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Research Article

High-Voltage Topological Architecture-Based Energy Management Strategy of the Plug-In Hybrid Powertrain System

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Hybrid technology (including plug-in hybrid) integrates the advantages of traditional automobile technology and pure electric technology, which can greatly reduce fuel consumption and improve emissions. It has become one of the main technologies developed at present and in the next 15~20 years. Energy management is the core algorithm of hybrid electric vehicle control strategy, and it is the focus of current research. However, these studies mainly focus on the high efficiency of control assembly, optimal management of power system energy, and maximum recovery of renewable energy but have not considered energy distribution management and optimization between the power battery and the low-voltage battery. Hence, based on the high-voltage topology of the plug-in hybrid system, this paper proposes the optimal energy management strategy between the power battery and the low-voltage battery under different working conditions. The charging and discharging characteristics of the power battery under different electric quantities are also combined. The experimental results show that based on the optimized energy management strategy, the pure electric driving range is increased by 6% under NEDC condition for a C-class plug-in hybrid car, and the energy-saving effect of the vehicle is further improved.

1. Introduction

The power unit of plug-in hybrid electric vehicle (PHEV) is a hybrid system composed of engine and electric drive system. Through the advanced vehicle control system, the two work together to distribute the driving force reasonably between engine and motor, so as to achieve high efficiency, energy saving, and low pollutant emission [1].

The real-time optimal distribution of driving force is realized through the whole vehicle energy management strategy. Energy management is the core algorithm of hybrid electric vehicle control strategy and the focus of current research results [2]. Yang et al. proposed a new type of an electromechanical-electrohydraulic coupling power vehicle model that combines the traditional motor and the piston pump into a unit and achieves the torque of electric and hydraulic torque. It ensures the reasonable use of vehicle energy [3]. You et al. used Matlab/Simulink to establish the IEEE 13 bus test feeder model with a cross-feedback end and conducted experimental testing on the hardware in the loop platform and proposed a control strategy for comprehensive voltage imbalance compensation to use standard operation procedures to alleviate the adjacent unbalanced voltage between feed lines [4]. Zhang et al. selected typical four types of urban conditions and applied the K average clustering algorithm to identify the working conditions and established the relationship between fuel coefficient and fuel consumption and proposed the minimum energy management strategy based on equivalent fuel [5]. Hofman et al. analyzed and evaluated the concept of IMA and Prius's transmission system, in order to reveal the potential limitations of fuel economy and performance, and the design and cost involved in the quantitative implementation (limited) fuel economy and performance trade off [6]. Torres et al. designed a rulesbased controller to ensure that the vehicle manages the power system in accordance with the standards of maximizing efficiency and autonomy [7]. Noyori et al. have developed a regenerative braking system. The regenerative braking energy obtained through the speed of vehicle deceleration or coast-down, through efficient power generation and charging, realized the improvement of fuel economy [8]. Masjosthusmann et al. carried out research on electric vehicle energy management, a type of electric vehicle energy management system proposed by testing on a test bench, and established a vehicle simulation model for the electric vehicle [9].

The study of the abovementioned hybrid vehicle energy management strategies mainly focuses on the energy distribution between power systems. At the same time, it is considered that the SOC of the power battery is maintained in a reasonable range, so that the entire system consumes the smallest energy, and the above work is considered during the design stage of the vehicle power system solution. However, by optimizing the power distribution between the power battery and the low-voltage battery, it can also improve the economic performance of the vehicle. No relevant research has been seen in this field.

The major contributions of this paper include the following:

(1) A special energy management strategy and optimization idea are proposed, namely, the optimized energy management strategy between the power battery and the low-voltage battery is considered.

(2) We construct a high-voltage topology of the plug-in hybrid system, while the special operation conditions are classified into charging conditions, electric driving conditions, and energy regenerating conditions.

(3) The energy management strategies under different operation conditions are carried out and verified as energy saving based on the charging and discharging characteristics of the power battery in different power.

This paper is organized as follows: in Section 2, we introduce the system overview of high-voltage system topology and vehicle and main components specifications. In Section 3, the energy management strategy and optimization solution are proposed under different operation conditions. Section 4 gives the experimental results to illustrate the effectiveness of the proposed control strategy. Some conclusions are stated in Section 5.

2. Problem Formulation

2.1. High-Voltage System Topology. The P2 configuration of a C-class car hybrid system is shown as Figure 1, which consists of a high-efficiency 4-cylinder gasoline direct injection boost engine, clutch coupling motor module, motor inverter, 7-speed dual clutch transmission, lithium-ion power battery, DC/DC converter, and on-board charger. The C-class vehicle and components main technical parameters are given in Table 1.

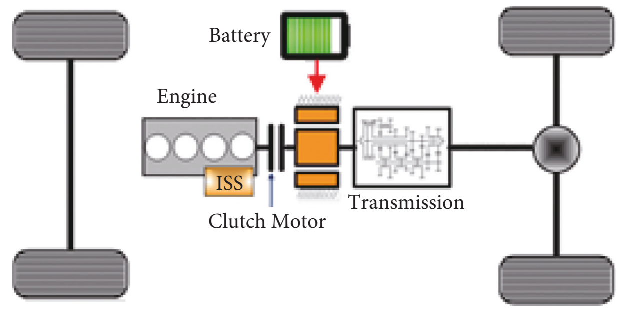

Figure 1: A certain C class plug-in hybrid system configuration.

The high-voltage system topology of the plug-in hybrid car is as shown in Figure 2, where the power battery high-voltage end is connected to the motor inverter, the on-board charger high-voltage output terminal and the DC/DC high-voltage input are connected together, and DC/DC low-voltage output and the low-voltage battery and the low-voltage load are connected. Based on the high-voltage system topology, the charging and discharge state of the power battery and the low-voltage battery can be managed to achieve optimize energy management purposes by adjusting the operating state of the motor, DC/DC, and on-board charger.

2.2. High-Voltage System Operation Conditions. Based on high-voltage system topology, several basic operation conditions of high-voltage systems can be determined.

2.2.1. Charging Conditions. The input 220 V AC electrically converted to the high-voltage of the power battery charged the power battery by on-board charger under the charging operation. DC/DC converts a portion of the charge output of on-board charger to the low-voltage output and supply charge to the power battery and the low-voltage load.

2.2.2. Electrical Drive Conditions. The power battery in the driving condition is in the discharge state. The motor inverter converts the DC power output from the power battery to the electricity of the motor, providing driving power for the motor, while DC/DC converts the power battery electrical energy to the low-voltage output terminal, which provides power to the power battery and the low voltage load. The DC/DC output can also be unpermitted to provide an energy source to a low-voltage load in the case of sufficient low-voltage battery power.

2.2.3. Energy Recovery Conditions. Under the energy recovery condition, the motor is in the energy feedback state of negative torque, and the inverter can transfer the feedback energy of the motor to the power battery and DC/DC [2]. When the power battery can recover energy, a part of the recovered energy transmitted by the inverter will charge the power battery and the other part will supply power to DC/DC. When the power battery cannot recover energy, all the recovered energy transmitted by the inverter can be stored in the battery and consumed by the low voltage load through DC/DC.

Table 1: Main technical parameters of the C-class vehicle and components.

Items	Technical indicator	Value
Vehicle parameters	$L\times W\times H$/axis/mm	5095 × 1875 × 1485/2970
	Curb weight/kg	2000
Powertrain configuration	P2	
Vehicle performance	Max. Speed/km	≥210
	0–100 acceleration time/s	≤8.6
	NEDC driving cycle fuel consumption L/100 km	≤2.4
	Pure electric driving range/km	≥50
Engine	Type	4-Cylinder GDI
	Power kW/torque Nm	145/280
Transmission	Type	DCT-7gears
Driving motor	Type	PM
	Peak power/kW	55
	Peak torque/Nm	280
Battery	Type	Lithium
	Energy/kWh	13
DCDC	Input voltage/V	200~400@DC
	Rated output voltage/V	14.5 ± 0.2@DC
	Rated output current/A	120
On-board charger	Rated power/kW	3.6
	Input voltage/V	180~260V@AC
	Output voltage/V	200~400
	Input current/A	≤16

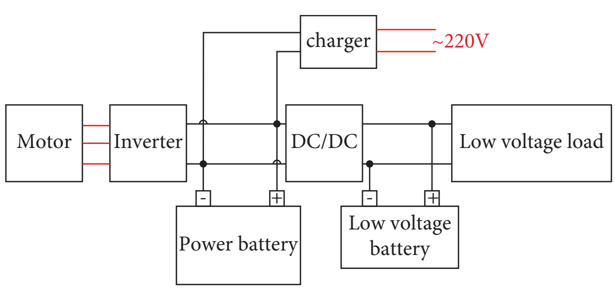

Figure 2: High-voltage system topology.

3. Energy Management Strategy

3.1. Power Battery Charge and Discharge Power Characteristics. Ternary lithium-ion batteries are often used as power batteries. Figure 3 shows the characteristic curve of the allowable charge and discharge power of the power battery. It can be seen from Figure 3 that the higher the battery temperature within the normal non-limit operating temperature range, the higher the allowable charge power and allowable discharge power of the battery. However, as battery power is higher than a certain value a%, the allowable charge power of the battery drops rapidly to close to zero, when battery power is lower than a certain value b%, the allowable discharge power of the battery drops rapidly to close to zero. The power battery power range in which the vehicle can run purely electric is between b% and 100%. Therefore, in terms of improving the driving range of purely electric, it is necessary to focus on solving the charging recovery problem in the power battery power range from a% to 100%.

3.2. Energy Optimization Solution. In the later stage of vehicle performance achievement, improving the pure electric driving range of the vehicle needs to be realized by optimizing the energy management strategy. The optimization work can be performed in the following two aspects, as described below.

3.2.1. Energy Recovery Optimization When the Low Permitted Charging Power of the Power Battery. According to the charging and discharging characteristics of the power battery, in order to solve the problem that the energy cannot be recovered when the allowable charging power of the power battery is low, an energy recovery scheme as shown in Figure 4(a) can be formulated. The recovered electric energy is absorbed through the low voltage load and the battery, and the recovered electric energy is used for the low voltage load part, which can reduce electric energy consumption of the power battery at the current time, while a small part of the recovered electric energy can be stored in the battery for later use.

3.2.2. Optimization of Low Voltage Battery Power. To make full use of the electric energy of the battery, the electric energy stored in the battery during charging and energy recovery can be released to the low voltage load under the electric driving condition, so as to further reduce the electric energy consumption when the power battery is driven, as shown in Figure 4(b).

3.3. Energy Management Strategies under Different Conditions. Figure 5 shows a complete energy management process, the period is a charging condition from t_0 to t_2, and

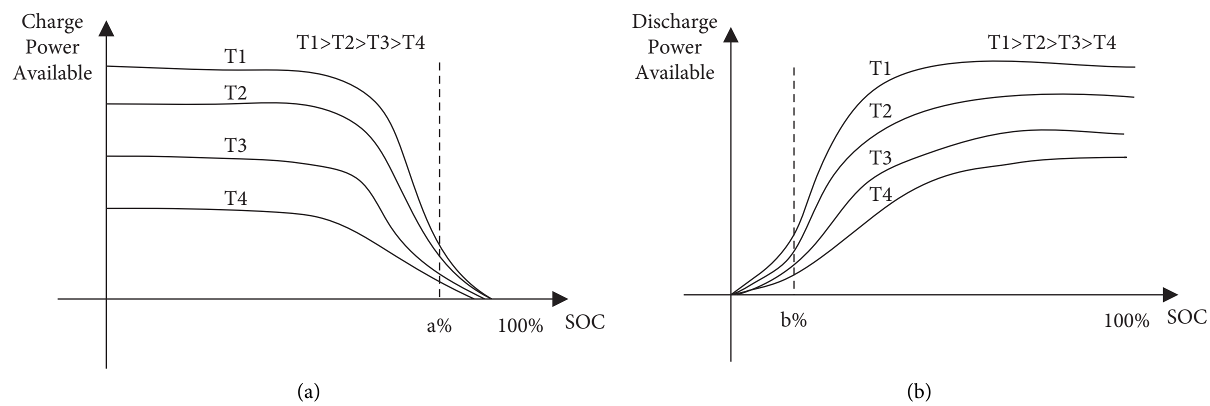

Figure 3: Power battery charging/discharging power characteristics. (a) Power battery charging power characteristics. (b) Power battery discharging power characteristics.

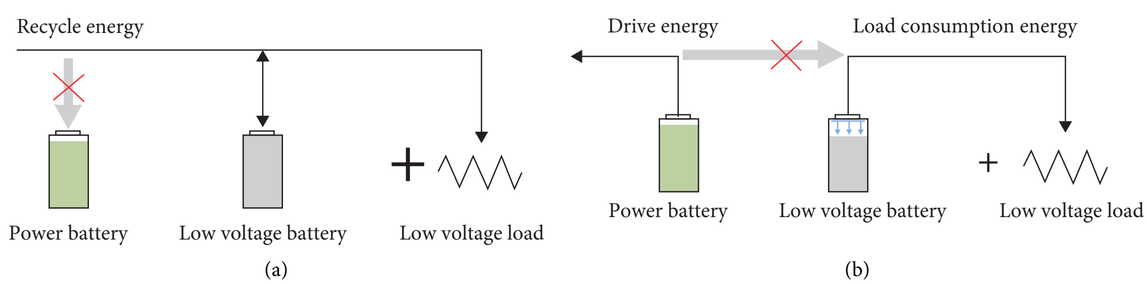

Figure 4: Energy management policy optimization scheme. (a) Energy recovery when the low permitted charge power of power battery. (b) Optimization of low-voltage battery power.

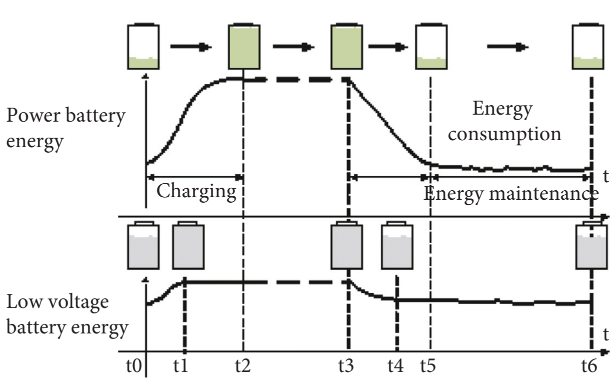

Figure 5: Energy management process.

power in the grid is stored in the power battery and the low-voltage battery. The period is a power consumption process from t_3 to t_5, stored power in the power battery and the low-voltage battery is converted to the kinetic energy of the vehicle by motor driving. The period is the power retention process from t_5 to t_6, the power battery and the low-voltage battery are maintained at a certain level.

The following is description for energy management strategies under different conditions of different conditions:

3.3.1. Charging Conditions. Since the power of the power battery is at a lower level due to the use of the power battery, meanwhile, low-voltage battery power has a certain lifting space, so the electric energy in the grid can be stored in the power battery and the low-voltage battery when the battery is charged, as shown in Figure 6. The power battery and the low-voltage battery can be filled in the full power state, which can increase the electric energy reserves stored in the low-voltage battery, and this stored electrical energy can be lately used for motor drive and low-voltage load consumption. The relation of input and out energy shown in (1) and (2).

$$E_{\text{grid}} = \frac{E_{\text{chargeout}}}{\eta_{\text{charger}}}. \tag{1}$$

$$E_{chargerout} = E_{batteryin} + \frac{(E_{lvbin} + E_{lvlin})}{\eta_{DC\ DC}}. \tag{2}$$

$E_{chargerout}$ is the energy output of charger; $E_{gri\ d}$ is the energy of grid; $\eta_{charger}$ is the efficiency of charger; $E_{batteryin}$ is the energy input of power battery; E_{lvbin} is the energy input of low-voltage battery; E_{lvlin} is the energy input of low-voltage load; and $\eta_{DC\ DC}$ is the efficiency of DCDC.

3.3.2. Electric Drive Conditions When Sufficient Low Voltage Battery Power. Under the electric drive, the power battery needs to provide driving power to the motor. The power

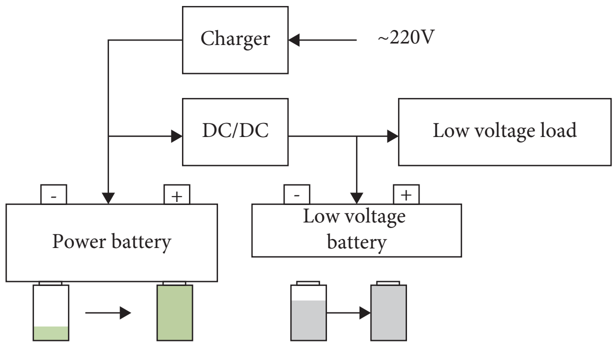

Figure 6: Energy management under charging conditions.

consumption of the low voltage load can be provided from the low-voltage battery in sufficient low-voltage battery power, as shown in Figure 7(a), i.e., during the electric driving process, stored power in the low-voltage battery can be released to a low-voltage load at this time, reducing the power consumption of the power battery.

The relation of input and output energy are shown in (3) and (4).

$$E_{batter\,yout} = \frac{E_{motorin}}{\eta_{inverter}}. \quad (3)$$

$$E_{lvbout} = E_{lvlin} \quad (4)$$

$E_{batter\,yout}$ is the energy output of power battery; $E_{motorin}$ is the energy input of drive motor; $\eta_{inverter}$ is the efficiency of inverter; E_{lvbout} is the energy output of low-voltage battery; and E_{lvlin} is the energy input of low-voltage load.

3.3.3. Electrical Drive Conditions When the Low Voltage Battery Power Balance. When the low-voltage battery is released to a better operating point, the low-voltage battery power balance mode is entered. In this mode, the target load of DC/DC is set to zero; that is, the zero with the target output current of DC/DC is closed-loop controlled, so that it can be protected to prolong the low-voltage battery life [9]. At this time, the power battery is not only supplied to the motor but also provides power consumption to the low-voltage load by DC/DC, as shown in Figure 7(b).

Because of the low-voltage battery in an electric quantity balancing control mode, the low-voltage battery is no longer acquired from the power battery, which can reduce the power consumption of the power battery.

The relation of input and out energy are shown in (5)–(7).

$$E_{batter\,yout} = E_{inverterin} + E_{DCDCin} \quad (5)$$

$$E_{motorin} = E_{inverterin} \times \eta_{inverter} \quad (6)$$

$$E_{DCDCout} = E_{lvbin} + E_{lvlin} \quad (7)$$

$E_{batter\,yout}$ is the energy output of power battery; $E_{inverterin}$ is the energy input of inverter; E_{DCDCin} is the energy input of DCDC; $E_{motorin}$ is the energy input of drive motor; $E_{inverterin}$ is the energy input of inverter; $\eta_{inverter}$ is the efficiency of inverter; $E_{DCDCout}$ is the energy output of DCDC; E_{lvbin} is the energy input low-voltage battery; and E_{lvlin} is the energy input low-voltage load.

3.3.4. Energy Recovery Conditions When Low Permitted Charging Power of the Power Battery. When the allowable charging power of the power battery is very low or even close to zero, if the power battery is charged through energy recovery, the battery cell voltage may be too high, resulting in cell failure. Hence, the power battery absorbed the energy recovery replacement of DC/DC, as shown in Figure 8(a). DC/DC passes the recovered energy to a low voltage load and the low-voltage battery, and the battery can store partially recovered energy and release it to the low-voltage load under electric drive conditions.

The relation of input and output energy are shown in (8)–(10).

$$E_{motorout} = \frac{E_{inverterout}}{\eta_{inverter}}. \quad (8)$$

$$E_{inverterin} = \frac{E_{DCDCout}}{\eta_{DCDC}}. \quad (9)$$

$$E_{DCDCout} = E_{lvbin} + E_{lvlin} \quad (10)$$

$E_{motorout}$ is the energy output of drive motor; $E_{inverterout}$ is the energy output of inverter; $\eta_{inverter}$ is the efficiency of inverter; $E_{inverterin}$ is the energy input of inverter; $E_{DCDCout}$ is the energy output of DCDC; η_{DCDC} is the efficiency of DCDC; E_{lvbin} is the energy input low-voltage battery; and E_{lvlin} is the energy input low-voltage load.

3.3.5. Energy Recovery Conditions When the High Permitted Charging Power of the Power Battery. When the power battery is in the normal power range, and the battery temperature is in the normal temperature range, the power battery has a higher charging power, and the energy of the sliding or braking can be recovered, as shown in Figure 8(b). The power battery stores most of the energy recovered by the motor, and a small portion is supplied to a low-voltage load through DC/DC, and the low-voltage battery is in a power balance. Thus, when the power battery is in the normal power range, it is possible to store most of the electric energy recovered by the sliding or braking.

The relation of input and output energy are shown in (11)–(13).

$$E_{motorout} = \frac{E_{inverterout}}{\eta_{inverter}}. \quad (11)$$

$$E_{inverterout} = \frac{E_{batter\,yin} + E_{DC\,DCout}}{\eta_{DC\,DC}}. \quad (12)$$

$$E_{DCDCout} = E_{lvbin} + E_{lvlin} \quad (13)$$

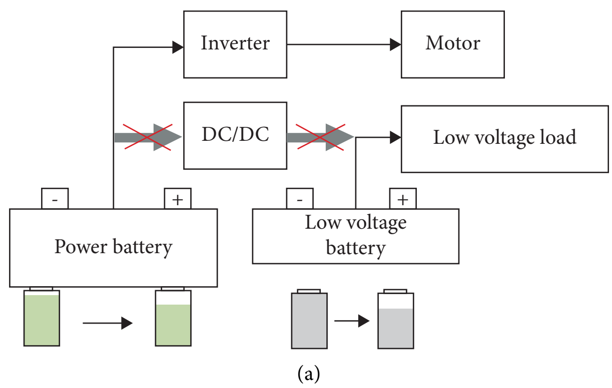

Figure 7: Energy management of electric drive conditions. (a) Energy management under sufficient power of the low-voltage battery. (b) Energy management under power balance of the low-voltage battery.

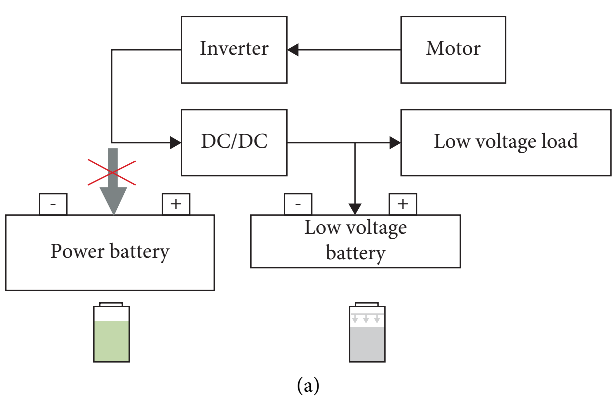

Figure 8: Energy management of energy recovery. (a) Energy management when the low power of the power battery permitted charge power of the power battery. (b) Energy management when the sufficient power of the power battery permitted charge power of the power battery.

$E_{motorout}$ is the energy output of drive motor; $E_{inverterout}$ is the energy out of inverter; $\eta_{inverter}$ is the efficiency of inverter; $E_{batteryin}$ is the energy input of power battery; $E_{DCDCout}$ is the energy output of DCDC; η_{DCDC} is the efficiency of DCDC; E_{lvbin} is the energy input low-voltage battery; and E_{lvlin} is the energy input low-voltage load.

3.4. Energy Management Strategy Implementation. According to the abovementioned energy management policy and optimization, the key of implementation is to adjust the energy of the DC/DC output. Based on the situation, it can be achieved by controlling the output voltage of DC/DC at different operation conditions, as shown in Table 2. The current conditions should be identified through the vehicle state, the state of the power battery, and the state of the low-voltage battery, and then the corresponding DC/DC target output voltage command is output according to the identified operation condition and finally implements the energy management policy and optimization.

4. Test Verification

In order to verify the effect of the optimized energy management strategy, a comparative test of two groups of pure electric driving range tests was carried out on the vehicle. One group used the original strategy that was not optimized and the other group used the optimized strategy. The final test results are shown in Table 3. It can be seen from the table that the total electric energy consumption after the strategy optimization is 0.642kWh lower than that of the non-optimization when driving the same 50 km.

Figure 9 shows the curve comparison of two groups of tests in the first NEDC cycle. It can be seen from the figure that in this cycle, compared with the nonoptimized strategy, the optimized strategy can discharge the battery when driving and charge when recovering, realizing the optimal management of energy.

Table 4 shows the comparison results of the pure electric driving range of the two groups of tests when the power consumption of the power battery is the same. It can be seen from the table that the optimized energy management

Table 2: Target output voltage of DC/DC.

Num.	Conditions	Target output voltage before optimization of DC/DC (V)	Target output voltage after optimization of DC/DC (V)
1	Charging condition	14.5	14.5
2	Electric driving condition under sufficient power of low-voltage battery power	14.5	12.0
3	Electric driving condition under balance power of low-voltage battery power	14.5	12.0
4	Energy recovery condition when low permitted charging power of the power battery	14.5	14.5
5	Energy recovery condition when sufficient permitted charging power of the power battery	14.5	14.5

Table 3: Energy management comparison test data.

Num.	Electric driving range (km)	Energy consumption of low-voltage battery (kWh)	Energy consumption of power battery (kWh)	Total energy consumption (kWh)
Before optimization	50	0.637	10.297	10.934
After optimization	50	0.289	10.009	10.298

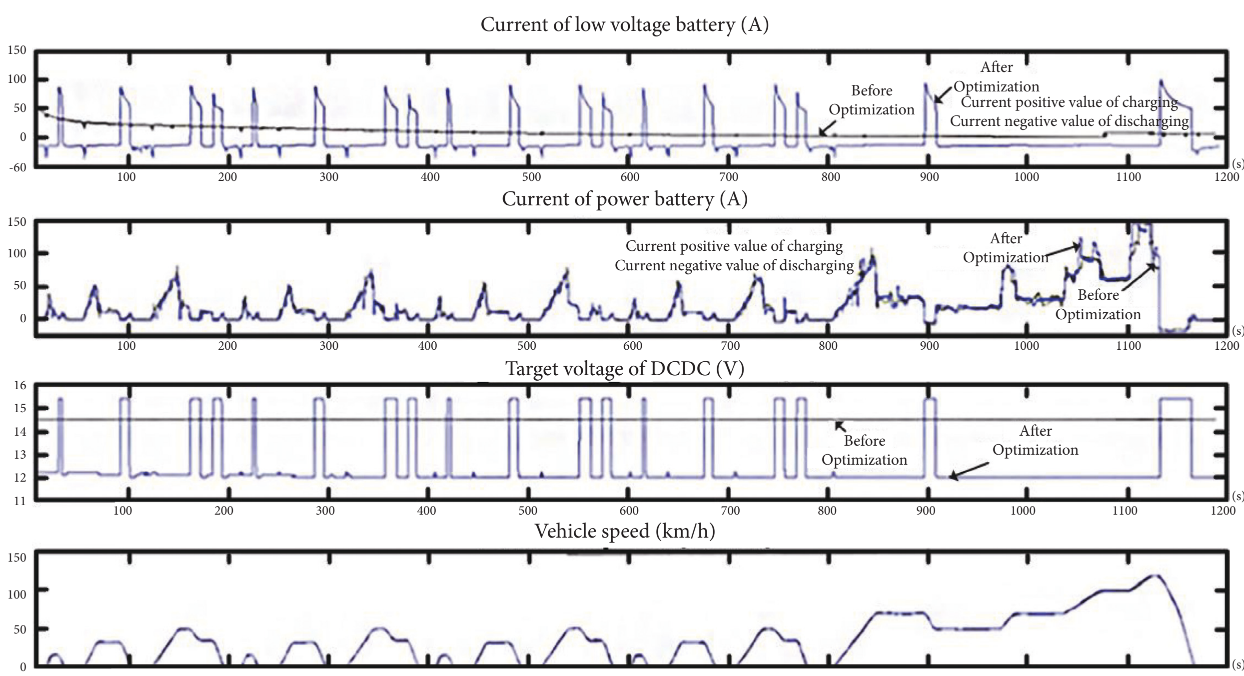

Figure 9: Comparison of two sets of tests under the first NEDC cycle.

Table 4: Comparison of electric range.

Test num.	Window range SOC of power battery (%)	Pure electric range (km)
Before optimization	80	50
After optimization	80	53

strategy can increase the pure electric driving range of the vehicle from 50 km to 53 km; that is, the driving range is increased by 6%, and the expected goal is achieved.

5. Conclusion

In the later stage of the vehicle performance, in order to further improve the pure electric driving range of the vehicle, the strategy of energy management optimization between the power battery and the battery under different working conditions is proposed. The strategy fully considers the allowable charge discharge power characteristics of the power battery and summarizes five service conditions for optimizing energy management, namely, charging condition, electric driving condition when the battery is full, electric driving condition when the battery is balanced, energy recovery condition when the allowable charging power of the power battery is low, and energy recovery condition when the allowable charging power of the power battery is high.

Then the corresponding energy management optimization strategy is formulated for each working condition. Finally, based on the energy management optimization strategy under different working conditions, the corresponding target output voltage of DC/DC is controlled to achieve the expected results. Through the NEDC pure electric driving range test results of C-class plug-in hybrid power, it can be seen that when the optimized energy management strategy is used for control, the pure electric driving range of the vehicle is increased by 6%, and the purpose of improving the pure electric driving range is achieved.

Data Availability

The data are available upon request.

Conflicts of Interest

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

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