A Dual-motor Drive and Battery Charge-discharge Balance Control Strategy for PHEV Based on MMC

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Abstract. At present, more and more people use electric vehicles. Due to its applicability, Plug-in Hybrid Electric Vehicles (PHEV) have strong market demand. The research on the integration of PHEV power conversion is mainly based on the multi-level converter topology, but this topology can only connect one motor. This paper proposes a battery charge-discharge balance control strategy for PHEV based on Modular Multilevel Matrix Converters (M3C). This strategy takes into account dual-motor drive and battery management at the same time, and solves the problem that traditional MMC only applies single-motor speed control. By establishing a small signal model of the system and analyzing the power relationship of each part, a comprehensive control strategy combining multi-level battery State-of-Charge (SOC) charge-discharge balance control and motor control is proposed. The direct control of the M3C bridge arm current is the core of battery SOC balance. This strategy includes dual-motor speed control, balanced charge-discharge of battery SOC between phases and bridge arms. The Matlab hardware-in-the-loop simulation experiment platform was built, and the experimental results verified the effectiveness and feasibility of the proposed strategy. While realizing the quick start and stable operation of the motor, it ensures the balanced charge-discharge of the battery SOC.

1. Introduction
Due to the rapid development of the automobile industry, cars have become a necessity for most families, but the resulting environmental problems such as smog have also become increasingly prominent. The emergence of Electric Vehicle (EV) technology can effectively reduce gasoline consumption and help improve the environment [1]. Limited by battery technology and market factors, Battery Electric Vehicles (BEV) will be difficult to replace fuel-vehicles in the future, PHEV has strong market demand as an intermediate transition product. No matter which type of EV, it is inseparable from the power conversion system. At present, the EV power conversion system is mainly divided into two-level converter topologies and multi-level converter topologies [2].

For the EV integrated topology of the multilevel converter, the most representative one is the BMS and EV motor drive integrated system based on MMC [3]. This integrated topology can realize the system integration of Battery Management System (BMS) and EV motor drive functions at the same time. In different applications, each topology in the MMC topology family has its own advantages in performance and feasibility. The literature [4,5] proposed a Samsung-type MMC topology for high-voltage and high-power AC motor speed regulation. The control strategy adopts double αβ/0
coordinate transformation, which effectively avoids the influence of current regulation on the input and output sides, but the calculation is cumbersome and the control is complicated. Many documents [3, 4, 6] have studied the advantages of MMC topology in the application of AC variable frequency speed regulation, but they have not combined energy storage components with it.

Literature [7] proposed a PHEV integrated conversion system based on M3C (M3C-PHEV) and its external power supply charging control scheme, which demonstrated its feasibility and effectiveness in power density, SOC equalization charging, etc., but it has not studied its motor drive and discharge equalization control strategy.

This paper proposes a charge-discharge balance control strategy for PHEV based on M3C. The strategy can not only realize the integration of dual-motor drive and battery management system, but also integrate with energy storage components, as compared with the EV integrated topology of the traditional multi-level converter. For the battery, there is no need to consider the voltage equalization of the DC side of each sub-module, which reduces the control complexity. Through power analysis and the establishment of a small signal model, a control strategy is given, combining Permanent Magnet Synchronous Motor (PMSM) $i_d=0$ control and multi-level battery SOC charge and discharge balance control, the core of which is the bridge arm current direct control [8]. The Rtlab hardware-in-the-loop simulation experiment platform was built, and the experimental results verified the effectiveness and feasibility of the proposed motor drive and battery SOC charge and discharge balance control strategy.

2. MMMC-PHEV system topology

Figure 1 shows the main circuit topology based on the M3C-PHEV in this research. The generator side on the input side and the motor side on the output side are linked by 9 bridge arms, and each bridge arm is formed by cascading bridge arm inductance $L_0$ and $N$ H-bridge sub-modules, which is composed of 4 power switch tubes, capacitors and power batteries. This topology directly connects the three-phase generator and motor of the PHEV, while taking account into the BMS control. The M3C-PHEV conversion system has a variety of working modes, including pure electric drive mode, pure oil drive mode, hybrid drive mode, etc. This paper focuses on the research of the control strategy of the M3C-PHEV system under the hybrid driving mode.

3. MMMC-PHEV integrated control strategy

3.1. Power Analysis

When considering the internal circulating current, the bridge arm current can be expressed as
\[ i_{xy} = \frac{1}{3} i_x + \Delta i_{xy} + \frac{1}{3} i_y \]  

(1)

The frequency and phase of internal circulating current are the same as the input side current, and satisfied

\[ \sum_{x=a,b,c} \Delta i_{sx}^{ov} = \sum_{y=u,v,w} \Delta i_{sy}^{ov} = 0 \]  

(2)

Assuming that the active power emitted by the generator is \( P_{in} \), the active power absorbed by the bridge arm is \( P_{xy} \), the active power consumed by the motor is \( P_{out} \), and the generator power cycle is \( T \), then it is known from the law of conservation of energy

\[ P_{in} = \sum_{y=u,v,w} P_{xy} + P_{out} \]  

(3)

\[ P_{xy} = \sum_{x=a,b,c} \frac{1}{T} \int_0^T u_x i_x dt \]  

(4)

\[ P_{out} = \sum_{y=u,v,w} \frac{1}{T} \int_0^T u_y i_y dt \]  

(5)

\[ P_{sy} = \frac{1}{T} \int_0^T u_y i_y dt = \frac{1}{T} \int_0^T \frac{1}{3} u_x i_x + u_y \Delta i_{sy}^{ov} - \frac{1}{3} u_x i_y \]  

(6)

In order to balance the SOC of each layer of the battery, it can be achieved by adjusting the distribution of active power of each layer. For the input phase unit, if \( u_x \) is unchanged, the SOC balance of the phase unit can be adjusted by adjusting the active current component \( i_{xy} \) with the same frequency and phase as \( u_x \). The circulating current only exists inside the system, and does not flow into the input side and the output side. The distribution of active power on the bridge arms can be adjusted by adjusting the distribution of active current in the circulating current between the in-phase bridge arms, and then the SOC balance between the bridge arms can be adjusted. The given reference current of the bridge arm current is \( i_{xy} = \frac{1}{3} i_x + \frac{1}{3} i_y + \Delta i_{xy}^{ov} \).

3.2. Motor control

Permanent Magnet Synchronous Machine has the advantages of small size, light weight, high power density, high reliability, and high efficiency. Therefore, the integrated conversion system in this paper uses PMSM as the power source. Since the control method of PMSM is relatively mature, this paper adopts the \( i_d=0 \) control method in PMSM vector control.

According to the literature [9,10], the physical equations, torque equations, and motion equations of the PMSM are obtained, and the mathematical model is established. The PMSM is equivalent to a DC motor through coordinate transformation, the stator current is converted to the q-axis current. Let \( i_d=0 \), by controlling \( i_q \) to generate the electromagnetic torque required to maintain the target speed to ensure the normal operation of the motor.

4. Realization of integrated control strategy

In order to achieve the above-mentioned purpose of adjusting the active power and motor speed absorbed between each phase and each bridge arm in the same phase, this paper adopts the direct control of the bridge arm current as the core, combined with the motor \( i_d=0 \) control, it realizes the multi-level closed-loop control strategy of SOC average value feedback control between phases, bridge arm in the same phase, and double closed loop control of motor speed and current. The system control block diagram is shown in the figure 2.
In figure 2, \( \text{soc}_{xy} \), \( \text{soc}_{x} \), \( \text{soc}_{y} \) are respectively indicate the average SOC of all sub-modules of xy bridge arm, x-phase bridge arm, and y three-phase bridge arm. Both the phase balance controller and the bridge arm balance controller adopt the proportional integral (PI) controller.

The motor \( i_{r}=0 \) control is shown in figure 2(a). Since this control method is relatively mature, I will not repeat it here. The command value of the three-phase stator voltage of the generator and the motor is obtained by the motor control, and the static duty cycle of each bridge arm can be calculated by the voltage, which is added to the total duty cycle calculation as a feedforward amount. The three-phase stator current command values of the generator and the motor is added to the calculation of the command current of the bridge arm as a feedforward amount.

The block diagram of the SOC charge-discharge balance between the three phases is shown in figure 2(b). The deviation of the battery SOC between phases is processed by the phase-to-phase SOC balance controller \( \Delta \text{soc} \) to obtain the fine adjustment of the active power of each phase, after dividing by the voltage coefficient, the amplitude of each phase current fine-tuning quantity is calculated. After multiplying with the phase sequence, the adjustment current adds to the stator current of the generator and subtracts with the zero-sequence current to obtain the fine-tuning quantity of each phase active current. The three-phase SOC balance can be adjusted by adjusting the distribution of active current among the three phases. Due to the limitation of circulating current, the current fine-tuning amount of the third bridge arm can be given by the other two, which is \( \Delta i_{x} = -\Delta i_{a} - \Delta i_{b} \). \( \delta_{x} \) (x = a, b, c) is initial phase angle of phase voltage, \( i_{0} \) is zero-sequence current.

The block diagram of SOC charge-discharge balance between each bridge arm in the same phase is shown in the figure 2(d). The adjustment method is similar to that of the phase-to-phase balance control. By adjusting the distribution of the active component of the phase current among the bridge arms, the SOC charge-discharge balance between the bridge arms can be realized. Due to the limitation of circulating current, the current fine-tuning amount of the third bridge arm can be given by the other two, which is \( \Delta i_{x} = -\Delta i_{a} - \Delta i_{b} \). After the adjustment currents are added, the given current of each bridge arm is obtained, which is \( i'_{x} = \frac{1}{3} i'_{a} + \frac{1}{3} i'_{b} + \Delta i_{x} + \Delta i_{x} \). The given current includes internal circulating current and motor phase current, which can be independently controlled at the same time.
The block diagram of the direct control of the bridge arm current is shown in figure 2(e). The output of the current controller is superimposed with the static duty cycle $D_{xy}$ to obtain the duty cycle signal $d_{xy}$ of each bridge arm. The zero-sequence current calculation is shown in figure 2(c).

5. Experimental results

In order to verify the dual-motor drive and battery charge-discharge balance control strategy for PHEV based on M3C, this paper uses Rtlab real-time simulators to form a hardware-in-the-loop system. Rtlab model is op5600. In order to make the experiment real-time and representative, 4 sub-modules are selected for each bridge arm. The simulation step is 60us, the battery rated voltage is 60V, and the capacity is 2Ah. Motor parameters and the initial battery SOC of the bridge arms are shown in Table 1.

| Parament | Value | Bridge arm | SOC(%) |
|----------|-------|------------|--------|
| Stator phase resistance $R_s$ | 0.958Ω | au | 80 |
| Inductances $L_d, L_q$ | 5.25e-3H, 12e-3H | av | 79 |
| pole pairs $p$ | 4 | aw | 78 |
| Generator rated speed $n$ | 750r/min | bu | 77 |
| Motor rated speed $n$ | 1000r/min | bv | 76 |
| Inertia coefficient $J$ | 0.01kg.m$^2$ | bw | 75 |
| Viscous friction coefficient $F$ | 0.008N.m.s | cu | 74 |
| Torque constant $C_t$ | 1.0962 | cv | 73 |
| Flux linkage $\phi_t$ | 0.1827V.s | cw | 72 |

Case 1: Both the generator and the motor are started at rated speed, the mechanical torque of the generator is 18N.m, and the motor starts without load, the mechanical torque is increased to 3N.m at $t=0.4s$.

Case 2: The motor condition are the same as Case 1, and the initial battery SOC of each bridge arm is shown in Table 2, to verify the battery charge balance control strategy.

Case 3: Both the generator and the motor are started at rated speed, the mechanical torque of the generator and motor are 9N.m and 12N.m respectively, the initial battery SOC of each bridge arm are the same as Case2, to verify the battery discharge balance control strategy.

The experimental results under each working condition are shown in figure 4 to figure 6. It can be seen from figure 4 that the generator and motor start quickly, and the speed quickly reaches the rated speed. After the mechanical torque of the motor increases from 0 to 3N.m, the speed drops slightly and then quickly returns to the steady state. In the steady state, the motor speed is stable and the stator current waveform is ideal, which verifies that the motor control has good starting and anti-interference performance. Due to the imbalance of the battery SOC between phases, it is necessary to adjust the current distribution between the phases to achieve SOC balance. Therefore, the three-phase stator current of the generator is unbalanced, and the generator speed fluctuates slightly in the steady state.

The figure 5 shows that when the generator power is greater than the motor power, the battery SOC between the phases and each bridge arm in the same phase can be quickly balanced to realize balanced charge, which ensures the stability of the system. It can be seen from figure 6 that when the generator power is less than the motor power, the battery SOC also can achieve balanced discharge.
6. Conclusion
This paper proposes a charge-discharge balance control strategy for PHEV based on M$^3$C. The strategy can not only realize the integration of dual-motor drive and battery management system, but also integrate with energy storage components, as compared with the EV integrated topology of the traditional multi-level converter. This comprehensive control strategy combines multi-level battery SOC charge-discharge balance control, the core of which is the direct control of the bridge arm current, and motor $i_d=0$ control. While realizing the quick start and stable operation of the motor, it ensures the balanced charge-discharge of the battery SOC of each phase and each bridge arm sub-module of the system. The hardware-in-the-loop experiment verifies the effectiveness and feasibility of the comprehensive control strategy given in this paper. This paper focuses on the dual-motor drive and
charge-discharge balance control strategy on M1C-PHEV conversion system. Its application in the PHEV energy feedback operation mode of the motor drive control, Vehicle-to-Grid (V2G) control and system temperature control strategy still needs further research.

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