Finally, a comparative analysis is provided to highlight the advantages and potential improvements achieved by integrating the supercapacitor with the battery in the regenerative braking system.

4.1 Simulation of Battery-only Energy Storage System

4.1.1 UDDS Drive Cycle Using Battery-only

During the simulation, the Battery State of Charge (SoC) gradually decreased from around 95% to 92.6% over a period of 1400 seconds, as depicted in Fig 4. The standard drive cycles do not account for road slope, and the vehicle speed profile varies. In this scenario, the battery provides the total load current, and no regenerative energy is captured by the battery. Fig 5, shows the power required by the EV battery based on the UDDS drive cycle selected in this research.

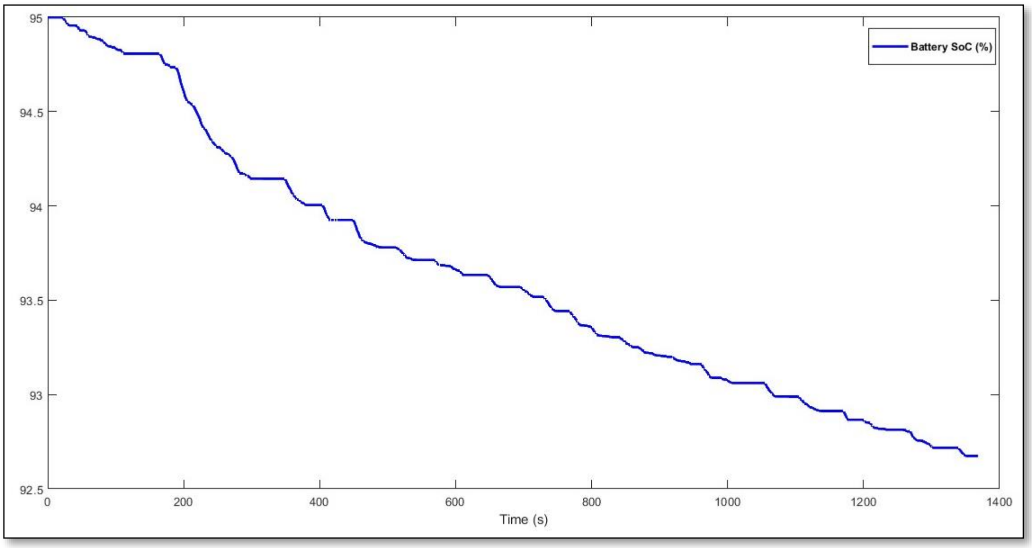

Fig. 4 *Battery State of Charge (SoC) in UDDS drive cycle for battery-only energy storage system*

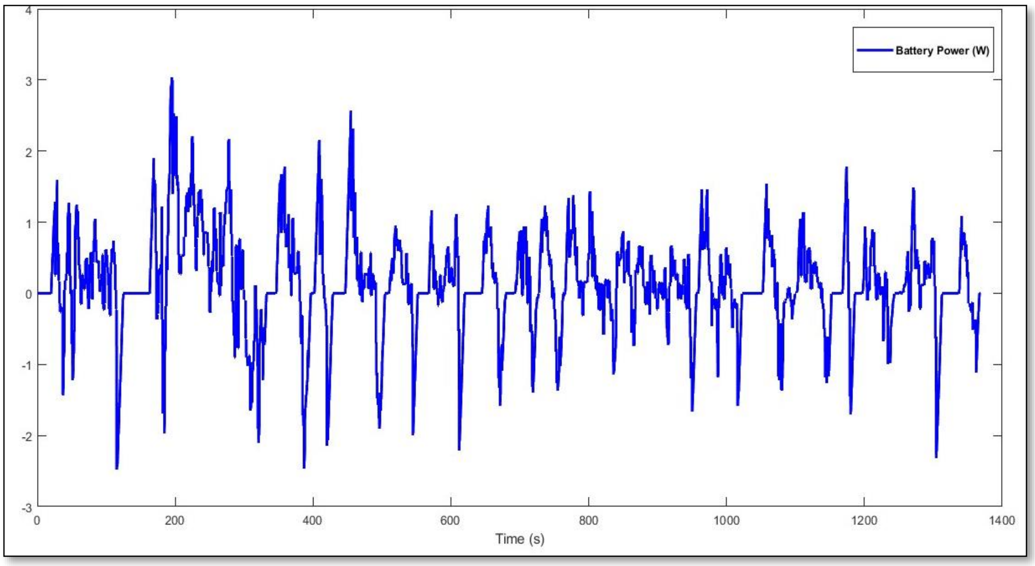

Fig. 5 *Power required by the EV under UDDS drive cycle for battery-only energy storage system*

4.1.2 NYCC Drive Cycle Using Battery-only

The Battery State of Charge (SoC) throughout the simulation gradually decreased from an initial state of charge of 95% to 94.49% over 600 seconds. This can be seen in Fig 6. Fig 7 illustrates the power required by the battery based on the NYCC drive cycle selected for this research. These figures offer valuable insights into the EV battery's performance and operational efficiency under urban driving conditions.

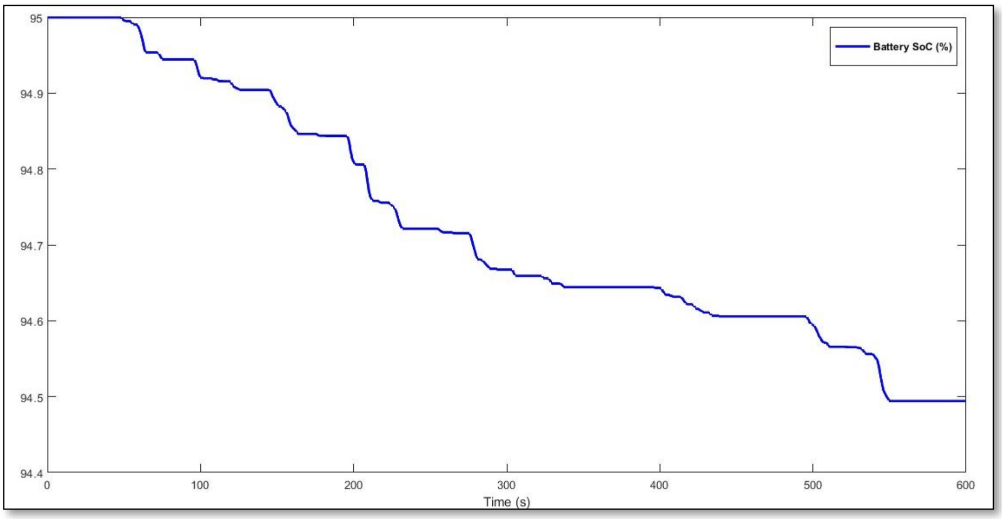

Fig. 6 *Battery State of Charge (SoC) in NYCC drive cycle for battery-only energy storage system*

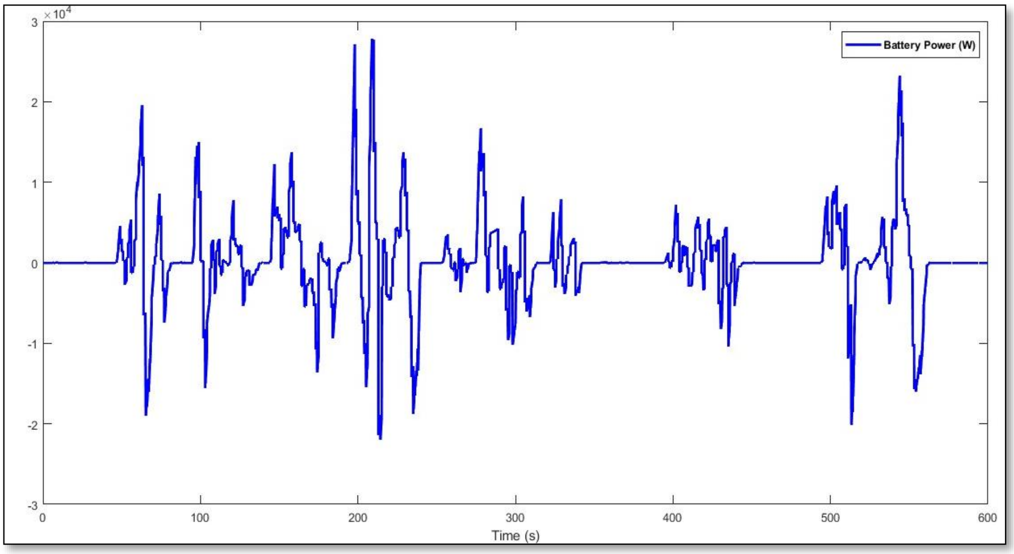

Fig. 7 *Power required by the EV under NYCC drive cycle for battery-only energy storage system*

4.1.3 NEDC Drive Cycle Using Battery-only

As demonstrated in Fig. 8, the battery's State of Charge (SoC) progressively declined over the course of the simulation, from the initial value of 95% to 92.8% over 1180 seconds. Based on the NEDC drive cycle chosen for this study, the battery power requirements are shown in Fig 9. These numbers offer crucial insights for analysing the performance and efficiency of the EV battery in urban driving conditions.

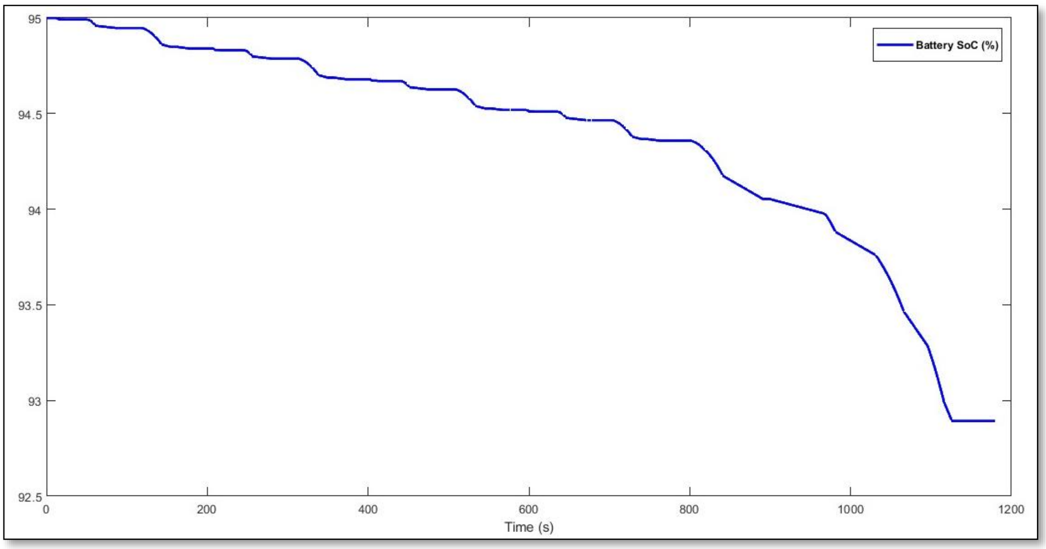

Fig. 8 *Battery State of Charge (SoC) in NEDC drive cycle for battery-only energy storage system*

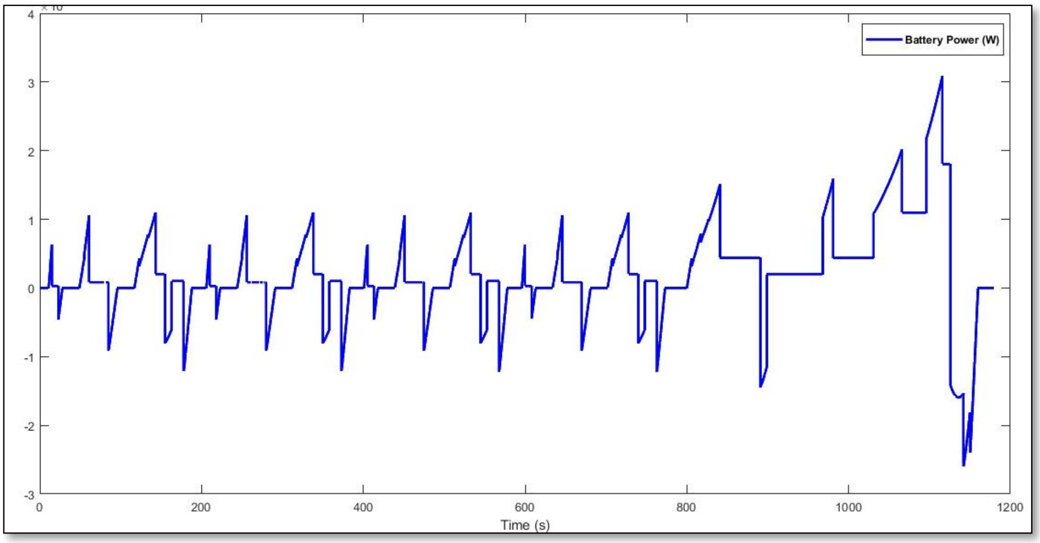

Fig.9 *Power required by the EV under the NEDC drive cycle for battery-only energy storage system*

4.2 Simulation of Battery-Supercapacitor Hybrid Energy Storage System (HESS)

4.2.1 UDDS Drive Cycle Using HESS

Figures 10, 11, 12, and 13 illustrate key aspects of the battery-supercapacitor hybrid energy storage system (HESS) during the Urban Dynamometer Driving Schedule (UDDS) drive cycle. Specifically, Figure 10 depicts the battery State of Charge (SoC), which gradually decreases from 95% to 93.82%, reflecting the steady consumption of stored energy as the vehicle operates. In contrast, Figure 11 shows the battery current, which exhibits significant variability with prominent peaks that correspond to energy demands and regenerative braking events. This variability highlights the battery's response to fluctuating power requirements throughout the drive cycle. Figure 12 presents the supercapacitor current, which fluctuates in response to the dynamic charging and discharging cycles that occur during acceleration and deceleration. These fluctuations underscore the role of the supercapacitor in buffering the battery by temporarily absorbing or delivering energy, thereby stabilizing the overall power flow and improving efficiency. Figure 13 shows the supercapacitor State of Charge (SoC), which increases from 69.5% to 71.3%. The increase in SoC is accompanied by periodic dips that align with current spikes, indicating moments when the supercapacitor is heavily engaged in supporting the battery.

Collectively, these figures demonstrate the complementary roles of the battery and supercapacitor in managing power demands and optimizing vehicle performance. The battery handles steady energy needs and regenerative braking, while the supercapacitor smooths out power fluctuations, contributing to an efficient and responsive energy management system under the UDDS drive cycle.

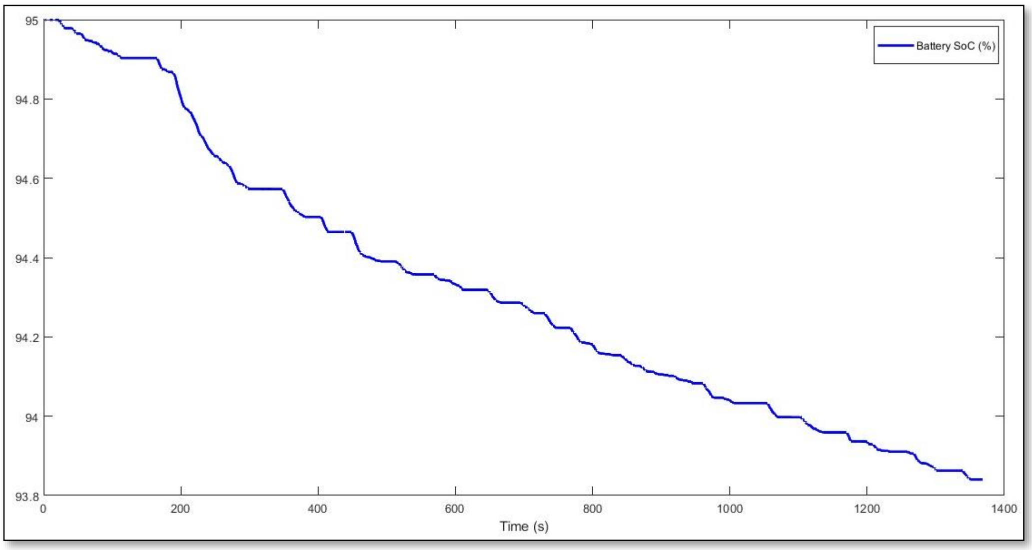

Fig. 10 *Battery State of Charge (SoC) under the UDDS drive cycle for HESS*

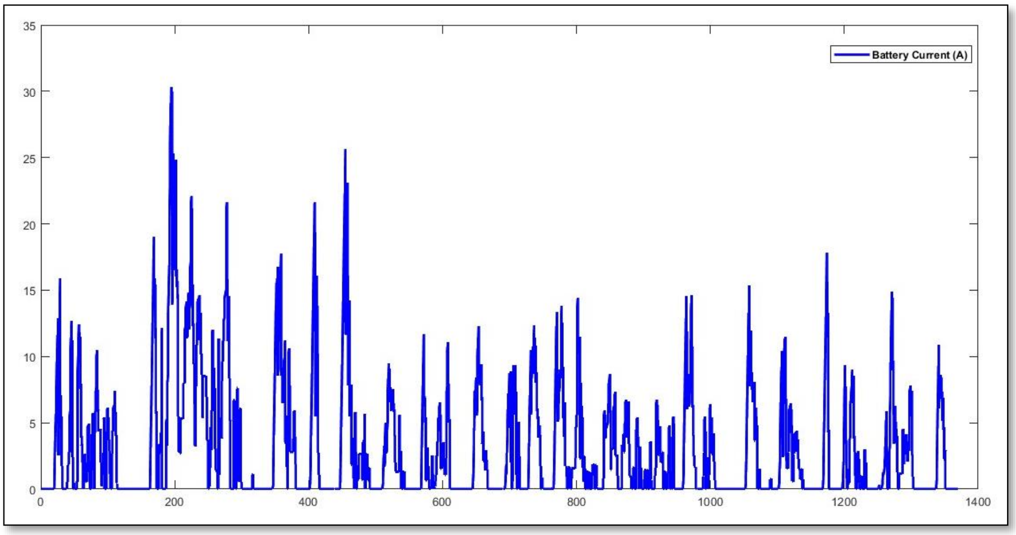

Fig. 11 *EV battery load current under the UDDS drive cycle for HESS*

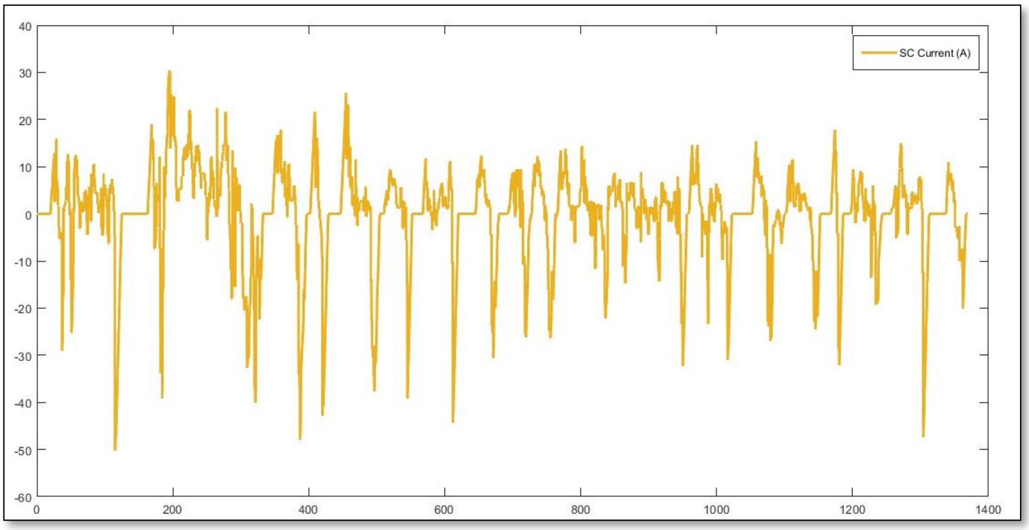

Fig. 12 *Supercapacitor load current under the UDDS drive cycle for hybrid energy storage system*

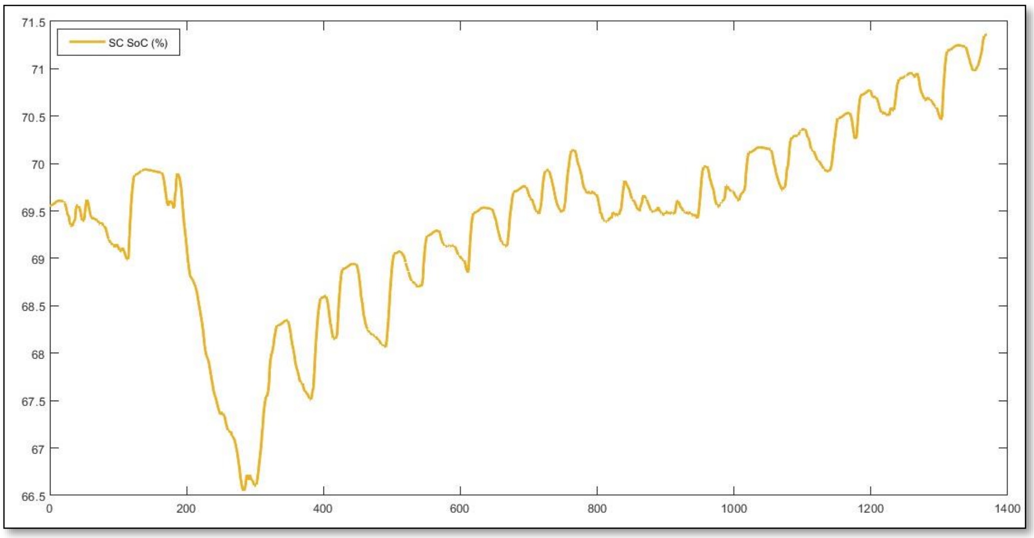

Fig. 13 *Supercapacitor State of Charge (SoC) under the UDDS drive cycle for HESS*

4.2.2 NYCC Drive Cycle Using HESS

Figures 14 through 17 show how a battery-supercapacitor hybrid energy storage system (HESS) performs during the New York City Cycle (NYCC) drive cycle. Figure 14 tracks the battery's State of Charge (SoC), which drops slightly from 95% to 94.74% during the test, indicating that the battery is steadily used as the vehicle drives. This small decrease shows how the battery supplies continuous energy throughout the cycle. Figure 15 displays the battery current, which varies a lot with noticeable peaks. These peaks occur during times of high energy demand and when regenerative braking kicks in, highlighting how the battery responds to changing power needs. Figure 16 shows that the supercapacitor's State of Charge (SoC) increases from 69.5% to 71.7% during the cycle. This rise is linked to the fluctuations in the supercapacitor current shown in Figure 17, which reveals how the supercapacitor manages energy by absorbing and releasing power during acceleration and braking.

Overall, these figures illustrate how the battery and supercapacitor work together. The battery handles steady energy needs and regenerative braking, while the supercapacitor helps balance power flow and improve performance during the NYCC drive cycle.

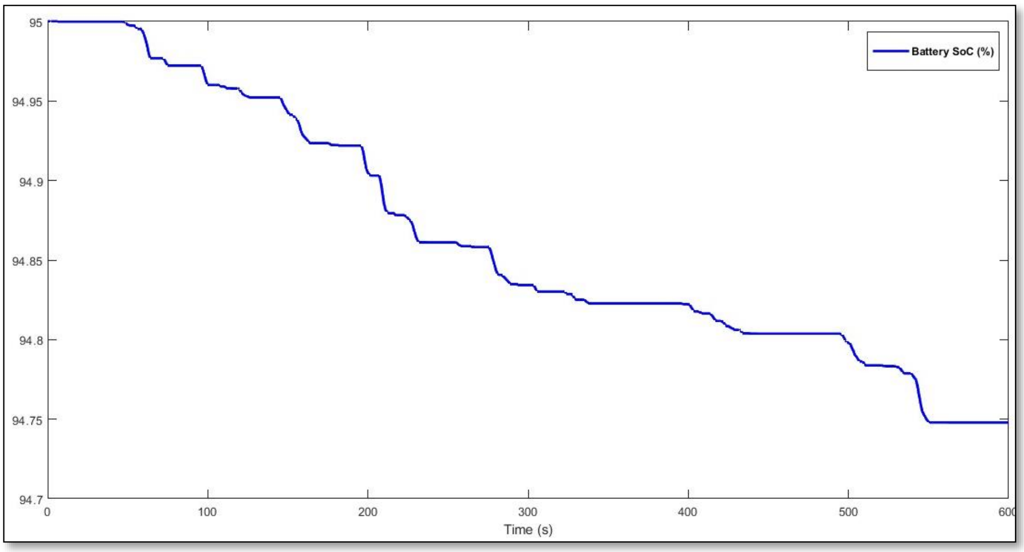

Fig. 14 *Battery State of Charge (SoC) under the NYCC drive cycle for HESS*

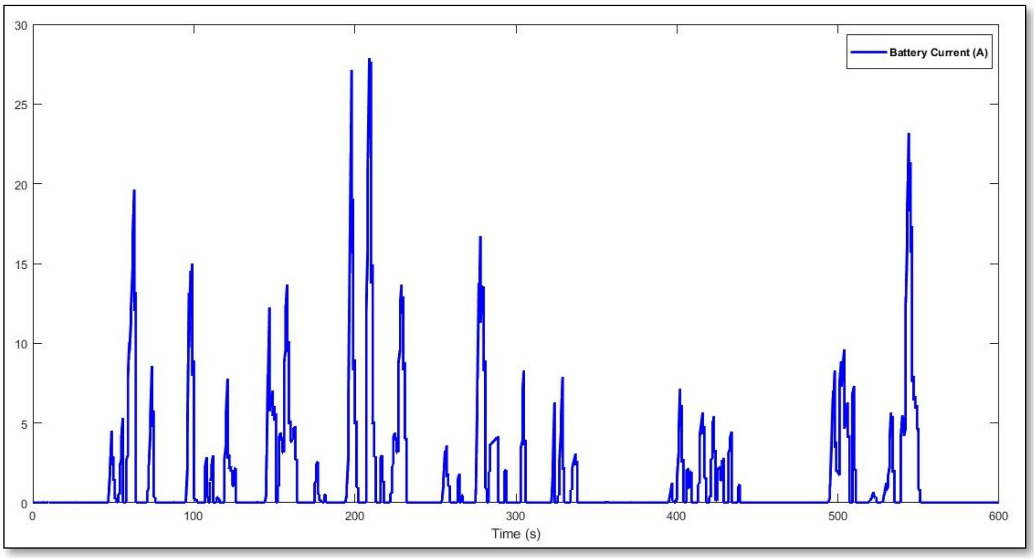

Fig. 15 *EV battery load current under the NYCC drive cycle HESS*

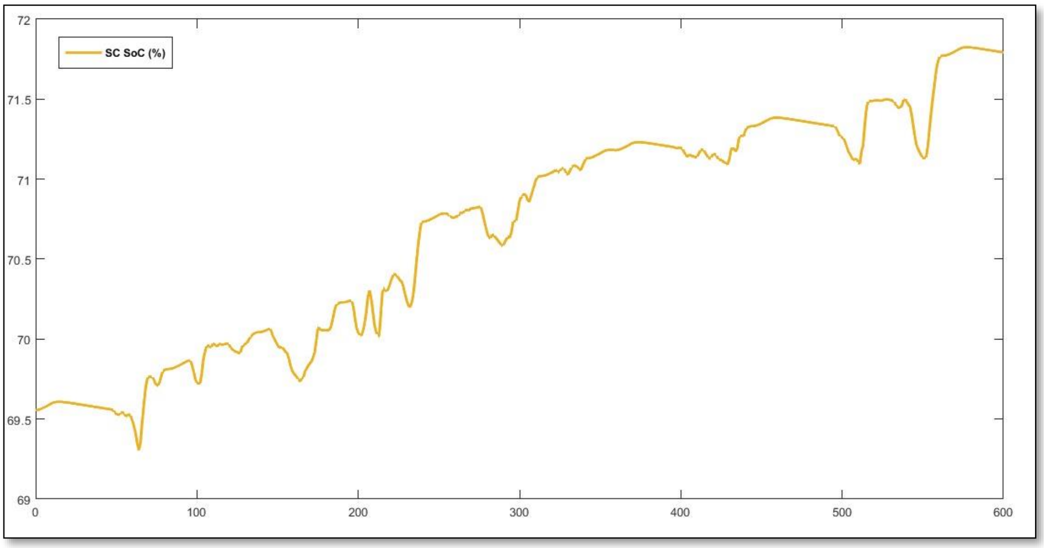

Fig. 16 *Supercapacitor State of Charge (SoC) under the NYCC drive cycle for HESS*

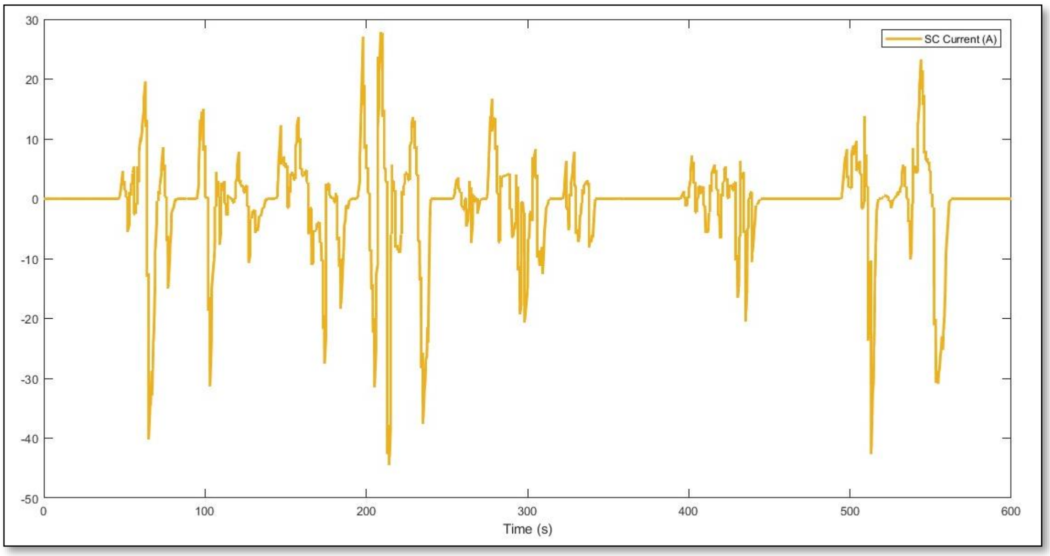

Fig. 17 *Supercapacitor load current under the NYCC drive cycle for HESS*

4.2.3 NEDC Drive Cycle Using Hybrid Energy Storage System

Figures 18, 19, 20, and 21 showcase the performance of a hybrid energy storage system (HESS) consisting of a battery and supercapacitor during the New European Driving Cycle (NEDC). Figure 18 reveals that the battery's State of Charge (SoC) decreases from 95% to 93.88% throughout the simulation, indicating a gradual use of stored energy as the vehicle operates under NEDC conditions. This steady decline demonstrates how the battery consistently supplies power during the drive cycle. Figure 19 illustrates the battery current, which displays noticeable peaks. These peaks signify periods of high energy demand and regenerative braking, highlighting how the battery adjusts to varying power requirements. Figures 20 and 21 provide insights into the supercapacitor's performance. Figure 20 shows the supercapacitor's State of Charge (SoC), while Figure 21 depicts its current. These figures together reveal how the supercapacitor helps manage energy flow, absorbing and delivering power as needed.

Overall, these figures illustrate the complementary roles of the battery and supercapacitor in the HESS. The battery supports continuous energy needs and regenerative braking, while the supercapacitor aids in stabilizing power and enhancing efficiency during the NEDC drive cycle.

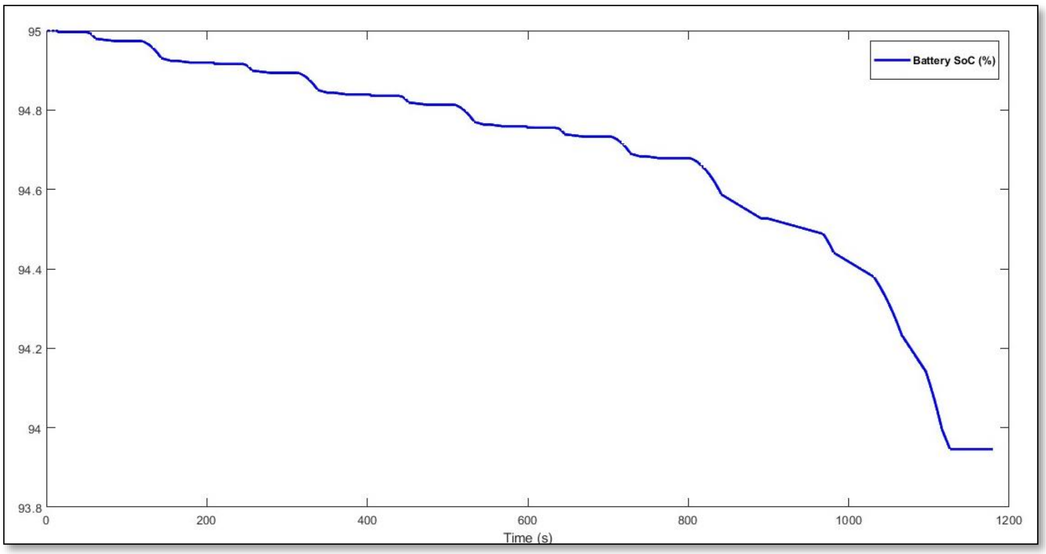

Fig. 18 *Battery State of Charge (SoC) under the NEDC drive cycle for HESS*

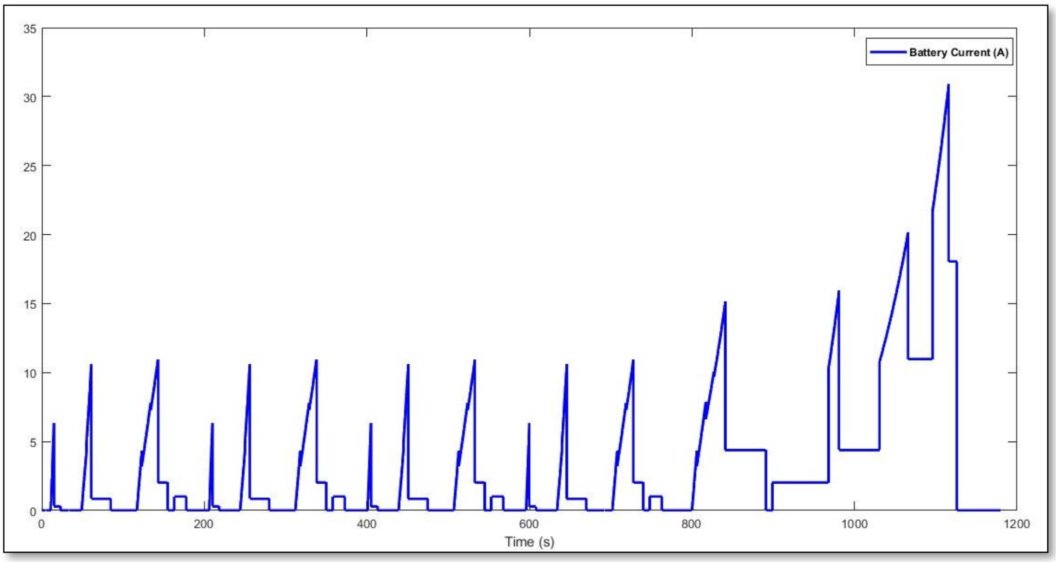

Fig. 19 *EV battery load current under the NEDC drive cycle for HESS*

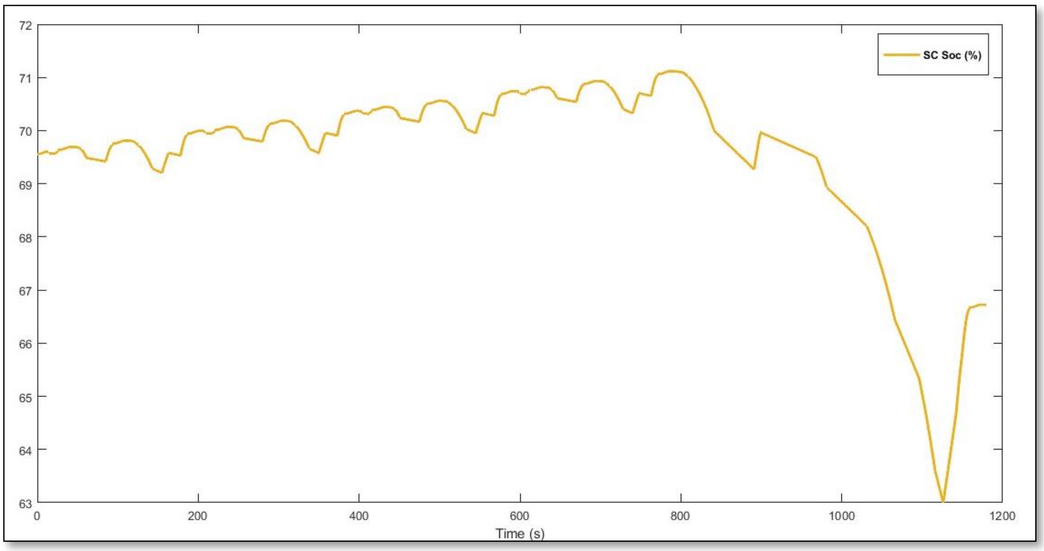

Fig. 20 *Supercapacitor State of Charge (SoC) under the NEDC drive cycle for HESS*

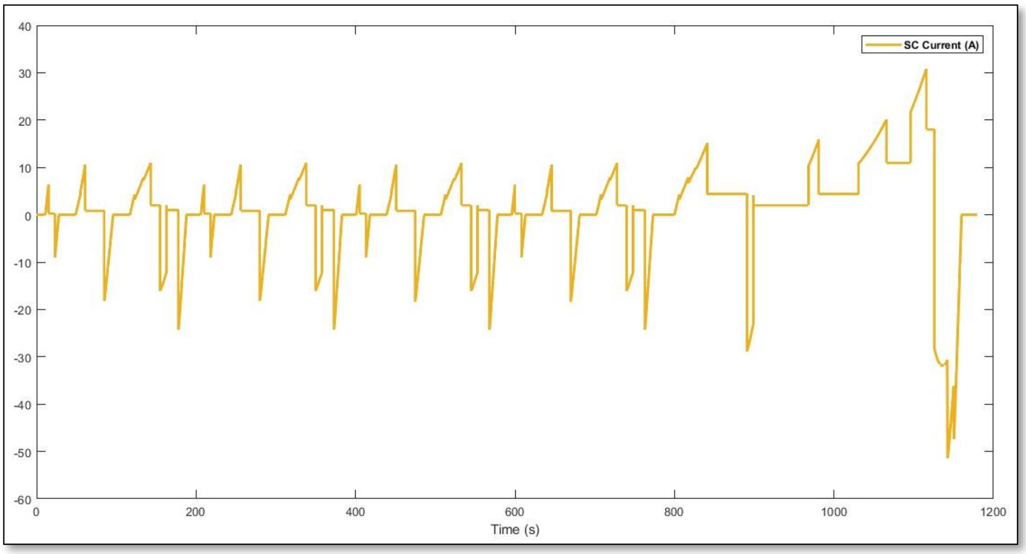

Fig. 21 *Supercapacitor load current under the NEDC drive cycle for HESS*

4.3 Comparative Analysis

A comparative analysis was conducted to assess the impact of integrating a battery-supercapacitor Hybrid Energy Storage System (HESS) into an electric vehicle, focusing on its effect on the battery's State of Charge (SoC) during different drive cycles. Figures 22, 23, and 24 respectively illustrate the variations in battery SoC with and without HESS integration under three distinct driving conditions: the Urban Dynamometer Driving Schedule (UDDS), New York City Cycle (NYCC), and New European Driving Cycle (NEDC).

In Figure 22, under the UDDS drive cycle, which simulates urban driving conditions with frequent stops and accelerations, the integration of the HESS helps to reduce the fluctuations in battery SoC compared to the case without HESS. This indicates improved energy efficiency and battery lifespan, as the HESS mitigates the high power demands during acceleration and regenerative braking events. Similarly, Figure 23 demonstrates the behavior of the battery SoC under the NYCC drive cycle, a more aggressive urban driving scenario with even more frequent stops and starts. The addition of the HESS results in a smoother SoC profile, showing that the HESS effectively manages the increased energy demands, providing better battery protection and energy recuperation in such stop-and-go traffic conditions. Figure 24 shows the SoC variations under the NEDC drive cycle, a mix of urban and highway driving conditions. The results highlight how the HESS helps to maintain a more stable SoC, reducing the battery's workload during both low-speed urban driving and high-speed highway segments.

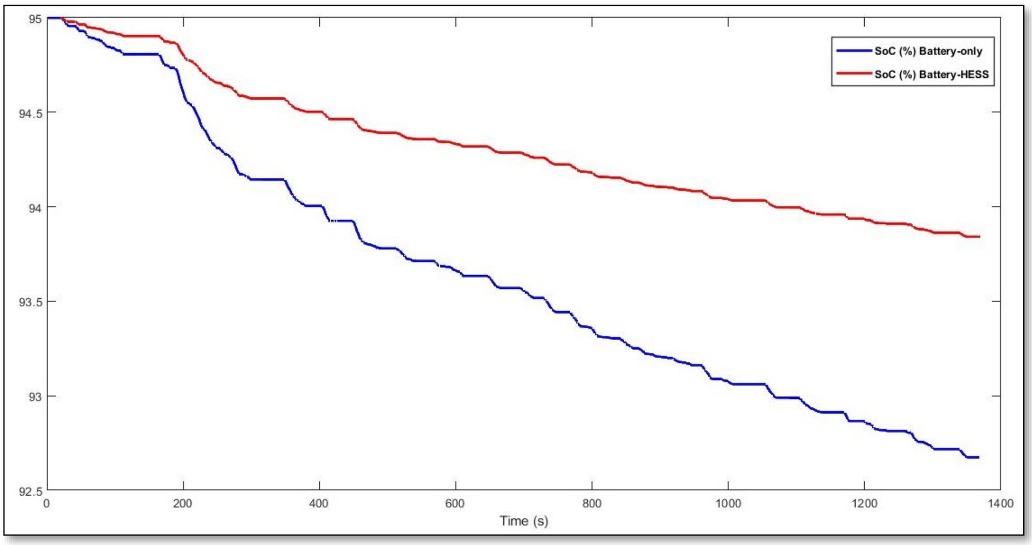

Fig. 22: *Battery State of Charge (SoC) with and without the HESS under UDDS drive cycle*

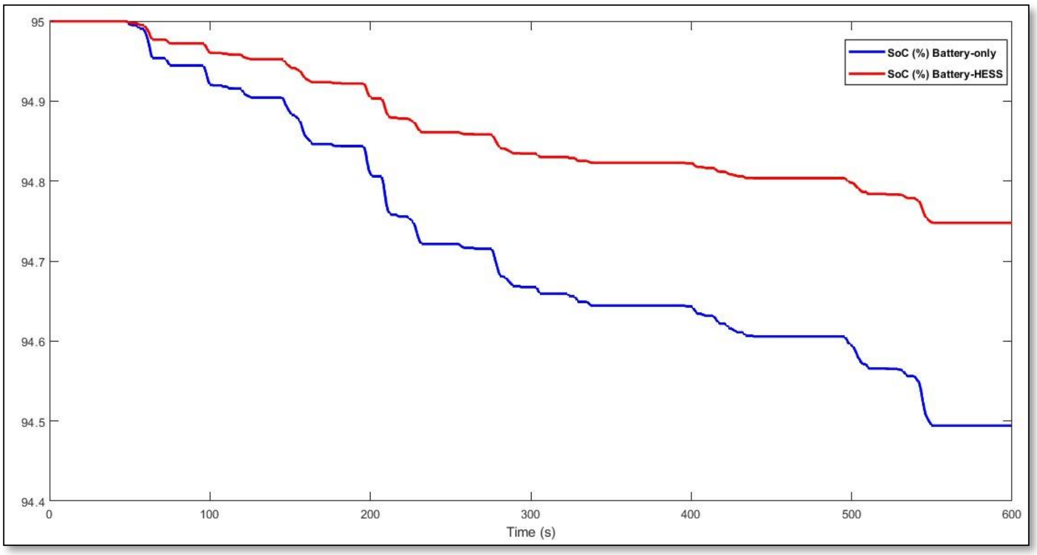

Fig. 23: *Battery State of Charge (SoC) with and without the HESS under NYCC drive cycle*

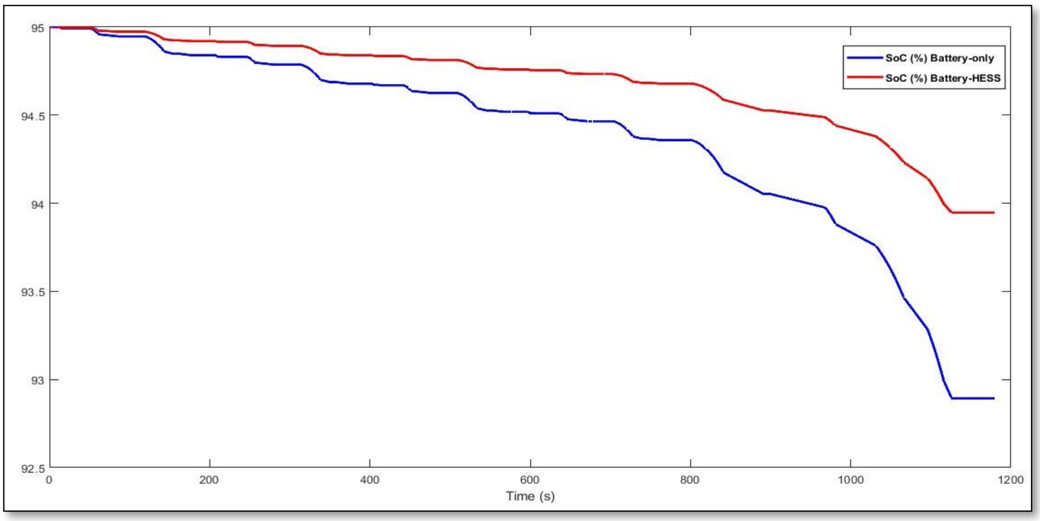

Fig. 24: *Battery State of Charge (SoC) with and without the HESS under NEDC drive cycle*

Table 4 provides the corresponding numerical data for the battery State of Charge and the number of possible cycles under each drive cycle for battery-only and HESS integration. The data highlights significant improvements in energy management, battery preservation, and the reduction of cycling stress when using the HESS. For instance, under the UDDS drive cycle, the battery's final SoC increased from 92.60% in the battery-only configuration to 93.82% with HESS integration, while the number of cycles more than doubled from 42 to 85. A similar figure is observed under the NYCC drive cycle, where the number of cycles increased from 196 in the battery-only case to 385 with HESS, and the final SoC saw a slight improvement from 94.49% to 94.74%. In the NEDC drive cycle, the final SoC increased from 92.80% to 93.88%, with the number of cycles increased from 46 to 90 by using the HESS.

These results quantitatively emphasize the enhanced energy efficiency and battery preservation provided by the HESS. The increased number of cycles reflects better power management, particularly in high-demand urban driving scenarios like UDDS and NYCC, while the higher final SoC values indicate more efficient use of available energy, ultimately extending battery life and improving vehicle performance across different driving conditions.

Table 4 *Comparison of the Battery State of Charge (%) with and without the integration of HESS*

	Battery-only			**HESS**		
Drive Cycle	B_SoC_0 (%)	B_SoC_{final} (%)	*Num. of cycles*	B_SoC_0 (%)	B_SoC_{final} (%)	*Num. of cycles*
UDDS	95.00	92.60	42	95.00	93.82	85
NYCC	95.00	94.49	196	95.00	94.74	385
NEDC	95.00	92.80	46	95.00	93.88	90

5. Conclusion

The study concludes that the integration of a battery-supercapacitor hybrid energy storage system (HESS) in electric vehicles (EVs) substantially improves both energy efficiency and overall vehicle performance. This enhancement is particularly pronounced during acceleration and regenerative braking phases, which are characteristic of urban driving cycles such as the UDDS, NYCC, and NEDC drive cycles. By effectively managing high power demands, the supercapacitors in the HESS alleviate stress on the battery and enhance regenerative braking efficiency. This integration not only improves the smoothness of the driving experience but also maximizes energy recovery, a critical factor in stop-and-go traffic conditions as modeled by the UDDS, NYCC, and NEDC drive cycles. For instance, under the UDDS drive cycle, the number of battery cycles increased from 42 to 85 with HESS integration. Similarly, under the NYCC cycle, the number of cycles rose from 196 to 385, and in the NEDC cycle, the cycles nearly doubled, from 46 to 90. These results highlight the significant reduction in battery cycling stress provided by the HESS. The energy sharing effectively regulates power flows between the battery and supercapacitor, further enhancing the overall performance of the EV.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the paper's publication.

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