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Optimal energy management of hybrid battery/supercapacitor storage system for electric vehicle application

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ABSTRACT

A proposed approach for efficient energy management for lithium-ion battery and supercapacitor hybrid energy storage system is outlined in this study. The primary aim is to ensure the electric vehicle receives a stable and high-quality supply of electricity. The suggested management strategy focuses on maintaining the bus voltage at a consistent level while meeting the varying load demands with high-quality power across different scenarios. To achieve this, a management controller is employed, which utilizes a metaheuristics technique to define the parameters of the integral sliding mode control. The supercapacitor units are responsible for controlling the direct current (DC) bus, while the lithium-ion battery plays a role in balancing power distribution on the common line. This study evaluates the potential benefits of integrating salp swarm algorithm techniques into the controller's performance. The findings of the study suggest combining metaheuristic optimization methods with integral sliding mode control. Can lead to improvements in power quality. The proposed management algorithm not only efficiently allocates power resources but also safeguards them, ultimately ensuring a consistent and high-quality power supply for the electric vehicle.

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1. INTRODUCTION

The surge in urban development has given rise to heightened emissions stemming from transportation, presenting a significant challenge in our pursuit of maintaining a steady climate scenario [1]. Consequently, society is actively working to curb its carbon footprint by 2050 in response to climate change, catalyzing transformations within the transportation sector [2]. This evolution is marked by a shift away from conventional fossil fuels towards low-emission alternatives, centered on electric vehicle (EV) batteries and hydrogen fuel cell technology as primary energy sources [3]. Notably, the EV market is experiencing remarkable growth, with progresses in battery technology leading to increased range and a notable decrease in battery costs [4], [5]. These improvements, coupled with a substantial boost in driving distance, now exceeding 400 km [6], [7], have positioned EVs as a compelling choice for achieving transportation decarbonization.

To meet the diverse requirements of EVs and optimize their performance, a hybrid power system (HPS) has emerged, combining the capabilities of batteries and supercapacitors (SCs). This hybridization offers a multitude of advantages encompassing energy density, power output, discharge rates, lifespan, and cost [8]. While batteries excel at energy storage, they often struggle to deliver high power output swiftly due to their lower power density. In contrast, SCs boast the ability to provide rapid bursts of power, albeit with limited storage capacity [9]. The strategic integration of batteries and SCs in parallel enables them to complement each other, ensuring the seamless fulfillment of energy storage and peak current requirements [10].

One key motivation behind employing HPS lies in extending the lifespan of batteries, which tend to degrade over time, especially when confronted with unexpected energy demands during acceleration or significant currents generated during regenerative braking [9]. By diverting such transient currents to the SC, it becomes possible to enhance the overall longevity of the battery. However, the successful implementation of HPS relies heavily on selecting an appropriate topology and devising an effective energy management strategy (EMS). The EMS produces two power references: one for the supercapacitor to control the direct current (DC) bus voltage and the other for the battery, determined using the SC's state of charge and the load power. The optimum load distribution between Li-ion battery and SC was discussed in [11]. The proposed strategy has been built based on particle swarm optimization. The results demonstrated that integrating flatness theory and modern optimization improved the power quality. An efficient experimental EMS for FC/battery/SC vehicles based on a hybrid artificial neural networks and passivity control has been proposed by Benmouna *et al.* [12]. The suggested nonlinear control permits dispatching the demanded power/energy between sources considering its restrictions. A new design of EMS with model-free DC-bus voltage control for the FC/SC/battery has been proposed by Mohammed *et al.* [13]. In this work, an effective frequency-separating based-EMS is introduced and the results demonstrated that the proposed EMS efficiently enhanced the fuel economy.

The configuration of the HPS can vary based on energy demands and DC-DC converter setups, with options ranging from passive and semi-active topologies to the more complex active topology [14]. Likewise, EMS strategies come in two primary types: online strategies, including rule-based and fuzzy approaches, are relatively straightforward to implement in real applications. Conversely, offline approaches like Pontryagin's minimum principle (PMP) and dynamic programming (DP) can offer optimum results but are often avoided because of their high computational costs [15], [16].

In recent research, the application of integral sliding mode control to enhance power quality has yielded promising results [17], [18]. However, determining the optimal parameters for integral sliding mode control remains a challenging task, and classical methods often fall short in delivering peak performance. This study aims to address this challenge by evaluating the optimization of parameters using metaheuristic optimization algorithm (MOA). Among these algorithms, the salp swarm algorithm (SSA) is selected.

As previously mentioned, improving power quality is imperative to extend the lifecycle of HPS. In the current research, an optimized integral sliding mode control-based control strategy is introduced, leveraging metaheuristic optimization algorithm, specifically the SSA, to enhance the energy management. This enhancement increases the lifespan of the battery. The subsequent sections of the paper will delve into the HPS description in section 2. The suggested EMS and the classical integral sliding mode control-based EMS, along with the optimization approach for control parameters are demonstrated in section 3. The obtained results are discussed in section 4. Lastly, the paper concludes with the main findings and insights.

2. POWER SYSTEM CONFIGURATION

2.1. Description of HPS

The HPS-based electric vehicle employs an active topology designed to match the engine's power requirements. This hybrid system contains a battery and a supercapacitor, as illustrated in Figure 1. These components are linked to the DC bus via bidirectional boost converter. Additionally, the vehicle's motor is supplied with power through a bidirectional DC/AC converter. This means power may be transported from the DC-link to the motor during acceleration, as well as in the opposite direction during regenerative braking.

2.2. Analyzing the dynamics of vehicle

The overall traction forces (FT) can be determined by considering the various physical forces. Such factors acting on the vehicle structure. As explained in reference [19], The overall traction forces can be represented as the sum of different components:

$$F_{total} = F_{trac} + F_{roll} + F_{ad} + F_{grad} \tag{1}$$

where F_{total} represents the total force and F_{trac} is the traction force generated by the electric motor (s), F_{roll} is the rolling resistance accounts for the resistance encountered due to the friction, F_{ad} represents the aerodynamic drag considers the air resistance or drag experienced by the vehicle, F_{grad} represents the force due to the road gradient or slope. Detailed formulas and parameter definitions for each force are outlined in Table 1. The necessary load power for the traction motor on the DC bus is a consequence of the electrical (η_{mot}), mechanic gearbox (η_{trans}), and inverter (η_{inv}) efficiencies [20], subsequently may be expressed as (2):

$$P_{load}(t) = P_T(t).\eta = v(t).F(t)\eta_{mot}.\eta_{inv}.\eta_{trans} \tag{2}$$

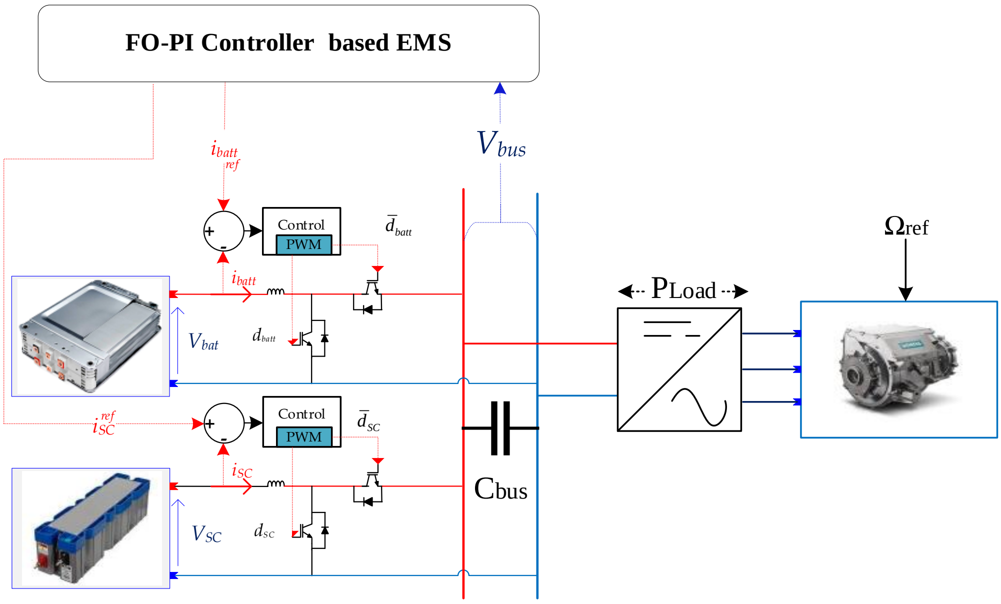

Figure 1. The HPS scheme

Table 1. Vehicle forces

Force	Formulas	Parameters
Traction force	$F_{trac} = M_{eq}a = \left(m_v + J_{em}\frac{\rho^2}{R_{tire}^2}\right)\frac{dv(t)}{dt}$	m_v: masse of vehicle v: vehicle speed J_{em}: the motor inertia moment
rolling resistance	$F_r = m_v g\mu$	g: the earth gravity μ: tire rolling resistance coefficient
aerodynamic drag	$F_a = 0.5\rho C_d A_f (v \pm v_w)^2$	C_d: the aerodynamic drag coefficient Af: area V_w: the wind speed
Gradient force	$F_{gr} = \pm m_v g \sin\alpha$	α: the angle of the slop

2.3. Characterization and modeling of Li-ion batteries

Various electrochemical models are present in the scientific literature, including the R_{int}, Thevenin and double polarization [21]. The Shepherd model, also known as the Shepherd equivalent circuit model, is one of the many electrochemical models used to describe and simulate the performance of Li-ion battery [22]. It can be used to analyze the electrical characteristics of a Li-ion battery and can be employed for tasks like state-of-charge estimation, voltage prediction, and understanding the internal dynamics of the battery. The Shepherd model represents the various electrochemical and physical processes occurring within a Li-ion battery. This circuit typically consists of several components, including resistors and capacitors, which mimic the behavior of the battery components. The discharging voltage of the battery and SoC can be presented as such:

$$V_{bat} = E_0 - K\frac{Q}{Q-it}it - R_b i_{bat} + A_b e^{(-Bit)} - K\frac{Q}{it+0.1Q}i^* \tag{3}$$

$$SOC(t) = SOCi - \frac{1}{Q}\int i_{bat}dt \tag{4}$$

where E_0, Q, and i_{bat} are the battery open-circuit voltage, nominal capacity and current respectively, R_b and A_b are the battery internal resistance and the exponential zone amplitude respectively, and SOC_i represent initial battery state of charge. Figure 2 illustrates the schematic of this model.

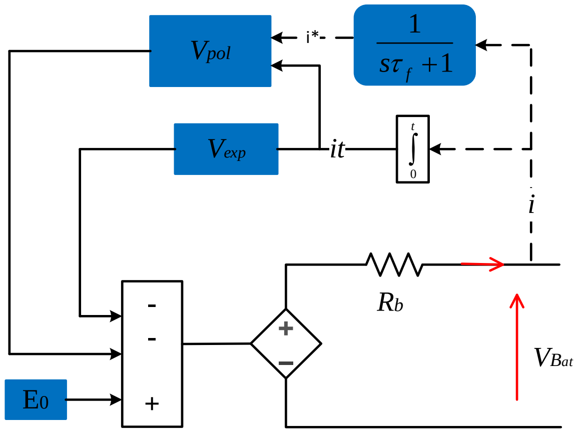

Figure 2. Li-ion battery model

2.4. Explanation and modeling of supercapacitors

Supercapacitors are energy storage devices with high capacitance, designed to provide rapid bursts of power and stabilize energy supply. They are not intended to replace batteries for long-term energy storage but rather complement them for immediate power needs. The supercapacitor model includes components like equivalent series resistance, capacitance, and equivalent parallel resistance, which impact its performance [23]. The output voltage and SOC may be defined using the following relations [24].

$$V_{cell} = i_{cell}R_s + \frac{1}{C_{sc}}\int i_c dt \tag{5}$$

$$soc_{sc}(t) = \left(\frac{V_{cell}(t)}{V_{nom}}\right)^2 \tag{6}$$

where V_{Cell} represents the nominal voltage of the SC.

3. SUGGESTED ENERGY MANAGEMENT STRATEGY

3.1. DC-bus voltage control

The integral sliding surface (ISS) is defined using the following relation.

$$S_v = k_{v1}e_v + k_{v2}\int e_v \tag{7}$$

where the k_{v1} and k_{v2} are the ISS coefficients and e_v is the output voltage error which may be expressed by the following relation.

$$e_v = V_{bus}^* - V_{bus} \tag{8}$$

The expression of the current i_c^* is given by (9).

$$i_c^* = \frac{c_{bus}}{k_{v1}}[\lambda_v sign(S_v) + k_{v2}(V_{bus}^* - V_{bus})] \tag{9}$$

From (9), the expression of the command can be defined as in (10).

$$i_{dc}^* = \frac{c_{bus}}{k_{v1}}[\lambda_v sign(S_v) + k_{v2}(V_{bus}^* - V_{bus})] + i_{Load}^* \tag{10}$$

The load power P_L^* can be estimated as (11).

$$p_L^* = V_{bus}^* i_{Load}^* \quad (11)$$

where λ_v are positive constants.

3.2. Optimizing ISMC generation parameters

The task of defining the optimal values for ISMC parameters poses a formidable challenge because of the absence of an exact model that accurately replicates the behavior of the physical system. In order to overcome this hurdle, the improvement of these parameters will be pursued through the utilization of metaheuristics. The fundamental concept behind this approach involves generating a set of diverse candidate solutions within a constrained search space. These candidate solutions will then be transmitted to the hybrid power system, where their performance will be assessed by estimating the root sum square error (RSSE) between the reference and measured DC bus voltage. Based on this evaluation, the optimizer will adjust the candidate solutions in accordance with the RSSE, effectively reflecting their fitness. The formulation of the objective function is as (12):

$$p_L^* = V_{bus}^* i_{Load}^* \quad (12)$$

The aim of the objective function, as expressed in (12), is to seek the optimal controller parameter values k_{v1}, k_{v1}, λ_v that lead to the minimization of the RSSE associated with an objective feature, thereby satisfying the majority of system requirements.

3.3. Salp swarm algorithm

The core idea of SSA is extracted from ocean's salps movement [25]. Throughout the movement and the hunting, the salps form a chain. The leaders and the followers are the two chief types of salps in the chain. This can be expressed mathematically as (13)-(15).

$$LP(n) = \begin{cases} FP(n) + c_1^{SSA}\left((ub - lb)c_2^{SSA} + lb\right) if\, c_3^{SSA} \geq \frac{1}{2} \\ FP(n) - c_1^{SSA}\left((ub - lb)c_2^{SSA} + lb\right) if\, c_3^{SSA} < \frac{1}{2} \end{cases} \quad (13)$$

$$c_1 = 2e^{-\left(\frac{4n}{N_{max}}0^2\right)} \quad (14)$$

$$FP_i(n) = \frac{1}{2}\left(FP_i(n-1) + FP_{i-1}(n)\right) \quad (15)$$

where LP and FP are the leader and follower locations, and the c_2^{SSA} and c_3^{SSA} are randoms. ub is the upper bound wheras lb is lower bound. The main optimization steps of SSA are explained in Figure 3 whereas Figure 4 depicts the overall architecture of the suggested EMS.

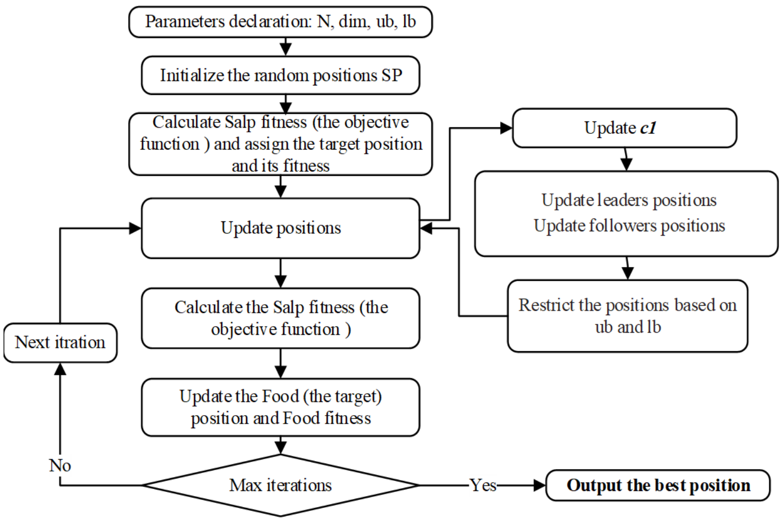

Figure 3. SSA flowchart

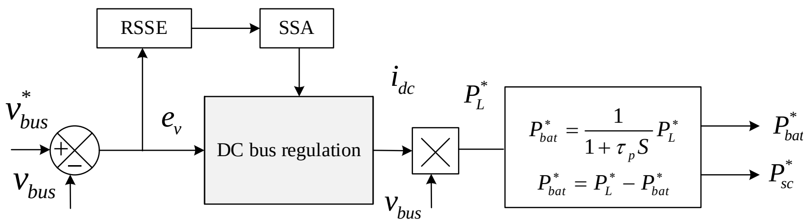

Figure 4. The suggested control schemes

4. RESULTS AND DISCUSSION

The proposed energy management has been applied for optimal load sharing of lithium-ion battery and supercapacitor hybrid energy storage system. The main target is to ensure the electric vehicle receives a stable and high-quality supply of electricity. Therefore, MATLAB software has been utilized to test the suggested management strategy. To simulate electric vehicle, the ECE-15 driving cycle has been considered. The overall system parameters are presented in Table 2.

Despite the changes in ECE-R15 cycle, the speed response of the EV depicted in Figure 5 exhibits good follow-up. Figure 6 shows the measured and reference torque. The motor gives its maximum torque when the EV speed approaches that of the reference route. As soon as EV has reached a steady state, the motor torque declines to adjust for the total load torque.

Table 2. Parameter values

Parameters	Value
r_{batt} Ω	0.1
r_{sc} Ω	0.1
L_{bat} mH	2
L_{sc} mH	2
V_{bus}^{ref} V	400
V_{SC}^{ref} V	200
c_{SC} F	80
c_{bat} Ah	450
c_{bus} µF	2,000

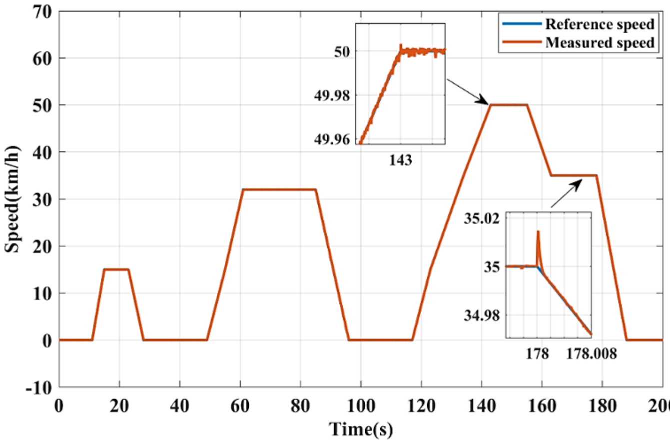

Figure 5. EV linear speed simulation results

The tractive forces of the EV are shown in Figure 7, where it can be seen that the acceleration and aerodynamic forces account for a significant amount of the overall tractive effort. As demonstrated in Figure 8, the proposed management method can promptly stabilize the DC voltage, even when the load power varies by a significant amount. the optimum integral sliding mode control with SSA (SSA-ISMC) suggested EMS minimizes the DC voltage ripples and voltage overshoots compared to classical ISMC (CISMC). Table 3 displays the results comparing the CISMC with the optimum integral sliding mode control with SSA (SSA-ISMC). Table 3 evaluates the overshoot difference $\Delta V = V_{busCISMC} - V_{busSSAISMC}$, where

$V_{busCSMC}$ and $V_{busSSASMC}$ are the DC-link voltage overshoots at time (t_n) for CSMC and optimized SMC, respectively.

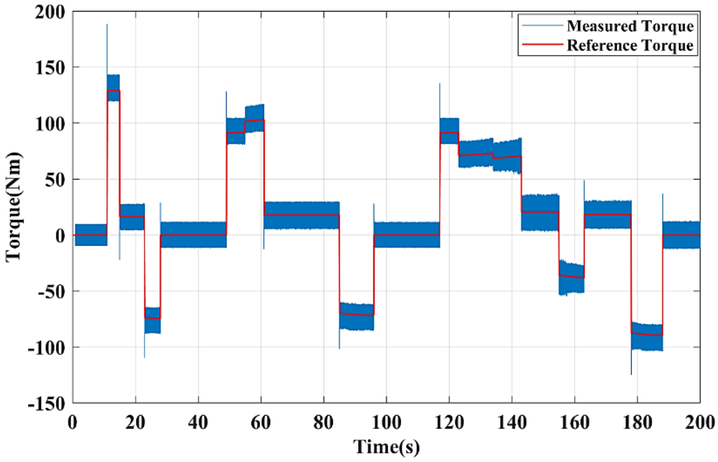

Figure 6. Measured torque against reference

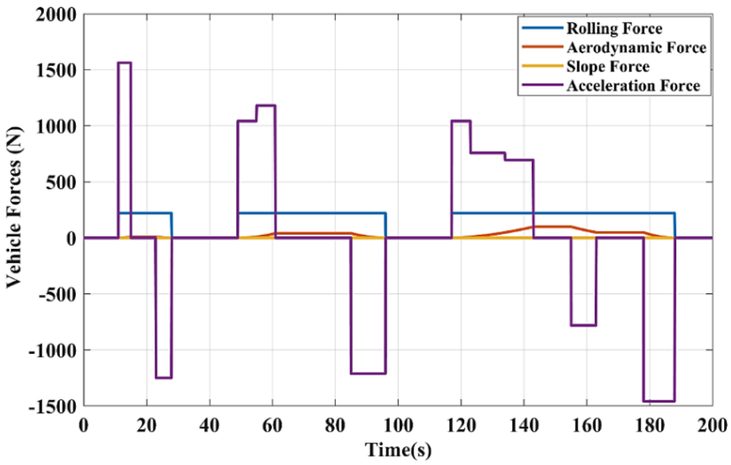

Figure 7. EV tractive forces

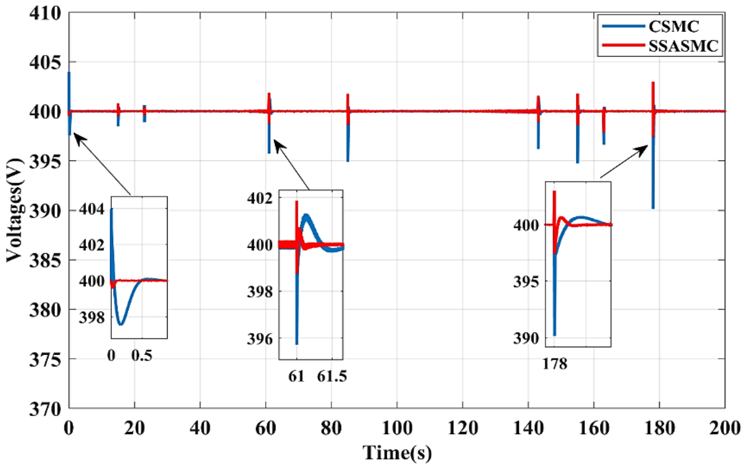

Figure 8. Voltage of DC link

Table 3. Difference in DC-link voltage overshoot

	ECE-R15				
Time (t_n) (s)	t_1=0	t_2=23	t_3=61	t_4=155	t_5=178
EV Speed (km/h)	0	15	32	50	35
$V_{busCISMC}$ (V)	6	1.5	5	6	11
$V_{busSSAISMC}$ (V)	0.5	0.25	2.75	3	5
ΔV (V)	5.5	1.25	2.25	3	6
ΔV (%)	1.37	0.31	0.56	0.75	1.5

Throughout acceleration stages, the battery delivers utmost of its power to the motor, causing a decrease of battery SOC. As shown in Figure 9, it takes energy throughout deceleration periods when the motor torque is negative, hence boosting the SOC battery. Table 3 presents a comparative study between the CISMC and proposed SSA-ISMC in the final SOC. Table 4 results and SOC curves in Figure 9 show that the proposed EMS can handle the battery SOC better than the conventional ISMC. In accordance with EMS, as illustrated in Figure 10, the battery delivers motor power and absorbs it throughout braking times, whereas the SC supports the battery throughout transient times namely acceleration and deceleration times.

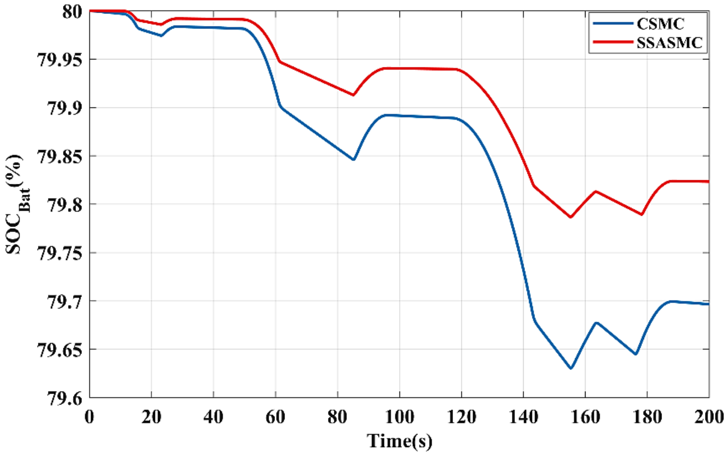

Figure 9. SOC of the battery

Table 4. Difference in the final SOC

	ECE-R15	
EMS	CISMC	Optimized-ISMC
Final SOC (%)	79.69725	79.82344
Diff Final SOC (%)	0.1262	

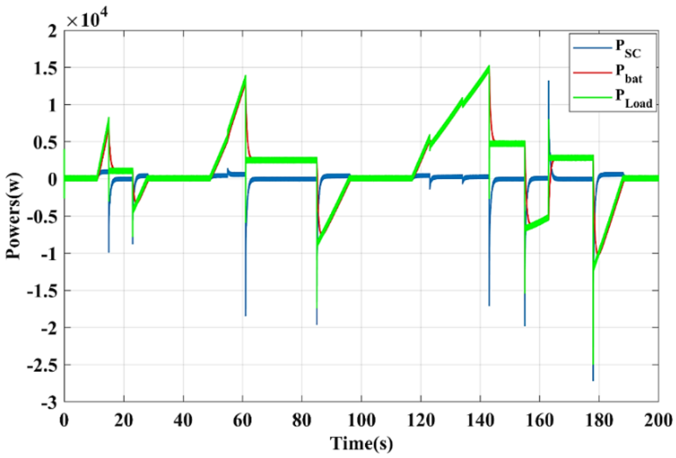

Figure 10. Output power profiles

5. CONCLUSION

This research has presented an efficient approach for managing energy in an electric vehicle (EV) equipped with a hybrid storage system (HSS). The HSS is composed of a lithium-ion battery and supercapacitor, with the primary goal being to supply high-quality power to the EV. The suggested EMS is designed to mitigate fluctuations in bus voltage while meeting various load demands associated with different driving profiles. Improving power quality not only extends the battery's lifespan but also enhances overall driving performance. In this study, an ISMC-based control theory is employed, and the controller parameters are determined by salp swarm optimization. This investigation will explore how these factors impact controller performance. Based on the results obtained, it is evident that combining ISMC theory with a metaheuristic optimization algorithm yields a noticeable enhancement in power quality. The suggested management algorithm effectively allocates power resources, safeguarding them and ensuring excellent power quality. The parameters are derived from an objective function rooted in the usage model. Following the “no-free-lunch” theory, it is possible that other metaheuristic optimization algorithms may offer superior optimization for the ISMC, which will be a subject of future research.

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