Power Distribution Strategy for Electric Vehicle Hybrid Power System

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Abstract. Aiming at the load power fluctuates greatly during the driving process of the electric vehicles, a large load current is required, it is difficult to meet the load demand by the lithium battery alone, so the super-capacitor is introduced. In order to give full play to advantages of both, and to reduce the transient high current fluctuation of lithium battery, a power allocation strategy based on adaptive frequency is proposed. The power supply current, super-capacitor and bus voltage are controlled with double closed-loop control, and the filter time constant is dynamically adjusted according to the state of charge and load requirements of the super-capacitor, the battery bears the low-frequency component of the load current, and the super-capacitor provides the residual component, therefore, the charge and discharge current of the battery can be reduced and reducing the large current fluctuation. The Matlab/Simulink the results show that the method fully utilizes the super-capacitor smooth load fluctuation, which effectively reduces the charge and discharge current of the lithium battery and reduces the fluctuation range, thus prolonging the service life.

Keywords: electric vehicles; lithium battery; Super-capacitor; hybrid power system; adaptation; power distribution.

1. Introduction

With the continuous improvement of people's living standards, automobiles have become an indispensable means of transportation in life. However, the energy crisis and environmental pollution caused by this problem have become increasingly serious. To this end, research on green and environmentally friendly electric vehicles has become a hot issue in the development of the automotive industry today.

Due to its high specific energy characteristics, lithium batteries are often used as the main power source for electric vehicles to meet the driving range of electric vehicles. However, in the process of sudden acceleration and deceleration of the vehicle, a large current supply is required when the load power changes greatly, while the lithium battery has a low instantaneous power capability, and the large current charge and discharge damages the service life of the lithium battery. The super-capacitor has high specific power characteristics, can quickly charge and discharge, provide instantaneous large current to reduce the large current charging of the lithium battery, so it can be used as an auxiliary power source, and a hybrid system with a lithium battery to compensate for the low power density and high current of the lithium battery. Problems such as insufficient power supply. In order to improve the power performance of electric vehicles, reduce the large current supply current of lithium batteries, and fully utilize the characteristics of high specific energy and high specific power through power distribution, thereby smoothing the instantaneous large current fluctuation of lithium battery and prolonging its service life. The earlier logic threshold control strategy is simple rule control, setting the logic gate value. When the power fluctuation is large, the power supply current cannot be adjusted in time to meet the load current requirement [1]. Professor Wang Qingnian and other fuzzy logic control the power distribution of the battery and super capacitor. The simulation results show that the fuzzy control is more robust and real-time than the logic threshold strategy [2-5]. Based on the fuzzy and fuzzy neural network power allocation strategy, the simulation results show that the battery discharge current is significantly reduced, the state of charge (SOC) is slowed down, and the driving range of the vehicle is improved. This strategy can better achieve power distribution [6]. Based on the traditional model predictive control theory, the controller predicts the total power distribution between the battery and the supercapacitor, optimizing the lithium battery energy storage, but involves a large number of complex mathematical calculations [7]. The literature [8-10] uses a nonlinear model predictive control system, and introduces a particle swarm algorithm to achieve global optimization. The simulation shows that the particle swarm optimization algorithm can improve the control ability of the model prediction, and the energy efficiency is improved by about 10%.

In this paper, the adaptive frequency strategy is adopted to realize the power distribution of lithium battery and super capacitor. Based on the double-closed loop voltage and current control of the two power sources and the bus voltage, the filter time constant is dynamically adjusted according to the super capacitor SOC and load requirements. Then, the duty ratio of the converter is controlled by the filter frequency to adjust the loop current, and the lithium battery provides a low component of the load demand, and the super capacitor provides a high frequency component, thereby reducing the large current charge and discharge of the lithium battery, reducing the fluctuation range thereof, and prolonging Service life.

2. Hybrid System Analysis and Mathematical Model

2.1 Hybrid Power System Structure

In this paper, the electric vehicle power system is a hybrid power system with lithium battery as the main power source and super capacitor as the auxiliary energy. The system structure diagram is shown in Figure 1. Both the lithium battery and the super capacitor are connected in parallel to the DC bus side through a bidirectional Buck-Boost converter. The DC/DC converter is a PWM-controlled IGBT that allows current to flow in both directions to ensure reverse flow of the electric motor during deceleration braking. Energy efficiency, electric drive uses a permanent magnet synchronous motor and is torque controlled by coupling to a DC bus inverter.

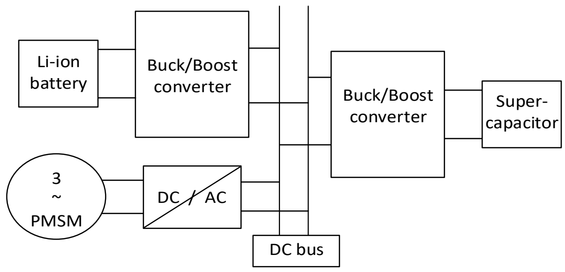


Figure 1. Hybrid system structure

2.2 Hybrid Power System Modeling and Problem Analysis

The motor driver draws the load current iL from the DC bus, and the two power supplies respectively supply currents i1 and i2 to the DC bus. The good dynamic performance of the motor drive depends on the constant DC link voltage, so the DC link voltage fluctuations should be minimized to ensure that current is transferred to the load. Based on the previous research, the power supply of the two power sources is controlled by changing the duty cycle of the converter. This indirect control method solves the bus voltage fluctuation problem and meets the performance requirements of the motor. The system works as shown in the figure. 2 is shown.

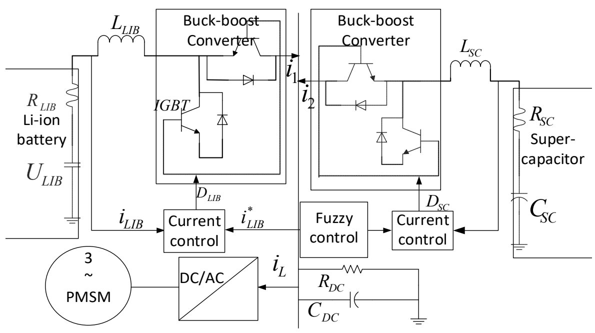


Figure 2. Hybrid system circuit diagram

Assuming that the switching frequency of the converter is much larger than the frequency bandwidth of the circuit, the converter operates in continuous conduction mode. The power supply circuit in Figure 2 can be expressed as its average model:

$$\begin{cases} U_{LIB} = R_{LIB} \cdot i_{LIB} + L_{LIB} \cdot \dfrac{di_{LIB}}{dt} + U_{DC} \cdot D_{LIB} \\ U_{SC} = R_{SC} \cdot i_{SC} + L_{SC} \cdot \dfrac{di_{SC}}{dt} + U_{DC} \cdot D_{SC} \\ i_{LIB} \cdot D_{LIB} + i_{SC} \cdot D_{SC} = C_{DC} \cdot \dfrac{dU_{DC}}{dt} + \dfrac{U_{DC}}{R_{DC}} + i_L \end{cases} \tag{1}$$

In the formula, C_{DC} and R_{DC} are DC bus capacitors and resistors respectively; R_{LIB} and U_{LIB} are lithium battery internal resistance and open circuit voltage respectively; C_{SC}, R_{SC} and U_{SC} are supercapacitor capacity, internal resistance and voltage respectively; D_{LIB} and D_{SC} are respectively lithium batteries, the duty cycle of the supercapacitor converter; L_{LIB} and L_{SC} are respectively lithium batteries and super capacitor inductors.

The classic cascade control structure can control the inductor current and the DC bus voltage. The DC bus voltage closed-loop bandwidth must be large enough to cover the entire frequency variation range of the load current. At this time, the bus current is equivalent to the load current. When the electric vehicle is in the process of rapid acceleration and deceleration, the load current is inevitably abrupt due to the large change of the load power demand, which causes the lithium battery to instantaneously charge and discharge the large current, thereby damaging its life. Since the lithium battery has a low specific power and cannot be quickly charged and discharged to meet the demand of the load current change, the power performance of the electric vehicle is degraded.

In view of the above problems, based on the previous research theories, this paper studies the hybrid system composed of lithium battery and super capacitor. The power performance of electric vehicles depends largely on the power flow of the hybrid power source. It is found that the dynamic adjustment of the load current frequency and thus the converter duty cycle to achieve a reasonable power distribution is an effective way to solve this problem.

3. Analysis based on Frequency'S Fuzzy Control Power Allocation Control Strategy

Figure 3 is a control block diagram of the proposed hybrid system energy management system. The control strategy consists of two parts, the bottom double closed loop control, that is, the current control of the two power supply loops; the upper layer is to realize the DC bus voltage adjustment based on the super capacitor voltage control. At this time, the frequency divider is added to realize the adaptive adjustment filter time constant. The divider consists of a pair of frequency adjustable low pass and high pass filters.

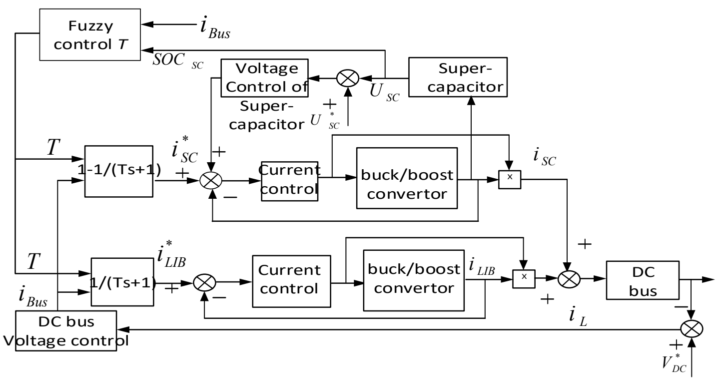


Figure 3. Hybrid power system control strategy

The low pass filter feeds the output i_{bus} of the DC bus voltage controller, i_{bus} is indicate the total power demand. The low frequency component of the total power demand is provided by the lithium battery current control loop, while the remaining high frequency portion is supplied by the super capacitor control loop. The smaller separation frequency 1/T ensures that the current of the lithium battery and the super capacitor is smoother, so the frequency nominal value is selected according to the maximum value of the lithium battery current, and the change of the separation frequency is based on the charging of the super capacitor at a given time. State and load current are adjusted in real time to achieve power distribution for both sources.

In view of the limited ability of the lithium battery to provide instantaneous large current, and the large current charge and discharge damage to the lithium battery, the adaptive control strategy requires that the super capacitor be used as an auxiliary when the vehicle is charging at a high current, by changing the load current frequency. Based on the super-capacitor characteristics, the super-capacitor voltage value is set to vary within the desired interval defined by U_{SCmin} and U_{SCmax}. In this way, ensure that the super-capacitor is used as an auxiliary energy source. The input of the adaptive control strategy is the super-capacitor SOC and the load current. Therefore, with the super-capacitor voltage control loop, the state of charge reference can be set in the interval [SOC_{SCmin} SOC_{SCmax}] to keep the super-capacitor running normally. An energy management system consisting of an adaptive frequency strategy and a super capacitor voltage control reduces the large current charging of the lithium battery, stabilizes the DC bus voltage fluctuation, and ensures good power performance of the vehicle.

3.1 Design of Current Control Loop

It is assumed that the DC bus voltage is adjusted at its set point, that is $U_{DC} = U_{DC}^*$, the transfer functions of the two current devices can be described by a system having a first-order linear invariance, respectively. Equation (1) represents the equation of the lithium battery and the super-capacitor. Transform:

$$\begin{cases} H_{LIB}(s) = \dfrac{i_{LIB}}{D_{LIB}} = \dfrac{-U_{DC}^*}{L_{LIB}\cdot s + R_{LIB}} \\ H_{SC}(s) = \dfrac{i_{SC}}{D_{SC}} = \dfrac{-U_{DC}^*}{L_{SC}\cdot s + R_{SC}} \end{cases} \tag{2}$$

Let the controller transfer function be expressed as:

$$H_{PI}(s) = K_P \cdot (1 + \frac{1}{T_i \cdot s}) \tag{3}$$

Where K_p is represent the controller gain and T_i integral time constant.

Set the closed-loop time constant to be set $T_i = \frac{T_f}{5}$, then the parameters of the two current control loop controllers are:

$$\begin{cases} K_{p1} = \dfrac{R_{LIB}}{U_{DC}} \cdot (10\xi^* - 1), \quad T_{i1} = \dfrac{L_{LIB}}{5R_{LIB}} \cdot (2\xi^* - 0.2) \\ K_{p2} = \dfrac{R_{SC}}{U_{DC}} \cdot (10\xi^* - 1), \quad T_{i2} = \dfrac{L_{SC}}{5R_{SC}} \cdot (2\xi^* - 0.2) \end{cases} \tag{4}$$

In the formula, T_{i1} and T_{i2} are the closed-loop time constants of the lithium battery and the supercapacitor circuit, respectively; and ξ^* is the desired damping coefficient.

3.2 DC Bus Voltage Control Design

Assuming that the currents i_{LIB} and i_{SC} change much faster than the DC bus voltage U_{DC}, the DC bus voltage control loop is placed at the bottom layer associated with the current control loop. Under this assumption, these currents will be treated as equivalent to their reference values i_{LIB}^*, i_{UC}^*. Ignoring the loss of the converter, the following relationship holds:

$$\begin{cases} D_{LIB} = \dfrac{V_{LIB}}{V_{DC}}, \quad i_1 = D_{LIB} \cdot i_{LIB} \\ D_{SC} = \dfrac{V_{SC}}{U_{DC}}, \quad i_2 = D_{SC} \cdot i_{SC} \end{cases} \tag{5}$$

The total current of the DC bus supplied by the two power supplies is:

$$i_{DC} = i_1 + i_2 = D_{LIB} \cdot i_{LIB} + D_{SC} \cdot i_{SC} \tag{6}$$

According to equation (5), it is known that the two currents are weighted by the duty cycle of their respective converters. In order to equalize their currents in a steady state, an equalization gain $\frac{U_{LIB}}{U_{SC}}$ is introduced to modify the reference value of the supercapacitor current, $i_{SC}^* = \frac{U_{LIB}}{U_{DC}} \cdot i_{SC}^0$, where i_{SC}^0 is the output of the high pass filter.

$$i_{DC} = D_{LIB} \cdot i_{LIB}^* + D_{SC} \cdot i_{SC}^* = \frac{U_{LIB}}{U_{SC}} \cdot i_{bus} \tag{7}$$

Where i_{bus} is the total current of the DC bus voltage loop.

The nonlinear description of the DC bus voltage dynamics is:

$$C_{DC} \frac{dU_{DC}}{dt} = \frac{U_{LIB}}{U_{DC}} \cdot i_{bus} - \frac{U_{DC}}{R_{DC}} - i_L \tag{8}$$

The steady state value of the DC bus voltage and the disturbance current is (U_{DC}^0, i_L^0), set to the ideal operating point of the UDC is $U_{DC}^* = U_{DC}^0$. Transfer function of DC bus voltage control:

$$\begin{aligned} \frac{\Delta U_{DC}(s)}{\Delta i_{bus}(s)} &= \frac{U_{LIB}}{C_{DC} U_{DC}^* \cdot s + 2U_{DC}^* / R_{DC} + i_L^0} \\ &= \frac{K_{DC}}{T_{DC} \cdot s + 1} \end{aligned} \tag{9}$$

Therefore, the gain K_{DC} and the time constant T_{DC} of the transfer function depend on the magnitude of the load current at the operating point, provided that the DC bus resistance R_{DC} typically has a large value. The ratio $\frac{K_{DC}}{T_{DC}} = \frac{U_{LIB}}{C_{DC} \cdot U_{DC}^*}$ is virtually constant for the operating point because the dynamics of the U_{LIB} and load currents are very slow. Therefore, a constant PI controller can be designed according to the required closed loop performance. For the first-order linearization function, the calculation is performed according to the same control design as the current controller. Therefore, the parameters of the DC bus voltage control are:

$$\begin{cases} K_P = \dfrac{1}{K_{DC}} \cdot \left(\dfrac{2\xi_{DC}^* T_{DC}}{T_{DC}^*} - 1\right) \\ T_i = 2\xi_{DC}^* T_{DC}^* - \dfrac{T_{DC}^{*2}}{T_{DC}} \end{cases} \tag{10}$$

Where, T_{DC}^* is the desired closed-loop time constant; ξ_{DC}^* is the desired closed-loop damping coefficient.

4. Frequency - based Energy Management System Design

4.1 Super-Capacitor Voltage Control Design

The design of super-capacitor voltage control loop ensures that the closed-loop dynamic change is slow. In this way, the mutation of super-capacitor current is allowed. To set K_{PSC} is the controller gain and T_{SC} is the controller time constant, ensuring zero steady state error. From this point of view, you can use the same control design steps as the current controller. Ultracapacitor voltage controller parameters:

$$\begin{cases} K_{PSC} = \dfrac{C_{SC}}{2\xi_{SC}^{*}T_{SC} - T_{SC}} \\ T_i = \dfrac{T_{SC}^{*2} \cdot K_{PSC}}{C_{SC}} \end{cases} \tag{11}$$

Where, CSC is super-capacitor capacity; T_{SC} is identifies the time constant; T_{SC}^{*} is expected closed-loop time constant and ξ_{SC}^{*} is damping coefficient.

4.2 Fuzzy Controller Design

In this paper, the fuzzy controller is a two-input single output, the load current i_L and the super-capacitor SOC_{SC} are the input of the fuzzy controller, and the time constant T of the shunt filter is the output.

Because the energy stored in the super-capacitor is:

$$E_{SC} = \int_0^t U_{SC} i_{sc} dt = \int_0^v C_{SC} U_{SC} dU_{SC} = \frac{1}{2} C_{SC} U_{SC}^2 \tag{12}$$

The SOC of its SOC state is:

$$SOC = \frac{0.5 C_{SC} U_{SC}^2}{0.5 C_{SC} U_{SC\max}^2} = \frac{U_{SC}^2}{U_{SC\max}^2} \tag{13}$$

In order to avoid over-charging and over-discharge of the super-capacitor, its fully charged voltage should be equivalent to the rated voltage, and the minimum discharge value should be about 30% of the total power, so as to ensure its use in a stable environment. Therefore, in this paper, the super-capacitor SOC is set as 0.25~0.95. When the SOC reaches the lowest point 0.25, the lithium battery will provide all the energy required by the load, while when the car accelerates rapidly SOC=0.95, the energy of the super-capacitor will be used first.

Set the fuzzy set of input iL as {VN, N, Z, P, VP}, respectively denoted as large negative value, negative value, zero, positive value and large positive value. The fuzzy set of super-capacitors is {VL, L, M, H, VH}; the output frequency division time constant is {VL, L, M, H, VH}. The Settings of each input and output variable are shown in figure 4-6:

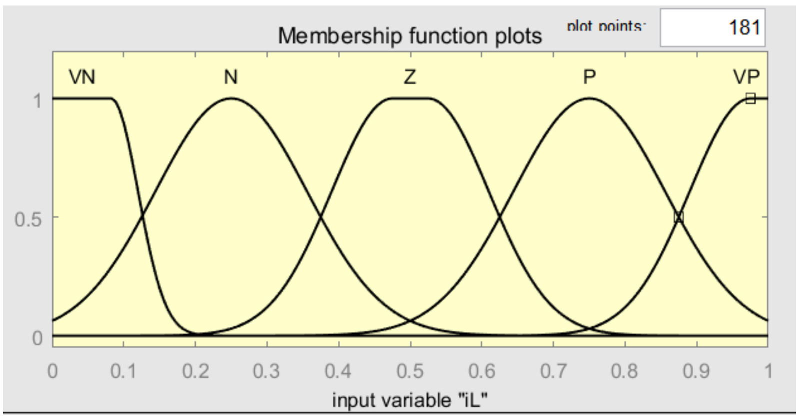


Figure 4. Membership function of load current

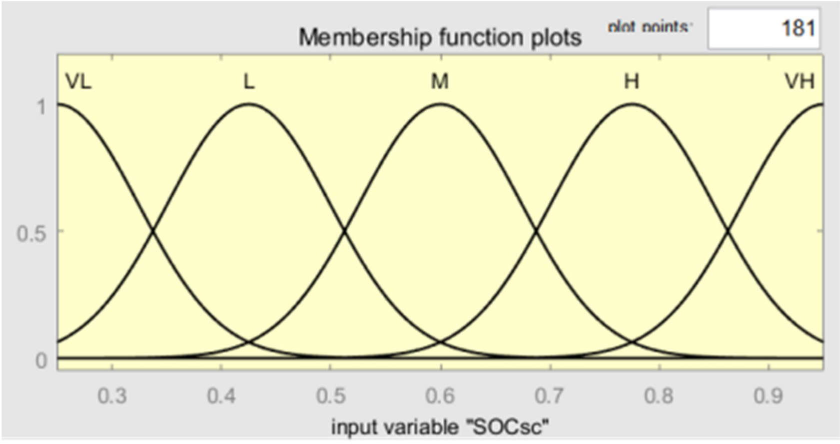


Figure 5. Membership function of super-capacitor SOC

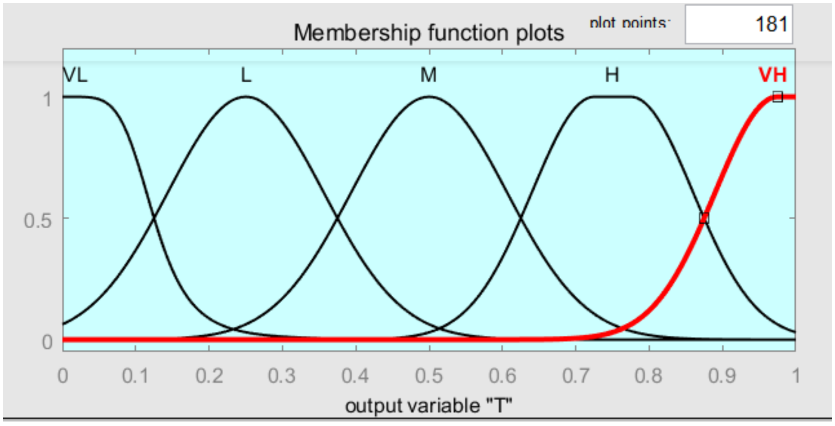


Figure 6. Membership function of filter shunt time constant

Electric vehicle hybrid power system power allocation strategy of fuzzy rules formulated mainly consider the following aspects: the car to start and accelerate the process, and load current is larger, if super-capacitors SOC is high, can reduce T in order to increase the super capacitor discharge current and reduce the current lithium battery, or increase the size of the T appropriately in order to avoid excessive use of super capacitor. During braking or deceleration, if the SOC of the super-capacitor is small, the super-capacitor needs to be charged first. When the load current is small, lithium batteries can provide most of the current, and the super-capacitors can provide a lower level of current. The essence of the whole energy management is to fully realize the function of "peak load reduction" of the super-capacitor. The fuzzy rules are shown in table 1:

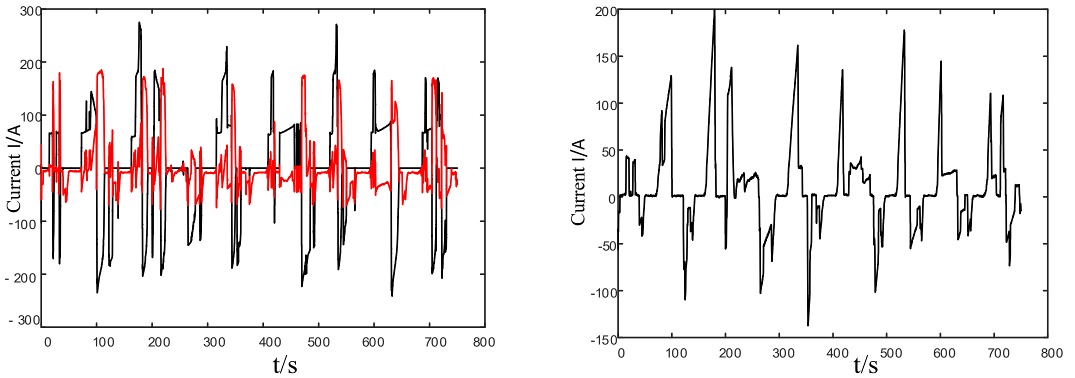
Table 1. Fuzzy control rules table

T		i_L VN	N	Z	P	VP
	VL	VH	VL	VH	VH	VH
	L	VH	L	VH	H	VH
SOC_{SC}	M	H	M	H	M	H
	H	M	H	H	L	M
	VH	M	VH	H	VL	M

5. Simulation Analysis of Hybrid Power System

In order to verify the feasibility and effectiveness of the power distribution control strategy of hybrid power system proposed in this paper, the driving conditions of vehicles were selected, and a model was built with Matlab/Simulink software for simulation verification.

The current comparison between the hybrid power system and a single lithium battery is shown in figure 7, where the red curve in the mixed energy storage is the charge and discharge current of lithium battery. It can be seen from the figure that when the load current fluctuates greatly, the current of lithium battery will change greatly when working alone. Lithium batteries and super capacitor and role at the same time can lithium battery current fluctuation slow, due to adopting adaptive frequency control power allocation strategy by adjusting the filter time constant to control the lithium battery and super capacitor charge and discharge current, the lithium electricity from around 180A to 80A well control, reduced the lithium battery charge and discharge current, reduce the damage by large current charge and discharge.

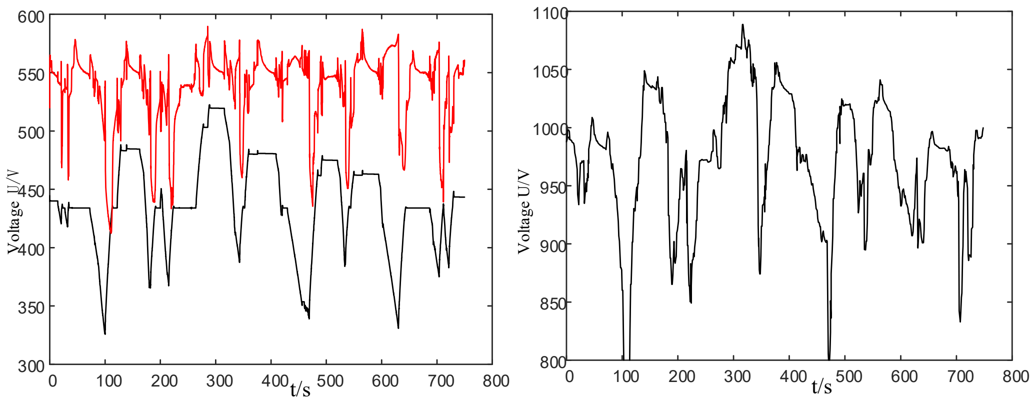


(a) hybrid power system current

(b) unitary Li-ion battery power current

Figure 7. Comparison of current between hybrid power system and single lithium battery

The voltage comparison between the hybrid power system and the energy storage of a single lithium battery is shown in figure 8. In the mixed energy storage, red is the voltage of lithium battery and black is the voltage of super-capacitor. As can be seen from the figure, the voltage of lithium battery in the hybrid power system decreased significantly and maintained around 500V, and the remaining super-capacitors played the role of peak-load clipping. In a single lithium battery, the voltage of the lithium battery changes to 850-1100V up and down, which indicates that the super-capacitor can bear the rest of the load to smooth the load fluctuation.



(a) hybrid power system voltage

(b) unitary Li-ion battery power voltage

Figure 8. Voltage comparison of hybrid power system and single lithium battery that the super-capacitor can bear the rest of the load to smooth the load fluctuation.

6. Conclusion

This article for electric vehicles, such as sharp deceleration case load mutation to cause large current charging and discharging lithium batteries, proposed based on adaptive frequency control strategy applied to hybrid system, on the basis of the double closed loop control, according to the super-capacitors charged state and load current real-time load frequency regulation, finally through the simulation, the method can give full play to the smooth load fluctuations of super-capacitors, effectively reduce the lithium battery charge and discharge current, the current volatility in a reasonable scope, prolong the service life and improve the robustness of the entire power supply system.

Acknowledgments

This work was financially supported by China Postdoctoral Science Foundation grants second-class funding (2018M632690), Shandong Provincial Natural Science Foundation Doctoral Fund (ZR201709180318) and Shandong Provincial Postdoctoral Innovation Fund Special Funding (201703022).

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