Research on Energy Management Strategy of Battery-Flywheel Hybrid Energy Storage Electric Vehicle

Hualei Lu, Binbin Sun, Zihao Hu

Abstract—Targeting the problems of poor durability and specific low power of pure vehicle electric batteries, a new lithium battery/ flywheel energy storage composite energy storage system has been proposed. By analyzing the functional characteristics of the energy storage flywheel system, according to its advantages of high power density and no limitation on discharge depth, a fuzzy control energy management strategy for driving and braking is developed. The forward simulation model of lithium battery-energy storage flywheel hybrid energy storage electric vehicle is built with Matlab/Simulink software, and the hardware-in-the-loop experiment of a control strategy based on the NI platform is carried out under typical urban and high-speed cycle conditions. The test results show that under UDDS, HWFET, and CLTC-P, the vehicle economy of the energy storage flywheel hybrid energy storage scheme is increased by 1.67%, 1.05%, and 8.11%, respectively, compared with the single battery system. The maximum peak performance reduction for lithium batteries is 70.44%, 66.95% and 48.91%, respectively. It has been proved that the proposed fuzzy control energy management strategy can give full play to the advantages of the hybrid energy storage system, improve the efficiency of the vehicle energy system, reduce the capacity loss of lithium battery and improve vehicle performance.

***Index Terms*—Energy storage flywheel system; energy management; fuzzy control; hardware-in-the-loop**

I. Introduction

As an essential part of contemporary energy vehicles, electric vehicles are favored by many researchers because of their non-pollution, low noise, and high energy efficiency during operation [1], [2]. However, as the primary energy source of electric vehicles, power battery is restricted by problems such as cost, cycle life, energy density, and power density can not be taken into account [3]. How to prevent the power battery from running under unfavorable conditions, improve the efficiency, and prolong the service life has become a research hotspot and difficulty. The energy storage flywheel system uses the high-speed rotation of the flywheel to store energy, which has the advantages of high power density and long cycle life-use of auxiliary energy sources. Lithium battery-energy storage flywheel system hybrid energy storage electric vehicle combines the "high energy density" of the battery with the "high power output" of the flywheel energy storage system to reduce the peak power of the power battery and improve the vehicle's economic performance.

Currently, the research focus of on-board flywheel energy storage systems is focused on flywheel materials, magnetic bearing technology, motor selection and control strategies, etc. [4]. In 2009, the energy storage flywheel hybrid system developed by Williams Hybrid Power Co., Ltd. in the United Kingdom built the control motor into the flywheel. He integrated the motor rotor with the flywheel rotor, which was successfully applied to the field of F1 racing [5]. Sun Zhongxin *et al*. applied the energy storage flywheel system to a traditional fuel vehicle, analyzed the feasibility of applying the flywheel energy storage device, and verified the maximum braking energy recovery of the flywheel energy storage device under operating conditions through simulation, reducing fuel consumption [6]. Wang Wei *et al*. used a genetic-based optimization algorithm to achieve optimal electric braking and current distribution of the hybrid energy storage system for the braking process of an electric vehicle with a battery-flywheel hybrid energy storage system. The total recovered energy of the battery was increased by 1.17 times, and the proposed adaptive PI vector control can adjust the speed of the flywheel motor to meet the requirements of the rapid dynamic response of the flywheel system [7].

In the above literature, the energy storage flywheel system is regarded as the auxiliary driving device of the engine, or the flywheel is used as the extra energy of the battery. The control problem of the flywheel motor in the braking process is discussed, and the corresponding driving and braking power distribution strategy are not used to supply energy for the vehicle. This document uses the lithium battery/ flywheel hybrid energy storage system for research purposes. The fuzzy control method conducts the energy distribution between the flywheel energy storage system and the power battery. While ensuring the vehicle's dynamic performance, the energy system is working in the high-efficiency range to obtain the optimal energy distribution effect, reduce the vehicle's energy consumption and improve the life of the lithium battery.

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II. Vehicle Configuration of Energy Storage Flywheel System

The structure of the energy storage flywheel system is shown in Fig.1, which is composed of motor/generator, flywheel, power electronic control device, vacuum chamber, vacuum pump, and bearing [8], [9]. The flywheel control motor rotor and flywheel rotor shall be mounted on the flywheel shaft. The permanent magnet's synchronous reciprocating motor is selected to reduce the volume and energy consumption of the system. Flywheel rotors store or release energy through high-speed rotation (10000-45000 rpm) and are generally made of high-strength materials. The bearing supports the movement of the steering wheel. The magnetic bearing is commonly used to reduce friction loss between the flywheel and the motor rotor. The electronic power controller controls the operating status of the flywheel control motor to perform bi-directional conversion of the DC power supply and the three-phase AC power supply. The vacuum chamber creates a vacuum environment, minimizes the loss of wind resistance when the flywheel rotates, and improves system performance. It also plays a protective role when the flywheel is turning at high speed. The flywheel energy storage system operates in three modes: charge, discharge and energy storage. When the flywheel is in load mode, the flywheel control motor drives the flywheel to swivel and store energy. When the flywheel is in energy-free mode, the flywheel drives the flywheel to control the motor so that it turns to provide energy to the load. When the flywheel is in energy storage mode, it can keep a particular rotational speed.

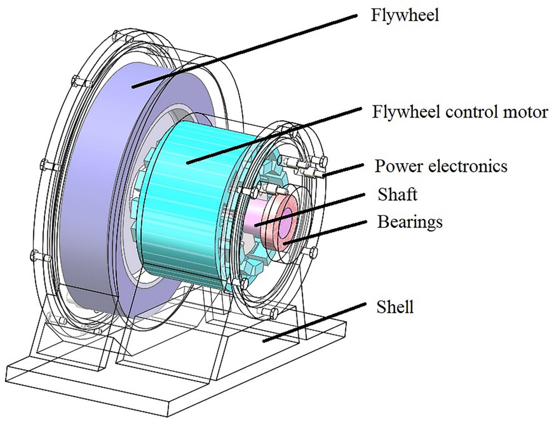

Fig. 1. Structure of energy storage flywheel system

For electric vehicles with an energy storage flywheel system, if the voltage range of the DC bus is the same as that of the energy storage flywheel system, the energy storage flywheel system can be directly connected in parallel with the lithium battery. If not, the energy storage flywheel system or battery side must match the DC/DC bidirectional converter to accommodate the voltage [10]. Consideration of coordination and voltage output stability between the energy storage flywheel system and power battery, the energy storage flywheel system adopts a back-connected bidirectional DC/DC converter, which is connected in parallel with the power battery to provide energy to the load. In this article, an energy storage flywheel system is set up on a pure electric vehicle to form a hybrid energy storage system with the battery. The structure of the post-construction vehicle is illustrated in Fig. 2.

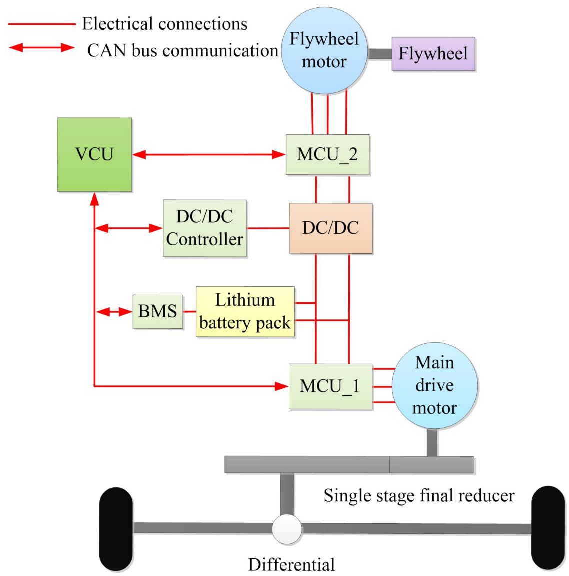

Fig. 2. Structure of composite energy storage electric vehicle

III. Parameter Matching of Energy Storage Flywheel System

The basic parameters of a domestic pure electric vehicle are shown in Table I. The energy storage flywheel system has the characteristics of low energy storage and high price (100-400 yuan/Wh). The composite energy storage system can release high-frequency energy, but it can not be continually discharged over a long period of time. Furthermore, the manufacturers of flywheel energy storage systems on the market are limited, so it is necessary to design specific flywheel sizes and energy.

TABLE I
Basic Parameters of Pure Electric Vehicle

Parameter Name	Parameter	Numerical Value
basic parameters of the vehicle	curb weight m_0 (kg)	1900
	full load quality m (kg)	2330
	frontal area A (m^2)	2.307
	wind resistance coefficient C_D	0.32
	drivetrain mechanical efficiency η_T	0.9
	main reduction ratio i_0	8.5
	wheel radius r (m)	0.324
	rolling resistance coefficient f	0.015
	rotating mass conversion factor δ	1.05
motor parameters	rated power (kW)	50
	rated speed ($r{\cdot}min^{-1}$)	4000
	rated torque (N·m)	119.4
	peak power (kW)	120
	maximum speed ($r{\cdot}min^{-1}$)	12000
	peak torque (N·m)	286.5
battery pack parameters	number of series and parallel	105 series 5 parallel
	capacity (A·h)	200
	standard (V)	336

A. Flywheel Parameter Design

In typical city driving conditions, the energy stored in the flywheel should meet the maximum energy value required for the starting acceleration power E_{sacc}, the continuous peak power E_{conp} within a specific time, and the continuous recovery braking power E_{reg}. The flywheel energy storage E_{fw} satisfies the following calculation formula:

$$E_{fw} \geq \max(E_{sacc}, E_{conp}, E_{reg}) \quad (1)$$

The formula used to calculate the flywheel energy store is as follows:

$$E_{fw} = \frac{1}{2}J(\omega_{\max}^2 - \omega_{\min}^2) \quad (2)$$

where J is the moment of inertia of the flywheel. $\omega_{\min}$ is the minimum angular velocity of the flywheel. $\omega_{\max}$ is the maximum angular velocity of the flywheel.

The energy status of the *SOE* flywheel is defined as the ratio of the current stored energy of the flywheel to the maximum energy that the flywheel can store. The specific formulation is:

$$SOE = \frac{0.5J\omega^2}{0.5J\omega_{\max}^2} \quad (3)$$

where ω is the real-time angular velocity of the flywheel.

Refer to "(3)," we observed that when the minimum speed of the flywheel is one-third of the maximum speed, the flywheel can reach a discharge depth of nearly 90%, much higher than that of a conventional chemical battery [11]. Referring to the technical parameters of mature foreign products, the maximum speed of the flywheel is 38000 r/min, the minimum speed is 13000 r/min, and the corresponding *SOE* range is [0.11, 0.95]. At this time, the energy storage of the flywheel should be 0.47 kw·h considering the discharge depth. Combined with "(2)," the rotational inertia of the flywheel is 0.242 kg·m^2.

AS4C carbon fiber composite material with high energy density is selected as the material of the flywheel rotor. The material density is 1510 kg·m^3, the tensile strength Rm is 1650 MPa, and the maximum energy density w is 150 Wh·kg^{-1} [12]. The flywheel adopts a hollow cylindrical type, and the calculation formula of its moment of inertia is:

$$J = \frac{1}{2}\pi h \rho (R_{fw}^4 - r_{fw}^4) \quad (4)$$

Where R_{fw} is the outer radius. r_{fw} is the inner radius. h is the height of the flywheel rotor, and ρ is the flywheel material density.

To verify that the tangential stress of the flywheel during high-speed rotation meets the material strength requirements, the calculation formula for the maximum tangential stress is as follws:

$$\sigma_{\max} = \rho\omega^2 R_{fw}^2 \quad (5)$$

where $\sigma_{\max}$ is 516 MPa<1650 MPa, the safety factor ratio of the flywheel is more than 2 times, and the flywheel meets the design requirements. The specific parameters of the flywheel are shown in Table II.

TABLE II
FLYWHEEL PARAMETERS

Parameter Name	Parameter Value
moment of inertia (kg·m^2)	0.242
outer circle radius (cm)	14.7
inner circle radius (cm)	10.4
thickness of flywheel rotor (cm)	29.4
peak speed (r·min^{-1})	38000
energy storage (kw·h)	0.47
quality (kg)	9.8

B. *Design of Parameters of Flywheel Control Motor*

The peak demand power of the energy storage flywheel system is 62 kW under typical urban conditions. Considering the efficiency of the DC/DC converter, the peak power of the flywheel control motor is set to 65 kW. To ensure that the energy storage flywheel system outputs high efficiency between the highest speed and the lowest speed, the rated speed of the flywheel control motor is set to 18000 r/min. Specific parameters for the flywheel control motor can be found in Table III.

TABLE III
FLYWHEEL CONTROL MOTOR PARAMETERS

Project	Parameter Value
motor type	permanent magnet synchronous motor
peak power (kW)	65
rated power (kW)	30
peak speed (r·min^{-1})	38000
peak torque (N·m)	34.5

IV. BATTERY-FLYWHEEL COMPOSITE ENERGY STORAGE ELECTRIC VEHICLE MODEL

Based on Matlab/Simulink simulation software, the forward simulation model of the whole vehicle is built, which mainly includes driver module, control system module, motor module, main reducer module, wheel axle module, vehicle dynamics module, lithium battery module, flywheel module, flywheel control motor module and DC/DC converter module. The driver model with PID control to achieve operating speed and actual speed to follow, the output drive and brake pedal opening. The control system model is mainly based on pedal opening, the current state of charge, flywheel energy state, speed, and other system signal state, to achieve the driver intention analysis, energy distribution. The following will be presented in detail to the EV Composite Energy Storage System model.

A. *Flywheel Model*

The energy state *SOE* of the flywheel is:

$$SOE = SOE_0 - \frac{\int_{t_0}^{t_1} P_{fw} dt}{\frac{1}{2}J\omega_{\max}^2} \quad (6)$$

where SOE_0 is flywheel initial *SOE*. P_{fw} is flywheel power.

The flywheel speed is:

$$\omega = \sqrt{\omega_{\max}^2 \cdot SOE} \quad (7)$$

where n_{fw} is the speed of the flywheel. n_{fw_max} is the maximum speed of the flywheel.

The flywheel energy consumption E_{fw_cons} is:

$$E_{fw\_cons} = \frac{J\omega_{\max}^2}{2}\left(SOE_0 - SOE\right) \quad (8)$$

Since the energy storage flywheel adopts the magnetic suspension bearing and vacuum chamber structure, the problem of wind resistance loss and bearing friction loss during flywheel rotation is no longer considered here. The efficiency of the flywheel energy storage system is primarily dependent upon the efficiency of the flywheel control motor.

B. Flywheel Control Motor Model

The speed of the flywheel control motor changes with the speed of the flywheel, and it needs to meet the requirements of high speed, high efficiency, low self-loss, and adaptability to a wide speed range. The flywheel control motor model mainly calculates and outputs the actual working power of the motor according to the demand power of the flywheel control motor and the flywheel speed signal. The calculation formula for the working power P_{mot_fw} of the flywheel control motor is:

$$P_{mot\_fw} = \begin{cases} \dfrac{P_{motfw\_req}}{\eta_{motfw}}, & P_{motfw\_req} > 0 \\ P_{motfw\_req}\eta_{mot\_fw}, & P_{motfw\_req} \le 0 \end{cases} \tag{9}$$

where P_{mot_fw} is the power of the flywheel control motor. P_{motfw_req} is the demand power of the flywheel control motor. η_{mot_fw} is the efficiency of the flywheel control motor.

C. Main Drive Motor Model

The hybrid energy storage electric vehicle drive motor is responsible for the driving and braking of the whole vehicle and requires a higher speed range under the condition of satisfying the performance of the whole vehicle. The main drive motor model primarily calculates and produces the true torque and power of the motor based on the motor demand torque and motor speed. The real-time efficiency of the motor is obtained from the real-time torque and speed of the motor with the help of the search table module. The motor performance map is shown as Fig.3.

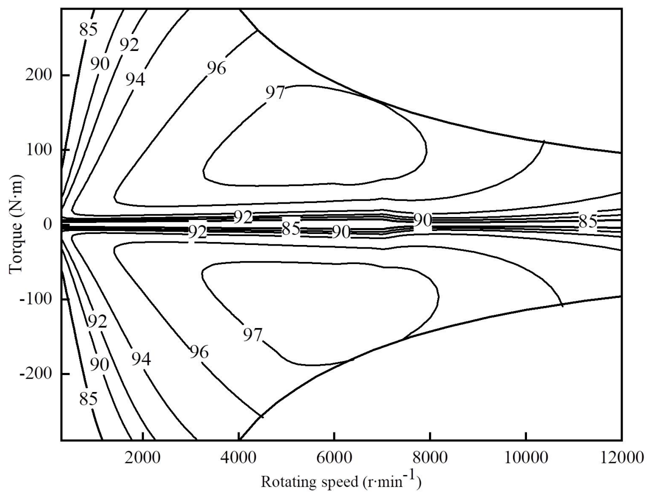

Fig. 3. Motor efficiency MAP

Thus, the working power of the motor is obtained by:

$$P_{mot} = \begin{cases} \dfrac{T_{mot}n_{mot}}{9550\eta_{mot}}, T_{mot} > 0 \\ \dfrac{T_{mot}n_{mot}\eta_{mot}}{9550}, T_{mot} \le 0 \end{cases} \tag{10}$$

where P_{mot} is the motor power. T_{mot} is the motor output torque. n_{mot} is the motor speed.

D. Lithium Battery Model

This article selects the R_{int} equivalent circuit model, which consists of an ideal voltage source V_{oc} and an internal resistance R_{int}, as shown in Fig.4.

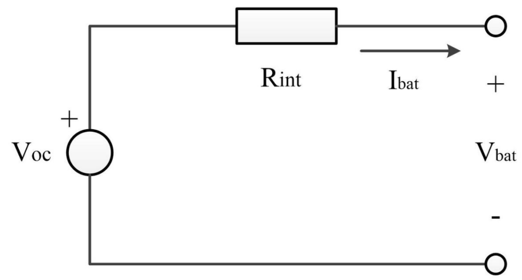

Fig. 4. Equivalent circuit model of lithium battery pack

According to Kirchhoff 's law, the equivalent circuit equation can be written like this:

$$V_{bat} = V_{oc} - R_{int}I_{bat} \tag{11}$$

where V_{oc} is the open circuit voltage of the lithium battery. I_{bat} is the charging and discharging current of the lithium battery, and the specified current flowing from the positive electrode is positive, that is, the discharge is positive. R_{int} is the equivalent internal resistance of the lithium battery.

When the output power P_{bat} of the lithium battery pack is determined, the output current of the lithium battery pack can be obtained as:

$$I_{bat} = \frac{V_{oc} - \sqrt{V_{oc}^2 - 4P_{bat}R_{int}}}{2R_{int}} \tag{12}$$

The *SOC* of the lithium battery pack can be estimated by the ampere-hour integration method:

$$SOC = SOC_0 - \frac{1}{C_N}\int_0^t I_{bat}dt \tag{13}$$

where SOC_0 is the initial state of charge of the lithium battery pack, C_N is the rated capacity, and t is the time.

The discharge efficiency η_{dis_bat} of the lithium battery pack is related to the *SOC* range and the required discharge power P_{dis_bat} of the battery. The relation matrix may be obtained by experimental adjustment as follows:

$$\begin{aligned} \eta_{dis\_bat} &= \\ &\left[-3.913\times10^{-5}, -7.126\times10^{-4}, -3.929\times10^{-1}\right]\begin{bmatrix} P_{dis\_bat}^3 \\ P_{dis\_bat}^2 \\ P_{dis\_bat} \end{bmatrix} \\ &-\left[8.988\times10^{-6}, 2.031\times10^{-3}, 9.226\times10^{-2}\right]\begin{bmatrix} SOC^3 \\ SOC^2 \\ SOC^1 \\ SOC^0 \end{bmatrix} \\ &+\left[-1.842\times10^{-5}, 1.192\times10^{-3}, 3.021\times10^{-5}\right] \\ &\begin{pmatrix} P_{dis\_bat} & & \\ & P_{dis\_bat} & \\ & & P_{dis\_bat}^2 \end{pmatrix}\begin{bmatrix} SOC^2 \\ SOC \\ SOC \end{bmatrix} \end{aligned} \tag{14}$$

The health state (SOH) of the battery pack is an important indicator of battery aging, and the internal manifestation is the increase in the attenuation and the increase in the capacity of the capacity. Existing literature's research on capacity attenuation is mostly committed to the experimental fitting data under the temperature of the constant current, while the real car battery is mostly in the dynamic current working conditions and uncertain charging and discharge cycle. Because according to the cumulative damage theory [13], [14], the mathematical model of the fitted attenuation is:

$$Q_{loss} = 0.0032e^{-\left(\frac{15162-1516C_{rate}}{RT_{bat}}\right)}(A_h)^{0.824} \quad (15)$$

where Q_{loss} is the loss of battery capacity. T_{bat} is the temperature. *R is the ideal gas function.* C_{rate} is the charge-discharge rate.

E. Vehicle Dynamics Model

The composite energy storage electric vehicle may not use gearboxes, and the driving force is [15], [16]:

$$F_t = \frac{T_{tq} i_0 \eta_T}{r} \quad (16)$$

where T_{tq} is the motor torque, F_t is the driving force acting on the driving wheel.

The whole vehicle shall overcome external forces such as rolling resistance, air resistance, slope resistance, acceleration resistance, etc. Depending on the driving equation of the vehicle, this can be achieved:

$$F_t = Gf\cos\alpha + \frac{C_D A}{21.15}u_a^2 + G\sin\alpha + \delta m\frac{du}{dt} \quad (17)$$

where u_a is the speed of the vehicle, G is the gravity acting on the vehicle, and α is the slope angle.

V. Energy Management Strategy of Composite Energy Storage System

A. Energy Management Strategy Design Principles

When designing the energy management control strategy, the energy distribution between the energy storage flywheel system and the lithium battery must satisfy the following requirements:

(1) The lithium battery and power storage flywheel all work within the effective range.

(2) Make full use of the operating advantages of high power density and high cycle life of the energy storage flywheel system.

(3) Reduce the unfavourable working conditions of lithium batteries and improve the lifespan of lithium batteries.

(4) Reduce energy consumption across the vehicle and improve the profitability of the electric system.

B. Fuzzy Based Energy Management Strategy

During the driving process of the vehicle, the motor is in the driving or braking state, and the power distribution of the power battery and the energy storage flywheel system is different in different states. Consequently, this document defines the driving and braking dual fuzzy controllers to perform the vehicle check.

Membership Function Design of Input and Output Parameters

The input of the driving fuzzy controller is the motor demand power P_{req_q} when driving, the lithium battery state of charge *SOC* and the energy state of the energy storage flywheel *SOE*. The input of the braking fuzzy controller is the motor demand power P_{req_z} during braking, the lithium battery state of charge *SOC* and the energy state of the energy storage flywheel *SOE*. The fuzzy control output is the K_{bat} ratio of lithium battery power to total power. The relationship between K_{bat} and the demand power P_{req} of the motor, the P_{bat} power supplied by the battery and the P_{fw} power supplied by the energy storage inertia wheel satisfies the formula:

$$\begin{aligned} P_{bat} &= K_{bat} P_{req} \\ P_{fw} &= P_{req} - P_{bat} \end{aligned} \quad (18)$$

The actual universe, fuzzy universe, fuzzy subset and other related settings of the input and output variables of the fuzzy controller are shown in Table IV. NB means negative big, NM means negative medium, NS means negative small, NV means negative small, ZO means positive zero, VS means positive small, S means positive small, M means positive medium, B means positive big, VB means positive relatively big. According to the working characteristics of the lithium battery/energy storage flywheel composite energy storage system, the membership functions of the input and output parameters are designed, as shown in Fig.5.

TABLE IV
Related Parameter Settings of Input and Output Variables

Working Status	Input and Output Variables	Actual Universe	Fuzzy Universe	Fuzzy Subset
drive	P_{req_q}	[0, 70]	[0, 1]	VS S M B VB
drive	K_{bat_q}	[0, 1.2]	[0, 1.2]	VS S M B VB
brake	P_{req_z}	[-50, 0]	[-1, 0]	NB NM NS NV
brake	K_{bat_z}	[-0.2, 1]	[-0.2, 1]	NS ZO VS S M B
drive/brake	*SOC*	[0.2, 0.95]	[0.2, 0.95]	S M B
drive/brake	*SOE*	[0.1, 0.95]	[0.1, 0.95]	S M B

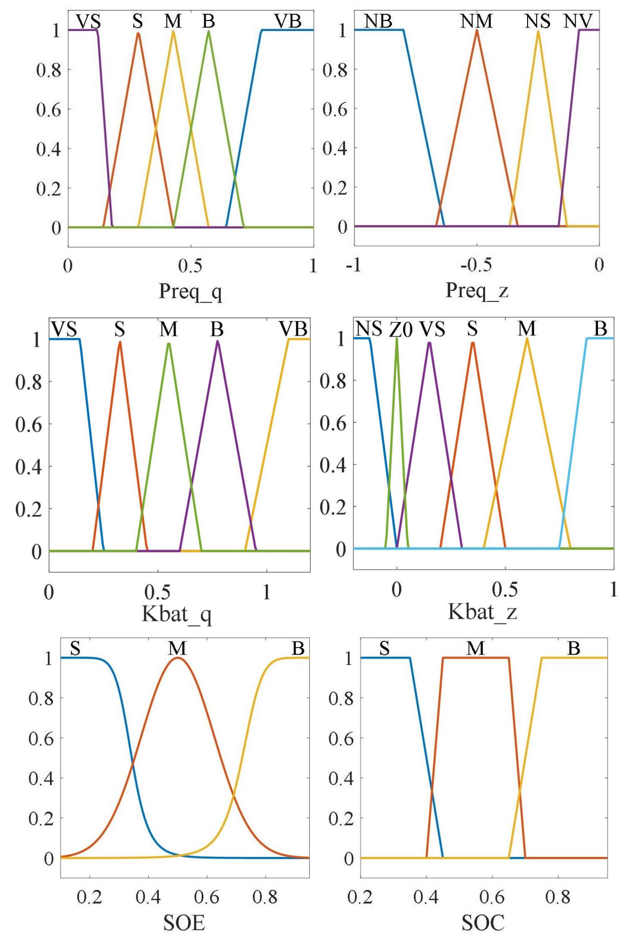

Fig. 5. Membership function of input and output parameters

Formulation of Fuzzy Rules

To ensure that the energy distribution of the hybrid energy storage system is reasonable, the following principles must be respected when formulating the unclear rules:

(1) When the vehicle demand power P_{req} is greater than 0, if the energy storage flywheel *SOE* is low, the battery should provide full drive power. If the battery *SOC* is high at this time, the battery needs to be charged to the energy storage flywheel to restore its energy level rapidly.

(2) When the vehicle demand power P_{req} is greater than 0, if the energy storage flywheel *SOE* is sufficient, the energy storage flywheel system is superior to the battery to provide peak discharge power. When the vehicle demand power is small, the battery provides the main power, energy storage flywheel supplement. When the demand power of the vehicle is immense, the battery works stably at small and medium power as far as possible, and the energy storage flywheel provides the residual power demand. Under the condition of ensuring the battery performance, the energy storage flywheel is discharged as much as possible to prepare for the recovery of braking energy.

(3) When the vehicle demand power P_{req} is less than 0, the energy storage flywheel system is better than the battery to absorb braking energy. If the energy storage flywheel *SOE* is low, the energy storage flywheel should preferentially recover all braking energy, and the battery does not absorb braking energy. If the battery *SOC* is high, the battery should be charged to the energy storage flywheel, as far as possible to restore the energy storage flywheel energy state, to prepare for considerable driving power. If the battery *SOC* and the energy storage flywheel *SOE* are high, the braking energy is not recovered, and the energy is lost in the form of thermal energy through mechanical braking.

The fuzzy driving rules based on the above principles are set out in Table V and the fuzzy braking rules are set out in Table VI.

TABLE V
DRIVING FUZZY RULES

K_{bat_q}		P_{req_q} VS	S	M	B	VB
SOE（*SOC*=S）	S	VB	VB	*B*	B	B
	M	VB	VB	VB	VB	VB
	B	VB	VB	VB	VB	VB
SOE（*SOC*=M）	S	B	B	M	S	VS
	M	B	B	M	M	S
	B	VB	VB	B	M	S
SOE（*SOC*=B）	S	B	S	S	VS	VS
	M	B	B	M	S	VS
	B	B	B	B	M	S

TABLE VI
BRAKING FUZZY RULES

K_{bat_z}		P_{req_z} NB	NM	NS	NV
SOE（*SOC*=S）	S	S	S	M	B
	M	Z0	Z0	Z0	Z0
	B	NS	NS	NS	NS
SOE（*SOC*=M）	S	VS	S	B	B
	M	VS	VS	S	M
	B	Z0	Z0	Z0	VS
SOE（*SOC*=B）	S	S	M	B	B
	M	VS	S	M	B
	B	VS	S	M	M

VI. HARDWARE-IN-THE-LOOP TEST ANALYSIS

To check the accuracy of the vehicle model and the real-time effectiveness of the control strategy, a hardware-in-the-loop simulation test system based on the NI Verstand and MotoTron platform is designed. The specific test procedure is illustrated in Fig.6:

1) MotoTron is a rapid prototyping development platform for VCU. The Moto Hawk library is installed in the Simulink development environment to develop the VCU control strategy. The Moto Hawk library contains sensor input interface module, actuator output interface module, and CAN communication module. These modules can complete the mapping of VCU hardware input and output pins and control strategy input and output.

2) Based on Moto Hawk VCU underlying software module selection and configuration, including controller definition module, CAN channel and communication baud rate definition module: here set CAN1 channel for code writing, CAN2 channel for vehicle communication. Mototune CAN communication protocol definition module, compiler software definition modules, etc.

3) The simulation model based on Simulink is imported into the NI real-time simulator using the NI Veristand software to run the simulation model in real-time and dynamically update the vehicle parameters according to the control strategy feedback. NI Veristand software completes the mapping between model input and output and board hardware I/O.

4) Based on the NI Veristand library installed in the Simulink environment with its input and output interface, the VCU can be connected to the simulation model, the required mapping of the output.

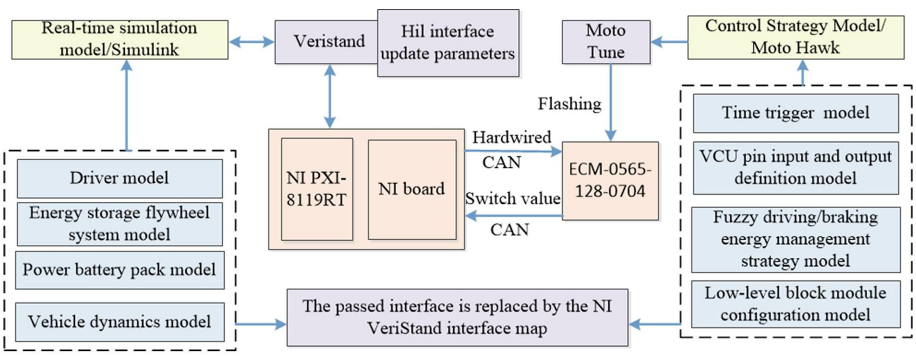

Fig. 6. Hardware-in-the-loop test system design flow

In this article, the hardware-in-the-loop test takes place under UDDS (Urban Dynamometer Driving Schedule), HWFET (American road driving cycle) and CLTC-P (Chinese passenger vehicle driving cycle). The test platform is pictured in Fig.7. Because only the analysis of the control strategy of energy management, therefore no fault injection. To study the superiority and difference of energy storage flywheel battery hybrid energy storage electric vehicle compared with single battery energy, pure electric vehicle on vehicle economy, the hardware-in-the-loop test results of the two models are compared and analyzed.

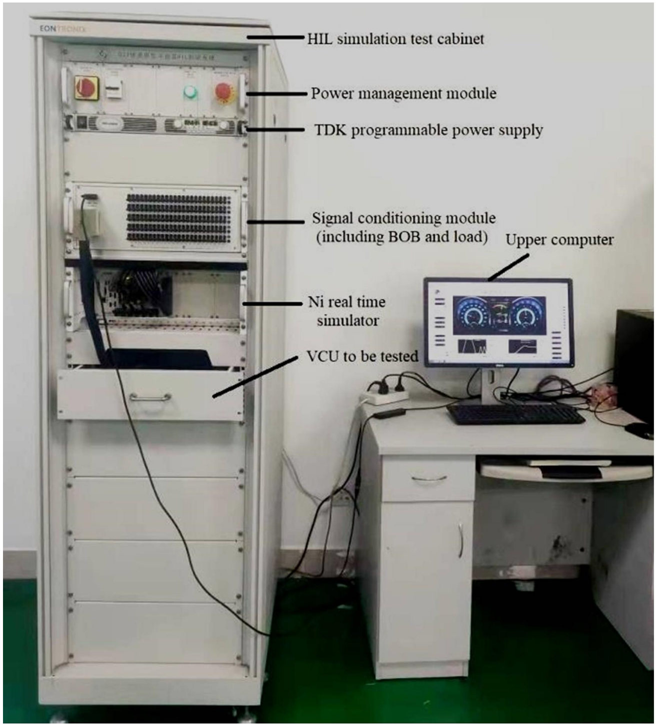

Fig. 7. Hardware-in-the-loop test platform

Fig.8 shows the operational status according to the curve obtained from the test under the UDDS operational status. The curve shows that the power system model, the fuzzy energy management strategy and other models meet the working conditions requirements.

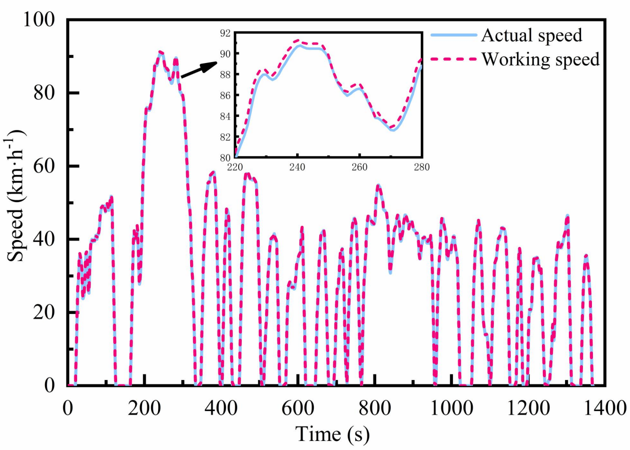

Fig. 8. Working condition following curve

Under the fuzzy control strategy, the output power distribution curve between the power battery and the energy storage flywheel in the hybrid energy storage system is shown in Fig.9, and the *SOE* curve of the energy storage flywheel under multiple UDDS (Driving mileage is about 35.97 km) is shown in Fig.10. It can be seen from Fig.9 that the energy storage flywheel system gives full play to its role of "peak load shifting" and provides peak power under heavy load discharge conditions, thereby significantly reducing the output power of the lithium battery. In braking or deceleration conditions as much as possible to recover braking energy, reducing lithium battery frequent times of significant current absorption. In combination with Fig.9, we can see that the additional power of the flywheel energy storage system is timely, which can better prepare for the next power surge. We can also see in Fig.10 that the flywheel speed can still be maintained above the minimum speed, and the system has operated in the high efficiency range.

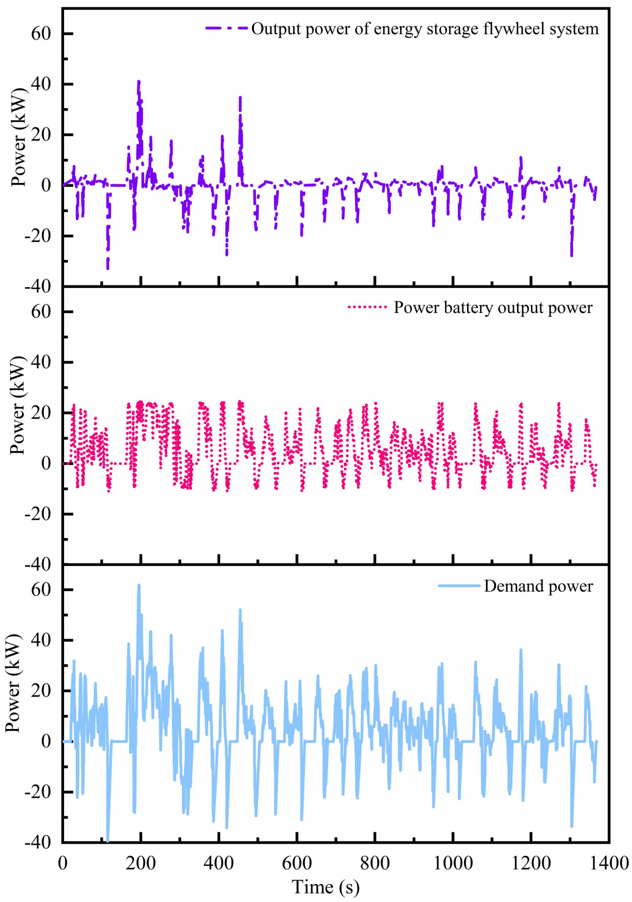

Fig. 9. Output power distribution curve

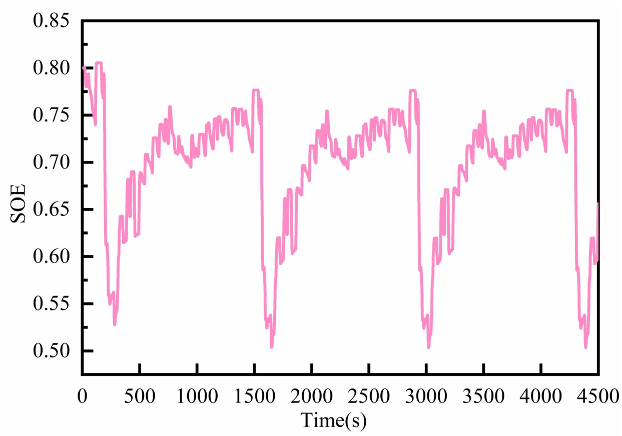

Fig. 10. *SOE* curves under multiple UDDS conditions

We can see in Fig.11 that in a single UDDS cycle condition, the battery strength of the hybrid energy storage system decreases slowly relative to the single battery system. The *SOC* of the battery goes from 91.69% to 91.84% when the energy status of the flywheel is maintained, and the energy consumption is reduced by 0.16%. We noted that to avoid the problem of battery power consumption reduction caused by the energy consumption of the energy storage flywheel, it is often impossible for the flywheel to alleviate the high-power and large-current impact in time for subsequent operating conditions. The battery must still charge the flywheel for storing energy. Currently, battery energy consumption does not necessarily decline. As a result, to evaluate the overall battery *SOC*, the fuzzy energy management strategy keeps the *SOE* flywheel in a state.

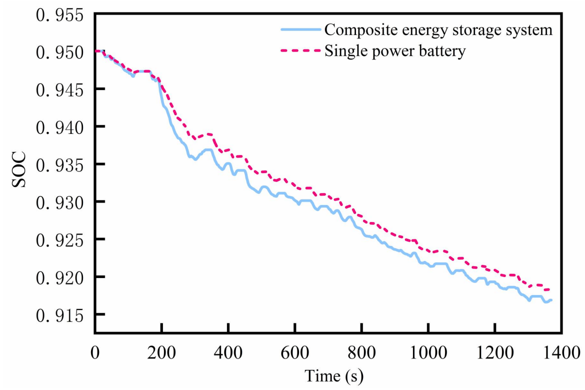

Fig. 11. Comparison curve of power battery *SOC* drop

The comparative results of the total system power consumption test are presented in Table VII. The overall energy consumption of the hybrid energy storage system compared to the single cell system in UDDS, HWFET, CLTC-P three requirements are reduced, followed by 1.67%, 1.05% and 8.11%. As can be seen from Table VII: in three kinds of comprehensive conditions, lithium battery/energy storage flywheel scheme in improving the economic level of energy storage system shows the superiority of single energy. On the one hand, the flywheel has the characteristics of a high efficiency of operation, and the lifetime is not limited by the number of cycles. Thereby relieving the frequent need for high-power battery conversion. On the other hand, because the flywheel has a certain potential for braking energy recovery, the reasonable energy distribution between the flywheel and the battery makes the energy storage system more energy-efficient. But there are also differences in energy consumption according to working conditions. The deceleration process of the HWFET expressway is lower, and the energy that the flywheel can collect is limited. Consequently, lithium batteries often need to discharge at high peak power, and the effect of reducing energy consumption is not apparent. In typical urban road conditions, even if the recovery energy of the flywheel increases, the conversion of mechanical and electrical energy into frequency will also lead to a certain loss of energy. In addition, the energy consumption in the CLTC-P state is substantially reduced at the same time, which is achieved by sacrificing part of the energy retention of the flywheel.

TABLE VII.
COMPARISON CURVE OF TOTAL VEHICLE ENERGY CONSUMPTION CURVE

System Energy Consumption (kW ·h)			
cycle condition	UDDS	HWFET	CLTC-P
single battery energy	2.2012	3.4598	2.8861
battery-flywheel composite energy	2.1645	3.4236	2.6519
Maximum peak current reduction(%)	70.44	66.95	48.91

Fig.12 to 13 show the battery outlet current and efficiency curves of the electric vehicle, electric vehicle and hybrid energy storage system. We can see from the curve that the positive peak current of the lithium battery in the single energy system is 274.09 A, the negative peak current is 105.58 A, and the discharge rate exceeds 1C. The vehicle equipped with an energy storage flywheel system under fuzzy control can control the battery charging and discharging current at [-30, 85] A, and the maximum reduction can reach 70.44%, which effectively avoids the impact of peak current on the battery and prolongs the battery life. We can see from Fig.13 that the hybrid energy storage system can improve the efficiency distribution of the lithium battery pack as a whole compared with the single battery system (up to over 85%). This results in a reduction in the combined effect of charge and discharge current and output power. Meanwhile, the efficiency of power battery packs is negatively correlated with the energy consumption of vehicles, and the improvement of the efficiency of power battery packs has a certain inhibitory effect on the energy consumption of vehicles.

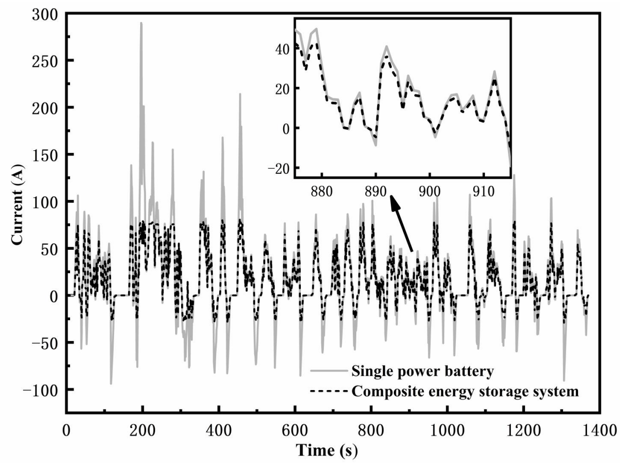

Fig. 12. Output current curve of power battery

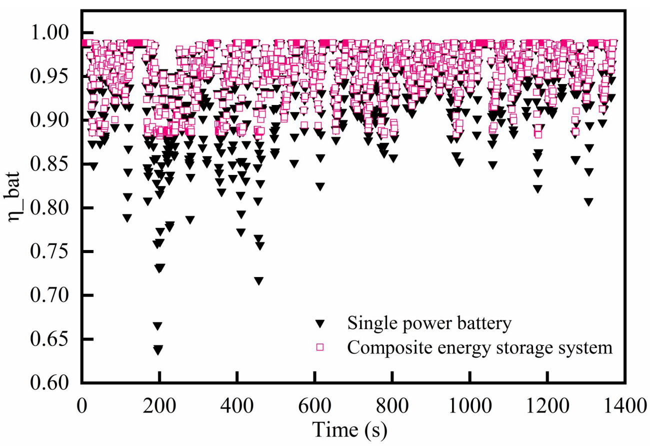

Fig. 13. Efficiency curve of battery pack

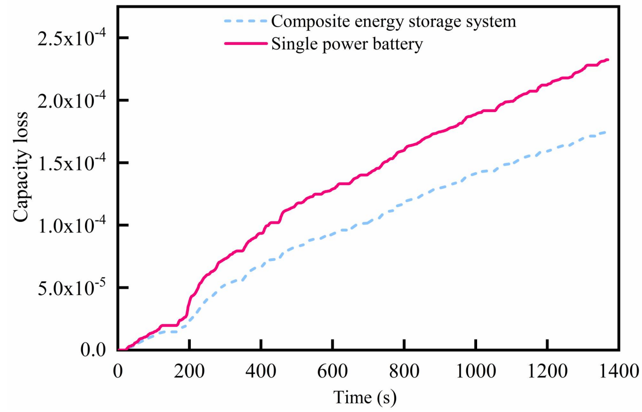

Fig. 14. Lithium battery capacity fading curve

The degree of attenuation of battery capacity under typical urban road conditions on both models is illustrated in Fig.14. The graph shows that the proposed power allocation methodology can reduce the capacity loss of lithium batteries under dynamic conditions. It is primarily a matter of reducing the high frequency output power of the lithium battery, which results in a decrease in the current and capacity that circulate in the lithium battery. And the increase in surface temperature of the lithium battery tends to be steady. That provides better working environment for the battery, which reduces the capacity consumption of the lithium battery.

To further investigate the durability of lithium batteries, the test results of both models under UDDS, HWFET and CLTC-P cycle conditions are compared and analyzed. Specific information is presented in Table VIII.

TABLE VIII
COMPARISON RESULTS UNDER DIFFERENT WORKING CONDITIONS

Battery Charge and Discharge Peak Current (A)			
cycle condition	UDDS	HWFET	CLTC-P
single battery energy	274/-106	195/-118	313/-137
battery-flywheel composite energy	81/-30	82/-39	223/-70
Maximum peak current reduction (%)	70.44	66.95	48.91
Capacity attenuation of battery (10^-3)			
single battery energy	5.3	3.4	5.0
battery-flywheel composite energy	4.1	3.2	4.0
Capacity attenuation reduction (%)	22.64	5.88	20

The deteriorating performance of lithium batteries is the result of an accumulation of long-term alternative constraints. Full life cycle simulation of lithium batteries is difficult. As a result, we tested the full discharge cycle of a single lithium battery (*SOC* 0.95-0.2) to better estimate the decrease in lithium battery capacity. As shown in Table VIII, the flywheel hybrid energy storage system is capable of controlling the maximum discharge rate of the lithium battery to the nearest 1.12C. The decrease in lithium battery capacity can therefore be considerably reduced. Of these, the CLTC-P mode covers suburban and high-speed conditions, and the vehicle's speed varies greatly. In addition, due to the large power range of the motor, less energy storage of the flywheel itself, and inability to predict future working conditions, the flywheel has been consumed in the subsequent high-power auxiliary energy. Thus, the current efficiency of releases is not as good as HWFET and UDDS, and the current reduction is not as important as these two. In the actual operation of the vehicle, due to the different working conditions, specific models and scenarios should be taken into consideration.

VII. CONCLUSION

Taking the composite energy storage system composed of lithium battery/energy storage flywheel system as the research object, based on a selected model, the parameters of the energy storage flywheel system are designed, and the forward simulation model of lithium battery-flywheel composite energy storage electric vehicle is established. The real time and accuracy of the control strategy are verified on the hardware-in-the-loop test platform. Comparing the results of the tests with the pure electric vehicle, the main conclusions of the research are as follows:

1) The proposed battery-energy storage flywheel, new composite energy system can make the lithium battery run efficiently, stably, and for a long time, effectively reducing the number of high-current operations of the lithium battery and significantly improving its durability of the lithium battery.

2) The fuzzy control energy management strategy can give full play to the specific high power characteristics and long lifetime of the flywheel energy storage system. Compared with the single battery system vehicle, it reduces the battery power consumption of the composite energy storage system to a certain extent, improves the efficiency of the energy power system, and improves the economy of the vehicle.

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