Multi Objective Fuzzy Energy Management Strategy of Hybrid Electric Vehicles

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Abstract:
To address the shortcomings of the current lithium battery-supercapacitor composite energy electric vehicle in a single fuzzy control measure, a multi-fuzzy joint control energy management measure is put forward and designed. Combining with the actual parameters of the experimental rig, the whole system model is constructed in MATLAB context, and the fuzzy square wave regulation control strategy, the power distribution factor fuzzy control strategy and the improved fuzzy square wave regulation based joint control strategy are compared and analyzed by ECE and UDDS operating conditions, and finally the fuzzy square wave regulation based joint control strategy with the best effect is selected to be embedded in the experimental rig for verification. According to the experimental simulation outcomes, the control strategy herein can achieve smooth control of lithium battery charging and discharging current within 1C under different SOC in both test conditions, so it is profit to the safe operation of lithium battery pack and effectively reduce the driving cost of the whole vehicle control system.

Keywords: electric hybrid electric vehicle, energy management strategy, multi-fuzzy control, fuzzy square wave regulation

INTRODUCTION

As energy and environmental problems become increasingly serious, major domestic and foreign automobile manufacturers and R&D institutions have accelerated their research on clean energy vehicles. Pure electric vehicles have the merits of simple framework, clean and environmental protection, so its are vigorously promoted in the automotive field. At present, two important factors that hinder the development of electric vehicles are range and battery cycle life. To address these shortcomings, a composite energy system of power battery, supercapacitor and bi-directional DC/DC converter is proposed. Supercapacitor has the advantages of long cycle life and high power density, and lithium batteries have the advantage of high energy density, so it is greatly significant to increase the cycle life of power battery, and can improve the recovery of energy generated during the braking process of the onboard system. Therefore, this method can improve the overall operating efficiency and the driving scope [1-4].

The current common energy administration measures for hybrid power system development are classified into strategies on basis of simplified models or logic rules, strategies based on intelligent control methods such as fuzzy control and predictive control, and strategies on basis of dynamic improvement approaches including dynamic programming and the minimum value theory. Among the above methods intelligent methods based on fuzzy control are widely used for their advantages such as high adaptability and obvious control effects [5-7]. Considering that a single control method cannot better adapt to the complex working conditions of the vehicle, the combination of multiple controllers to adjust multiple parameters can improve the intelligence of the controller and can better adapt to the complex system. Among them, a fuzzy controller on basis of particle swarm optimization was put forward in the literature [8] to solve the power system energy distribution problem, but it can only be optimized by solving offline and cannot update the affiliation function online, which is difficult to cope with the complex changing operating conditions; adaptive PI fuzzy control method was proposed in the literature [9], using super capacitors to play the role of peak cut in the literature [10], adaptive PI fuzzy control is put forward to play the role of "peak and valley reduction" by using supercapacitor, but the control process relies heavily on expert experience and is not universal; in the literature [11], a power distribution factor control algorithm based on optimal fuzzy rules is proposed, which achieves a better control effect, but the optimization process relies too much on expert experience and the single fuzzy control has the problem of adaptability.

The integration of multiple control methods can enhance the adaptability and stability of the controller [12-18], but it also makes the control strategy more complex. Therefore, the member algorithm of the combined control should have the characteristics of simple structure and ideal control effect. After analysis, the joint control strategy based on fuzzy square wave modulation is proposed herein to achieve the efficient energy allocation for the composite power mechanism with a simple and intelligent algorithm. A fuzzy torque control measure aims at optimizing the energy administration measure of hybrid electric vehicle. A mathematical model of the hybrid electric driving mechanism is set up based on MATLAB/simulink, and based on this model, a multi-variable fuzzy control algorithm is further presented to improve the fuzzy rules. Through simulation testing and on-site experiments, it displays that the fuzzy control algorithm can achieve good effect of hybrid electric vehicle, the system efficiency after optimization is increased by 3.4%.

SYSTEM TOPOLOGY AND PARAMETER SELECTION

There are many kinds of topologies for EV complex energy power system [19-24], among which the topology of series connection of supercapacitor group and bidirectional DC/DC converter, then shunt connection with the battery pack and then connected to the power bus has the merits of simple framework and convenient control, and is widely used in theoretical research. Therefore, this topology is used herein, according to Figure 1.

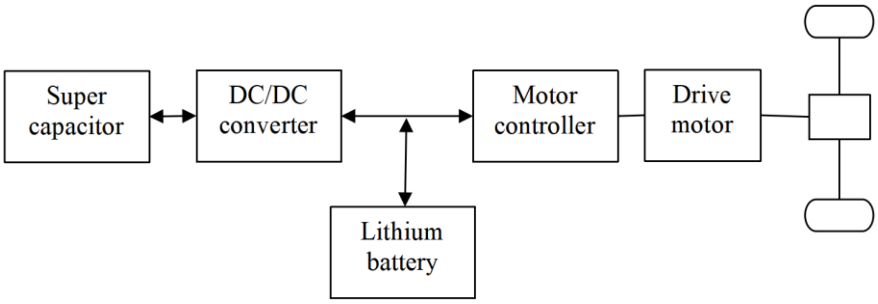

Figure 1. Power system topology

A small electric vehicle is adopted as a prototype to design the experimental rig, and the parameters of the whole vehicle are designed as follow: The windward area is 1.51 A/m^2 ;The wind resistance parameter C_D is 0.3;The road rolling resistance parameter ρ is 0.009;The transmission performance η_T is 0.95;The transmission ratio i_0 is 4;The wheel radius R is0.282m;The rotational inertia coefficient σ is 1.1;The maximum acceleration of the vehicle startup is 1.48 m/s^2 ;The maximum speed during vehicle operationis 85 km/h.

According to the vehicle coefficients, the maximum drive capacity of the PEV can be calculated as 12.19kW, the maximum motor torque as 58.2Nm, and the maximum motor speed as 3577.6r/min. The selected drive motor and Bench parameters are: the battery system consists of 22 lithium batteries with rated capacity of 40Ah and rated voltage of 70V;the super capacitor consists of 2 super capacitors with rated capacity of 165F and rated voltage of 48.6V and its voltage range is 28-48V; The rated (maximum) power is 7.5(15)kW, rated voltage is 70V, rated (maximum) torque is 35(70) Nm and rated (maximum) speed is 2000(4500) $r/\min$ in the permanent magnet synchronous motor system; The conversion rated power of the converter is 8kW, the input voltage range is 20-50V, the output voltage range is50-80V and the rated conversion efficiency is 95%.

The rated voltage and rated power of the motor show that the bus voltage level of DC system is 70 V and the maximum output current of the battery pack is 107 A. therefore, AVIC lithium battery 40ah lithium iron phosphate is chosen as the power battery. The nominal voltage Power battery is 3.4 V and the maximum discharge rate is 3C. It is composed of 22 monomers in series. The supercapacitor module is composed of two groups of 48.6 V/ 165F commercial Max well supercapacitor modules in parallel and 8 kW bidirectional DC/DC in series as an auxiliary energy source.

ENERGY MANAGEMENT CONTROLLER DESIGN

In the composite energy power system, the supercapacitor output power is mainly regulated by bi-directional DC/DC to make the lithium battery work in the appropriate output range [25-28]. Generally speaking, the charge/discharge multiplier and the working temperature of the power battery are the two major factors affecting the battery operation life, so the regulation principle of supercapacitor can be divided into two categories: (1) the high-frequency part of the energy demand change is borne by the supercapacitor; (2) supercapacitor offsets the high amplitude part of the demand power. Considering the communication delay and bi-directional DC/DC response time, there is a control real-time problem when supercapacitor takes up the high-frequency part of the demand power, so the regulation principle of supercapacitor taking up the high amplitude part of the demand power is used in this paper to control the lithium battery discharge multiplier within 1C (The lithium battery pack charge and discharge power ≤ 2500W, the following current multiplier will be described by the battery output power), reduce the loss on the internal resistance of the lithium battery and extend the pack life. Considering the adaptability problem of a single fuzzy controller, the research in this paper adopts a power distribution factor-based fuzzy control algorithm combined with a simple fuzzy square wave regulation control algorithm to realize the complementary advantages of the two control methods, and Figure 2 shows its specific structure.

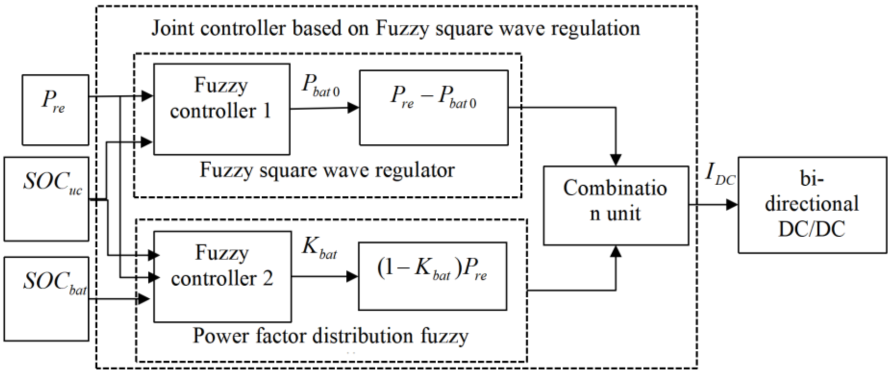

Figure 2. Framework diagram of joint controller based on Fuzzy square wave regulation

Fuzzy Square Wave Regulation Controller Design

The square wave regulation control follows the control principle of "peak-shaving and valley-filling" and can be set as follows:

When the demand power $P_{re} > 0$, the output power of lithium battery to a certain value P_{bat0} ,the output power of super capacitor can be obtained:

$$P_{uc} = P_{re} - P_{bat0} \tag{1}$$

Then the Li-ion battery output power can be modulated into a limiting square wave, which is referred to as square wave regulation control in this paper. However, when the system operates frequently at $P_{re} \pm \Delta = P_{bat0}$ (Δ is the allowed start power of bidirectional DC/DC), it will cause the supercapacitor output power P_{uc} to oscillate between charging and discharging, and the bidirectional DC/DC switches too frequently, shortening the service life. To settle this problem, the output power P_{bat0} of Li-ion battery is modified in a certain range according to the demanded power size, thus eliminating the oscillation of P_{uc} between ±Δ. At the same time, in order to reduce the start-up frequency of bidirectional DC/DC, the following restrictions need to be made according to the parameters of the experimental platform in this paper:

$$P_{uc} = \begin{cases} 0, |P_{re} - P_{bat}| < 600 \ \& 0 \le P_{re} \le 1300 \\ 0, P_{re} - P_{bat} \le 0 \ \& \mathrm{SOC_{uc}} \ge 1 \\ P_{re} - \mathrm{P_{bat}}, \mathrm{others} \end{cases} \tag{2}$$

In order to realize that P_{bat0} can be reasonably varied within a certain range, the fuzzy control method is chosen to regulate P_{bat0} in this paper, and this is called the fuzzy square wave regulation controller. The key parameters demand power P_{re} and supercapacitor SOC_{uc} are selected as the controller input, P_{bat0} is the controller output power of lithium battery and P_{re} is the demand power, supercapacitor SOC_{uc} and lithium battery output power P_{bat0} are divided into 7 subsets, 3 subsets and 7 subsets respectively on their theoretical domain, and 21 control rules are designed, and the affiliation function of each variable is shown in Figure 3 to Figure 6 ,Table. 1 displays the whole fuzzy control rules, and Figure 7 shows the surface schematic of the control rules. of fuzzy controller.

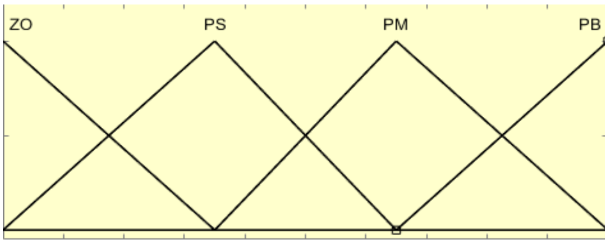

Figure 3. Membership function image of demand power

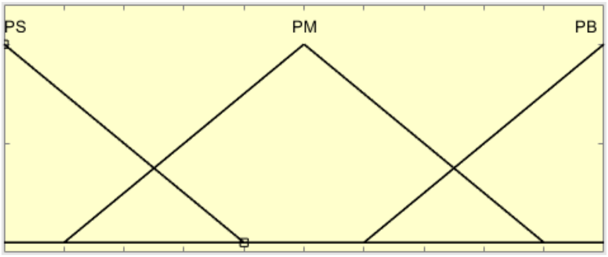

Figure 4. SOC membership function image of lithiumion battery

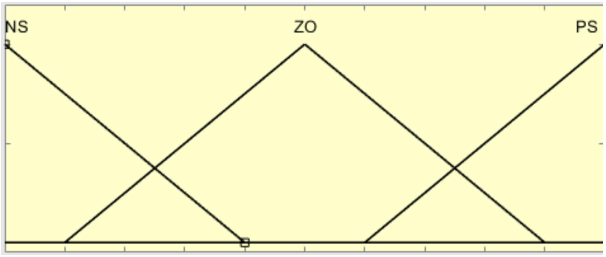

Figure 5. Supercapacitor SOC membership function image

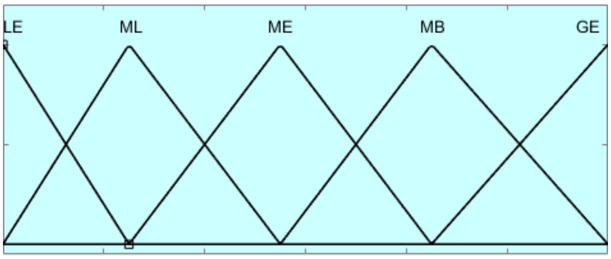

Figure 6. Membership function image of distribution coefficient

Table 1. Fuzzy control rules

SOC_{uc}	P_{req}	SOC_{bat}		
		PS	PM	PB
NS	ZO	GE	GE	MB
	PS	GE	GE	MB
	PM	MB	MB	MB
	PB	MB	MB	ME
ZO	ZO	GE	MB	ME
	PS	MB	MB	ME
	PM	MB	MB	ME
	PB	MB	ME	ME
PS	ZO	ME	ME	ML
	PS	ME	ME	ML
	PM	ME	ME	LE
	PB	ML	LE	LE

Power Allocation Factor Fuzzy Controller Design

Power allocation factor fuzzy control is a common control approach in the composite energy system. K_{bat} is the power allocation factor of the lithium battery, K_{uc} is the power allocation factor of the supercapacitor.The output power P_{bat} of the lithium battery pack and the power P_{uc} of the supercapacitor during the vehicle movement meet the following association in the formula (3).

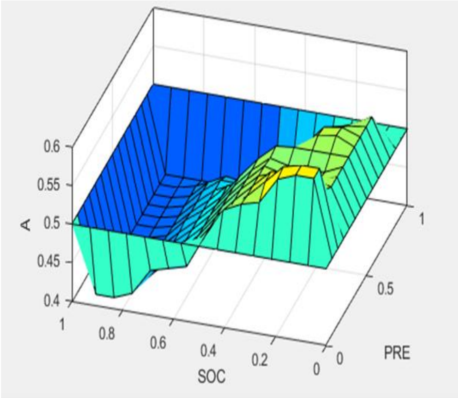

Figure 7. Surface rule diagram of square wave regulation fuzzy controller

$$\begin{cases} P_{req} = P_{bat} + P_{uc} \\ K_{bat} = P_{bat}/P_{req} \\ K_{uc} = P_{uc}/P_{req} \\ P_{uc} = P_{req} - P_{bat} = (1-K_{bat})P_{req} \\ K_{bat} + K_{uc} = 1 \end{cases} \tag{3}$$

The load demand power P_{req} ,Li-ion battery pack SOC_{bat} and supercapacitor SOC_{uc} are three important influencing factors of the power allocation factor, so in this paper, P_{req}, SOC_{bat}, SOC_{uc} are regarded as the power allocation input of the system fuzzy controller, and the Li-ion battery power allocation factor K_{bat} is taken as the controller output. The P_{req}, SOC_{bat} and SOC_{uc} are divided into 7 subsets, 3 subsets, and 3 subsets on their theoretical domains, and the P_{req} output K_{bat} is divided into 7 subsets on its theoretical domain, and 63 control rules are set.

Fuzzy Square Wave Based Joint Controller Design

From Figure 4 and Figure 6, it can be found that the two fuzzy control strategies have completely different characteristics: (1) The power distribution factor fuzzy control strategy has a large change in the distribution factor when the power changes, and can better suppress the rising rate of Li-ion battery power under the working condition of rapid power change, but lacks the supercapacitor charging condition, which is not conducive to regulating the supercapacitor voltage. (2) The square wave regulation fuzzy control strategy basically maintains the battery output power in a stable interval under all working conditions, and has a better limiting ability. (3) The square wave regulation fuzzy control strategy basically maintains the battery output power in a stable interval with good limiting ability under all operating conditions, and the square wave regulation fuzzy control exists for super capacitor charging condition, which can regulate the super capacitor voltage and keep it in a good working voltage interval, but under the condition of fast changing demand power, it may cause the Li-ion battery output power to produce higher amplitude spikes due to the untimely response of bidirectional DC/DC.

For the topology of supercapacitor and bi-directional DC/DC, there is only one control object supercapacitor, i.e., the controller has only one output, and reducing the output power of Li-ion battery is its core control idea within the range of supercapacitor voltage allowed. The joint controller designed in this paper adopts the simplest combination: merit output, and the one with the highest output power of supercapacitor at the current moment among the two sub-controllers is used as the output of the joint control control. The fuzzy square wave regulator output P_{bat0} and the power allocation factor fuzzy controller K_{bat} are processed as follows:

$$I_{DC}=\begin{cases}\max\left(\frac{P_{re}-P_{bat0}}{U_{Li}},\frac{(1-K_{bat}).P_{re}}{U_{Li}}\right),P_{re}>600\\ \frac{P_{re}-P_{bat0}}{U_{uc}},P_{re}-P_{bat0}\leq -600\\ 0,P_{re}-P_{bat0}\leq 0\ \&SOC_{uc}\geq 1\\ 0,\text{others}\end{cases} \tag{4}$$

In which: I_{DC} means the given current of bidirectional DC; U_{Li} refers to the battery pack voltage; U_{uc} stands for the voltage of supercapacitor terminal.

ANALYSIS OF SIMULATION AND BENCH EXPERIMENT RESULTS

System Modeling

Combined with the actual parameters of the experimental rig in Section 1, the Simulink simulation environment under MATLAB is used to build the system model in this paper [29-30]. The load model consists of the actual load data of the experimental bench drive motor (bus voltage and current, motor torque and speed); the ideal transformer with an efficiency of 95% and a variable proportion of the quotient of the bus voltage and the supercapacitor terminal voltage is adopted as the bidirectional DC/DC model; the Rint model of the lithium battery is used as the lithium battery model (the experimental battery pack in this paper uses laboratory constant temperature air conditioning and natural air cooling of the chassis, and the temperature varies within 30 ± 5 ℃ within the change, so the temperature can be ideally set as a non-influencing factor, do not establish a thermal model for the time being), the specific model as shown in equation (4) ~ equation (9).

$$SOC_{bat}=\frac{C_{max}-\int_0^t I_{bat}dt}{C_{max}} \tag{5}$$

$$U_{oc}=f_v(SOC_{bat}) \tag{6}$$

$$I=\frac{U_{oc}-\sqrt{U_{oc}^2-4R_0P}}{2R_0} \tag{7}$$

$$U=U_{oc}-I_{bat} \tag{8}$$

$$P=U_{oc} \tag{9}$$

$$R_0=f_R(SOC_{bat}) \tag{10}$$

In which: U_{OC} is equal to the open circuit voltage when the two terminal network of the energy storage circuit is open; $C_{\max}$ stands for the battery maximum capacity; $f_v(SOC_{bat})$ and $f_R(SOC_{bat})$ represent both polynomials fitted to the high order of the measured data in the laboratory experimental platform. The Rint model with linear power supply and supercapacitor internal resistance R1 in series is used as the supercapacitor model, and its specific model is shown in Eqs. (10) to (14).

$$SOC_{uc}=\frac{Q_{max}-\int_0^t I_{uc}dt}{Q_{max}} \tag{11}$$

$$U_{oc}=SOC_{uc}(U_{max}-U_{min})+U_{min} \tag{12}$$

$$U_{uc}=U_{oc}-I_{uc}R_1 \tag{13}$$

$$R_1=f(I_{uc}) \tag{14}$$

$$Q_{max}=\frac{C(U_{max}-U_{min})}{3600} \tag{15}$$

In which: $U_{\max}$ is the maximum working voltage of supercapacitor; $U_{\min}$ is the cutoff discharge voltage of supercapacitor; $f(I_{uc})$ is the polynomial of high order fitting of the measured data in the laboratory experiment platform; $Q_{\max}$ is the maximum available capacity of supercapacitor; C stands for the capacitance of supercapacitor; U_{oc} represents the open circuit voltage during the supercapacitor group operation; U_{uc} means the terminal voltage of supercapacitor.

The controller fuzzy rules are generated in Matlab's fuzzy logic toolbox embedded in the Fuzzy module of the Simulink simulation environment, and combined with the design of the combination unit in Chapter 2, the energy management controller is composed. Figure 8 shows the simulation system.

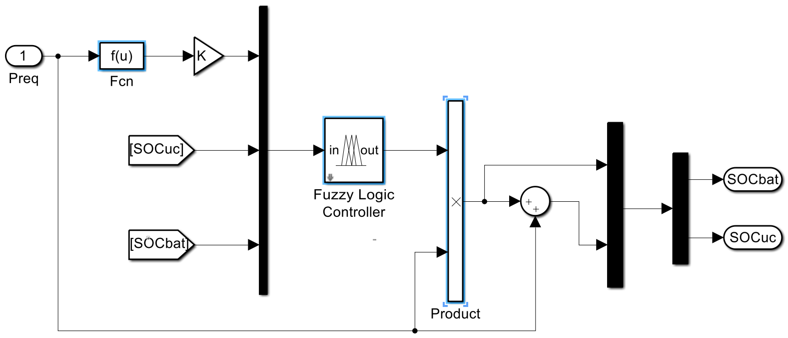

Figure 8. Fuzzy control simulation model

Controller Power Distribution Performance Comparison Chart

Among the three control strategies, the fuzzy square wave control lacks the input variable of lithium battery SOC, so the initial value of lithium battery SOC is set to 0.6 and supercapacitor SOC is set to 1 herein, and the performance performance of the three strategies is compared under this premise. Firstly, the performance is compared under 5 ECE cycles with a simulation time of 985s and a step size of 0.01s. Figure 9 to Figure 11 show the simulation outcomes.

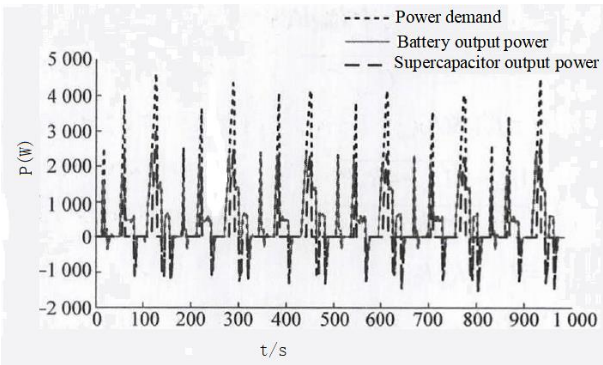

Figure 9. Fuzzy square wave regulation control under ECE condition

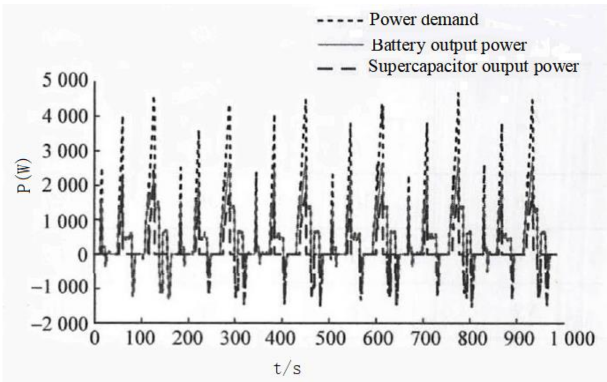

Figure 10. Fuzzy control of power distribution factor under ECE condition

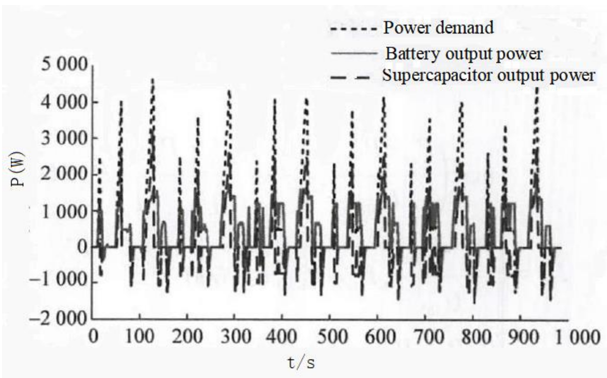

Figure 11. Joint control based on Fuzzy square wave regulation under ECE condition

To further compare the performance differences of the three controller strategies, simulation analysis was performed using more complex UDDS conditions, and Figure 12 to Figure 14 show the specific outcomes.

The limit situation of UDDS condition appears between simulation time 150-250s, the demand power amplitude change rate is larger in this interval, the fuzzy square wave regulation control strategy completely controls the battery pack output power this interval below 2000W, which is in favor of reducing the battery decay; the output power of Li-ion battery under power allocation factor fuzzy control appears greater than 3000W in this interval For the joint control based on fuzzy square wave regulation in the whole UDDS working condition, the output power of Li-ion battery is basically kept around 2000W and the energy is completely absorbed back by the super This not only maintains the supercapacitor in a better output state and keeps the Li-ion battery in a relatively stable state, but also greatly reduces the time-ampere accumulation of the battery, thus reducing the battery degradation.

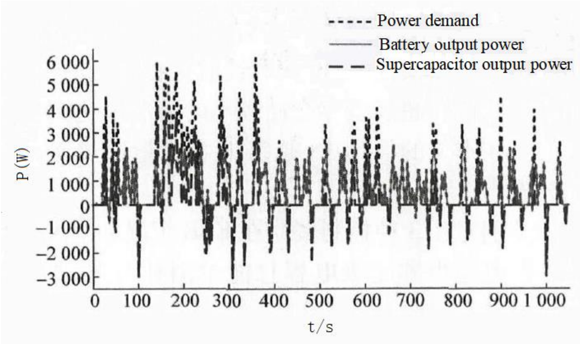

Figure 12. Fuzzy square wave regulation control under UDDS working condition

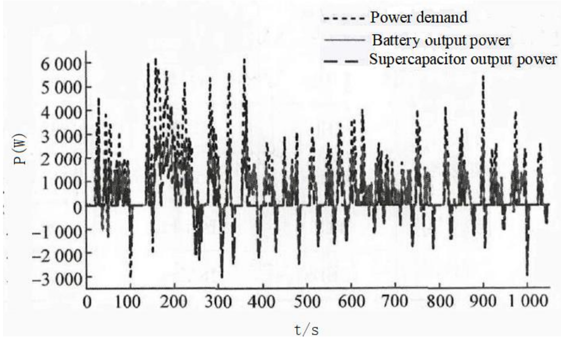

Figure 13. Fuzzy control of power distribution factor under UDDS working condition

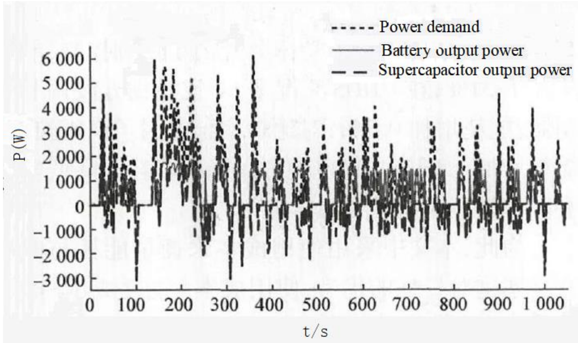

Figure 14. Joint control based on Fuzzy square wave regulation under UDDS working condition

In addition, the joint control strategy based on fuzzy square wave regulation can automatically adjust the maximum output power of Li-ion battery according to the SOC of Li-ion battery. The comparative analysis of the control effect when the SOC values range from 0.3 to 0.6, taking UDDS working condition as an example, Figure 15 and Figure 16 show the battery output power and the supercapacitor output power under different SOC, Figure 17 displays the SOC change curve of supercapacitor.

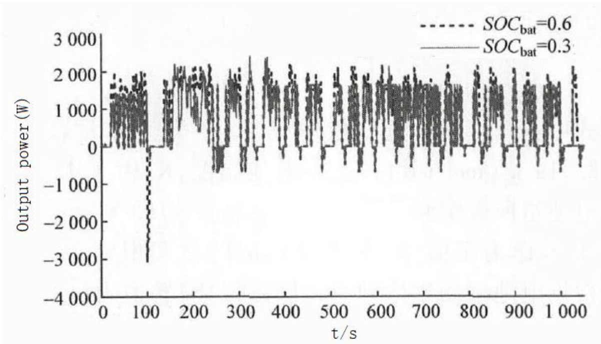

Figure 15. Comparison of lithium battery output power under different SOC

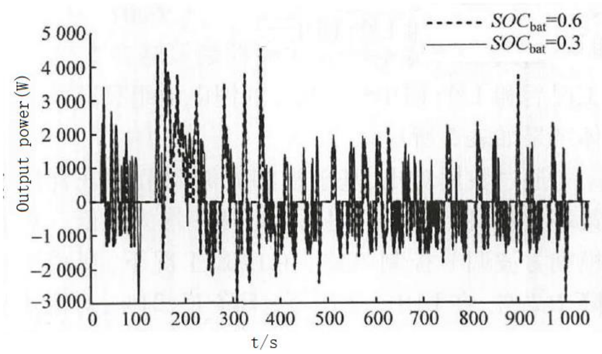

Figure 16. Comparison of supercapacitor output power under different SOC

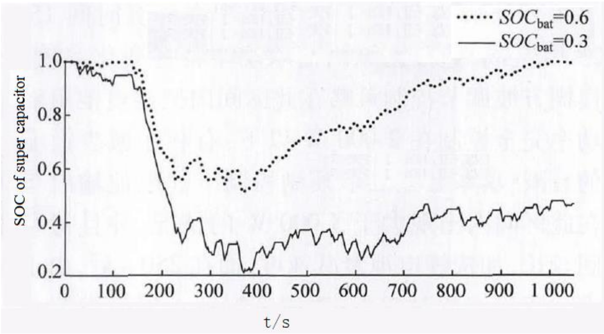

Figure 17. Comparison of supercapacitor SOC changes with different lithium battery SOC

When the lithium battery SOC of PEV decreases, Figure. 15 and Figure. 16 fully reflect that the joint control strategy based on fuzzy square wave regulation will further limit the output power of lithium battery, increase the output power of super capacitor, reduce the Joule heat generated by the increase of internal resistance in case of low SOC of Li-ion battery, and facilitate battery thermal management system to control the battery temperature, make the battery work in the moderate temperature condition and reduce the rate of battery decay.

Comparison of the Decay Rate of Li-ion Battery under Different Control Strategies

To assess the efficiency of the three control strategies more scientifically and finely, the battery decay rate is introduced as a comparative index in this paper (only battery decay is considered, the decay rate of supercapacitor is very small and is not considered), which is expressed by the reduction of SOH, denoted as Q_{loss}. by citing the Arrhenius model identified in the literature [11] as the decay model of lithium iron phosphate battery, the specific model is shown in equation (15).

$$Q_{loss} = 0.0032e^{-(\frac{15162-1516C\_Rate}{RT_{bat}})}A_h^{0.824} \tag{15}$$

Where:C_Rate is the battery charge/discharge multiplier; R means the gas constant, 8.314J/(mol-K); RT_{bat} stands for the battery temperature, K. Since the experimental conditions of the battery in this paper can be basically constant at 30±5°C, 30°C is taken as a constant value; Ah is the time-Ampere integral of the battery current, A-h. According to the theory of battery damage accumulation, equation (15) can be converted to

$$Q_{loss} = \sum \Delta Q_{loss} = \sum 0.0032\, e^{-\left(\frac{15162-1516C_{Rate}}{RT_{bat}}\right)}(\frac{I_{bat}\Delta t}{3600})^{0.824} \tag{16}$$

The lithium battery pack decay rates after 5 ECE conditions and 1 UDDS condition are calculated by equation (16) for the three control strategies. Table 2 shows the specific outcomes. By comparing the data, the joint control strategy based on fuzzy square wave regulation has the lowest lithium battery decay rate under both operating conditions. Comparing with the fuzzy square wave regulation control strategy, the decay rate decreases by 2.29% under ECE condition and 15.21% under UDDS condition; comparing with the power allocation factor fuzzy control strategy, the decay rate decreases by 5.4% under ECE condition and 16.58% under UDDS condition. It can be seen that the joint control based on fuzzy square wave regulation combines the advantages of each combination member and can better improve the control performance.

Table 2. Lithium battery decay rate under different control strategy

Control strategy	Working condition	battery decay rate / %
Fuzzy square wave regulation control	ECE	6.985×10^{-5}
	UDDS	10.461×10^{-5}
Power distribution factor fuzzy control	ECE	7.214×10^{-5}
	UDDS	10.332×10^{-5}
Combined fuzzy control based on square wave regulation	ECE	6.827×10^{-5}
	UDDS	8.862×10^{-5}

Comparison of Energy Consumption and Usage Cost

Considering the performance of bidirectional DC/DC (the efficiency value is 0.95 in this paper), if the supercapacitor often needs to be replenished by the lithium battery, there will be high energy loss and reduce the range of the car, so the control strategy must ensure that the control purpose is achieved with less energy consumption of the supercapacitor. In the design of this paper, the supercapacitor is charged by braking back as much as possible.

The total energy consumption of Li-ion battery pack and supercapacitor under ECE and UDDS operating conditions are compared among the three control strategies, according t0 Table 3.

Table 3. Energy consumption of the system

Control strategy	Working condition	Energy consumption / Wh	Energy consumption cost / yuan
Fuzzy square wave regulation control	ECE	152.25	0.0982
	UDDS	249.32	0.1612
Power distribution factor fuzzy control	ECE	152.57	0.0985
	UDDS	250.72	0.1615
Combined fuzzy control based on square wave regulation	ECE	154.14	0.0992
	UDDS	253.24	0.1628

Analyzing the experimental results, it can be found that the joint control strategy based on fuzzy square wave regulation has higher energy consumption than the other two control strategies in both operating conditions. In the ECE operating condition, the energy consumption increases by 1.52% compared to the fuzzy square wave regulation controller, and by 1.31% compared to the power allocation factor based on fuzzy control; in the UDDS operating condition, the energy consumption increases by 0.7% compared to the fuzzy square wave regulation controller, and by 1.03% compared to the power allocation factor fuzzy control. In the UDDS condition, the energy consumption increases by 0.7% compared to the fuzzy power allocation factor control and by 1.03% compared to the fuzzy power allocation factor control. This also verifies that reducing energy consumption and reducing battery decay rate are conflicting goals.

For this reason, the use cost is used in this paper to measure the advantages and disadvantages of the pair of objectives of energy consumption and battery decay rate, use cost = energy cost + battery decay cost. In this paper, the cost of use of three control strategies under different working conditions is calculated with a 40A-h lithium iron phosphate battery with a unit price of 340 yuan/battery, a market electricity cost of 0.58 yuan/(kWh) and a charging efficiency of 0.9, as shown in Table 4. Through data analysis, the joint control strategy based on fuzzy square wave regulation has the lowest usage cost under both working conditions. Comparing with the fuzzy square wave regulation control, the usage cost is basically the same in ECE operating condition and decreases by 1.92% in UDDS operating condition; comparing with the power distribution factor fuzzy control strategy, the usage cost decreases by 0.38% in ECE operating condition and decreases by 2.15% in UDDS operating condition.

Through the above series of comparisons, the joint control strategy based on fuzzy square wave regulation has better control performance compared to the single fuzzy control strategy and achieves the design objective.

Table 4. Use cost of the system

Control strategy	Working condition	Battery cost / yuan	Use cost / yuan
Fuzzy square wave regulation control	ECE	0.02614	0.1243
	UDDS	0.03906	0.1997
Power distribution factor fuzzy control	ECE	0.02689	0.1253
	UDDS	0.03864	0.2012
Combined fuzzy control based on square wave regulation	ECE	0.02556	0.1247
	UDDS	0.03315	0.1957

CONCLUSION

Through simulation comparison, the joint control strategy based on fuzzy square wave regulation with more obvious control effect is successfully embedded into the actual experimental rig in this paper, and a better control effect is obtained, and a better balance is found between energy loss and battery decay rate, which reduces the system usage cost and achieves the desired effect of the design. However, because the communication delay of the system and the actual model of bidirectional DC/DC are not considered in the simulation model, the actual experiment does not match the simulation results. Further research will focus on the system response time and simulation model optimization in the future.

ACKNOWLEDGEMENTS

The research was supported by Henan provincial key R&D and promotion special project (232102240062; 222102210024); Key scientific research projects of colleges and universities in Henan Province (22A460013; 22B413004).

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