Drive Control Strategy for Plug-in Hybrid Electric Vehicle System Based on Modular Multilevel Converter

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Abstract. A power conversion system for plug-in hybrid electric vehicles (PHEV) based on "back-to-back" modular multilevel converter (BMMC) is proposed to solve the problem that the traditional MMC-EV can only work with one motor. The power flow of BMMC system with two motors is complex and no one has ever studied it. The state of charge (SOC) balance control strategy of the integrated power converter is studied in various driving modes by this paper. Based on the bridge arm current control, this strategy combines the vector control of permanent magnet synchronous motor (PMSM) with the hierarchical SOC equalization control, realizes the high performance drive control of PHEV system, and high-efficiency power transfer and management among motor, generator and battery, and avoids the battery and energy loss caused by the redundant charge and discharge process. At the same time, it is convenient to switch freely between different driving modes. The correctness and feasibility of this control strategy are verified through RT-LAB real-time simulation.

1. Introduction
Modular multilevel converters have been applied in the field of AC speed regulation, and there have been related researches. They have better performance and unique advantages in speed regulation. Compared with the two-level converter, its output voltage and current have lower harmonic distortion rate and Electromagnetic Interference (EMI). The battery unit is embedded in the DC side of the modular multilevel converter sub-module (SM) to form an energy storage type modular multilevel converter. This structure has been used in energy storage, new energy grid connection and electric vehicle motor speed regulation. Reference [1] proposed an electric vehicle using modular multilevel converter (MMC-EV), which achieves extremely low battery SOC imbalance without the need for BMS (Battery management system, BMS). However, a large number of PI controllers puts forward higher requirements for the adjustment of control parameters. Model predictive control (MPC) has been widely used in the field of power electronic Control due to its excellent advantages in dealing with complex constrained problems of nonlinear systems [2]. In Reference [3], a Hybrid Model Predictive Control (H-MPC) method for B-MMC structure is proposed, H-MPC effectively reduces the number of PI controllers and the design complexity of the control system. Reference [4] proposed a novel hybrid model predictive control method for MMCs, this method has improved the performance of circulating current and reduced calculation burden. MPC also has unique advantages in motor drive. Reference [5] proposed a new direct predictive speed control (DPSC) method for PMSMs. DPSC simplifies parameter configuration and achieves better speed regulation performance. Reference [6, 7] verified the numerical simulation of the control algorithm and proved that the modular multi-level converter topology can effectively ensure the balance of the battery during
charging even under the assumption that the initial battery SOC is unevenly distributed. However, the above literatures are all about the situation when the modular multi-level converter works with one single motor or one AC output port, which is not applicable to plug-in hybrid electric vehicles. Reference [8] proposed a new PHEV integrated power converter topology based on Back-to-back MMC (BMMC-PHEV) and its external single-phase AC power supply charging control scheme. However, the corresponding motor drive control strategy is not discussed in the paper. In this paper, the motor drive control strategy and power flow of BMMC system is studied. MPC and SOC sorting algorithm can be combined to solve the problem that there are too many PI controllers to simplify parameter setting. The related control strategies need to be further studied.

2. BMMC-PHEV system
The topology of BMMC is shown in Figure 1 and Figure 2. Each SM consists of a half-bridge converter, filter capacitor and battery pack. It is assumed that each arm consists of N SM and a reactor in series. The MMC on both sides are connected back to back by a DC bus, and there are two three-phase AC output ports, so you can bring one AC generator and one AC motor. According to the different operating conditions of generators and motors, BMMC-PHEV has multiple driving modes. When the car is running normally, the motor works alone. In this case, it’s called electric vehicle (EV) mode. If the batteries of MMC on the generator side and motor side provide the same power to motor, the SOC balancing of batteries on both sides can be maintained. When it is necessary to provide sufficient power for the car and the remaining battery power is sufficient, the generator can be operated in an electric state, that is, the two motors drive the car together at this time. When the remaining power of the car batteries is insufficient, the generator runs to generate electricity to charge the battery and provide the power required for the operation of the motor. In this case, it’s called hybrid mode. In addition, energy recovery must be achieved when the car is braking. At this time, the motor can be operated alone in the power generation state. In this case, it’s called brake recovery mode. The DC bus plays the role of voltage support and power transmission. The specific working principle of the DC bus will be explained below.

In order to facilitate the description of the various arms and sub-modules of BMMC, a total of 12 arms on both sides are marked here, and each arm is represented by \(xyz\), where \(x=l, r\) represent the arms of the MMC on the left, \(r\) represents the arms of the MMC on the right; \(y=A, B, C\), where A, B, and C represent the three-phase arms of A, B, and C respectively; \(z=p, n\) represent the upper arm, and \(n\) represents the lower arm. After marking each arm, using the mark as a variable subscript can accurately represent the voltage, current and average SOC of each arm. For example, the average SOC of the upper arm of A phase on the generator side can be expressed as \(\text{SOC}_{lAp}\). Add a number after the mark to indicate the corresponding SM of the arm. For example, the first sub-module SOC of the upper arm of A phase on the generator side can be expressed as \(\text{SOC}_{lAp1}\).
3. Drive control strategy of BMMC - PHEV

The generator and motor used in this article are permanent magnet synchronous motors. The rotor of the permanent magnet synchronous motor is a permanent magnet, no excitation current is required during normal operation, no brushes and slip rings, which simplifies the motor structure and has better maintainability.

3.1. Control strategy of permanent magnet synchronous motor

The permanent magnet synchronous motor is controlled by $i_d=0$ control strategy. The arm current control strategy [9] can be used to control the arm current. Since the resistance of the bridge arm inductance was ignored in the process of modeling MMC, referring to the regulator parameters engineering design method, the arm controller adopts a proportional regulator, which generates a duty cycle signal $d_{yz}^*$ according to the difference between the reference value of arm current and the actual value of arm current, which is superimposed with the static duty cycle $D_{yz}^*$ to generate the arm’s common duty cycle $d_{yz}$. The PI controller is not used here because the integral link does not work on the tracking of the AC current at this time. Eliminate static error as much as possible by superimposing static duty cycle $D_{yz}^*$. And then the BMMC is controlled by an improved phase shifted carrier PWM. The outer speed loop uses a PI controller. The control schematic diagram of permanent magnet synchronous motor is shown in the Figure 3.

![Figure 3. The control schematic diagram of permanent magnet synchronous motor](image)

Figure 3. The control schematic diagram of permanent magnet synchronous motor

3.2. MMC control strategy of hybrid mode on the motor side

The idea of the control strategy is to realize the balanced control of the SOC of batteries on the motor side while realizing motor control, that is, to realize balanced discharge. This paper adopts the basic idea of hierarchical control and divides SOC balance control into three levels: Phase SOC balancing, Arm SOC balancing and Sub module SOC balancing. All controllers use PI controllers. Arm SOC balancing is realized by superimposing AC current increment. Phase SOC balancing is realized by superimposing DC circulating current. Sub module SOC balancing is realized by superimposing duty cycle increment. The control block diagram is shown in Figure 4. As the SOC imbalance between the upper and lower bridge arms of each phase may be different, after the current increment is superimposed in the command current, the three-phase upper (or lower) bridge arm current will...
contain zero sequence component, which affects the phase SOC balancing. The zero sequence current suppressor should be used to filter it. The structure of the zero sequence current suppressor is shown in Figure 5. The relationship between three phase DC circulating current is shown in Figure 6. $i_{xyz}^{*}$ is the command current. $I_{a}$ is the amplitude of the command current. The calculation method of SOC average value is shown in Formula 1.

$$\text{SOC}_{xyz} = \sum_{n=1}^{N} \text{SOC}_{xyz,n}$$
$$\text{SOC}_{y} = \frac{\text{SOC}_{yp} + \text{SOC}_{yn}}{2}$$
$$\text{SOC}_{r} = \frac{\text{SOC}_{rk} + \text{SOC}_{rl} + \text{SOC}_{rc}}{3}$$

### 3.3. MMC control strategy of hybrid mode on the generator side

The generator control strategy is basically the same as that of the motor. If the motor is to run in power generation, keep the direction of the motor speed unchanged and change the load torque to the opposite direction. There are three control objectives of MMC on the generator side: drive the motor to operate normally, maintain the balance of the battery SOC of SM on the generator side, maintain the DC bus voltage and control the power transmitted by the DC bus. The SM of the "back-to-back" MMC in the traditional flexible DC transmission and transformation field do not have batteries embedded, so it is necessary to control the DC bus voltage directly[9]. $U_{d}$ represents the DC bus voltage. The battery is embedded in the BMMC SM in this article. When the SM is charged or discharged, the energy can be absorbed or released by the battery, so the voltage of the SM can still be kept constant. When the BMMC drives the motor, in any phase, there are always N SMs in the ON state, and couple with the voltage of arm inductance, $U_{d}$ has only a small change due to the change of arm current. At this time, DC bus voltage can be equivalent to a voltage source relative to the motor side, so we do not need to control the DC bus voltage directly. This paper adopts the outer voltage loop and inner current loop to control the DC bus current directly and DC bus voltage indirectly on the generator side. If we choose to store the power generated by the generator in the batteries on the generator side first, and then transfer it from the batteries on the generator side to the motor side, it will have an adverse impact on the SOC equalization speed of the batteries, and the batteries have redundant charging and discharging process, resulting in battery loss and power loss. The electric power generated by the generator should be used to drive the generator first, and the excess electric rate will be stored in the batteries of each SM evenly. After the power of the generator is given as $P$, the power of the motor must be measured and calculated. Subtracting the power of motor from the power of generator is the power to be stored in the batteries. Figure 7 is the DC bus current control block diagram. $I_{d}$ is composed of two parts, one is the DC current $I_{d2}$ caused by the unbalanced average SOC between left and right MMC batteries, and the other is the DC current $I_{d1}$ caused by the power difference between generator and motor during operation. Because the arm current controller uses a proportional regulator, the calculated given current $I_{d1}$ cannot be directly superimposed on the command current, otherwise there will be static error. This paper uses DC bus controller to achieve the above goals. The output $I_{d}$ of the DC bus current controller is superimposed on the current $I_{xyz}^{*}$ generated in the process of control strategy on the motor side to obtain the control strategy on the generator side. DC bus current controller is PI controller. We just need to change the calculation method of the DC bus current to get control strategies for other drive models, including double motors for electric operation and motor operation alone.

### 3.4. MMC control strategy of EV mode on the motor side

The control strategy of MMC on the motor side does not need to be changed when BMMC works in the EV mode. But the control strategy of MMC on the generator side needs to be changed. Since the
generator does not work at this time, the MMC on generator side has no AC output, so the method of superimposing AC increments can no longer be used to arm SOC balancing. The control strategy of MMC on the generator side is shown in Figure 8. Arm SOC balancing is achieved by superimposing the duty cycle increment. The batteries on both sides of BMMC provide half of the power required for the operation of motor. If the motor power is $\mathbf{P}_1$, then $I_{d^*}=0.5\times\mathbf{P}_1/\mathbf{U}_d+I_{d2}$. It can be foreseen that when a single generator is working or a single motor is running (brake recovery electric energy), the arm SOC balancing is realized by superimposing the duty cycle increment for the side which motor or generator does not work under the corresponding working state. And by changing the calculation method of the DC bus command current, the comprehensive control method under the corresponding working mode can be obtained, which will not be repeated here.

![Figure 7. Control block diagram of DC bus current](image)

![Figure 8. Control block diagram of MMC on the generator side](image)

### 4. Experimental results

In order to verify the feasibility and effectiveness of the above control strategy, this article uses the RT-LAB real-time simulator model OP5600 for experimental verification. Due to the limitation of real-time computing capability of the real-time simulator, each arm of the BMMC drive system consists of only 4 SMs, and the real-time simulation step is 50μs. The reference direction of arm current is shown in Figure 2. The current and voltage waveforms of each channel can be observed with an oscilloscope through the RJ45 port on the front panel of OP5600. The battery in SM have a rated voltage of 126V and a rated capacity of 20Ah. The size of the arm reactor is 5mH, and the motor parameters are shown in Table 1. The parameters of generator and motor are the same.

| Parameter                | Value          |
|--------------------------|----------------|
| Stator phase resistance  | 0.958Ω         |
| Armature inductance      | 10mH           |
| Voltage Constant         | 98.67V_peak L-L / krpm |
| Inertia                  | $1.79\times10^9$kg·m² |
| Viscous damping          | $1.79\times10^4$N·m·s |
| pole pairs               | 2              |
| static friction          | 0N·m           |

| Arm | SOC(%) | Arm | SOC(%) |
|-----|--------|-----|--------|
| lAp | 61     | rAp | 56     |
| lAn | 59     | rAn | 54     |
| lBp | 57     | rBp | 52     |
| lBn | 55     | rBn | 50     |
| lCp | 53     | rCp | 48     |
| lCn | 51     | rCn | 46     |

#### 4.1. Working condition one

Set SOC of the batteries in lower arm to 60% and SOC of the batteries in upper arm to 50%. The initial given speed of the motor is 1576r/min, the given speed becomes 1795r/min in 1s, and the load torque is always 10N·m. The given speed of the generator is always 1576r/min, the initial given load...
torque is -30N·m, and it becomes -20 N·m at 0.8s. Figures 9 and 10 are the speed waveform diagrams of generator and motor respectively. It can be seen that both the generator and the motor can run stably and have good dynamic performance during acceleration and deceleration. Figure 11 shows the three-phase current of the motor stator, which is a symmetrical three-phase AC current. Figure 12 shows the generator stator three-phase current. At 0.8s, the load torque decreases, the current also decreases and tends to stabilize, and the generator power decreases. Figure 13 is the waveform of command DC bus current. Figure 14 is the waveform of actual DC bus current, both $I_d$ and $I_q$ are about 3.7A before 0.8s, and the DC bus current becomes 3.3A due to the generator torque change at 0.8s. Due to the change of the motor speed at 1s, it becomes 3.4A again. By comparing figure 13 and figure 14, it can be seen

![Figure 9. Waveform of motor speed](image1)

![Figure 10. Waveform of generator speed](image2)

![Figure 11. Three phase current of motor stator](image3)

![Figure 12. Three phase current of generator stator](image4)

![Figure 13. Command value of DC bus current](image5)

![Figure 14. Actual value of DC bus current](image6)

![Figure 15. Waveform of upper and lower arm of phase A on the generator side](image7)

![Figure 16. Waveform of upper and lower arm of phase A on the motor side](image8)
that the DC bus current can accurately and quickly follow the command value, the generator side can accurately transmit power to the motor side, and the SOC balance of the MMC batteries on both sides can be quickly achieved while driving the motor, avoiding repeated charging. Discharge causes battery loss and power loss. Figures 15 and 16 are the waveforms of upper and lower arms of phase A on the generator side and motor side, respectively. The upper arm current and the lower arm current differ by a certain AC increment, which is used to achieve SOC balancing between upper and lower arm. The upper arm current amplitude of phase A on generator side is larger than lower arm current amplitude of phase A on generator side, because the charging current flows through the arms at this time; The lower arm current amplitude of phase A on motor side is larger than upper arm current amplitude of phase A on motor side, because the discharge current flows through the arms at this time. The currents of upper and lower arms also contain DC currents of the same magnitude and opposite directions, which are caused by the current $I_0$ superimposed on the arms. Their directions are opposite because the reference directions of the upper and lower arms are opposite.

4.2. Working condition two

In order to verify the effectiveness of the proposed motor drive and SOC equalization control strategy furtherly, the data generated by the target machine is received by the host computer in a longer time scale and sorted out. Verification is carried out for each working condition. The initial average SOC of each arm in the experiment is shown in Table 2, and the remaining parameters are consistent with the foregoing. The rated capacity of the battery in SM is changed to 10Ah in EV mode. The equalization
processes of hybrid mode and EV mode are shown in Figure 17, 18, 19 and Figure 20, 21, 22 respectively.

5. Conclusion
Aiming at PHEV system based on BMMC topology, this paper presents a dual-motor control strategy based on hierarchical battery SOC equalization, which realizes the power transmission and management among generators, motors and batteries, and facilitates free switching between different drive modes. It is conducive to the integrated design of the whole vehicle and improves the power density of the converter. It is of great significance to the development of PHEV. The correctness and feasibility of the control strategy are verified through RT-LAB real-time simulation. BMMC topology can also be used for multi-port energy storage, so the research in this article has universal significance and good application prospects. Experimental verification will be carried out and MPC will be used to improve control strategies in the next step.

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