

## Research Article

# Vehicle Speed Optimized Fuzzy Energy Management for Hybrid Energy Storage System in Electric Vehicles

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Received 13 May 2020; Revised 26 June 2020; Accepted 3 July 2020; Published 24 July 2020

Guest Editor: Qiang Chen

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Energy management strategy (EMS) is a key issue for hybrid energy storage system (HESS) in electric vehicles. By innovatively introducing the current speed information, the vehicle speed optimized fuzzy energy management strategy (VSO-FEMS) for HESS is proposed in this paper. Firstly, the pruned fuzzy rules are formulated by the SOC change of battery and super-capacitor to preallocate the required power of vehicle. Then, the real-time vehicle speed is used to optimize the pre-allocated results based on the principle of vehicle dynamics, so as to realize the optimal allocation of required power. To validate the proposed VSO-FEMS strategy for HESS, simulations were done and compared with other EMSs under the typical urban cycle in China (CYC-CHINA). Results show that the final SOC of battery and super-capacitor are optimized in varying degrees, and the total energy consumption under the VSO-FEMS strategy is 2.43% less than rule-based strategy and 1.28% less than fuzzy control strategy, which verifies the effectiveness of the VSO-FEMS strategy.

## 1. Introduction

The development of vehicle technology has helped to improve people's lives, but at the same time has created adverse effects such as environmental pollution and energy shortages. Electric vehicles are becoming the focus of vehicle development [1]. Compared with traditional internal combustion engine (ICE) vehicles, electric vehicles have the advantages of low pollution, high efficiency, and abundant energy [2]. Currently, the most common power source used in electric vehicles is the battery [3]. Although a battery has high energy storage density, it has drawbacks such as small specific power, weak current charging and discharging capability, and short service life [4]. These shortcomings limit the practical application of electric vehicles. Hence, it is necessary to discover an auxiliary energy source that can make up for battery limitations [5]. Super-capacitors (SCs) have the characteristics of high-power density and long service life, which can compensate for battery power shortages [6]. Therefore, super-capacitor and DC/DC

converter are introduced to form the HESS, which can utilize these advantages to prolong battery life and increase the driving distance of electric vehicles [7].

As the key issue of HESS control, energy management strategy (EMS) has a vital impact on battery life, economy, and power performance of electric vehicles. The physical characteristics and working modes of the battery and the super-capacitor are also quite different. Hence, it is crucial to achieve effective energy management for both of them [8]. Previously, some researchers considered using HESS instead of the pure battery in electric vehicles and presented some EMSs. In [9], an algorithm of battery state-of-power prediction based on parameters identification is proposed, which provides a new idea for energy management in hybrid energy storage system. In [10, 11], the dynamic programming (DP) approach is used to deal with the integrated optimization problem for deriving the best configuration and energy split strategies of HESS. However, DP algorithm is too complex, and its practical adaptability is not high. In [12, 13], Pontryagin's Minimum Principle (PMP) was

applied to find the optimal global power allocation results for prolonging battery life and improving vehicle economy; the optimization effect is obvious, but it is difficult to realize in real vehicle. In [14], a deep neural network was used to learn from actual driving experiences and to discover an optimal energy management strategy for reducing energy costs. However, the neural network model needs a lot of raw data as samples, and the data calculation is too large. In [15], the pseudospectral method was used to optimize the power allocation of HESS to achieve an optimal allocation effect and reduce the energy loss of the battery. In [16], a Grey Wolf Optimizer (GWO) was proposed for the efficient power management of a fuel-cell/super-capacitor HESS and for increasing the fuel-cell lifespan by mitigating harmful current transients. In [17], particle swarm optimization (PSO) was used to determine the optimal power allocation and reduce energy losses in the driving process. However, these optimization algorithms are easy to fall into the local optimal solution and can not get the optimal allocation results. In addition, some literatures use model prediction energy management strategy [18], rule-based energy management strategy [19], filtration-based energy management strategy [20], and fuzzy energy management strategy [21] to manage the energy of HESS. In [22], comparisons among several EMSs are done, and the simulation results show that the rule-based energy management strategy and fuzzy energy management strategy have the best performance. Compared with the rule-based energy management strategy, fuzzy energy management strategy has no need of accurate mathematical model and has strong robustness and a better control effect.

However, the fuzzy control rules are predesigned and cannot be adjusted according to real-time changes in driving cycle. Consequently, the vehicle speed optimized fuzzy energy management strategy (VSO-FEMS) for HESS is proposed in this paper. The VSO-FEMS analyzes the driving state of electric vehicles, monitors changes of battery and super-capacitor SOC in the driving process, and formulates corresponding fuzzy control rules. The required power is preallocated by the fuzzy controllers. Then, based on the principle of vehicle dynamics, the reference value of super-capacitor SOC is calculated according to the real-time vehicle speed, and the error between the reference value of super-capacitor SOC with its actual SOC is obtained. The final allocation result is optimized by the error value to achieve a reasonable power allocation. To the best of our knowledge, it is the first time to directly introduce the vehicle speed information into the EMS design among the research literature.

In this paper, the vehicle model is built in ADVISOR (Advanced Vehicle Simulator), and the VSO-FEMS strategy is compared with other EMSs. The simulation results show that under the same driving cycle, the total energy consumption of pure battery is the smallest, but the vehicle required power is provided by the battery, which causes great damage to the battery. Compared with rule-based strategy and fuzzy strategy, VSO-FEMS strategy has better performance in prolonging battery life, covering longer vehicle driving distance, and improving energy economy.

This paper is organized as follows: In Section 2, the system model is introduced; the design of VSO-FEMS

strategy is presented in Section 3; in Section 4, the VSO-FEMS strategy is simulated in ADVISOR, and the simulation results are compared to those of pure battery, rule-based strategy, and fuzzy strategy; at the end, the conclusion is presented in Section 5.

## 2. System Model

*2.1. Structure of HESS.* Currently, the conventional structures of HESS can be divided into three types: passive, semiactive, and fully active [23]. The passive HESS has a simple structure and low cost, but it cannot fully exert the working characteristics of the super-capacitor. Further, the control effect is not efficient, which significantly reduces the advantages of the HESS. The semiactive HESS controls one of the batteries and the super-capacitor, which is easily controlled and has high energy transfer efficiency. The fully active HESS needs to control the battery and super-capacitor separately, which has high cost and a more complex control strategy design. Therefore, considering cost and efficiency, the semiactive HESS (see Figure 1) is selected in this paper. The super-capacitor is connected in series with the DC/DC converter and then connected to the load in parallel with the battery. The battery is utilized as the primary energy source, and the output power is directly applied to the load to maintain the load side voltage stability. The super-capacitor is used as an auxiliary energy source and is connected to the load through a DC/DC converter to provide peak power to the load and recover the braking energy. This topology can enable super-capacitor to work in a broader voltage range and prevent damage of voltage fluctuation and peak current in the battery, thus protecting the battery.

*2.2. Model of Battery/SC.* The focus of this paper is the energy management strategy of hybrid energy storage system, where the battery model is optional and the battery model shown in Figure 2(a) is utilized. This model is mainly composed of an open circuit voltage source  $E_{\text{bat}}$  and an equivalent series resistance  $R_{\text{bat}}$ . This model can simulate the charging and discharging process of the battery and is widely used in the hybrid energy storage system. The main advantage of this model is its simple structure and satisfactory accuracy. The model of the super-capacitor is shown in Figure 2(b), which is composed of an ideal capacitor  $C$  and an equivalent series resistance  $R_{\text{sc}}$ .

The corresponding state space equations are shown in equations (1) and (2):

$$\dot{V}_{\text{bat}} = E_{\text{bat}} - i_{\text{bat}} \cdot R_{\text{bat}}, \quad (1)$$

$$\dot{V}_{\text{sc}} = E_{\text{sc}} - i_{\text{sc}} \cdot R_{\text{sc}}, \quad (2)$$

where  $i_{\text{bat}}$  is battery current,  $i_{\text{sc}}$  is super-capacitor current,  $V_{\text{bat}}$  and  $V_{\text{sc}}$  represent the terminal voltage of battery and super-capacitor, respectively. The state of charge (SOC) is defined as the ratio between the remaining charge to the total charge of the battery or super-capacitor, which can be calculated from equations (3) and (4):

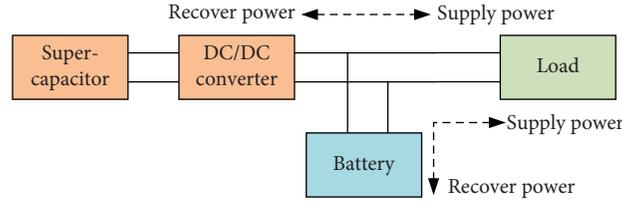


FIGURE 1: Structure of the semiactive HESS.

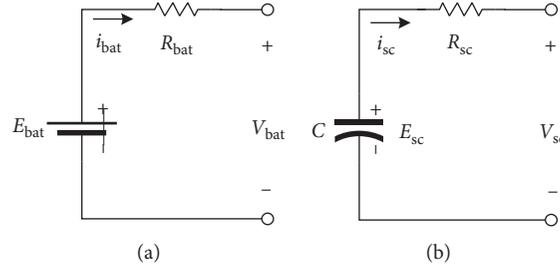


FIGURE 2: The models of battery and super-capacitor. (a) Battery. (b) Super-capacitor.

$$\text{SOC}_{\text{bat}} = \frac{Q_{\text{remain}}}{Q_{\text{total}}} = \frac{Q_{\text{total}} - \int i_{\text{bat}} dt}{Q_{\text{total}}}, \quad (3)$$

$$\text{SOC}_{\text{sc}} = \frac{Q_{\text{remain}}}{Q_{\text{total}}} = \frac{V_{\text{sc}} - V_{\text{sc,min}}}{V_{\text{sc,max}} - V_{\text{sc,min}}}, \quad (4)$$

where  $Q_{\text{remain}}$  represents the remain charge,  $Q_{\text{total}}$  represents the total charge,  $\int i_{\text{bat}} dt$  represents the charge of charging or discharging of the battery,  $V_{\text{sc,max}}$  is the maximum operation voltage of super-capacitor,  $V_{\text{sc,min}}$  is the minimum operation voltage of super-capacitor, and  $V_{\text{sc}}$  is the real-time voltage of super-capacitor. Figure 3 shows the change of charge and discharge efficiency of the battery under different current. The charge efficiency  $\eta_{\text{ch}}$  and discharge efficiency  $\eta_{\text{disch}}$  can be calculated by equations (5) and (6) [24]:

$$\eta_{\text{ch}} = \frac{E_{\text{bat}} i_{\text{bat}}}{(E_{\text{bat}} + i_{\text{bat}} R_{\text{bat}}) i_{\text{bat}}}, \quad (5)$$

$$\eta_{\text{disch}} = \frac{(E_{\text{bat}} - i_{\text{bat}} R_{\text{bat}}) i_{\text{bat}}}{E_{\text{bat}} i_{\text{bat}}}. \quad (6)$$

From Figure 3, it can be seen that the change of SOC has little effect on the charge and discharge efficiency of the battery, while the current has a greater effect on the efficiency. The charge and discharge efficiency of the battery will decrease with the increase of the current.

**2.3. Model of DC/DC Converter.** As a key component of HESS, the DC/DC converter can not only effectively control the charge and discharge currents of the super-capacitor, but also ensure the high efficiency of HESS. In this paper, the efficiency of DC/DC converter is mainly considered, and the transient process of DC/DC is ignored. The efficiency of DC/DC converter is defined as the ratio of output power to input

power, which can be calculated by equation (7). Therefore, the efficiency model of DC/DC converter is established by two-dimensional table interpolation. The efficiency interpolation table of DC/DC converter is shown in Table 1.

$$\eta_{\text{dc/dc}} = \frac{I_{\text{out}} \cdot U_{\text{out}}}{I_{\text{in}} \cdot U_{\text{in}}} \times 100\%, \quad (7)$$

where  $\eta_{\text{dc/dc}}$  represents the efficiency of the DC/DC converter,  $I_{\text{out}}$  represents the output current,  $U_{\text{out}}$  represents the output voltage,  $I_{\text{in}}$  represents the input current, and  $U_{\text{in}}$  represents the input voltage.

**2.4. Required Power of Vehicle.** The vehicle is regarded as a discrete-time dynamic system, and the required power during the driving of the vehicle can be simplified as [25]

$$P_{\text{req}} = \frac{1}{3600\eta} (F_i + F_a + F_r)v, \quad (8)$$

where  $\eta$  represents the efficiency of the transmission system,  $v$  represents the speed of vehicle,  $F_i$  represents the inertial force,  $F_a$  represents the aerodynamic drag, and  $F_r$  represents the rolling resistance, and their can be calculated as follows:

$$F_i = \delta m \frac{dv}{dt},$$

$$F_a = \frac{C_a A}{21.15} v^2, \quad (9)$$

$$F_r = mgf \cos(\theta) + mg \sin(\theta),$$

where  $\delta$  represents conversion ratio of vehicle rolling mass,  $m$  represents the curb weight,  $C_a$  represents the air drag coefficient,  $A$  represents the fronted area,  $g$  represents the acceleration of the gravity,  $f$  represents the rolling resistance coefficient, and  $\theta$  represents the slope of the road.

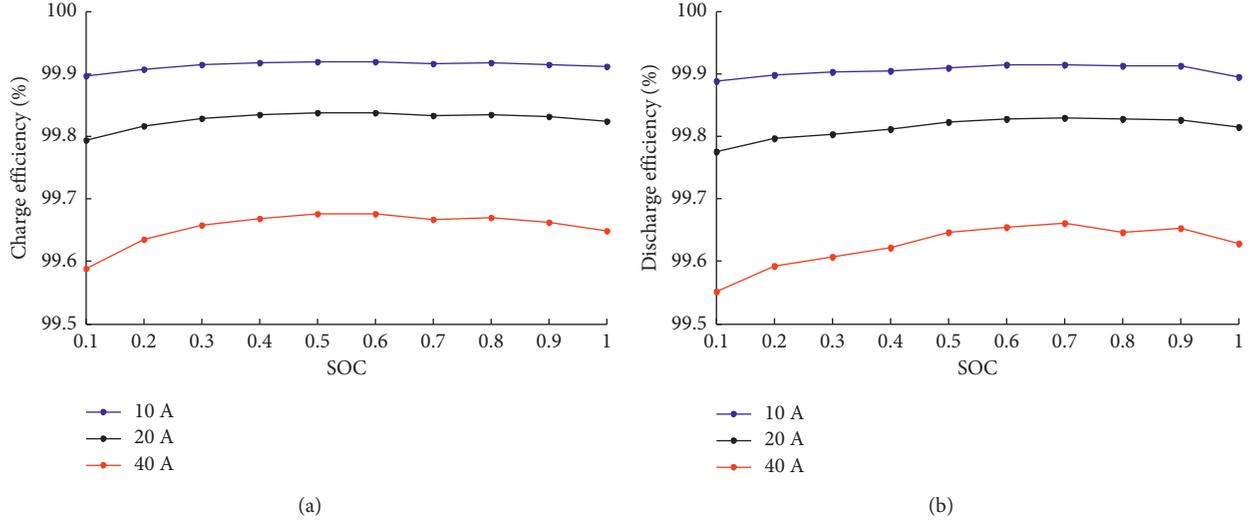


FIGURE 3: (a) Charge efficiency of battery. (b) Discharge efficiency of battery.

TABLE 1: Efficiency interpolation table of DC-DC converter.

DC/DC converter efficiency $\eta_{dc/dc}$	Power of super-capacitor (W)								
	2000	5000	10000	15000	20000	30000	40000	60000	
Voltage ratio ( $V_{bat}/V_{sc}$ )	0.2	0.8	0.854	0.910	0.941	0.954	0.952	0.949	0.946
	0.4	0.8	0.857	0.916	0.948	0.964	0.957	0.954	0.949
	0.6	0.8	0.861	0.923	0.950	0.965	0.960	0.956	0.952
	0.8	0.8	0.865	0.926	0.958	0.971	0.969	0.964	0.962
	1	0.8	0.872	0.930	0.963	0.975	0.973	0.968	0.966

### 3. Design of the Proposed VSO-FEMS Strategy

The goal of the energy management strategy design of HESS is to take full advantage of the characteristics of high-power density and long-cycle life of the super-capacitor, reduce the damage of high current on the battery, prolong battery life, increase vehicle driving distance, and improve energy economy. The overall scheme of the proposed VSO-FEMS strategy is shown in Figure 4, which consists of two stages: preallocation and final allocation.

The input synthetically considers three factors including required power, battery SOC, and super-capacitor SOC to get better reasonable allocation results. The preallocation uses fuzzy control to preallocate the required power in the VSO-FEMS strategy. Compared to traditional energy management strategies, fuzzy control uses the concept of fuzzy logic and membership function and has the advantage of good adaptability and robustness. The final allocation considering that super-capacitor needs to frequently provide the required peak power and recover braking energy, the voltage changes rapidly, and there will be errors between the actual SOC and the reference SOC, hence, the speed optimization module is introduced to optimize the pre-allocation results and get the optimal allocation results. Finally, the output allocates the power to the battery and the super-capacitor.

The power preallocation based on fuzzy control is presented in Section 3.1 and the final power allocation based on vehicle speed is presented in Section 3.2.

*3.1. Stage 1: Power Preallocation Based on Fuzzy Control.* During the operation of HESS, the parameters are not constant and may be varying. Also, HESS is a nonlinear system under complex driving cycle, which is difficult to be described with an accurate mathematical model. Compared with the traditional control strategy, fuzzy control has no need of accurate mathematical model of the system and uses natural language to describe system performance for effective control. It would be seen that the application of fuzzy control into EMS of HESS is very effective.

Considering that electric vehicles have both driving and braking conditions, the corresponding HESS has two working modes of discharge and charge. The different working modes require different control rules. Hence, two fuzzy controllers, fuzzy-discharge and fuzzy-charge, are designed that corresponds to the discharge and charge modes of the HESS.

In the discharging mode, the super-capacitor is mainly used to provide high instantaneous power to ensure that the battery discharges smoothly. The design is realized by detecting the SOC of the battery and super-capacitor. When the required power is small and the battery SOC is large, the power allocated to the battery should be large to utilize the characteristics of high energy density of the battery fully. When the required power is large and the super-capacitor SOC is also large, the power allocated to the battery should be small. Using the characteristics of the high-power density

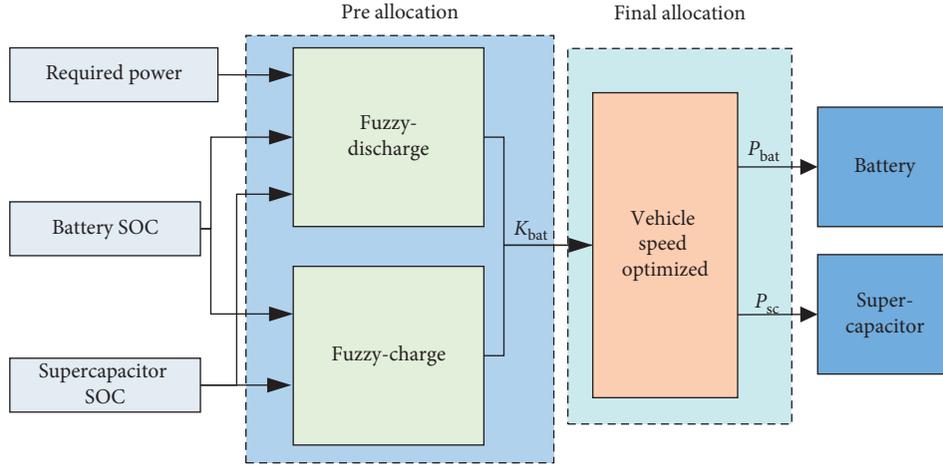


FIGURE 4: Structure of VSO-FEMS strategy.

of super-capacitor, high-current discharge of the battery is prevented. In the charging mode, the super-capacitor is used to receive high instantaneous power, fully recover the braking energy, and protect the battery from damage due to high currents.

According to the above mentioned rules, the required power  $P_{req}$ , the state of charge  $SOC_{bat}$  of battery, and the state of charge  $SOC_{sc}$  of super-capacitor are selected as the input of the fuzzy controller. The battery power allocation coefficient  $K_{bat}$  is used as the output of the fuzzy controller. The power  $P_{bat}$  of the battery is expressed as follows:

$$P_{bat} = K_{bat} \cdot P_{req}, \quad (10)$$

where  $P_{req}$  is the required power under the driving cycle of the vehicle. The loss in power transfer process is neglected. The power  $P_{sc}$  of the super-capacitor can be obtained by power conservation law:

$$P_{sc} = P_{req} - P_{bat} = (1 - K_{bat}) \cdot P_{req}, \quad (11)$$

When the battery SOC and super-capacitor SOC are too low or too high, the charging and discharging efficiency will be affected, so the SOC of the both should be controlled within an appropriate range. Through the analysis of the working HESS model under the vehicle's driving cycle, the domain of fuzzy sets of variable of the fuzzy controller is shown in Table 2. The actual domain of  $P_{req}$  is  $[0, P_{max}]$ , the quantitative factor  $K_p = 1/P_{max}$  is needed to change it from actual domain to fuzzy domain, where  $P_{max}$  is the maximum required power under driving cycle.

Due to the control precision and operation speed, the fuzzy control strategy will be affected by the number of fuzzy language values. After analyzing the fuzzy variables, the language value of the fuzzy variables is shown in Table 3: TS is too small, S is small, M is medium, B is big, and TB is too big. The membership functions of the fuzzy variables are illustrated in Figure 5. According to the division of the working mode of HESS, the Mamdani structure with two inputs, one output, and three inputs, one output is selected to correspond to the charging and discharging modes. The rules of the fuzzy controllers are shown in Tables 4 and 5,

TABLE 2: The domain of fuzzy sets.

Variables	$P_{req}$	$SOC_{bat}$	$SOC_{sc}$	$K_{bat}$
Domain	$[0, 1]$	$[0.2, 0.9]$	$[0.1, 1]$	$[0, 1]$

TABLE 3: The language value of fuzzy variables.

Mode	Variables	Language value
Discharge ( $P_{req} > 0$ )	$P_{req}$	TS, S, M, B, TB
	$SOC_{bat}$	S, M, B
	$SOC_{sc}$	TS, S, M, B
	$K_{bat}$	TS, S, M, B, TB
Charge ( $P_{req} < 0$ )	$SOC_{bat}$	S, M, B
	$SOC_{sc}$	TS, S, M, B
	$K_{bat}$	TS, S, M, B, TB

and the relation of the inputs and output of the fuzzy controllers are shown in Figure 6.

**3.2. Stage 2: Final Power Allocation Based on Vehicle Speed Optimized.** Under urban driving cycle, the super-capacitor needs to frequently provide the required peak power and recover braking energy, which leads to the rapid change of super-capacitor SOC. Hence, the speed optimization module is introduced. Based on the model of vehicle dynamics, the reference value of super-capacitor SOC is calculated according to the real-time vehicle speed, and the error between the reference value of super-capacitor SOC with its actual SOC is obtained. And the output variable  $K_{bat}$  of the fuzzy controller is optimized by the error value. The specific design is described below.

According to the theory of vehicle dynamics, there is a functional relationship between the super-capacitor and maximum speed as follows:

$$\frac{1}{2}C(V_{sc,max}^2 - V_{sc,min}^2)N = \frac{1}{2}mv_{max}^2. \quad (12)$$

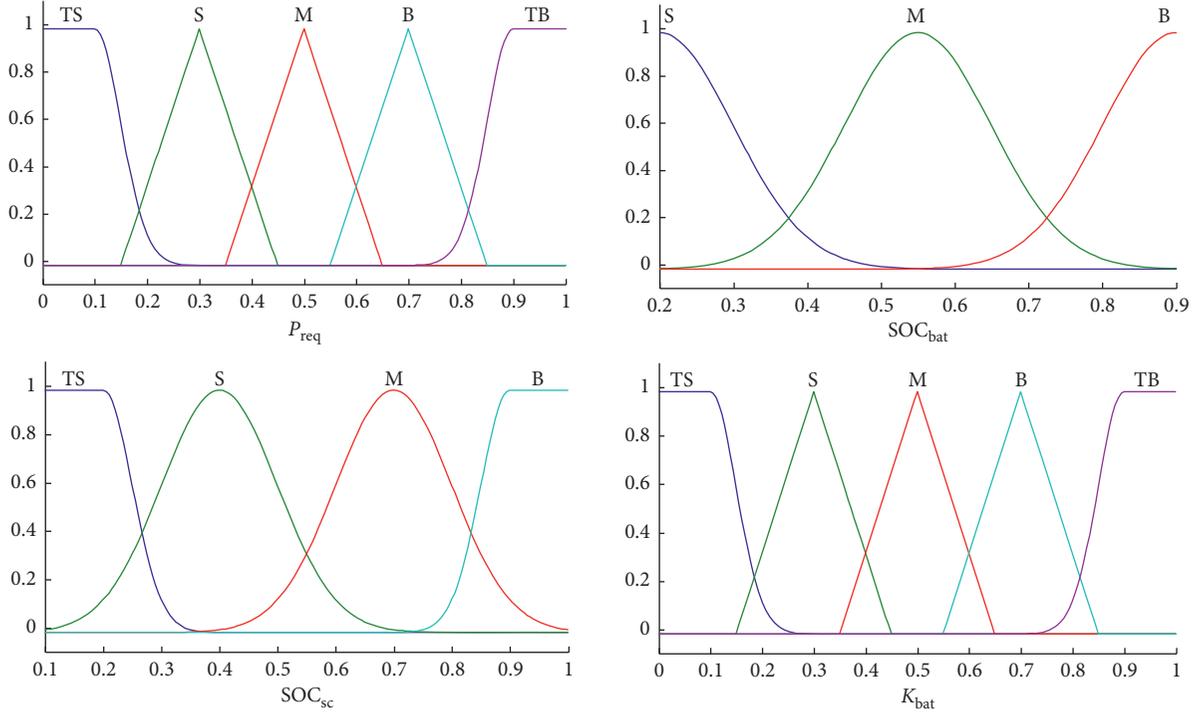


FIGURE 5: Membership function of fuzzy variables.

TABLE 4: Fuzzy rules in charge mode.

$K_{bat}$	SOC <sub>sc</sub>				
	TS	S	M	B	
SOC <sub>bat</sub>	S	TS	TS	M	B
	M	TS	TS	S	M
	B	TS	TS	TS	S

TABLE 5: Fuzzy rules in discharge mode.

$K_{bat}$	$P_{req}$					
	TS	S	M	B	TB	
SOC <sub>bat</sub> (SOC <sub>sc</sub> = TS)	S	TB	TB	TB	B	B
	M	TB	TB	TB	TB	TB
	B	TB	TB	TB	TB	TB
SOC <sub>bat</sub> (SOC <sub>sc</sub> = S)	S	TB	M	S	S	S
	M	TB	B	M	M	S
	B	TB	B	B	M	S
SOC <sub>bat</sub> (SOC <sub>sc</sub> = M)	S	M	S	S	TS	TS
	M	B	M	M	S	S
	B	B	B	M	S	S
SOC <sub>bat</sub> (SOC <sub>sc</sub> = B)	S	TS	TS	TS	TS	TS
	M	TB	B	M	S	S
	B	TB	B	M	S	S

Similarly, for other speeds, there is also the following relationship:

$$\frac{1}{2}C(V_{sc,max}^2 - V_{sc}^2)N = \frac{1}{2}mv^2. \quad (13)$$

From equations (12) and (13), the relationship between super-capacitor voltage and vehicle speed can be derived as follows:

$$\frac{V_{sc}}{V_{sc,max}} = \sqrt{1 - \left(1 - \frac{V_{sc,min}^2}{V_{sc,max}^2}\right) \cdot \left(\frac{v}{v_{max}}\right)^2}, \quad (14)$$

where  $C$  is the capacity of super-capacitor,  $N$  is the number of super-capacitor,  $v_{max}$  is the maximum speed under driving cycle, and  $v$  is the real-time speed of the vehicle. When the super-capacitor SOC is 0, its actual voltage is half the rated voltage, which can be expressed as follows:

$$V_{sc,min} = \frac{1}{2}V_{sc,max}. \quad (15)$$

Then, the reference value of super-capacitor SOC can be calculated from equation (4):

$$\begin{aligned} SOC_{sc,ref} &= \frac{V_{sc} - V_{sc,min}}{V_{sc,max} - V_{sc,min}} = \frac{V_{sc} - 0.5V_{sc,max}}{V_{sc,max} - 0.5V_{sc,max}} \\ &= \frac{2V_{sc}}{V_{sc,max}} - 1. \end{aligned} \quad (16)$$

Accordinging equations (14) and (16), the functional relationship between the reference value of super-capacitor SOC and real-time vehicle speed is found as follows:

$$SOC_{sc,ref} = 2 \sqrt{1 - 0.75 \left(\frac{v}{v_{max}}\right)^2} - 1. \quad (17)$$

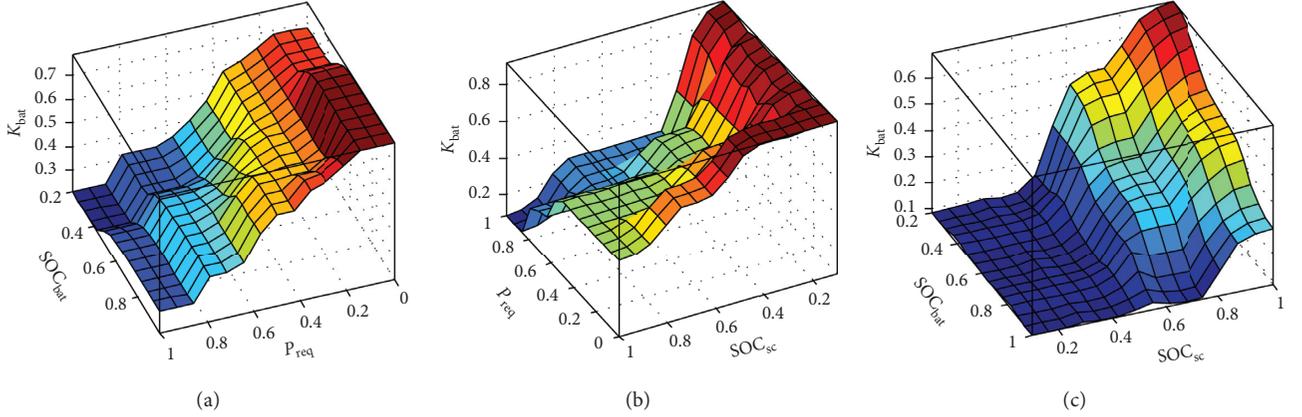


FIGURE 6: (a, b) Relation of inputs and output in discharge. (c) Relation of inputs and output in charge.

By comparing the reference value of super-capacitor SOC with its actual SOC, an error value  $\Delta SOC_{sc}$  is obtained:

$$\Delta SOC_{sc} = SOC_{sc} - SOC_{sc,ref}. \quad (18)$$

By  $\Delta SOC_{sc}$ , the output variable  $K_{bat}$  of the fuzzy controller in the pre-allocation module is optimized. In the discharge mode, when  $\Delta SOC_{sc}$  is positive, it shows that the actual value of super-capacitor SOC is larger than the reference value. Then  $K_{bat}$  is reduced appropriately to increase the power allocated to super-capacitor to avoid excessive battery discharge. When  $\Delta SOC_{sc}$  is negative, it shows that the actual value of super-capacitor SOC is less than the reference value. In this case,  $K_{bat}$  is increased correspondingly to reduce the power given to the super-capacitor so that the power of HESS can be allocated most reasonably. In the charge mode, when  $\Delta SOC_{sc}$  is positive, it shows that the actual value of super-capacitor SOC is larger than the reference value. Here,  $K_{bat}$  is increased appropriately to increase the power of battery recovery and avoid excessive charging of super-capacitor. In contrast, negative  $\Delta SOC_{sc}$  shows that the actual value of super-capacitor SOC is less than the reference value. Then,  $K_{bat}$  should be reduced appropriately to increase the power recovered by the super-capacitor and maximize the recovery of the braking energy.

Therefore, the final power allocation results in discharge mode are as follows:

If  $\Delta SOC_{sc} > 0$ ,

$$P_{bat} = (K_{bat} + K_1 \cdot \Delta SOC_{sc}) \cdot P_{req}, \quad (19)$$

If  $\Delta SOC_{sc} < 0$ ,

$$P_{bat} = (K_{bat} + K_2 \cdot \Delta SOC_{sc}) \cdot P_{req}. \quad (20)$$

In charge mode, the final power allocation results are:

If  $\Delta SOC_{sc} > 0$ ,

$$P_{bat} = (K_{bat} + K_3 \cdot \Delta SOC_{sc}) \cdot P_{req}, \quad (21)$$

If  $\Delta SOC_{sc} < 0$ ,

$$P_{bat} = (K_{bat} + K_4 \cdot \Delta SOC_{sc}) \cdot P_{req}, \quad (22)$$

where,  $K_1$ ,  $K_2$ ,  $K_3$ , and  $K_4$  are the proportional coefficients, used to optimize the allocation of the preallocation results and make the power allocation more valid.

Consider the optimal operation state of battery and super-capacitor with the following constraint range of parameters:

$$\begin{aligned} P_{bat} &< P_{req}, \\ P_{sc} &< P_{req}, \\ 0 &< K_{bat} + K_i \cdot \Delta SOC_{sc} < 1, \quad i \end{aligned} \quad (23)$$

where the values of  $K_1$ ,  $K_2$ ,  $K_3$ , and  $K_4$  in this paper are chosen by trial and error method and finally determined as in Table 6.

The overall flow chart of VSO-FEMS is depicted in Figure 7, which consists of two stages:

Stage 1: By analyzing the operation state of HESS, determine the input and output variables and formulate fuzzy control rules as well as the membership functions. The power allocation coefficient  $K_{bat}$  is obtained and the preallocation stage is completed.

Stage 2: Based on the model of vehicle dynamics, the reference value of super-capacitor SOC is calculated according to the real-time vehicle speed, and the error  $\Delta SOC_{sc}$  between the reference value of super-capacitor SOC with its actual SOC is obtained. The allocation results in Stage 1 are optimized by  $\Delta SOC_{sc}$  to complete the final allocation.

## 4. Results and Analysis

The vehicle model with VSO-FEMS strategy is built in ADVISOR. The parameters of the vehicle model are shown in Table 7. On this basis, the VSO-FEMS strategy proposed

TABLE 6: Parameters of VSO-FEMS strategy.

Parameters	$K_1$	$K_2$	$K_3$	$K_4$
Value	-0.05	0.1	0.1	-0.05

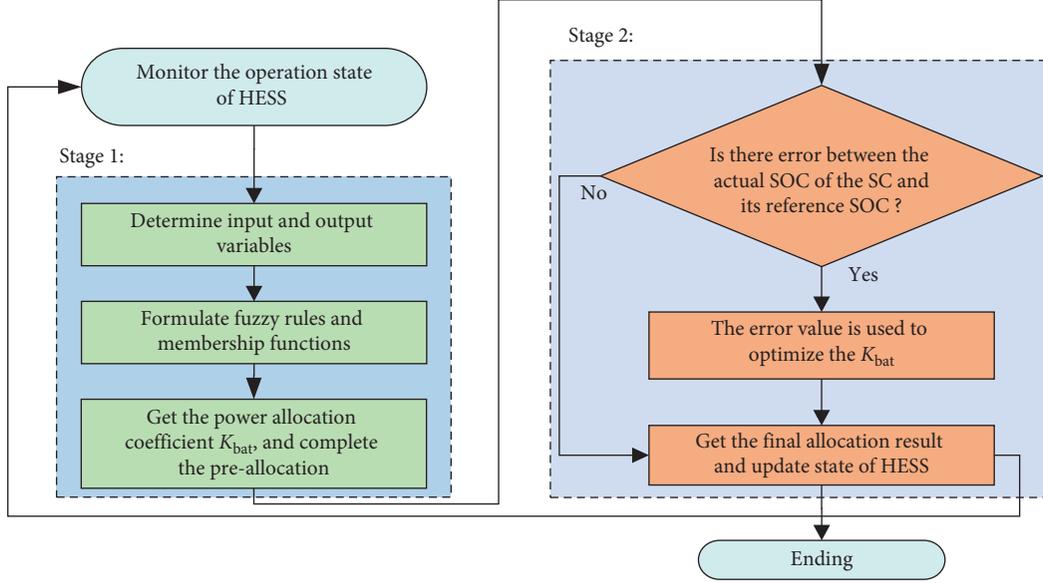


FIGURE 7: The flow chart of VSO-FEMS strategy.

in this paper is simulated and validated using the typical urban cycle in China (CYC-CHINA), which are provided in Figure 8(a). The driving cycle involve frequent acceleration and deceleration, which is a strong representation for testing the HESS and its EMS. To simplify the question in the research, the road slope is set to be zero. The required power (see Figure 8(b)) of CYC-CHINA can be calculated by equation (8).

**4.1. Simulation Results.** The power allocation of HESS in driving cycle are shown in Figure 9(a), and the currents of battery and super-capacitor are shown in Figure 9(b). It can be seen that VSO-FEMS strategy can effectively allocate power to battery and super-capacitor. When the required power is too large, VSO-FEMS strategy can reduce the power of the battery, allocate instantaneous peak power to the super-capacitor, optimize the battery current, prevent high-current discharge, and protect the battery.

**4.2. Performance Comparison.** Under road driving of electric vehicle, the operation states change of the battery and the super-capacitor (operating voltage, SOC, maximal current, etc.) and total energy consumption are the important indices of the performance of energy management strategy. In addition, many stress factors, like high fluctuations in battery SOC, high rates of required power, and operation in low and high temperatures have shown to be effective in battery aging. Therefore, the battery current root mean

TABLE 7: Parameters of electric vehicle model.

Parameters	Value
Air drag coefficient $C_a$	0.55
Transmission system efficiency $\eta$	0.9
Rolling resistance coefficient $f$	0.01
Frontal area $A$ ( $m^2$ )	8.7
Curb weight $m$ (kg)	12500
Capacity of battery (Ah)	60
Rated voltage of battery (V)	495
Capacity of super-capacitor (F)	9500
Rated voltage of super-capacitor (V)	780

square (BCRMS) has been used as the indicator of the aging parameters and used to evaluate the battery lifespan, which is defined as follows [26, 27]:

$$\text{BCRMS} = \sqrt{\frac{1}{T_f} \sum_{i=1}^{T_f} i_{\text{bat}}^2} \quad (24)$$

where  $T_f$  is the driving duration.

To demonstrate the effectiveness of the VSO-FEMS strategy, it is compared with the pure battery, rule-based strategy, and fuzzy strategy under CYC-CHINA. The comparison of performance results is presented in Table 8, the comparison of the change curve of the battery current is plotted in Figure 10(a), the comparison of the change curve of battery voltage is plotted in Figure 10(b), the comparison of the change curve of battery SOC is plotted in Figure 10(c),

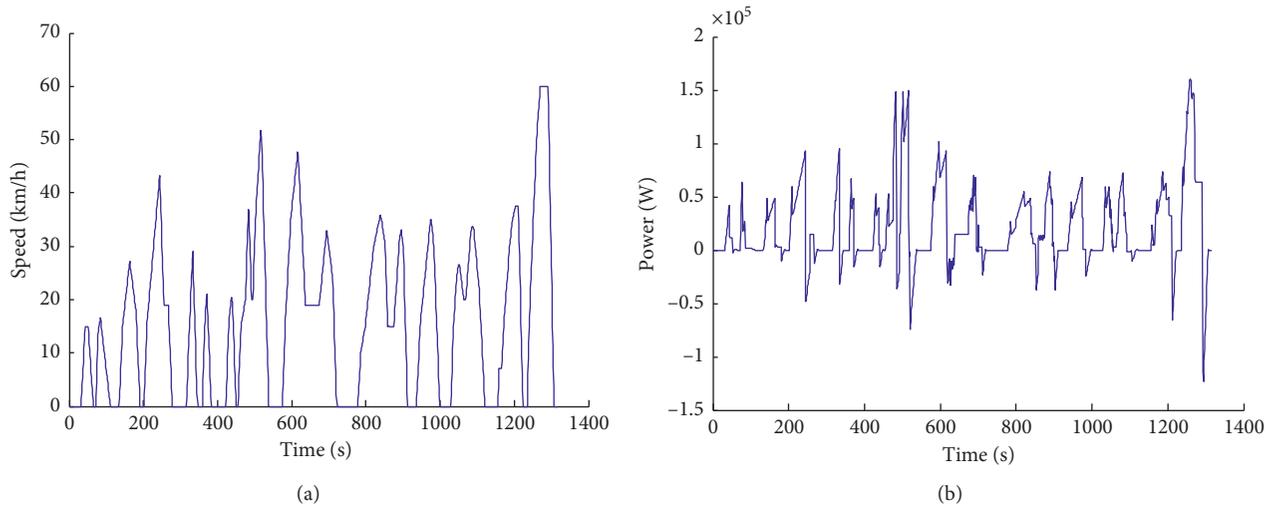


FIGURE 8: (a) The speed of CYC-CHINA. (b) The required power of CYC-CHINA.

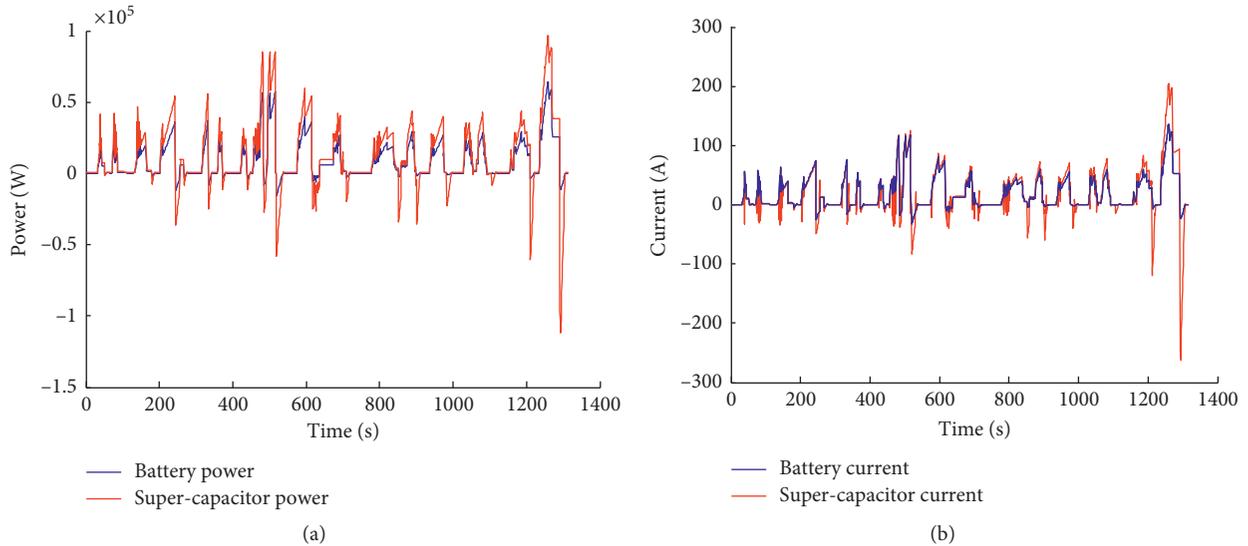


FIGURE 9: (a) Power allocation of HESS. (b) Comparison currents of battery and super-capacitor.

TABLE 8: Results comparison.

	Pure battery	Rule-based	Fuzzy	VSO-FEMS
Max battery current (A)	357.78	224.47	100.44	135.40
Final battery voltage (V)	462.64	476.68	483.59	479.39
Final battery SOC	0.7412	0.8648	0.9157	0.8846
Final super-capacitor SOC	N/A	0.4319	0.3938	0.5495
Energy consumption (kJ)	24929	26158	25853	25522
Time consumed (s)	3.76	3.88	4.30	4.21

the comparison of the change curve of super-capacitor SOC is plotted in Figure 10(d), and the BCRMS of different strategies is plotted in Figure 11.

From Figures 10 and 11 and Table 8, it can be seen that although the total energy consumption of pure battery is the lowest, the SOC of battery drops the fastest, and the BCRMS

of pure battery is the largest, which causes great damage to the battery and reduces the service life of battery. Compared with the rule-based strategy, in the VSO-FEMS strategy, the maximal current of the battery is obviously decreased, the voltage of battery changes more stably, the SOC of battery is increased by 1.98%, the SOC of super-capacitor is increased

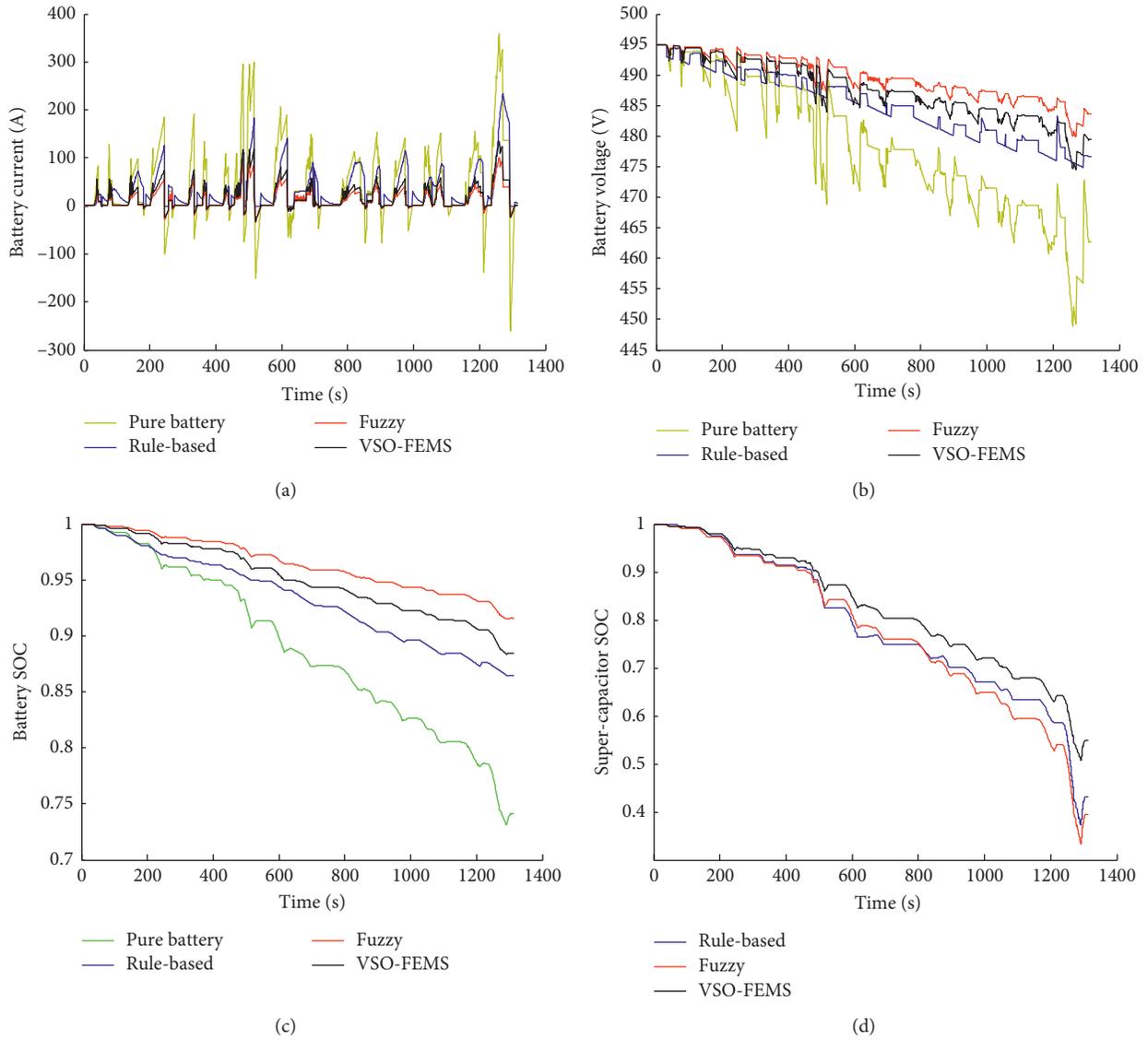


FIGURE 10: (a) Comparison of battery current. (b) Comparison of battery voltage. (c) Comparison of battery SOC. (d) Comparison of super-capacitor SOC.

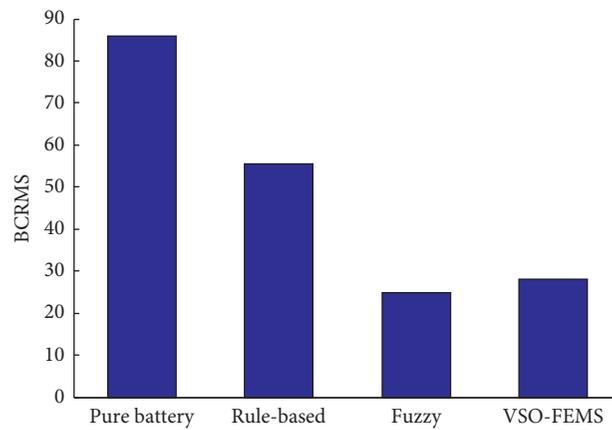


FIGURE 11: The BCRMS of different strategies.

by 11.76%, the BCRMS is reduced by 49.48%, and the total energy consumption is reduced by 2.43%; it shows that the performance of VSO-FEMS strategy is better than that of rule-based strategy. Compared with the fuzzy strategy, in the VSO-FEMS strategy, although the maximal current of the battery and BCRMS are slightly higher, and the SOC of the battery is reduced by 3.11%, the SOC of the super-capacitor is increased by 15.57%, the total energy consumption is reduced by 1.28%, and the battery is still in a suitable working state, which shows that the performance of the VSO-FEMS strategy is better than the fuzzy strategy. In addition, the time cost of the VSO-FEMS strategy is higher than pure battery and rule-based strategies, but lower than fuzzy strategy.

By comparing the simulation results, the VSO-FEMS strategy proposed in this paper can reasonably allocate the required power and achieve the design objectives of optimizing battery current to prolonging battery life, increasing the electric vehicle driving distance and improving energy economy. The effectiveness of VSO-FEMS strategy is demonstrated.

## 5. Conclusions

In this paper, the structure of HESS is analyzed, and a vehicle speed optimized fuzzy energy management strategy (VSO-FEMS) is proposed to allocate the required power between the battery and the super-capacitor. The specific work is as follows:

- (1) Two fuzzy controller is designed to control the charging and discharging modes of HESS, and fuzzy control rules are designed to realize preallocation of the required power.
- (2) Based on fuzzy control and the vehicle dynamics, for the first time, the speed optimization module is introduced to calculate the reference value of super-capacitor SOC according to the real-time vehicle speed. The preallocation results are optimized by the SOC error value to achieve reasonable power allocation results.
- (3) The vehicle model is built in ADVISOR, and the VSO-FEMS strategy is compared with other energy management strategies. The simulation results show that under the same driving cycle, the VSO-FEMS strategy has better performance in prolonging battery life, covering longer vehicle driving distance, and improving energy economy. The effectiveness of VSO-FEMS strategy is demonstrated.

## Data Availability

No data were used to support this study.

## Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

## Acknowledgments

This work was supported by the National Natural Science Foundation of China (61673164), the Natural Science Foundation of Hunan Province (2020JJ6024) and, the Scientific Research Fund of Hunan Provincial Education Department (17A048 and 19K025).

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