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Imbalance Mechanism of Capacitor Voltage and Control Strategy for Hybrid Modular Multilevel Converter with Negative Output

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Imbalance Mechanism of Capacitor Voltage and Control Strategy for Hybrid Modular Multilevel Converter with Negative Output

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Abstract: In a flexible DC transmission system with a large-capacity overhead line, a hybrid modular multilevel converter (MMC) consisting of the half bridge submodule (HBSM) and the full bridge submodule (FBSM) has become a research hotspot due to its self-cleaning capability of DC short-circuit fault. Under the operating conditions of reducing the DC voltage, due to the different charging and discharging characteristics of the half bridge submodule and the full bridge submodule, a capacitor voltage imbalance may occur between the two submodules. This paper first studies the number configuration of half-bridge submodules and full-bridge sub-modules in modular multilevel converters. Then, the capacitor voltage imbalance mechanism of the hybrid MMC sub-module is analyzed in detail, and the optimal control strategy of the capacitor voltage balance is derived according to the configuration requirements of the two sub-modules. Finally, a hybrid MMC-based flexible DC transmission system is established in the PSCAD/EMTDC simulation environment, low DC voltage operation of the system are simulated to verify the correctness and effectiveness of the control strategy.

1. Introduction

In long-distance large-capacity DC transmission systems, the inverter converter station of LCC-HVDC has the risk of commutation failure. The voltage source converter based high voltage direct current transmission system (VSC-HVDC) based on the fully controlled device does not have the problem of commutation failure. Among them, the modular multilevel converter (MMC) has become a development advantage of VSC-HVDC due to its advantages of small running loss, strong expandability and relatively low cost [1,2]. The MMC based on HBSM does not have the ability to clear the DC-side fault. When the DC-side fault occurs and the converter is blocked, the AC system can still form a loop through the anti-parallel freewheeling diode in the converter arm and the DC fault point. The MMC based on FBSM has attracted attention because it can operate at low DC voltage [3]. However, the number of power electronics of the FBSM is much higher than that of the HBSM, which increases the investment cost and operating loss of the converter. Therefore, some literature studies the operating characteristics of converter based on hybrid MMC[4].

In this paper, based on [5], the working principle and operating characteristics of the HBSM and the FBSM are analyzed in detail. The number configuration requirements of the HBSM and the FBSM under conditions of low DC voltage operation and satisfying DC fault ride through are derived. Then,



based on this, the mechanism of the imbalance of the capacitor voltage between the two sub-module segments under the condition of over-modulation operation of the hybrid MMC is analyzed in detail. An optimal control strategy for capacitor voltage balance of sub-modules is proposed. Finally, a flexible DC transmission system based on hybrid MMC is established in the PSCAD/EMTDC.

2. Basic principles of hybrid MMC

2.1 Hybrid MMC Topology

Figure 1 shows the circuit topology of a hybrid MMC. The first picture on the right side of figure 1 shows the topology of the HBSM. The second picture on the right side of Figure 1 shows the topology of the FBSM. Figure 2 shows the structure of the hybrid DC system.

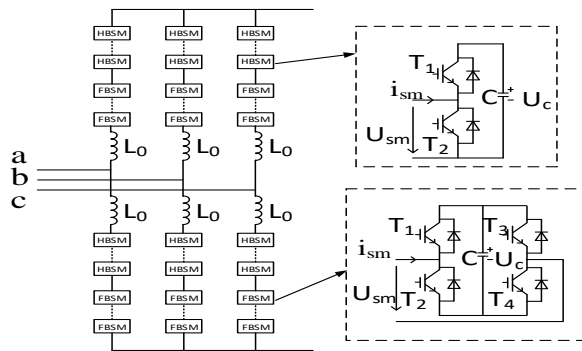


Figure 1. Hybrid MMC topology.

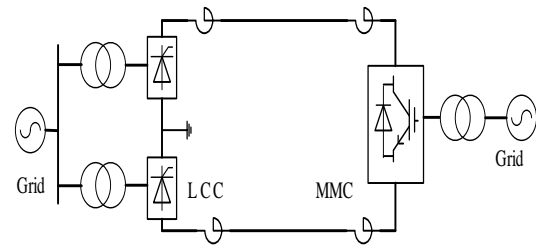


Figure 2. Topology of hybrid HVDC system.

2.2 Hybrid MMC submodule configuration principles

Since the number of switching devices and the on-state loss of the FBSM are higher than that of the HBSM, the proportion of the FBSM in the total number of bridge-arm sub-modules is reduced as much as possible under various constraints. Assume that the AC modulation index of the hybrid MMC is

$$m = U_m / (0.5U_{dc}) \quad (1)$$

where U_m is the phase voltage amplitude of the AC output of the converter, U_{dc} is DC voltage value

Since the voltage drop of the series inductance of the bridge arm is small relative to the DC voltage, the voltage drop across the inductor is ignored. Taking the A-phase upper arm as an example, the bridge arm voltage can be obtained.

$$u_{pa} = 0.5U_{dc} - u_{va} = 0.5U_{dc}(1 - m\sin(\omega t)) \quad (2)$$

According to formula (2), the variation range of the bridge arm voltage is

$$0.5U_{dc}(1 - m) \leq u_{pa} \leq 0.5U_{dc}(1 + m) \quad (3)$$

The total number of bridge arm submodules is

$$N = H + F = \max \{ [0.5U_{dc}(1 + m)] / U_{cn} \} = [0.5U_{dcn} + U_m] / U_{cn} \quad (4)$$

When the bridge arm voltage is negative, the full bridge submodule needs to be put into operation. And when the DC voltage takes the minimum value, the number of full bridge submodules that need to be input is the largest. Therefore, the number of full bridge submodules in the bridge arm is

$$F = [U_m - 0.5U_{dc\min}] / U_{cn} \quad (5)$$

It can be known from equations (4) and (5) that the number of half bridge modules is

$$H = N - F = [0.5(U_{dcn} + U_{dc\min})] / U_{cn} \quad (6)$$

When a short-circuit fault occurs on the DC side, the converter is blocked, and the FBSM in the bridge arm provides a reverse potential to reduce the short-circuit current to zero. Therefore, the condition that the reverse potential provided by the FBSM in the (PTP) fault circuit is greater than the

amplitude of the AC line voltage. Based on this condition, the number of full bridge modules in the bridge arm.

$$F = \begin{cases} \left[(\sqrt{3}m_0) / (2 + 2m_0) \right] N & m_0 \leq m \leq 7.464 \\ \left[(m_0 - U_{dc\min} / U_{dcn}) / (1 + m_0) \right] N & m > 7.464 \end{cases} \quad (7)$$

When the hybrid MMC is running stably, the power on both sides of the AC and DC should be equal. In order to maintain the balance of the capacitor voltage of the HBSM, the bridge arm current has both positive and negative values in one cycle, that is $m < 2/\cos\varphi$. If $m \geq 2/\cos\varphi$, only the full bridge submodule can be input. Therefore, according to equations (7),

$$F = \begin{cases} \left[m_0 / (1 + m_0) \right] N & m_0 \leq m \leq 2 / \cos\varphi \\ \left[(2m_0 + m_0 \cos\varphi) / (2 + 2m_0) \right] N & m > 2 / \cos\varphi \end{cases} \quad (8)$$

3. Capacitor voltage imbalance mechanism of hybrid MMC

When the bridge arm of the hybrid MMC requires FBSM to output a negative voltage, due to the different charge and discharge characteristics of the HBSM and the FBSM, the capacitor voltage balance cannot be guaranteed by the algorithm of sorting input alone. The mechanism of the voltage imbalance of the two sub-modules in one cycle will be analyzed in detail below. Assume that the capacitor voltage of the same sub-module is always balanced, which is simplified to analyze the capacitor voltage imbalance between the FBSM and the HBSM, and ignore sub-module internal losses.

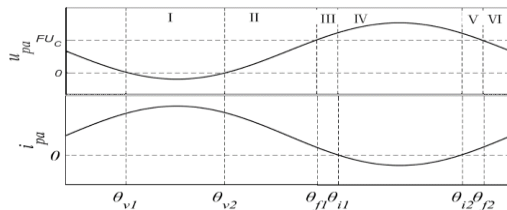


Figure 3. Bridge arm voltage and current.

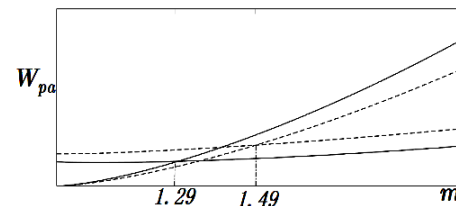


Figure 4. Energy changes during the first and second periods.

As shown in figure 3, the variation of the voltage and current of the bridge arm in one cycle is divided into six periods, and the time at which each period starts is

$$\begin{cases} \theta_{v1} = \arcsin(1/m) & m \geq 1 \\ \theta_{v2} = \pi - \arcsin(1/m) & m \geq 1 \\ \theta_{f1} = \pi + \arcsin(m \cos\varphi / 2) + \varphi & 1 \leq m \leq 2 / \cos\varphi \\ \theta_{f2} = 2\pi - \arcsin(m \cos\varphi / 2) + \varphi & 1 \leq m \leq 2 / \cos\varphi \\ \theta_{i1} = \pi + \arcsin[(2FU_c / U_{dc} - 1) / m] & m \geq 1 \\ \theta_{i2} = 2\pi - \arcsin[(2FU_c / U_{dc} - 1) / m] & m \geq 1 \end{cases} \quad (9)$$

Taking the time θ_{v1} as the beginning of a cycle, it is assumed that the capacitance of the HBSM is equal to the capacitance of the FBSM at that time, that is U_c .

During the first period, the bridge arm voltage is negative and the current is positive. At this time, the capacitor of the FBSM discharges, the capacitor voltage drops, and the HBSM is bypassed. At the end of the first period, the FBSM capacitor voltage is

$$u_{cf}(\theta_{v2}) = [U_c^2 + (2 \int_{\theta_{v1}}^{\theta_{v2}} u_{pa} i_{pa} d\omega t) / (FC)]^{1/2} = \{U_c^2 - [U_{dc} I_m \cos\varphi (m^2 - 1)^{3/2}] / (2\omega m FC)\}^{1/2} \quad (10)$$

The energy released by the FBSM during the first period is

$$W_{If} = \int_{\theta_{v1}}^{\theta_{v2}} u_{pa} i_{pa} d\omega t = [U_{dc} I_m \cos\varphi (m^2 - 1)^{3/2}] / (4\omega m) \quad (11)$$

During the second period, the bridge arm voltage and current are both positive, and the capacitor

voltage of the inserted sub-module rises. However, in the first period, the FBSM is put into operation, and its capacitor voltage is lower than that of the HBSM. Therefore, the FBSM is preferentially input during this period until the capacitor voltage of FBSM is equal to that of the HBSM. Assuming that only the FBSM is input in the second period, the FBSM capacitor voltage is at the end of the second period

$$u_{cf}(\theta_{f1}) = \left(U_c^2 + (2 \int_{\theta_{v1}}^{\theta_{f1}} u_{pa} i_{pa} d\omega t) / (FC) \right)^{1/2} \quad (12)$$

The energy absorbed by the FBSM during the second period is

$$W_{\text{II}f} = \int_{\theta_{v2}}^{\theta_{f1}} u_{pa} i_{pa} d\omega t = [(U_{dc} I_m) / 8\omega] \int_{\theta_{v2}}^{\theta_{f1}} m^2 \sin(\omega t) \cos \varphi - 2 \sin(\omega t - \varphi) - m \cos(2\omega t - \varphi) d\omega t \quad (13)$$

If $W_{\text{I}f} < W_{\text{II}f}$, the FBSM capacitor voltage can rise to the same as the HBSM capacitor voltage at some point during the second period. In figure 4, the solid line indicates the energy variation of the FBSM in the first period and the second period when $\cos\varphi=1$, and the two submodule capacitor voltages may be equal at some time in the second period when $m < 1.29$ is satisfied. The dashed line indicates the energy variation of the FBSM when $\cos\varphi=0.8$, and $m < 1.49$ should be satisfied at this time. If the above conditions are not satisfied, it will be judged whether the capacitor voltage balance can be maintained according to the conditions of other time periods. According to the analysis of each time period, the HBSM is only input during the III, IV, and V periods, so the energy added by the HBSM in one cycle is

$$\begin{aligned} \Delta W_h = & \int_{\theta_{f1}}^{\theta_{h1}} [0.5U_{dc}(1-m\sin\omega t) - v_{cf}(0.5m_0U_{dcn} + m_0U_m) / (U_{cn} + m_0U_{cn})] \times 0.5I_m [0.5m\cos\varphi + \sin(\omega t - \varphi)] d\omega t \\ & + \int_{\theta_{f2}}^{\theta_{h2}} [\frac{U_{dc}}{2}(1-m\sin\omega t) - v_{cf}(0.5m_0U_{dcn} + m_0U_m) / (U_{cn} + m_0U_{cn})] \times 0.5I_m [0.5m\cos\varphi + \sin(\omega t - \varphi)] d\omega t \\ & + \int_{\theta_{h1}}^{\theta_{h2}} [v_{ch}(0.5U_{dcn} + U_m) / (U_{cn} + m_0U_{cn})] \times 0.5I_m [0.5m\cos\varphi + \sin(\omega t - \varphi)] d\omega t \end{aligned} \quad (14)$$

If ΔW_h is less than zero, the capacitor voltages of the HBSM and the FBSM can be balanced; if ΔW_h is greater than zero, the capacitor voltages of the HBSM and the FBSM cannot be balanced.

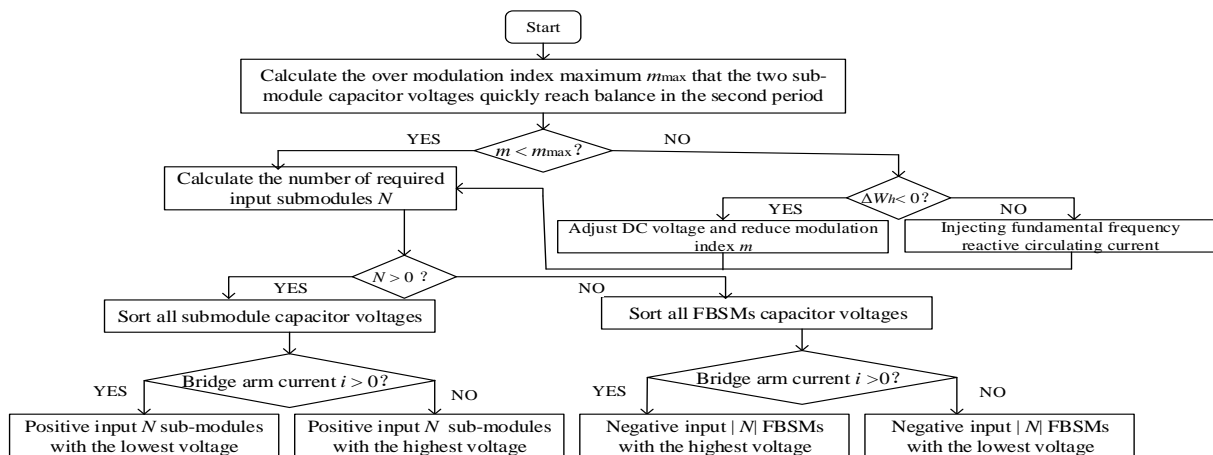


Figure 5. Two-module capacitor voltage balance control strategy.

According to equation (14), the voltage imbalance of the HBSM and the FBSM is mainly related to the modulation index m and the power angle φ . If the calculated ΔW_h is less than zero, the capacitor voltage balance of the two submodules can be ensured. When m and φ satisfy a certain condition, the HBSM and the FBSM can quickly reach the capacitor voltage balance in the second period. Based on the reference [2], as shown in figure 5, an optimized two-module capacitor voltage balance control strategy is proposed.

4. Simulation and verification

A simulation model as shown in figure 2 was built on the PSCAD/EMTDC platform. The rated DC voltage is 400kV. Each bridge arm has 108 HBSM and 108 FBSM. The rated voltage of the submodule is 1.85kV.

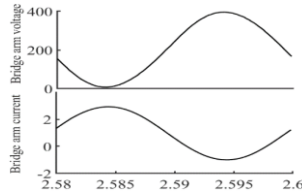


Figure 6. Bridge voltage and current when DC voltage is 400kV.

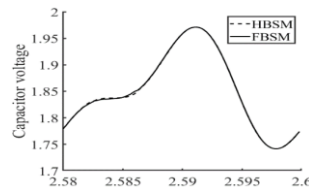


Figure 7. Capacitor voltage when the DC voltage is 400kV

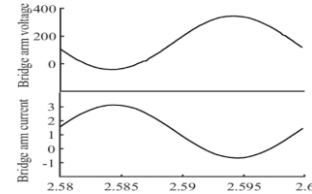


Figure 8. Bridge voltage and current when DC voltage is 300kV

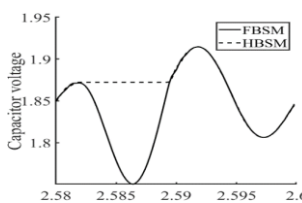


Figure 9. Capacitor voltage when DC voltage is 300kV.

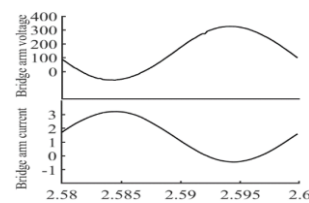


Figure 10. Bridge voltage and current when DC voltage is 260kV.

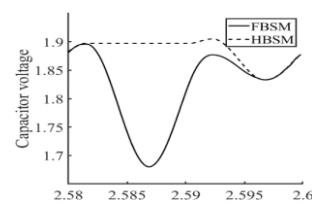


Figure 11. Capacitor voltage when the DC voltage is 260kV

In this paper, the simulation analysis is carried out by taking a period of 2.58s to 2.6s in steady state operation as an example. As shown in figure 6 and figure 7, when the DC voltage is running at the rated value of 400kV, the bridge arm voltage is always positive, and the FBSM is not negatively input. At this time, the voltage changes of the two sub-modules are also the same. Figure 8 shows that when the DC voltage drops to 300kV, the bridge arm outputs a negative voltage for a certain period of time. At this time, the FBSM is to be negatively input. It can be seen from the figure 9 that when the bridge arm outputs a negative voltage, the HBSM is blocked. During this period, the capacitor voltages of the two sub-modules are not equal. However, before the HBSM is put into operation, the capacitor voltages of the two sub-modules can be balanced by selecting sort and controlling input. Figure 10 shows the variation of the bridge arm voltage and current when the DC voltage is running at 260 kV. Figure 11 shows the change in the capacitor voltage of the two sub-modules for this period. It can be seen from the figure that before the HBSM is put into operation, the FBSM cannot reach the capacitor voltage equal to the HBSM, so in a certain period of time, the two submodules operate under the condition that the capacitor voltage is unbalanced. When the DC voltage continues to drop to a certain value, the capacitor voltage of the HBSM will continue to rise, and the capacitor voltage of the FBSM will continue to drop until the DC system cannot operate.

5. Conclusion

The following conclusions were obtained: (1) For hybrid MMC, the total number of bridge arm submodules can be determined by the rated DC voltage and the submodule capacitor voltage. Under the various constraints, the minimum proportion of full bridge submodules is derived. (2) According to the configuration requirements of the HBSM and the FBSM in the hybrid MMC, in the period from the bridge arm output negative voltage to the HBSM input, m and ϕ should satisfy certain conditions in order to quickly balance the capacitor voltages of the two sub-modules. (3) According to the modulation index m and energy variation of the HBSM in one cycle, it is concluded whether the two sub-modules can be balanced. Therefore, the optimal balance control strategy is proposed by using this criterion.

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