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A Novel Design of Hybrid Energy Storage System for Electric Vehicles

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***Abstract*--This paper presents a systematic framework for the modelling and comparative analysis of conventional and advanced energy storage system in electric vehicle (EV) applications. Conventional ESS, primarily based on lithium-ion batteries, is compared with hybrid configurations that combine multiple storage technologies, such as batteries and super-capacitors, to enhance both energy and power performance. Comprehensive mathematical models incorporating electrochemical dynamics and power management strategies are developed to simulate system performance under different driving cycles. Key performance indicators, including energy efficiency, power density, energy density, and lifecycle durability are evaluated. The results demonstrate that Hybrid ESS significantly improve peak power capability, extend battery lifespan, and enhance overall system efficiency. However, these benefits are accompanied by increased system complexity and cost considerations.**

Furthermore, optimization and control strategies for advanced ESS are investigated to maximize performance gains. Model validation through comparison with simulation data, along with sensitivity analysis, ensures the accuracy and robustness of the proposed framework. This work provides valuable insights for the design, analysis, and optimization of Hybrid energy storage systems in electric vehicles.

***Keywords*--Electric Vehicles (EVs), Energy Storage Systems (ESS), Hybrid Energy Storage System (HESS), Lithium-Ion Batteries, ultra-capacitors, Power density, Energy Efficiency, Lifecycle Analysis..**

I. INTRODUCTION

In recent years, electrical energy has gained significant attention due to its environmentally friendly nature and sustainable benefits.

Electric Vehicle Technology (EVT) has emerged as a promising solution for modern transportation systems. EVT mainly depends on energy storage sources such as fuel cells, ultra-flywheels, ultra-capacitors (UCs), and rechargeable batteries for storing and supplying electrical energy [1–5]. The performance comparison of various energy sources is commonly represented using the Ragone plot, which illustrates the relationship between specific energy and specific power. Specific energy determines the driving range or charging capability, whereas specific power indicates the acceleration performance of the vehicle, as shown in Fig. 1.

Most electric vehicles currently employ rechargeable battery technologies; however, the performance of battery energy management systems depends greatly on battery manufacturing technology and operating conditions. Batteries are highly affected by sudden peak power demands and fluctuating driving conditions caused by varying road and traffic situations. These conditions accelerate battery degradation, reduce battery life, and negatively impact overall performance [6]. Although several rechargeable battery technologies are commercially available, battery-powered electric vehicles still face challenges in competing with conventional internal combustion (IC) engine vehicles. The major limitations of existing batteries include lower specific energy (kWh/kg), energy density (kWh/L), and power density (kW/L) compared to petrol and diesel fuels. Due to low specific energy, a large number of battery packs are required to achieve longer driving distances, which increases vehicle weight, occupies more space, and raises the overall cost of the system [7].

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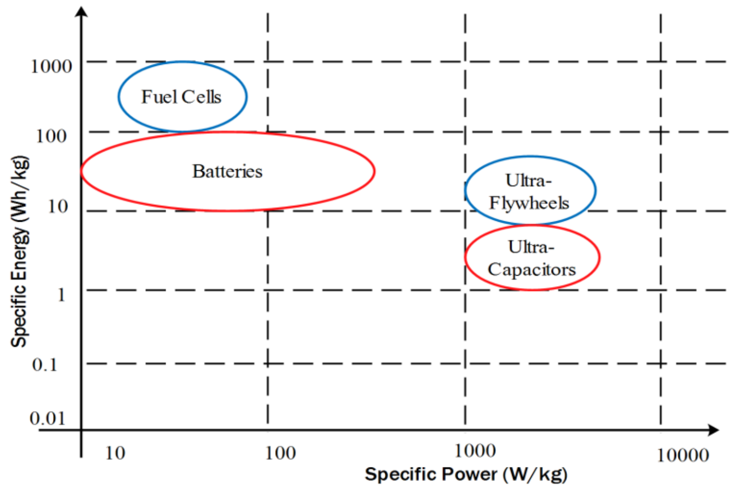

Fig.1 Ragone Plot- Comparison of Energy Sources

To overcome these limitations, hybrid energy storage solutions involving multiple energy sources have been proposed for EVT applications. Battery performance is generally evaluated based on parameters such as specific energy, specific power, life cycle, safety, and cost. Among the available battery technologies, Lithium-Ion (Li-Ion) batteries have demonstrated superior performance and satisfy most EVT requirements [8,9]. However, auxiliary energy storage devices such as ultra-flywheels and ultra-capacitors are often integrated with batteries to enhance system performance. Ultra-flywheels provide high specific power at high rotational speeds but possess low specific energy. In contrast, ultra-capacitors offer very high specific power, fast charging capability, and long life cycles, making them highly suitable for energy storage system (ESS) applications. Current research on ultra-capacitors focuses on advanced materials such as graphene and carbon nanotubes to improve surface characteristics and energy storage capability.

A Hybrid Energy Storage System (HESS) combines the advantages of Li-Ion batteries and ultra-capacitors to improve the overall performance of electric vehicles [10–15,19]. In such systems, ultra-capacitors act as peak power buffer units to handle fluctuating power demands, while batteries provide continuous energy supply due to their high energy storage capability. The proposed HESS in this work integrates Li-Ion batteries with ultra-capacitors, and its performance characteristics are thoroughly evaluated.

This combination enhances driving range, improves acceleration and braking performance, and increases the overall efficiency and reliability of the electric vehicle system.

The remainder of this paper is organized as follows. Section 2 presents the models and specifications of the energy sources used in the proposed HESS. Section 3 discusses the energy distribution strategy adopted in this work. Section 4 provides simulation results along with detailed discussions, and Section 5 concludes the paper with the main findings and future scope.

II. Modelling Of The Battery And Ultra-Capacitor

The Li-Ion battery and ultra-capacitor models were developed and simulated using the United States Simplified Federal Urban Driving Cycle (SFUDC) and the European Union Urban Driving Cycle (EUDC).

2.1 Battery Model

The battery model is primarily developed based on the Depth of Discharge (DOD) and State of Charge (SOC) characteristics. The DOD of the battery is an important parameter used to estimate the driving range of an electric vehicle for a selected driving cycle. Driving cycles vary depending on the road, traffic, and environmental conditions of different countries, states, and cities. Therefore, accurate battery modelling is essential for evaluating vehicle performance under varying operating conditions.

The open-circuit voltage of the Lithium-Ion battery is given by,

$$E = N*[(-3.268*DOD^6)+(9.1629*DOD^5)(10.847*DOD^4)+(5.876*DOD^3) \\ -(0.6717*DOD^2)-(0.8515*DOD+4.1495] \tag{1}$$

Where,

N is the number of cells in battery pack.

The operating power of the battery is given by

$$P_{batt} = V*I = (E-IR)*I \tag{2}$$

The battery current (I) is calculated from the battery power (P_{batt}) with the equation as

$$I = \frac{E-\sqrt{E^2-4RP_{batt}}}{2R} \tag{3}$$

Where,

R is the cell internal resistance.

If the vehicle is in regenerative mode, the battery power (P_{batt}) will be negative. The equation of battery current is

$$I = \frac{-E+\sqrt{E^2-4RP_{batt}}}{2R} \tag{4}$$

The battery capacity is reduced promptly, if the current drawn is more. This phenomenon is substantial for EVTs, as they draw the current at higher values. So, it is significant to forecast the effect of current on capacity.

At the n^{th} step, the DOD of a battery is the ratio of charge removed to capacity of the battery and it is given by [16]

$$DOD_n = \frac{CR_n}{C_p} \tag{5}$$

Where,

C_p is the Peukert capacity and it is given by the equation as [16]

$$C_p = I^k * T \tag{6}$$

Where,

k is the battery Peukert's Coefficient,

T is the time in hours

I is the constant current.

The Battery SOC is given by

$$SOC = \frac{Maximum\ usable\ capacity\ of\ the\ battery}{Nominal\ capacity\ of\ the\ battery} \tag{7}$$

The range of the vehicle can be reckoned with the simplified equation as

$$Range = \frac{90\%\ of\ battery\ charge}{DOD(\%)\ per\ cycle} * Distance/cycle \tag{8}$$

2.2 Ultra-Capacitor Model

Ultra-capacitors are characterized by high power density and low energy density [17]. Due to these characteristics, they can rapidly respond to high-frequency load variations, although their energy storage capability is limited.

Therefore, ultra-capacitors are mainly utilized as peak power buffer units, where they absorb energy during vehicle deceleration and supply energy during acceleration. In this work, the ultra-capacitor is modeled as an ideal capacitor connected in series with a resistor. The current flowing through the ultra-capacitor, denoted by (I_{UC}), is calculated using the corresponding mathematical relations.

$$I_{UC} = \frac{Q_{UC}(i)/C_{UC}}{2R_{UC}} - \frac{\sqrt{\left(Q_{UC}(i)/C_{UC}\right)^2 - 4R_{UC}P_{UC}(i)}}{2R_{UC}} \tag{9}$$

Where,

P_{UC}, Q_{UC}, C_{UC}, and R_{UC} represent the power, the charge stored, equivalent capacitance, and equivalent internal resistance of the Ultra-capacitor (UC) respectively.

The charge stored in the Ultra-capacitor Q_{UC} is given by

$$V_{UC} = \frac{Q_{UC}(i)}{C_{UC}} \quad (10)$$

Where,

V_{UC} represents the Ultra-capacitor equivalent voltage.

The SOC of UC is defined as the ratio of the Ultra-capacitor voltage (V_{UC}) at the i-th moment to its nominal capacity (V_{UC_nom}) [18]. The SOC of UC (SOC_{UC}) is given by

$$SOC_{UC}(i) = \left(\frac{V_{UC}^2(i)}{V_{UC\_nom}^2}\right) * 100 \quad (11)$$

The state of charge Q_{UC} is updated as

$$Q_{UC}(i+1) = Q_{UC}(i) - I_{UC}(i+1) * \Delta t \quad (12)$$

It is worth noticing that the minimum SOC_{UC} should be maintained above 25%, because the Ultra-capacitor voltage V_{UC} is only half of the nominal voltage V_{UC_nom} and still provides energy [1, 20].

III. HESS Modelling And Specifications

The proposed Hybrid Energy Storage System (HESS) is introduced in this section. By combining multiple energy sources, an energy storage system with both high energy density and high power density can be achieved. Such a system is referred to as a Hybrid Energy Storage System (HESS) [21]. In the proposed HESS, Li-Ion batteries and ultra-capacitors are integrated to utilize the advantages of both energy sources. The Li-Ion battery serves as the High Energy Source (HES) due to its superior energy storage capability, while the ultra-capacitor functions as the High Power Source (HPS) because of its excellent power delivery characteristics. This combination enhances the feasibility and overall performance of electric vehicles by improving driving range, acceleration, and regenerative braking efficiency.

The configuration of the proposed HESS is illustrated in Fig. 2, which includes a Li-Ion battery pack, an ultra-capacitor bank (UC bank), and a power converter (P.C). The battery pack provides continuous energy support, whereas the UC bank handles transient and peak power demands.

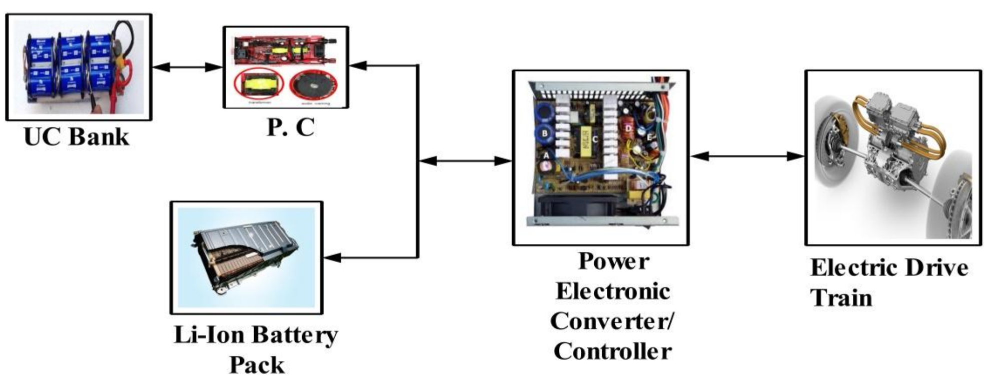

Fig.2 HESS for EVT

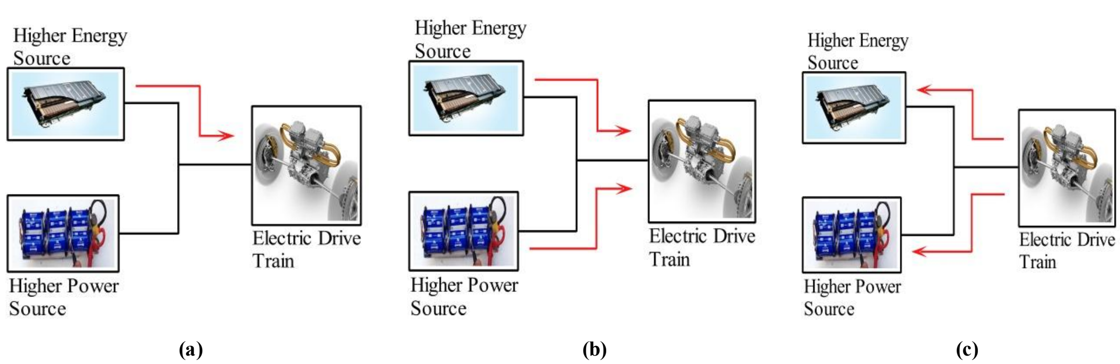

Fig. 3 HESS operations of EVT (a) Normal Drive (b) Acceleration (c) Braking

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The three HESS operating modes of EVT are shown in Fig. 3

Normal Drive: In this operation, the HES acts as energy source to the Electric Drive Train (EDT), and the HPS will be decoupled from the circuit.

Acceleration: This operation activate during the starting, overtaking, and hillclaimbing of the vehicle. In this operation both HES and HPS will supplies the energy to the EDT.

Braking: This operation activate during the speed breakers, downward from hills, and heavy traffic conditions. In this operation, the energy will supply from EDT to both HES and HPS through the power electronic converter. This operation is also called as regenerative braking; due to this overall efficiency will be improved.

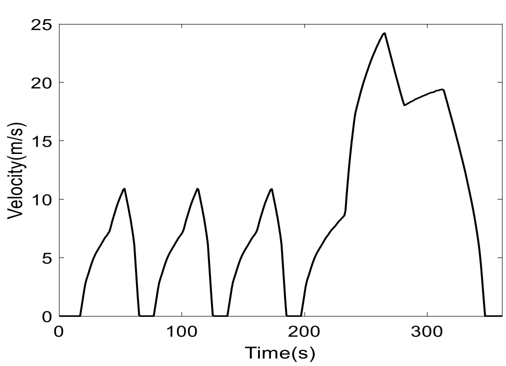
HESS is an energy system for EVT; its simulation model is developed by the KIA Company EV$^+$ car specifications are shown in Table.1.

Table.1 Energy Sources Specifications

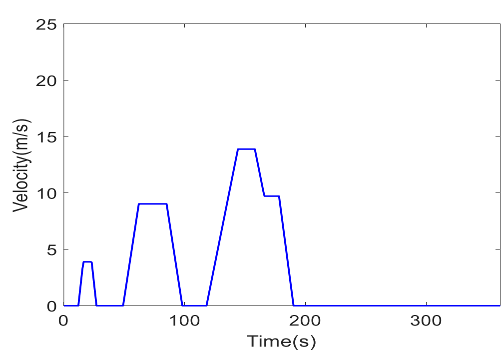
Parameters	Li-Ion cell	(Adopted) Li-Ion Battery KIA EV$^+$	Ultra-capacitor	Ultra-capacitor bank
Rated Capacity	2.5 Ah	75Ah	N/A	N/A
Nominal Voltage	3.6 V	375V	2.5 V	12 V
Weight	42.5 grams	274.4Kg	132.0 grams	660 grams
Internal Resistance / Capacitance	0.0034 Ω	0.0034 Ω/cell	0.0089 Ω /630 F	0.4431 Ω /126 F
Peukert Coefficient (k)	1.02	1.02	N/A	N/A
Operating Temperature	-20^{0}C to 70^{0}C	-20^{0}C to 70^{0}C	-40^{0}C to 85^{0}C	-40^{0}C to 85^{0}C
Life cycles	1000-2000	1000-2000	500 times above the battery	500 times above the battery

Table 1 presents the basic specifications of the Li-Ion cell and ultra-capacitor, along with the calculated specifications of the Li-Ion battery pack and ultra-capacitor bank. The design parameters of the KIA EV+ vehicle, including vehicle dynamics and Li-Ion battery specifications, are considered in this study [22, 24].

The HESS simulation model is developed using the specifications of the KIA EV+ vehicle. The performance of the proposed HESS is compared with that of the conventional energy storage system consisting only of a Li-Ion battery bank. The comparison is carried out for both the United States SFUDC and European Union EUDC driving cycles to evaluate the performance of the electric drivetrain under different driving conditions. The SFUDC and EUDC driving cycles considered in this work are shown in Fig. 4(a) and Fig. 4(b), respectively.



(a)



(b)

Fig. 4 Driving cycles of the Proposed Model (a) US drive cycle (b) EU drive cycle

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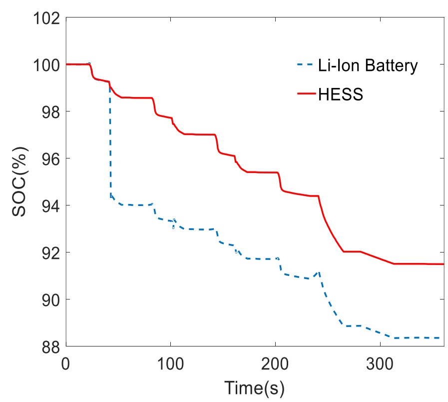
IV. Results And Discussion

The simulation results of the energy storage systems, including State of Charge (SOC), life loss, and power characteristics, are presented in Fig. 5, Fig. 6, and Fig. 7. The variations in SOC, life loss, and power for both the conventional energy storage system and the proposed Hybrid Energy Storage System (HESS) were analyzed and compared under the SFUDC and EUDC driving cycles. When the electric drive train (EDT) power demand varies smoothly, the battery pack mainly supplies the required power. However, during rapid and fluctuating power demands, the ultra-capacitor supports the system by delivering high peak power. The proposed HESS effectively improves battery life by transferring high-frequency power demands to the ultra-capacitor bank.

During low power demand conditions, the ultra-capacitor can provide energy support and can also recover energy through regenerative braking, thereby reducing the stress on the battery pack [23].

The SOC characteristics of the energy systems for both driving cycles are shown in Fig. 5(a) and Fig. 5(b). For the SFUDC driving cycle, the SOC values of the proposed HESS and the conventional energy storage system are maintained at 91.49% and 88.35%, respectively. This indicates that the proposed HESS maintains a higher SOC compared to the conventional system. Similarly, for the EUDC driving cycle, the SOC values of the proposed and conventional systems are 99.76% and 101.56%, respectively, as presented in Table 2. The higher SOC observed in the conventional system may lead to excessive current and temperature generation within the energy storage system, which can adversely affect battery lifespan and reliability.



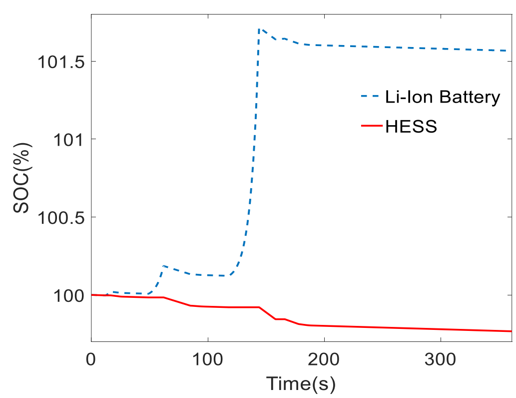


Fig. 5 SOC of energy system for drive cycles (a) SFUDC (b) EUDC

Table. 2 Energy systems SOC and Life Loss

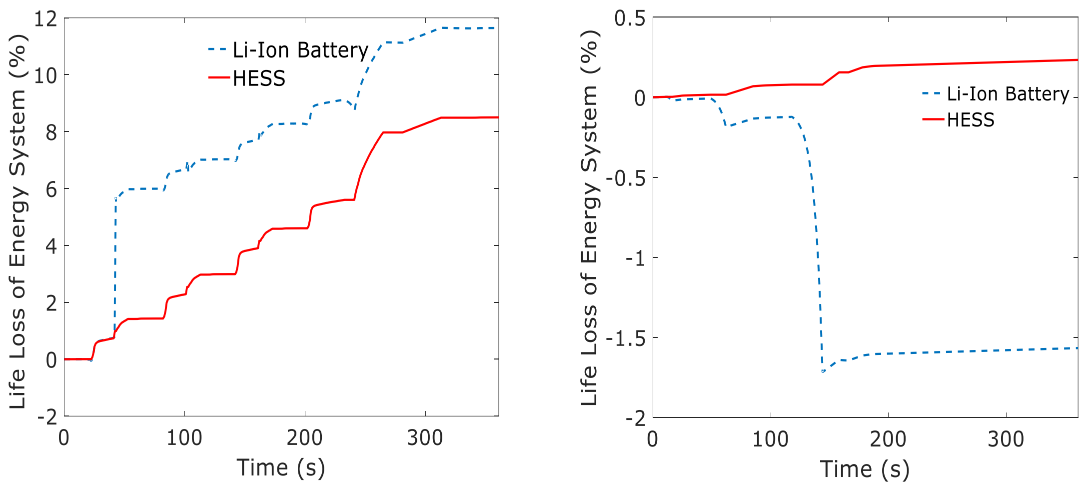
Drive Cycles/Energy System		SOC @ initial (%)	SOC @ final (%)	Life Loss (%)
SFUDC	Li-Ion Battery	100	88.35	11.64
	HESS	100	**91.49**	**8.5**
EUDC	Li-Ion Battery	100	101.56	-1.56
	HESS	100	**99.76**	**0.23**

Table 2 summarizes the initial and final SOC values along with the percentage life loss of both the proposed and conventional energy storage systems. For the SFUDC driving cycle, the percentage life loss of the proposed HESS is 8.5%, whereas the conventional system exhibits a higher life loss of 11.64%. This demonstrates that the proposed HESS reduces battery degradation and improves system durability.

In contrast, for the EUDC driving cycle, the life loss values of the proposed and conventional systems are 0.23% and –1.56%, respectively. The negative life loss value observed in the conventional system indicates continuous energy storage beyond the rated capacity, which may lead to excessive stress and rapid deterioration of the energy storage system. The life loss characteristics for both driving cycles are illustrated in Fig. 6(a) and Fig. 6(b).

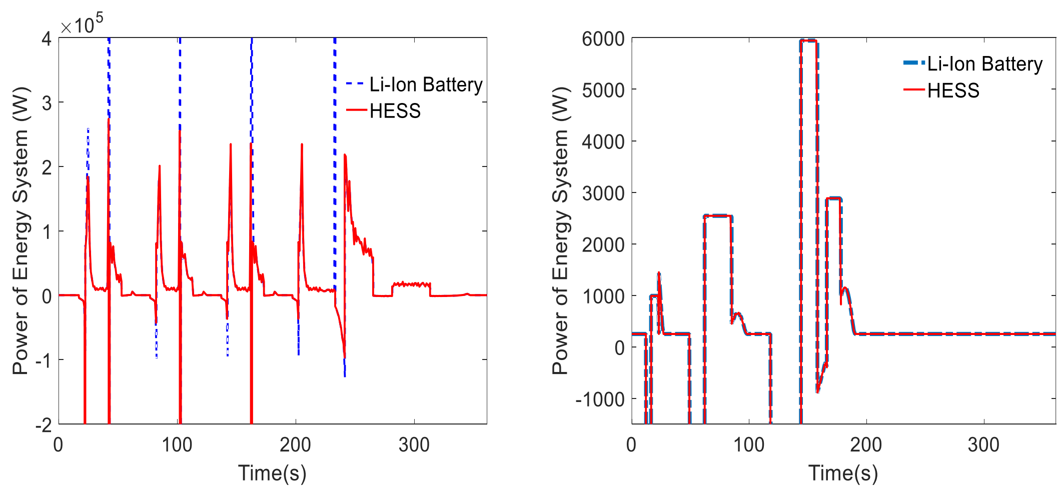
The power characteristics of the energy systems for the SFUDC and EUDC driving cycles are shown in Fig. 7(a) and Fig. 7(b), respectively. From Fig. 7(a), it can be observed that the conventional energy system experiences significant peak power fluctuations during vehicle acceleration.

These fluctuations are effectively minimized in the proposed HESS through the incorporation of the ultra-capacitor bank, which absorbs and supplies transient power demands. On the other hand, Fig. 7(b) shows that, under the EUDC driving cycle, only minor variations in power are observed for both the conventional and proposed energy systems.



(a) (b)

Fig. 6 Life Loss of Energy System for drive cycles (a) SFUDC (b) EUDC



(a) (b)

Fig. 7 Power of Energy System for drive cycles (a) SFUDC (b) EUDC

V. CONCLUSION

In this paper, a Hybrid Energy Storage System (HESS) consisting of a Li-Ion battery and ultra-capacitor has been modeled, simulated, and analyzed under SFUDC and EUDC driving cycles.

The performance of the proposed HESS was compared with the conventional Li-Ion battery system based on parameters such as State of Charge (SOC), life loss, and power characteristics.

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The simulation results show that the proposed HESS achieves approximately 3–4% higher SOC and 2.5–3% lower life loss compared to the conventional system. In addition, the integration of the ultra-capacitor effectively reduces peak power fluctuations during acceleration and regenerative braking conditions, thereby improving the reliability and lifespan of the energy storage system.

Future work will focus on the development of advanced control and energy management strategies for optimal power sharing between the battery and ultra-capacitor, along with the implementation of intelligent techniques to improve system efficiency and battery life in electric vehicles.

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