Constant power start-up control strategy for modular multilevel converter

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Abstract. HVDC system based on modular multilevel converter (MMC) usually adopts fixed DC bus voltage to realize the start-up control of converter, which will have a great impact on AC network during charging process. This paper presents a constant power start-up control strategy based on MMC arm current control, which can effectively control active power, reactive power, output current and submodule (SM) capacitor voltage. Based on the existing two-stage start-up control mode, according to the output characteristics of arm voltage in controlled charging process, the circuit topology of DC side open circuit of converter is proposed, and the mathematical model is established. Based on the derived instantaneous arm power calculation method and the average sliding filter of SM capacitor voltage, the double closed-loop fast response controller of fixed AC power in controlled precharging stage is given. The safety of the power electronic equipment in the converter is effectively guaranteed and the impact of converter on ac power grid is greatly reduced. Finally, simulation models of conventional start-up method and proposed start-up method are built on MATLAB/Simulink platform to verify the validity and correctness of the proposed start-up control strategy.

1. Introduction
In recent years, the start-up control of MMC can be divided into separately excited and self-excited, although the former is simple to operate and easy to realize[1-2], it increases the cost and time of the starting process and is not suitable for the fast starting of high voltage level converters. Therefore, a number of scholars have proposed such self-excitation methods for MMC start-up strategies[3-7]. Self-excited methods usually require the MMC to be connect to active network (dc/ac side), since the direction of dc charging current is fixed, the design of precharging control from dc side is relatively easier[3-4]. Compared with dc side startup, in the black startup state (most of the generators in practical engineering are alternators), ac side startup is particularly important. In literature [5-6], the startup control based on C-MMC and FC-MMC topologies were presented respectively, which realized controllable precharging on the ac side by controlling the fast switching of SMs, but it was not applicable to other typical topologies. In order to overcome the dependence of startup control strategy on topological structures, the precharging strategy of several types of module topologies was proposed in literature [7-9]. All SMs should be grouped according to the real-time capacitor voltage balance control and be switched on and off quickly for capacitor voltage control, which has a good applicability, but the switching process will have a great impact on ac power grid and the switch frequency is much higher than the normal operating frequency[9]. Literature [10] proposed a two-stage ac side start-stop control strategy. In the non-controlled precharging stage, the blocking SM obtains a certain voltage from the ac side through the continuation diode. In the controllable precharge
stage, constant dc voltage control is adopted to continue charging the capacitors. Although the rated state can be reached quickly, a large impact current will be generated at the start moment, and the controller output will appear over-modulation phenomenon. Considering the influence of the start-up process on the reactive power of the power grid, literature [11] analyzed the impact of reactive power shock on the ac power grid during the starting process of the ac side, but did not give corresponding control measures. Literature [12-14] proposed a closed-loop control strategy, which can effectively control the output power of the converter, but the upper and lower arms of the converter must be charged separately, which reduces the charging efficiency, increases the even frequency multiplier component of the output current, and reduces the power quality of the converter output[13]. The start-up analysis of the multi-terminal dc system is presented in reference [15] and verified by simulation. However, the impact current is relatively large in the charging process.

The existing AC side start-up control strategy can realize the precharging control of the converter quickly, but it will produce large AC impulse current at the initial moment or early stage, which not only has a serious impact on the power quality and safe and stable operation of the power grid, but also will cause permanent damage to many power electronic devices in the converter. For this reason, in view of the whole process of converter start-up control, this paper adopts the arm current direct control strategy, through tracing the AC line voltage and arm current of MMC, charges the SMs in a constant power way, and has a good transition process at the beginning and the end of the controllable precharging. There is no obvious impact on the real-time power of ac side of the whole process converter. In addition, the output current waveform of converter has good symmetry and low harmonic content. While improving power quality and system control performance, it can effectively restrain the voltage and current impact on AC power grid and power electronic devices, and has good control performance in the whole process of controllable precharging of SMs capacitors.

2.  Analysis of MMC precharging process

In practical projects, since there is no voltage on the SM capacitor at the initial time of precharging, the power supply to IGBT’s drive circuit cannot be provided. Generally, two-stage precharging method is adopted for precharging process. In this paper, it is considered that the dc side of the converter is always open because the converter dc side’s voltage is always lower than the rated dc voltage during the start-up process.

2.1.  Uncontrolled precharging

In the first stage (uncontrolled precharging), the controller does not work. Although its precharging transient process is related to the hardware parameters in the charging circuit, the terminal capacitor voltage value is fixed. Here, take the HB-MMC as an example, the capacitor voltage can rise to

\[ u_{1..m} = \frac{\sqrt{2} U_{ac}}{N} \]  

Where \( U_{ac} \) is ac line voltage, and \( N \) is the number of SMs per arm. Since this voltage is much lower than the rated capacitor voltage, The normal operation control requires that the sum of the SMs capacitor voltage of one arm must not be less than the peak-to-peak value of the phase voltage. Obviously, the charging voltage of first stage does not meet this condition, which will lead to over-modulation and over-current of the controller, so the second stage(controllable precharging) is necessary.

2.2.  Controllable precharging

As shown in Figure 1, \( u_j \) and \( i_j \) (\( j=a, b, c \)) represent three-phase ac voltage and current respectively. \( u_{pq}, u_{nj}, i_{pq} \) and \( i_{nj} \) represent three-phase upper and lower arm voltage and arm current respectively (p and n represent upper arm and lower arm respectively), and \( U_{dc} \) represents the dc side voltage of the converter. According to the circuit theory, we can obtain
Where \( u_p \) and \( u_n \) represent the voltages of positive and negative terminals on the dc side of the converter. Take the upper arm as an example, when the voltage of a certain phase is maximum, the charging currents can only flow to the other two phases with lower voltage, so the SM capacitors of these two phases can be charged. Therefore, in the controllable charging stage, there are always two arm capacitors in MMC bypassed at the same time. Through searching for appropriate control methods, the capacitors of six arm can be charged equally.

\[
\begin{align*}
    u_{pj} &= u_p - u_{qj} + L_0 \frac{di_{pj}}{dt}, \quad u_p = \max(u_{sa}, u_{sb}, u_{sc}) \\
    u_{nj} &= u_{qj} - u_n - L_0 \frac{di_{nj}}{dt}, \quad u_n = \min(u_{sa}, u_{sb}, u_{sc})
\end{align*}
\]

(2)

Figure 1. Topology of MMC and HBSM(half bridge submodule) in precharging process.

Figure 2. Topology of MMC single phase equivalent circuit.

3. Design of fast response start-up controller

3.1. Design of inner loop controller

According to (2), the arm voltage is related to the maximum line voltage of the phase in which it is located. Therefore, the arm current can be tracked in real time by controlling each SM of the arm. The unit value of static modulated wave in the start-up control process can be defined as

\[
\begin{align*}
    V_{pj} &= \frac{u_p}{N u_c^{ave}} - \frac{u_{qj}}{N u_c^{ave}} \\
    V_{nj} &= -\frac{u_n}{N u_c^{ave}} + \frac{u_{qj}}{N u_c^{ave}}
\end{align*}
\]

(3)

Where \( u_c^{ave} \) represents the mean SM capacitor voltage after average sliding filter, and the window time of the filter is power frequency period. Static modulated values will change with the rise of capacitor voltage, but the time constant of capacitor voltage changes is much greater than the current loop controller of inertial time constant, so the design of the current controller can ignore this change. Using static modulation wave can ensure the stability of the controller and improve the dynamic performance of the inner loop control effectively. In addition, it can be seen from Figure 2 that the upper and lower arms of the same phase have parallel structures, and the current of the arms can be independently controlled without affecting each other, so that the power distribution and internal circulating current between the arms can be effectively controlled.

According to the classical control theory, the first-order inertial link is used to replace the output delay of PWM modulation. By constructing appropriate transfer function \( W(s) \) in the forward channel, the inner loop can be corrected into a typical type I control system, which can track the power frequency signal in real time[16]. The inner loop current controller is shown in Figure 3.
Figure 3. Inner loop arm current control block diagram.

In the Figure 3, \( i_{pj,ref} \) is the reference value of upper arm current, \( i_{pj} \) is the measured value of upper arm current, and \( v_{pj} \) is the modifier of upper arm voltage modulated wave. \( V_{pj} \) represents the static voltage modulation wave of upper arm, \( v_{pj,ref} \) is the real-time voltage modulation wave of upper arm finally output by the controller, and \( i_{nj,ref}, i_{nj}, V_{nj}, V_{nj,ref} \) respectively represent the corresponding quantity of lower arm.

Figure 4. Diagram of arm current vector: (a) upper arm current, and (b) lower arm current.

Figure 5. Outer loop power control block diagram.

3.2. Design of outer loop controller

Based on the definition of three-phase ac instantaneous power, we can obtain

\[
\begin{align*}
    p_s &= u_{a}i_{a} + u_{b}i_{b} + u_{c}i_{c} \\
    q_s &= u_{a}(i_{b} - i_{c}) + u_{b}(i_{c} - i_{a}) + u_{c}(i_{a} - i_{b}) \\
    w &= \frac{1}{\sqrt{3}} \left[ (u_{a} - u_{b})i_{c} + (u_{b} - u_{c})i_{a} + (u_{c} - u_{a})i_{b} \right] \\
    q &= \frac{1}{\sqrt{3}} \left[ (u_{a} - u_{b})i_{c} + (u_{b} - u_{c})i_{a} + (u_{c} - u_{a})i_{b} \right] \\
\end{align*}
\]

(4)

According to (2), since variables \( u_p \) and \( u_n \) change dynamically, there are always two of six arm voltage static modulated waves (in different poles) are zero, and the active power of these two arms almost zero. Therefore, the remaining arms will undertake the task of absorption of active power from the ac power grid. We can assume that at a certain moment, the \( k \) is the phase with the highest voltage among the three upper arms, and \( k^+ \) and \( k^- \) represent the other two phases of leading and following \( k \), respectively. The \( t \) is the lowest voltage phase of the three lower arms, and \( t^+ \) and \( t^- \) represent the other two phases of leading and following \( t \), respectively. So the active and reactive power absorbed by the arms of the converter can be obtained as

\[
\begin{align*}
    P_{ch} &= -u_{pk}i_{pk} - u_{pk}i_{pk} + u_{pk}i_{pk} + u_{pk}i_{pk} + u_{pk}i_{pk} \\
    &= -u_{pk}i_{pk} - u_{pk}i_{pk} + u_{pk}i_{pk} + u_{pk}i_{pk} + u_{pk}i_{pk} \\
    &= u_{pk}(i_{pk} + i_{pk} + i_{pk} + i_{pk}) + u_{pk}(i_{pk} + i_{pk} + i_{pk}) \\
    &= u_{pk}(i_{pk} + i_{pk} + i_{pk} + i_{pk}) + u_{pk}(i_{pk} + i_{pk} + i_{pk}) \\
    &= u_{pk}i_{pk} + u_{pk}i_{pk} + u_{pk}i_{pk} + u_{pk}i_{pk} \\
    &= u_{pk}i_{pk} + u_{pk}i_{pk} + u_{pk}i_{pk} + u_{pk}i_{pk} \\
    &= (u_{pk}i_{pk} + u_{pk}i_{pk} + u_{pk}i_{pk} + u_{pk}i_{pk}) \\
    &= (u_{pk}i_{pk} + u_{pk}i_{pk} + u_{pk}i_{pk} + u_{pk}i_{pk}) \\
\end{align*}
\]

(5)
The definition of \( q_{pki}^- \), \( q_{pki}^+ \), \( q_{pki}^- \) and \( q_{pki}^+ \) can be represented by Figure 4.

According to the above formula, the balance of the power of the four arms inside the converter can be expressed by the active and reactive currents of the six arms at the outlet of the ac side. Therefore, the power reference value can be obtained as follows

\[
P_{s\_ref} = 3\left(U_j I_{p\_j}^p + U_j I_{n\_j}^p\right)
\]

\[
Q_{s\_ref} = -3\left(U_j I_{p\_j}^q + U_j I_{n\_j}^q\right)
\]

Where, \( I_{p\_j}^p \), \( I_{p\_j}^q \), \( I_{n\_j}^p \) and \( I_{n\_j}^q \) represent the reference value of active and reactive current in upper and lower arms, respectively.

The upper and lower arms current in the same phase will evenly divide the phase current. If the three-phase current balance is maintained, the active power of each arms module can be guaranteed to be equal. According to equation (3-4), the measured instantaneous power is introduced into the controller as a feedback quantity, and the delay time of the modulation link and the inner loop controller can be ignored. By constructing an appropriate closed-loop control system, the outer loop power controller with rapid response is formed, as shown in Figure 5, and the constant power start-up control of converter can be realized. \( I_{p\_j} \) and \( I_{n\_j} \) are the current feedforward to improve the response speed of the outer loop. Through reasonable parameter selection, the typical type I controller can track the power change value at the beginning and end of controllable precharge in real time, and eliminate the steady-state error with good dynamic characteristics.

### 3.3. Design of charging power controller

In addition, the charging process of each capacitor unit is alternating in a converter. At the end of charging process, the capacitor voltage of each unit is required to be consistent, which requires the power value and derivative value at the end to be zero. Therefore, the reference value of active power adopts sinusoidal waveform. According to the principle of energy conservation, ignoring the energy loss in the charging process, the ac active power absorbed by the converter during the power decline is equal to the energy required by the voltage rise of all capacitor.

\[
\int_{t_1}^{t_2} P_{\text{rated}} \frac{1}{2} \cos(t) dt = 3CN(U_{c\_t1}^2 - U_{c\_t2}^2)
\]

Due to the alternating charging of each SM capacitor, the power drop time length is at least one power frequency cycle. If we know that the capacitors is charged to the rated voltage \( U_c \) at time \( t_2 \), the average capacitor voltage \( U_{c\_t1} \) at time \( t_1 \) can be obtained. The uncontrolled precharging terminal makes the capacitor voltage equal, and it is necessary to make the capacitor voltage into an alternating boost state through a similar buffer process, so as to reduce the equilibrium current at the start moment. The control block diagram is shown in Figure 6.

![Figure 6. Power reference selection block diagram.](image)

After all the SM capacitors are charged, the converter can start to work in the normal operation mode (constant dc voltage and constant reactive power control). The converter is then connected to the dc grid at the dc side and the output power is gradually increased until the rated power is reached. The entire start-up process is complete.
4. Simulation and results
The MMC converter has been built in MATLAB/Simulink to verify the effectiveness of the proposed start-up control strategy. Simulation parameters are shown in Table 1.

| Table 1. Simulation parameters of MMC. |
|---------------------------------------|
| Rated charging power (MW) | AC voltage (kV) | SM rated voltage (kV) | SM capacitance (mF) | Arm inductance (mH) |
|---------------------------|-----------------|-----------------------|---------------------|---------------------|
| 10 | 110 | 2.5 | 3 | 90 |

Figure 7. Start-up waveform with conventional control method from [10]: (a) active and reactive power, (b) six arm capacitor voltages, (c) three-phase charging current, and (d) upper and lower arm current of phase A.

At the initial moment of simulation, the converter is blocked for uncontrolled precharging, and the voltage of the SM capacitor remains stable after 0.6s, which can be regarded as the starting point of controllable precharging stage. At the moment, the SM capacitor voltage is 1.944 kV, which is consistent with the analytical value from (1). Figure 7 shows the start-up waveform using the constant dc voltage control method. The reference dc voltage gradually rises to the rated value with the average power of 10MVA. From Figure 7(a), we found that ac grid will have a great impact at the initial moment and the impact current waveform in Figure 7(c) was corresponding. The main reason of this great impact is that the modulation wave output by this operation controller is over-modulated. Combined with the unbalanced voltage waveforms in Figure 7(b) and the inconsistent arm current waveforms in Figure 7(d), it can be found that the converter will generate internal circulating current to balance the capacitor voltage of different arms, which is also a factor leading to controller instability.

Figure 8. Control variable waveform: (a) active and reactive power, (b) three-phase charging current, and (c) upper and lower arm current of phase A.

Figure 9. SM capacitor voltage waveform: (a) average capacitor voltages of all SMs, (b) capacitor voltages of a-phase upper and lower arm, and (c) six arm capacitor voltages.
Figure 8(a) shows the active and reactive power absorbed by the converter in the ac power grid. The converter enters the stage of controllable charging from 0.62s, and the real-time power closely follows the change of the reference value, which shows that the outer loop power controller has better control performance. Since the reference value of reactive power is zero, the waveform of reactive power always fluctuates around 0, and the fluctuation amplitude is very small. From the whole process, the power curve is very smooth, so the precharging process has little power and voltage shock to the ac power grid. Figure 8(b) shows the three-phase ac current output by the converter during precharging. The current waveform has high symmetry and smooth amplitude change with no current shock occurs during the whole process of start-up. The upper and lower arm currents shown in Figure 8(c) are consistent with each other, with almost no internal circulating current generated, indicating a good capacitor voltage balance between the converter arms.

Figure 9 shows the mean and instantaneous capacitor voltage of each unit of the converter. Figure 9(a) shows the capacitor’s real-time voltage after filtering. It is easy to find that the capacitor average voltage changes smoothly, which also indicates that the active power control is better. Figure 9(b) shows the instantaneous capacitor voltage of all SMs of phase A, and we find the capacitor voltage of upper and lower arms rises alternately in a complementary form in time. Voltage waveform of capacitor in six arms is shown in Figure 9(c). During the whole controllable charging stage, the rise and fluctuation of capacitor voltage of each arm is always kept in two parallel envelopes. At the charging terminal, the capacitors’ voltage of each arm is well maintained. Compared with traditional start-up methods shown in Figure 7, the proposed method has better dynamic stability.

5. Conclusions
Based on the typical topology of HB-MMC, a constant power start-up control strategy is proposed in this paper. By means of average sliding filter of SM capacitor voltage, the filter value of capacitor is introduced into the inner loop current controller with fast response. The static modulation amplitude in the controller is corrected in real time, so as to realize the purpose of stable output voltage of arm and fast tracking of ac current. According to the instantaneous power theory, considering that there are always two arms flowing through the reverse parallel diode to be bypassed, the calculation methods of active and reactive power of the three-phase arms in the process of charging are derived, and the control methods of external loop power are given. From the simulation results, it can be seen that the capacitor voltage rises steadily with constant rate and the charging current keeps a good coordination feature, which verifies the effectiveness of the proposed start-up control strategy.

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