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A Research of Different Energy Management Strategies of Lithium-ion Battery-Ultracapacitor Hybrid Energy Storage System

Dongjie Zhang, Lin Hu, Qingtao Tian, and Changfu Zou

Abstract Given the exacerbating effect of fossil fuel use in conventional vehicles on the greenhouse effect, the imperative development of electric vehicle technology becomes evident. To address the high energy and power density demands of electric vehicles, a lithium-ion battery-ultracapacitor hybrid energy storage system proves effective. This study, utilizing ADVISOR and Matlab/Simulink, employs an electric vehicle prototype for modeling and simulating both logic threshold and fuzzy logic control strategies. It aims to analyze the average output power and state of charge (SOC) of the lithium-ion battery, as well as the SOC of the ultracapacitor, within hybrid energy storage systems governed by these differing strategies. The findings indicate that the fuzzy logic control strategy results in a reduction of 2.73 kW in the average output power of the lithium-ion battery and a 20% increase in the SOC drop rate of the ultracapacitor compared to the logic threshold control strategy. Under the logic threshold control strategy, lithium-ion batteries demonstrate superior output stability, albeit within a broader amplitude range. Conversely, the fuzzy logic control strategy maximizes the utilization of ultracapacitors but leads to frequent fluctuations in the output power of lithium-ion batteries, thereby exhibiting reduced stability. These results underscore the inherent trade-offs between stability and utilization efficiency in hybrid energy storage systems for electric vehicles under different control strategies. The selection of a control strategy should be contingent upon specific

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performance priorities and objectives within the context of electric vehicle design and operation.

Keywords Hybrid energy storage system · Energy management · Logical threshold control strategy · Fuzzy logic control strategy

1 Introduction

In recent years, the gas emitted by traditional fuel vehicles has aggravated air pollution and fossil energy is non-renewable. Therefore, it's essential to develop and enter a period of accelerated development of electric vehicles (EV).

In [1], it indicates that high discharge rates and depth of discharge will cause high rate of capacity fade and a shorter useful life of lithium-ion battery (LiB). Studies have shown that when the LiB faces a high-power impact, it may lead to over-discharge of the LiB, leading to the reduction of the number of charge and discharge cycles of the LiB. Ultracapacitors (UC) can meet the high-power requirements of EV, but their low energy density makes it difficult for vehicles to have a long life. The hybrid energy storage system (HESS) composed of LiB and UC plays a role of "peak cutting and valley filling" for LiB. In [2], the results show that HESS with appropriate size and enabled energy management can significantly reduce the battery degradation rate by about 40% compared to battery energy storage systems (ESS), and at only 1/8 of the additional cost of the system.

HESS primarily encompass three types of topologies: passive topology, semi-active topology, and active topology [3]. Pratim Bhattacharyya et al. [4] proposed an improved LiB and UC hybrid semi-active structure for EVs where the size and space of the energy storage system (ESS) are critical. Zhu et al. [5] proposed that bidirectional DC/DC converters can be divided into isolated (IBDC) and non-isolated bidirectional DC/DC converters (NBDC) according to whether electrical isolation is realized between ports. Li et al. [6] conducted an optimization design for a UC-based semi-active HESS and interleaved parallel bidirectional Buck/Boost converters, and analyzed the reasons behind the optimization results.

A good energy management strategy (EMS) of HESSs can improve performance in different and complex driving conditions and reduce driving costs. HESS energy management methods [7–9] in EV applications can be summarized into the following two categories, namely model-based methods and rule-based methods. Model-based energy management methods usually cooperate with other control methods for power distribution, such as the global optimization algorithm dynamic programming (DP) [10], which can obtain the optimal control input by minimizing the cost function, and it's suitable for offline calculation to provide parameter setting values for determining rule control. After analyzing different data sets according to the optimal power distribution strategy, Shen et al. [11] proposed a neural network-based (NN-based) HESS control method for medium-sized EVs. Rule-based methods consist of a set of predefined, empirical control rules [12]. Wang et al. [13] proposed a rule-based control method to realize mode selection and current distribution of multi-mode HESS in EV applications. Yin et al. [14] proposed an adaptive fuzzy logic control (FLC) scheme for EV energy management, where the output membership functions are periodically refreshed to adapt to changing driving patterns. The experimental results in An et al. [15] conducted under the HWFET condition demonstrate that the fully active dual-energy source HESS, along with the EMS based on FLC, effectively safeguards the LiB against the detrimental effects of substantial current fluctuations, consequently prolonging the battery's lifespan. Based on the advantages of flexibility and robustness of the fuzzy logic controller, Gao et al. [16] proposed an optimization method of fuzzy controller hybridization (DOH) and membership function based on the golden section rule. In [17], The optimal logical threshold control (LTC) can fully leverage the high-power UC's characteristics and conduct hardware-in-the-loop (HIL) experiments to further validate the real-time and dependable nature of the near-optimal LTC. The gray wolf optimization (GWO) is used in Hu et al. [18] to optimize the battery output power upper limit and UC charging upper limit of mature multi-mode control (MMC). In [19], frequency-based energy management distributes high- and low-frequency power requirements to batteries and ultracapacitors respectively. Min [20] proposed a multi-objective EMS for EV HESS based on separating load power. The impact of different sorting methods on the results by using elite strategy non-dominating sorting genetic algorithms (NSGA-II).

With the widespread adoption of EVs, experts and scholars have initiated research into artificial intelligence power distribution strategies. On the basis of existing algorithms, it's necessary to improve the robustness of EV under driving conditions and optimize the control strategy algorithm. The sections of this article are as follows. In the second section, we introduce vehicle parameters, HESS components, and the simulation model. Section 3 provides an overview of the LTC and FLC strategies. Sections 4 and 5 present the simulation results and draw conclusions, followed by future prospects.

2 Parameters and Hybrid Energy Storage System Model

2.1 Vehicle Parameters

The parameters of the electric vehicle are designed according to a benchmark model. The main vehicle parameters are shown in Table 1.

2.2 Lithium-ion Battery

The equivalent circuit models of LiB include Rint model, RC model, PNGV model, etc. Due to its concise structure and convenient calculation method, the Rint model

Table 1 Main vehicle parameters

Parameter type	Value
Body size	4694 × 1849 × 1443 mm
Frontal area	2.4m^2
Air resistance coefficient	0.24
Full load mass	1320 kg
Tire rolling radius	0.45 m
Rolling resistance coefficient	0.009
Fixed speed ratio	1
Centroid height	0.4
Front track/rear track	1580/1580 mm

Table 2 Parameter settings of LiBs

Parameter type	Value
Cell rated voltage/V	3.7
Cell rated capacity/Ah	4.8
Series number	96
Parallel number	46

was selected in this research. There is a certain relationship between the open circuit voltage U_{OC} and the load voltage U_b, as shown in equation: $U_b = U_{OC} - I_L \cdot R_0$. The parameter settings of the LiBs are shown in Table 2.

2.3 Ultracapacitor

Under high power requirements, ultracapacitor can provide excellent output power, effectively reduce the load of LiB, and significantly improve the efficiency of the system. The parameter settings of the UCs are shown in Table 3.

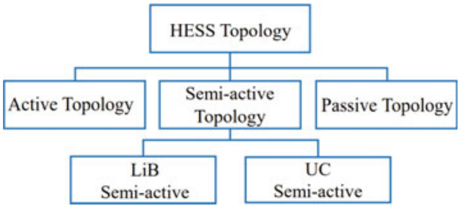
Table 3 Parameter settings of UCs

Parameter type	Value
Cell rated voltage /V	2.7
Cell rated capacity /F	3400
Series number	120
Parallel number	3

2.4 Topology Structure

Figure 1 shows the specific classification of HESS topology. We used a UC semi-active topology in this study for the following reasons: passive topology makes it difficult to achieve energy conversion between LiB and UC, while active topology is more expensive and harder to control. In the semi-active topology of LiB, the linear charge and discharge characteristics of UC can lead to sharp fluctuations in DC circuit voltage. The UC semi-active topology effectively improves capacity efficiency. The formed topology model is presented in Fig. 2.

Fig. 1 Topology structure classification of HESS



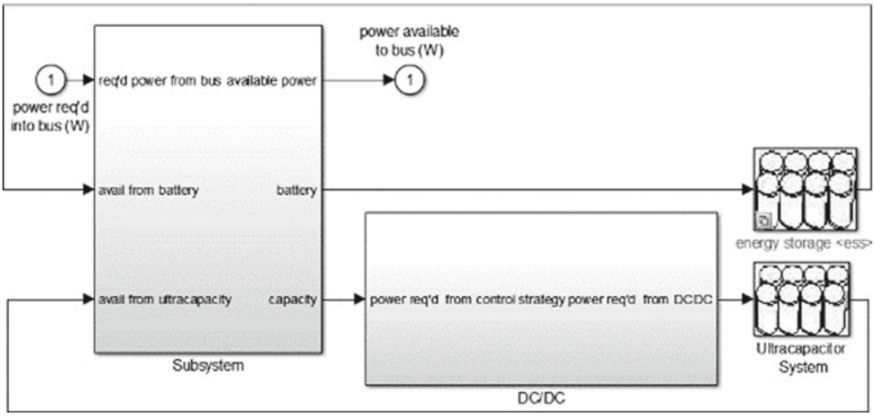


Fig. 2 UC semi-active topology simulation model

Table 4 Average power required in UDDS

Condition	Time/s	Average required power/kW
Driving	973	10.20
Braking	155	−3.79

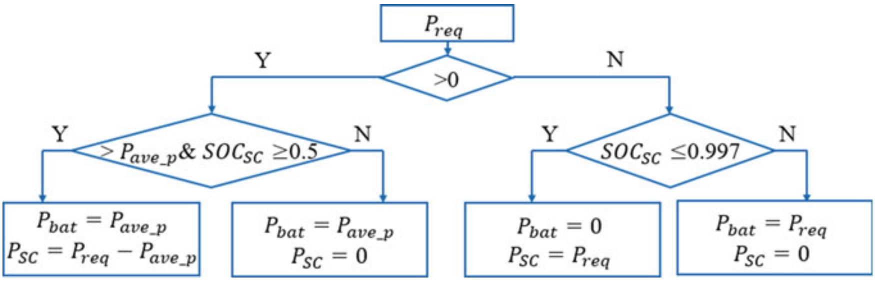


Fig. 3 Logic threshold control strategy flowchart

3 Control Strategy

3.1 Logical Threshold Control Strategy

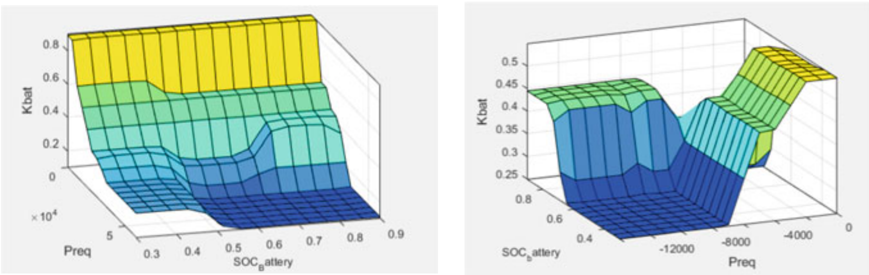
In this study, writing an integrated program in Matlab to calculate the energy demand according to the required power of the UDDS model of an electric vehicle with a single power supply, to get the P_{ave_p} logic threshold, the related parameters are listed in Table 4. The logic flow of the LTC strategy is presented in Fig. 3.

3.2 Fuzzy Logic Control Strategy

This research employs the Madamni structure fuzzy logic controller, where the input signals consist of requested power, SOC_{uc}, and SOC_{bat}. The output is denoted as the power allocation factor K_{bat}. The domains and subsets of the membership functions are presented in Table 5.

Table 5 Function domain and subset division

Parameter	Domain	Subset
P_{req} (>0)	[0 60000]	AS BS CS MS MB DB EB FB
P_{req} (<0)	[−14000 0]	ZB ZBM ZM ZS
SOC_{bat}	[0 1]	S M B
SOC_{uc}	[0 1]	S M B
K_{bat}	[0 1]	AS BS CS MS MB DB EB FB



(a) $P_{req}>0$, under driving conditions (b) $P_{req}<0$, under braking conditions

Fig. 4 FLC rule surface under driving and braking conditions

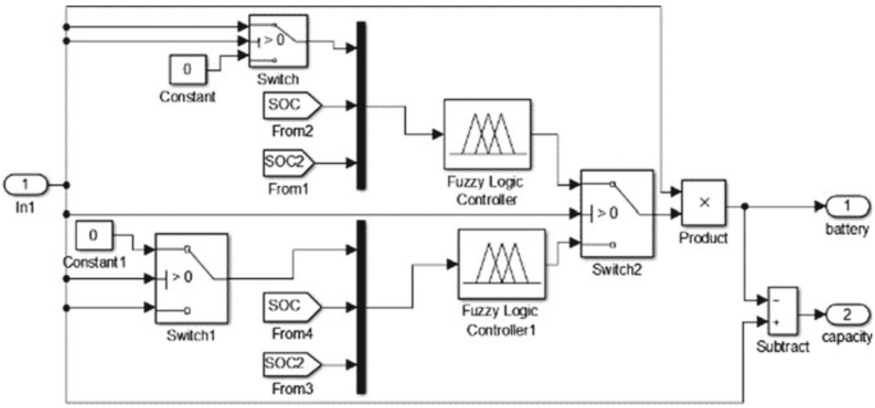


Fig. 5 FLC simulation model

By dividing the intervals as outlined above, we derive a total of 108 control rules. The surface of FLC rules under both driving and braking conditions is illustrated in Fig. 4, and its model is further visualized in Fig. 5.

4 Simulation Results

In this study, we conducted simulation verification within the Matlab and ADVISOR environments to align vehicle parameters and EV control models. Both the LiB and UC were initialized with a State of Charge (SOC) of 1. As depicted in Fig. 6, the speed request curves generated by the two distinct control strategies closely match the actual speed curves. This substantiates that the HESS control strategy proposed in this paper adequately fulfills the vehicle's speed requirements.

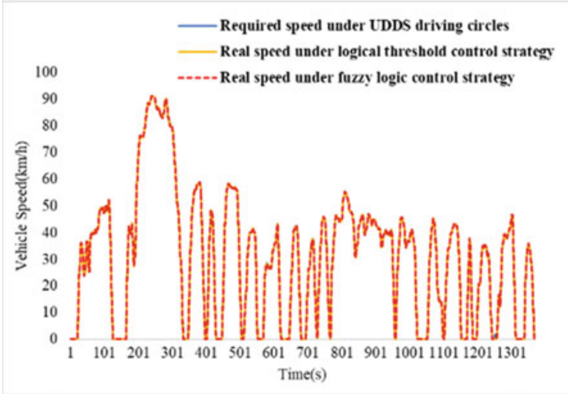


Fig. 6 Vehicle speed tracking results of two control strategies in UDDS

In Fig. 7, within the single-power controlled EMS, the peak output power of the LiB reaches 50.72 kW. This is notably higher, by 40.52 and 39.33 kW, than the values obtained using LTC and FLC strategies in the HESS, as detailed in Table 6. In Fig. 8, the SOC drop of the LiB within the HESS is more than 30% lower compared to the EMS relying on a single power supply. This observation underscores the crucial role of well-distributed power in the HESS, effectively extending the lifespan of the LiB and potentially increasing the mileage range of EVs.

In LTC, the output power of the LiB is precisely controlled around the threshold value of 10.20 kW, signifying superior output stability of the LiB with a wider

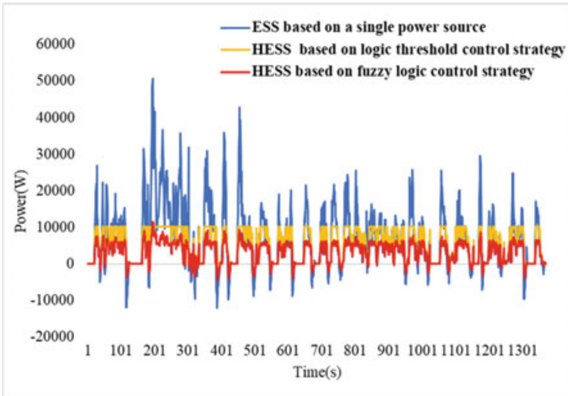


Fig. 7 Power distribution of LiB based on different energy management strategies

Table 6 Output peak and average power of LiB and UC under driving conditions in UDDS

Classification	Peak power/kW	Average power/kW
Single power supply	50.72	10.20
Logic threshold	10.20	7.44
Fuzzy logic	11.39	4.71

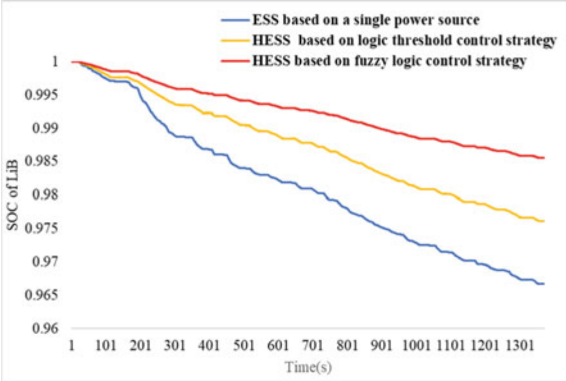


Fig. 8 The solutions of LiB SOC in UDDS

amplitude range. In contrast, FLC employs 108 flexible rules to control the LiB's output power. Since this paper focuses on UC's role in recovering braking energy in LTC, we have compared the average LiB output power under driving conditions in Table 6. In the FLC, the average LiB output power is 2.73 kW lower than that in LTC, highlighting a narrower amplitude range. Figure 7 further illustrates that the LiB's output power curve exhibits more frequent fluctuations in FLC, indicating inferior stability compared to LTC.

The output power of the UC in the FLC strategy consistently surpasses that of LTC during most driving instances. Additionally, the SOC of the UC in FLC and LTC decreases by approximately 37 and 17%, respectively, signifying a deeper utilization and better alignment of capacity parameters in FLC. However, it's important to note that this approach may ultimately render the HESS ineffective in the long term, as depicted in Fig. 9.

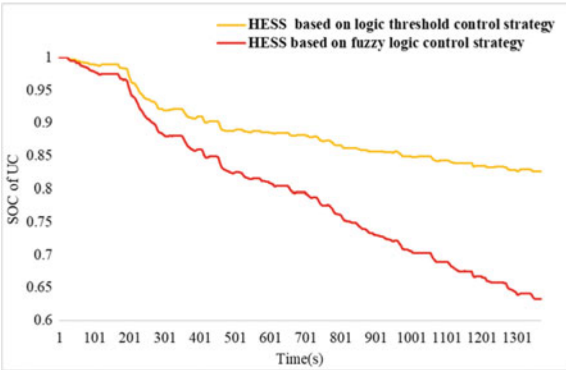


Fig. 9 The solutions of UC SOC in UDDS

5 Conclusions and Prospect

In this paper, we investigate the EMS for both single power supply and hybrid power supply configurations. The LTC and FLC power distribution strategies effectively regulate the output power of the LiB within an appropriate range. The high-power discharge characteristics of the UC efficiently mitigate excessive LiB discharge, thus ensuring its prolonged service life, exemplifying the significance of the LiB-UC HESS.

In the future, we will consider utilizing the LiB to supply power to the UC in order to meet the power requirements of the UC. Concurrently, further research is required to enhance the alignment of UC capacity parameters and control strategies, incorporating diverse driver behavior patterns and various system topologies into our algorithm design. This will enable us to optimize system costs and control effectiveness while facilitating the flexible selection and application of control strategies based on real-world driving scenarios.

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