Junction temperature consistency analysis of MMC submodule

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Abstract:Although modular multilevel converter(MMC)is currently widely used in the field of DC power transmission due to its excellent topology performance, the natural DC bias characteristics inevitably cause thermal imbalance of internal devices. Too high temperature at the junction of power devices is one of the major causes of damage. Therefore, it is necessary to further investigate the factors that affect the device junction temperature. This paper calculated the power loss and junction temperature by combined the thermal impedance model and compared junction temperature under two typical modulation strategies .

Keywords:modular multilevel converter;modulation strategy; power loss; junction temperature fluctuation

1. Introduction

Modular multilevel converter (MMC) is widely applied in the field of flexible DC transmission due to its low switching frequency and favourable transmission characteristics, but a large number of studies in the industry have focused on the topology, redundancy control, control strategy, optimization and improvement of MMC, etc.. Only a few studies have focused on the junction temperature and reliability of the power devices.

With the spread of MMC, reliability evaluation of MMC has become very important, and research on device junction temperature is drawing attention. The most important power device of the MMC system, IGBT, is too hot to fail. So it is important to evaluate the heat loss. Although the actual operating temperature is often designed to be below the maximum operating temperature, the control strategy sets a lower reference current so that the device temperature does not exceed the maximum operating temperature.

In this paper, we study the factors that influence the junction temperature based on the half-bridge topology, estimate the power loss and the junction temperature of the power device, and compare the junction temperature from the Nearest Level Modulation (NLM) strategy and Carrier Phase Shift Pulse Width Modulation (CPS-PWM) strategy, respectively.

2. MMC Topology

Fig. 1 shows a three-phase MMC, consists of six-bridge arms, each arm connected directly in series by several submodules and an arm inductor , allows two-way flow of energy. Half-bridge topology of submodule is selected as shown in Fig. 2, consists of two IGBTs and their antiparallel diodes, and an energy storage capacity. The switch state of the submodule is controlled by the fully controlled switch element IGBT. Where T1 and T2 represents the two IGBTs, and D1 and D2 represents their antiparallel diodes, respectively. The switch state of the half-bridge submodule is as shown in Fig. 3. When the direction of the current changes from A to B, if T1 opens and T2 turns off, the current through D1 and the capacitor is charged, and the submodule is in the on state; if T1 is off and T2 is on, the current will flow through T2 and the submodule will be in the cut state. When the current direction goes from B to A, if T1 is open and T2 is closed, the current flows through the T1 and the capacitor is discharged, leaving the submodule in the on state; if T1 is off and T2 is on, the submodule is in the cut state and current flows through D2. It can be seen that when T1 opens, the submodule is inserted, and when T2 opens, the submodule is excised.

Ignoring the effects of the inductance and resistance of the bridge arm, AC side voltage Ua and DC bus voltage Udc are as follows:

$$U_a = \frac{U_l - U_u}{2} \tag{1}$$

$$U_{dc} = U_u + U_l \tag{2}$$

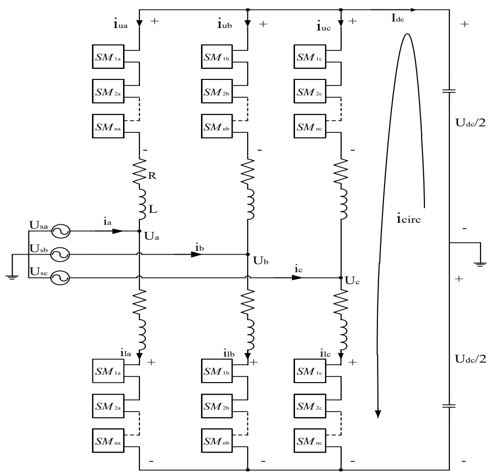

Figure 1. A three-phase MMC topology under a rectified condition

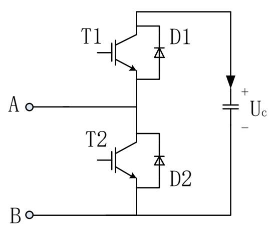

Figure 2. Half bridge submodule topology consists of two IGBTs

3. Modulation Strategy

Currently, the two widely studied modulation strategies are the Nearest Level Modulation (NLM) strategy and Carrier Phase Shift Pulse Width Modulation (CPS-PWM) strategy. The principle of NLM strategy is simple and convenient to control, but the output waveform is distorted when there are few submodules. In the CPS-PWM strategy, a control signal can be assigned to each submodule individually, but the switching frequency is significantly increased.

Nearest Level Modulation strategy

NLM use an integer function to find the number of submodules to put into the bridge arm, nu represent the number of upper bridge arm submodules, nl represent the number of lower bridge arm submodules. The number of submodules which turn on at any time is N. The DC bus voltage is superimposed on each submodule voltage.

$$\begin{cases} n_u = round(\frac{U_u}{U_c}) \\ n_l = round(\frac{U_l}{U_c}) \end{cases} \tag{3}$$

Carrier Phase Shift Pulse Width Modulation strategy

In the carrier phase shift pulse width modulation strategy, a triangular wave is adopted as a carrier wave, the upper bridge arm contains n submodules, and each submodule is assigned a modulated wave which having the same amplitude and the same frequency but a phase difference of 2π/n. Compare the sine reference wave with the modulated wave. If the modulated wave is larger than the reference wave, it is input to the submodule. If the modulated wave is smaller than the reference wave, cut out the corresponding submodule.The reference wave usually uses the power frequency.

Junction Temperature Estimation

Currently, a thermal impedance model is generally used for estimating the temperature of a power device junction. There are mainly Foster model and Cauer model in the thermal impedance model. The Cauer model builds a thermal impedance network based on the physical structure, and the thermal resistance of each layer corresponds to the actual physical structure. The Foster model uses a series of thermal resistances that have no real meaning, so it is not possible to handle the exact temperature difference between the heat transfer layers, but it is easy to obtain the junction temperature difference between the power device and the measurement point directly.

In the thermal impedance model, the power loss can be seen as the power source, the junction temperature can be seen as the voltage, and the heat conduction is analyzed as the voltage conduction of the circuit.The junction temperature is expressed as follows:

$$T_{\mathrm{j}} = P_{loss} * Z_{th}\left(t\right) + T_{a} \quad (5)$$

Where Tjrepresent the junction temperature of power device , Ploss represent the power loss, Ta represent the environment temperature.

When the device is turned on, there is a constant conduction pressure drop, so the power loss caused by that conduction current is called the conduction pressure loss. The conduction pressure drop is expressed by using the vendor data sheet as follows:

$$P_{cond} = U_{CE}\ (T_j) \cdot I_C + R_{CE}\ (T_j) \cdot I_C^{\ 2} \quad (6)$$

The switching loss occurs during the switching operation of the power device, and the relationship between one switching energy and the conduction current is shown in the data sheet. The switching loss is expressed as follows:

$$P_{sw} = E_{sw}\left(I_C\right) f_{sw} \frac{U_C}{U_{CE}^{ref}} \quad (7)$$

Power loss is the sum of conduction loss and switching loss.

Results Contrast

A simulink simulation model was constructed by comparing the junction temperature fluctuations of the half-bridge submodules with the two modulation strategies of nearest level modulation and carrier phase shift modulation, using 4 submodules with 5 level systems. The system adopts submodule capacitance C 50mF, bridge arm inductor L 70mH, DC bus voltage 10kV and other parameters.

Fig. 4 shows the junction temperature fluctuations of each switching device in the submodule modulated by NLM strategy. Fig. 5 shows the junction temperature fluctuations of each switching device in the submodule modulated by CPS-PWMstrategy. Both working under the same condition of rectifier and system parameters.

Contrast Fig. 4 and Fig. 5, the switching devices within the submodule have roughly the same temperature fluctuations, and the temperature of D2 is the highest both in the two modulation strategies.

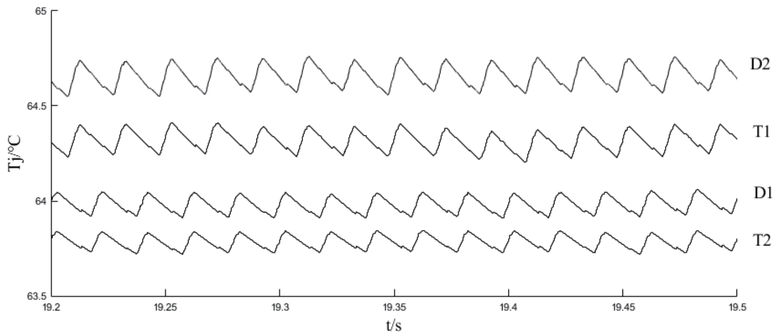

Figure 3. Junction temperature of switching device in the half-bridge submodule by NLM strategy

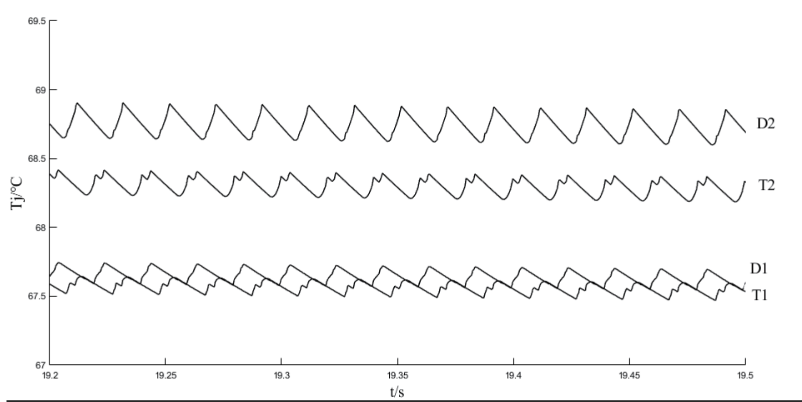

Figure 4. Junction temperature of switching device in the half-bridge submodule by CPS-PWM strategy

It turns out the junction temperature fluctuation of the switching device that adopted the CPS-PWM method is more higher than that of the NLM method. The junction temperature of the switching element that adopts the carrier phase shift modulation method is higher, and taking the maximum junction temperature D2 as an example, the difference in junction temperature when the carrier phase shift modulation method is adopted. It is about 4°C higher than when the NLM method is adopted.

From the junction temperature fluctuation analysis inside the module, when the junction temperature of D2 is the highest, the temperature of each submodule is expressed by the junction temperature of D2.

Fig. 6 shows the junction temperatures of the four submodules of the upper bridge arm are reciprocating between the sub-modules by NLM method. It can be seen that the maximum temperature difference does not exceed 0.2°C in the reciprocating cycle of the temperature between the submodules of the NLM method. On the other hand, in the carrier phase shift modulation method, the temperature fluctuation waveforms between the submodules are almost the same, but the maximum temperature difference value reaches 0.7°C far more than the temperature difference in NLM method.

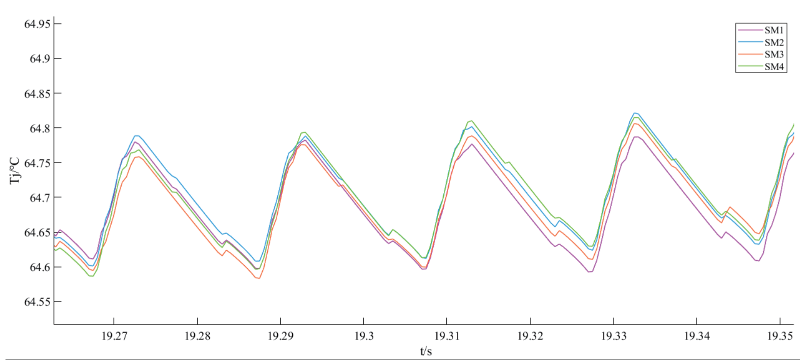

Figure 5.Junction temperature fluctuation of four submodule of upper brige arm modulation by NLM strategy

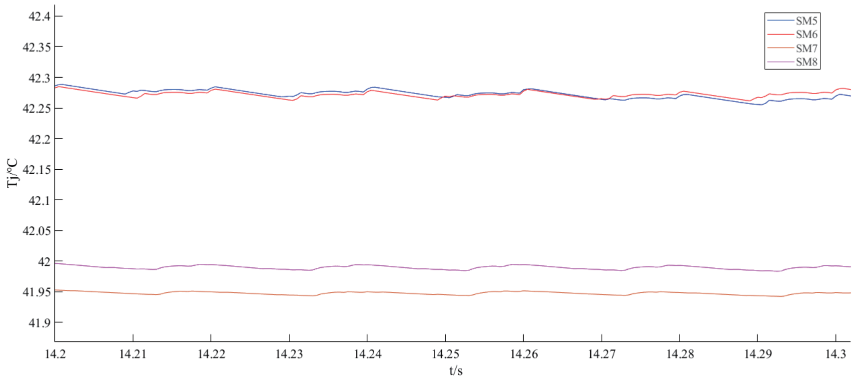

Figure 6. Junction temperature fluctuation of four submodule of upper brige arm modulation by NLM strategy

6. Conclusion

Comparing the junction temperature fluctuations of the two modulation strategies, the nearest level modulation strategy show that the junction temperature fluctuations of the switching devices in the module are small and the heat loss between the submodules circulates periodically, there is a good consistency.

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