A new precharging strategy for hybrid MMC based on HBSM and FBSM

Lei Han1*, Junfeng Jiang1 and Haitao Yao1

1 School of Electrical and Information Engineering, Jiangsu University, Zhenjiang, Jiangsu, 212013, China

*Corresponding author’s e-mail:1294119299@qq.com

Abstract. Precharging of the modular multilevel converter (MMC) is an important basis for ensuring the normal operation of MMC-HVDC system. The hybrid MMC based on full bridge sub-module (FBSM) and half bridge sub-module (HBSM) has reliable performance in DC fault ride-through capability and is receiving more and more attention. Due to the different charging characteristics of FBSM and HBSM, the sub-modules (SMs) capacitor voltages may be different at the end of the uncontrolled precharging process. This paper introduces conventional uncontrolled precharging strategy of the hybrid MMC and points out the problems in the process. Then a three-stage precharging strategy is proposed in this paper. This strategy can eliminate the capacitor voltages imbalance of different SMs and solve the problem of unsuccessful self-taking energy of HBSM during precharging process. Finally, simulation and analysis of the uncontrolled precharging process based on the proposed strategy are carried out.

1. Introduction
Modular multilevel converter (MMC) has attracted increasing attention due to its advantages in recent years[1-2]. Most of the MMCs that are currently in operation are based on half-bridge sub-module[3]. However, MMC based on half-bridge sub-modules cannot block DC faults by themselves. In order to enable MMC to block DC faults, scholars have proposed many new topologies. Among them, the MMC based on the full bridge sub-module (FBSM) has many switching devices but large losses. The hybrid MMC based on half-bridge sub-module and full-bridge sub-module combines the advantages of HBSM and FBSM, and therefore has broad application prospects.

At present, the research on hybrid MMC is mainly focused on DC fault ride-through capability, but less research on its charging process. Since the charging process is the basis of the normal operation of the system, it is necessary to analyze the charging strategy of the hybrid MMC. There are many researches on the precharging strategy of MMC based on HBSM[4-5], but few studies on hybrid MMC. Most precharging strategies of the hybrid MMC still follow the charging process of the HBSM-MMC. Since the charging speed of the FBSM is twice that of the HBSM during charging process, the capacitor voltages of two kinds of SMs are different at the end of the uncontrolled precharging stage. Theoretical and mathematical analysis of start-up process were introduced in[6]. The current limiting resistor protection for the start-up process is proposed in[7]. Group charging strategy is proposed in[8]. This charging strategy can eliminate voltage imbalance, but it will lead to longer charging time and complicated operation.

In this paper, a three-stage precharging strategy is proposed to solve the problem of unsuccessful self-taking energy of HBSM during conventional precharging process, and the theoretical conditions of this charging strategy are analyzed. Finally, the feasibility of the charging strategy is verified by
simulation in PSCAD/EMTDC.

2. Analysis of conventional uncontrolled precharging process

The hybrid MMC consisting of HBSM and FBSM is shown in figure 1. Each arm consists of \( N_h \) HBSMs and \( 2N_f \) FBSMs which are connected in series with each other. \( L_0 \) is the arm inductor used to suppress the circulating current.

\[
N_h U_{ch} + 2N_f U_{cf} = U_i
\]

As shown in figure 2, the FBSM is always in charge regardless of the charging current direction, but the HBSM is only charged when the charging current is positive. Therefore, the charging time of the HBSM is only half of that of the FBSM. Then the voltage of the FBSM is twice that of the HBSM at the end of the uncontrolled charging process.

\[
U_{dc} = (N_f + N_h) U_{cr}
\]

So the ratio of \( U_{cr} \) to \( U_{ch} \) can be expressed by
\[ \frac{U_{ch}}{U_{cr}} = \frac{\sqrt{3}}{2} M \frac{N_h + N_f}{N_h + 4N_f} = \frac{\sqrt{3}}{2} M \frac{1 + k}{1 + 4k} \]  \hspace{1cm} (4)

\( k \) is the ratio of the number of FBSM to HBSM in each arm, \( M = 0.85 \). As shown in figure 3, the value of \( \frac{U_{ch}}{U_{cr}} \) decreases as \( k \) increases. The triggering of the IGBT depends on the self-extraction energy of the module capacitor. Therefore, the capacitor voltage should not be too low, generally not lower than 25% of the rated voltage. The voltage of HBSM is less than 25% of the rated voltage when \( k > 2.5 \), so the HBSM at this time is uncontrolled and system cannot enter the controllable charging process. This paper proposes a new charging strategy, which can solve the problem of voltage imbalance between HBSM and FBSM while enabling HBSM capacitor obtains sufficient power.

3. Improved uncontrolled precharging strategy

The uncontrolled charging is divided into three stages: HBSM charging stage, FBSM boost stage and semi-controlled charging stage.

3.1 HBSM charging stage

Isolate the FBSM when the system is started, and the system is equivalent to the uncontrolled charging stage of HBSM-MMC. The charging of MMC is a RLC circuit. Since the SM capacitor voltage is 0, an inrush current occurs when the system starts up. Therefore, current limiting resistors are necessary.

3.2 FBSM boost stage

When the HBSM capacitor voltage reaches a certain value, the FBSM will put into charging. The FBSM charging speed is twice the characteristics of the half-bridge sub-module, so that its capacitor voltage quickly catches up the HBSM. When the FBSM and HBSM capacitor voltages are the same, the system will enter the semi-controlled charging stage. The capacitor voltage of each SM at the end of the stage depends on the moment the FBSMs put into charging. It is worth noting that if FBSMs put into charging prematurely, the capacitor voltage will not reach 25% of the rated when the FBSM and HBSM voltages are equal. If FBSMs put into charge too late, the capacitor voltage of the FBSM does not reach the corresponding level of the HBSM. Therefore, it is necessary to discuss when to put FBSM into charging.

Assuming that the voltages of the two types of SMs are equal, the sum of the SM voltages in the charging loop is exactly equal to the line voltage amplitude. The capacitor voltage of SM at this time can be solved as
\[ U_{cl} = \frac{U_i}{N_h + 2N_f} \]  

\[ U_{cr} = \frac{\sqrt{3}}{2} M \frac{N_h + N_f}{N_h + 2N_f} = \frac{\sqrt{3}}{2} M \frac{1 + k}{1 + 2k} \]  

\( M \) takes 0.85. \( U_{cl}/U_{cr} \) is always greater than 25%. That is to say, the capacitor voltage of SM can always meet the requirements. Assume that the capacitor voltage of HBSM is \( U_{hi} \) when FBSMs put into charging. Based on the characteristics of uncontrolled charging, the voltage of all sub-modules at the end of the stage is \( 2U_{hi} \), which should satisfy the following condition.

\[ \frac{1}{4} U_{cr} \leq 2U_{hi} \leq \frac{\sqrt{3}}{2} M \frac{1 + k}{1 + 2k} U_{cr} \]  

When FBSMs are put into charging, the range of HBSM capacitor voltage can be expressed as

\[ \frac{1}{8} U_{cr} \leq U_{hi} \leq \frac{\sqrt{3}}{4} M \frac{1 + k}{1 + 2k} U_{cr} \]  

3.3 Semi-controlled charging stage

Keep T4 switch on until the end of charging. At this stage, the FBSM operates in the HBSM mode and the charging speed is the same. At the end of charging, the capacitor voltage of each SM can be introduced

\[ U_{c2} = \frac{U_i}{N_h + N_f} \]  

4. Simulation result

In order to verify the charging strategy proposed in this paper, a hybrid MMC system model was built in PSCAD/EMTDC. The system parameters of the hybrid MMC-HVDC are shown in table 1.

| Items                        | Values  |
|------------------------------|---------|
| AC side voltage/kV           | 300     |
| HBSM per arm \( N_h \)       | 12      |
| FBSM per arm \( N_f \)       | 12      |
| SM capacitor \( C/\mu F \)   | 5000    |
| Arm inductor \( L_f/\text{mH} \) | 5       |
| DC side voltage/kV           | ±280    |

Figure 4. FBSM capacitor voltage \( U_{cf} \) and HBSM capacitor voltage \( U_{ch} \)
The capacitor voltages of FBSM and HBSM are shown in figure 4. When the system starts charging, the capacitor voltage of the HBSM rises slowly while the capacitor voltage of FBSM remains 0. As can be seen from figure 5, the inrush current reaches the maximum value at the moment of system start-up. The current limiting resistor limits the inrush current to an appropriate value. It should be noted that the value of resistance should not be too large, otherwise it will affect the charging efficiency and increase the charging time. FBSM starts charging at \( t=0.15s \), and the capacitance voltage of FBSM rises rapidly. The charging speed of FBSM at this time is twice that of HBSM. The capacitance voltage of FBSM and HBSM is equal when \( t=0.45s \) and the capacitor voltage in each SM is greater than 25% of the rated voltage. The system will enter the third stage at which the FBSM works in the HBSM mode. Since the number of FBSMs in the charging circuit is reduced, the inrush current appears again. The arm current decreases as the SM capacitor voltage rises. After 0.45s, FBSM and HBSM are charged at the same speed until uncontrolled charging ends.

5. Conclusion

This paper analyzes the uncontrolled charging process of hybrid MMC. The HBSM voltage is about half of the FBSM voltage during the uncontrolled precharging process. In order to solve the problem of different charging speeds between two kinds of SMs, a three-stage charging strategy is proposed. The voltages of two kinds of SMs are equal at the end of FBSM boost stage. Then FBSM will work in HBSM mode to complete uncontrolled charging. This precharging strategy has broad adaptability to hybrid MMC based on HBSM and FBSM. The charging strategy proposed in this paper is only verified on the simulation platform, and can be further verified on the actual hybrid MMC system.

References

[1] Zhao, C.Y., Chen, X.F. (2011) Control and Protection Strategies for MMC-HVDC under DC Fault. Automation of Electric Power Systems, 35(23): 82-87.
[2] Solas, E., Abad, G., Barrena, J.A., Autenetxea, S., Carcar, A., Zajac, L. (2013) Modular multilevel converter with different submodule concepts-part I: capacitor voltage balancing method. IEEE Transactions on Industrial Electronics, 60(10):4525 - 4535.
[3] Dong, Y.L., Ling, W.J., Tian, J. (2016) Control & protection system for Zhoushan multi-terminal VSC-HVDC. Automation of Electric Power Systems, 36(7): 169-175.
[4] Kong, M., Qiu Y.F., He Z.Y. (2011) Pre-charging Control Strategies of Modular Multilevel Converter for VSC-HVDC. Power System Technology, 35(11): 67-73.
[5] Zhou, Y.B., JIANG, D.Z., GUO, J. (2012) Start/Stop Control of Modular Multilevel Converter Based HVDC Transmission System. Power System Technology, 36(3): 204-209.
[6] Zhao, W.Q., Gao, D.L., Ma, Y.L. (2018) Startup Strategy of Hybrid HVDC Transmission System Based on Hybrid MMC. Automation of Electric Power Systems, 42(7): 62-70.
[7] Li, C., Li, G., Dong, Y.L. (2019) Protection Strategy of Current Suppression Resistor Used in MMC-HVDC Startup Process. High Voltage Engineering, 36(1): 39-45.
[8] Zeng, R., Xu, L., Yao L. (2014) Precharging and DC fault ride-through of hybrid MMC-based HVDC systems. IEEE Transactions on Power Delivery, 30(3): 1298-1306.