A Novel Start-up Strategy for MMC-based Medium-voltage DC Distribution System with Low Inrush Current

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Abstract. To realize medium-voltage dc distribution system, the modular multilevel converter (MMC) is commonly adopted due to its high-level scalability and reliability for medium-voltage high-power energy conversion. Since the capacitors’ voltages of the MMC are insufficient when the uncontrolled pre-charging stage is finished, large inrush current exists when the MMC is unlocked for active charging, which can cause malfunction of protection and threat the successful start-up of the whole system. This paper presents a detailed analysis on the causes of inrush current during the MMC’s active charging process. Based on the analysis, a novel start-up strategy of the MMC is proposed to achieve improved controllability of the MMC’s ac-side currents for inrush current suppression. The simulation results from a full-scale simulation model demonstrate that the inrush current can be effectively suppressed during the MMC’s active charging process.

1. Introduction

DC distribution system is regarded as a promising solution to efficient and flexible power supply for widespread dc loads, renewable energy integration and modern ac-dc hybrid power system [1]-[3]. Since power supply reliability and ease of maintenance are very important for dc distribution systems, modular multilevel converter (MMC) is commonly adopted due to its high-level scalability and reliability for medium-voltage high-power energy conversion [4]. Various MMCs exist with different circuit topologies [5]. To realized dc distribution system, three-phase MMC equipped with half-bridge (HB) submodule (SM) is mostly adopted for interlinking ac and dc distribution systems by its ac and dc terminals [6]. The ac-dc interlinking system configuration and circuit topology of the MMC is shown in Figure 1.

Before the MMC starts normal operation, the submodule (SM) capacitors must be charged to its nominal value. Basically, the MMC must go through uncontrolled pre-charging stage and controlled active charging stage [7]. However, the capacitors’ voltages of the MMC are insufficient when the uncontrolled pre-charging stage is finished [8]. Therefore, large inrush current will appear when the MMC is unlocked for active charging, which can cause malfunction of protection and threat the successful start-up of the whole system.

To deal with the inrush current problem, many start-up strategies have been proposed in the existing literatures. The authors in [8] introduce a closed-loop pre-charge control method to actively regulate the charging current. Whereas, the control method is not very easy to implement in practice, and all the three-phase grid voltages must be measured and compared. A novel pre-charge scheme is
presented in [9], which uses external dc voltage source to charge each SM’s capacitor. However, additional switches and dc bus are needed. An effective start-up method is proposed in [10], which achieves zero inrush current. Unfortunately, this method is not suitable for HB-MMC. The authors in [11] present a novel start-up scheme for HB-MMC. However, this scheme is intended for start-up from the dc-side and not useful for start-up from the ac-side. In [12], an interesting start-up method with reduced dc voltage reference is proposed. Due to limitations of this method, the inrush current can only be suppressed to a certain extent but can’t be completely eliminated, which can be seen from the simulation results in [12].

This paper presents a novel start-up strategy for MMC-based medium-voltage dc distribution system. Different from the existing methods in the literatures, the proposed strategy uses the real-time values of the total and average capacitor voltages to calculate the dc voltage reference, arm output voltage references and the inserted SM numbers to compensate the arm output voltage error. In addition, zero-sequence voltage injection are applied to further enlarge the output ac voltage of the MMC under the arm maximum modulation constraint. By taking these methods together, the inrush current can be effectively suppressed. A full-scale simulation model is built, and simulation comparison between the proposed start-up method and the conventional methods are carried out. The superior performance of the proposed method is demonstrated by the simulation results.

![System configuration and circuit topology of the MMC.](image)

**Figure 1.** System configuration and circuit topology of the MMC.

2. Analysis on the cause of inrush current and the proposed start-up strategy

The cause of inrush current is the voltage difference between the ac grid voltage and the output ac voltage of the MMC. The relationship between the dc voltage reference, output ac voltage and ac current of the MMC is described in **Figure 2**.

When the uncontrolled pre-charging stage is finished, the capacitors are only charged to \( V_{\text{line}_{\text{max}}} / N \), which is lower than the nominal value \( V_{\text{dc}_{\text{nom}}} / N \). \( V_{\text{line}_{\text{max}}} \) is the amplitude of ac grid line-to-line voltage. \( V_{\text{dc}_{\text{nom}}} \) is the nominal dc-bus voltage. \( N \) is the SM quantity in each arm. When the conventional start-up method is adopted, the dc voltage reference \( E_{\text{dc}_{\text{ref}}} \) is set as the nominal value \( V_{\text{dc}_{\text{nom}}} \). Because the sum of the total capacitors’ voltages in each arm, represented by \( V_{\text{cap}_{\text{sum}}} \), is equal to \( V_{\text{line}_{\text{max}}} \), the maximum output ac voltage in each phase of the MMC is \( (V_{\text{line}_{\text{max}}} - V_{\text{dc}_{\text{nom}}} / 2) \) to avoid over-modulation. As can be seen from **Figure 2** (a)-(b), the amplitude of the output ac voltage \( E_a \) is much lower than the amplitude of the ac grid voltage \( V_a \). Consequently, the output ac current \( I_a \) can’t be effectively regulated and large inrush current will appear.

To increase the maximum ac voltage in each phase of the MMC, the dc voltage reference \( E_{\text{dc}_{\text{ref}}} \) should be equal to \( V_{\text{cap}_{\text{sum}}} \). In this way, the amplitude of \( E_a \) is increased from \( (V_{\text{line}_{\text{max}}} - V_{\text{dc}_{\text{nom}}} / 2) \) to
$V_{\text{line}_{\text{max}}}/2$ and the inrush current $I_s$ can be reduced, as can be seen from Figure 2 (c)-(d). The relationship between $E_{\text{dc}_{\text{ref}}}$ and $V_{\text{cap}_{\text{sum}}}$ is shown in Figure 3.

Figure 2. Relationship between dc voltage reference, output ac voltage and ac current of the MMC: (a), (b) nominal dc voltage reference is adopted; (c), (d) optimal dc voltage reference is adopted.

Figure 3. Relationship between $E_{\text{dc}_{\text{ref}}}$ and $V_{\text{cap}_{\text{sum}}}$.

However, the output ac voltage amplitude in each phase of MMC is still smaller than the ac grid voltage amplitude, i.e. $V_{\text{line}_{\text{max}}}/\sqrt{3}$. To further increase the output ac voltage of MMC, zero-sequence voltage (ZSV) $E_{\text{zsv}_{\text{ref}}}$ is injected in each phase of the MMC. $E_{\text{zsv}_{\text{ref}}}$ is defined in (1). $E_{a_{\text{ref}}}$, $E_{b_{\text{ref}}}$, $E_{c_{\text{ref}}}$ are the ac voltage references generated by the control loops. Figure 4 shows the waveform of $E_{a_{\text{ref}}}$ before and after ZSV injection. As can be seen, the amplitude of $E_{a_{\text{ref}}}$ can be scaled down with a ratio of $\sqrt{3}/2$. The control block diagram is shown in Figure 5. $V_{\text{cap}_{\text{ave}}}$ is real-time average capacitor voltage defined as $V_{\text{cap}_{\text{ave}}}(V_{\text{cap}_{\text{ave}}}{\text{ap}}+V_{\text{cap}_{\text{ave}}}{\text{an}}+V_{\text{cap}_{\text{ave}}}{\text{bp}}+V_{\text{cap}_{\text{ave}}}{\text{bn}}+V_{\text{cap}_{\text{ave}}}{\text{cp}}+V_{\text{cap}_{\text{ave}}}{\text{cn}})/6$. $V_{\text{cap}_{\text{ave}}j}$ is the average capacitor voltage of the arm j. $V_{\text{cap}_{\text{ref}}}$ is the nominal capacitor voltage reference. $\theta_s$ is the synchronous phase of the grid voltage obtained by the phase-locked loop (PLL). $V_d$, $V_q$, $I_d$, $I_q$ are the dq components of the grid-side voltages and currents. The arm voltage references for the phase a, b, c are expressed in (2). As can be concluded from Figure 4 and (2), the output line-to-line ac voltage amplitude of the MMC is increased from $V_{\text{line}_{\text{max}}} \times \sqrt{3}$ to $V_{\text{line}_{\text{max}}}$, which is equal to the grid line-to-line voltage amplitude. In this way, the inrush current can be effectively regulated and suppressed.

$$E_{\text{zsv}_{\text{ref}}} = -[\max(E_{a_{\text{ref}}}, E_{b_{\text{ref}}}, E_{c_{\text{ref}}}) + \min(E_{a_{\text{ref}}}, E_{b_{\text{ref}}}, E_{c_{\text{ref}}})]/2$$

$$E_{k_{\text{ref}}} = E_{d_{\text{ref}}}/2 - (E_{k_{\text{ref}}} + E_{\text{zsv}_{\text{ref}}})$$

$$k=a,b,c$$

$$E_{k_{\text{ref}}} = E_{d_{\text{ref}}}/2 + (E_{k_{\text{ref}}} + E_{\text{zsv}_{\text{ref}}})$$

$V_{\text{line}_{\text{max}}}/2$ and the inrush current $I_s$ can be reduced, as can be seen from Figure 2 (c)-(d). The relationship between $E_{\text{dc}_{\text{ref}}}$ and $V_{\text{cap}_{\text{sum}}}$ is shown in Figure 3.

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$$E_{\text{zsv}_{\text{ref}}} = -[\max(E_{a_{\text{ref}}}, E_{b_{\text{ref}}}, E_{c_{\text{ref}}}) + \min(E_{a_{\text{ref}}}, E_{b_{\text{ref}}}, E_{c_{\text{ref}}})]/2$$

$$E_{k_{\text{ref}}} = E_{d_{\text{ref}}}/2 - (E_{k_{\text{ref}}} + E_{\text{zsv}_{\text{ref}}})$$

$$k=a,b,c$$

$$E_{k_{\text{ref}}} = E_{d_{\text{ref}}}/2 + (E_{k_{\text{ref}}} + E_{\text{zsv}_{\text{ref}}})$$

$V_{\text{line}_{\text{max}}}/2$ and the inrush current $I_s$ can be reduced, as can be seen from Figure 2 (c)-(d). The relationship between $E_{\text{dc}_{\text{ref}}}$ and $V_{\text{cap}_{\text{sum}}}$ is shown in Figure 3.
Finally, the real-time average capacitor voltage $V_{\text{cap,ave}}$ is used to calculate the inserted SM number $N_{j,\text{ref}}$ in each arm of the MMC to compensate the arm output voltage error. The expression of $N_{j,\text{ref}}$ is shown in (3), where round $(\cdot)$ is the round function. When the active charging process is finished, the nominal capacitor voltage reference $V_{\text{cap,ref}}$ is then employed for inserted SM number calculation.

$$N_{j,\text{ref}} = \begin{cases} \text{round}(E_{j,\text{ref}} / V_{\text{cap,ave}}), & \text{during active charge} \\ \text{round}(E_{j,\text{ref}} / V_{\text{cap,ref}}), & \text{active charge is finished} \end{cases} \quad j=\text{ap,an,bp,bn,cp,cn}$$

3. Verification results

A ±10kV-20MVA MMC-based dc distribution system is built using the MATLAB/SIMULINK software. The basic simulation parameters are described as follows. $V_{\text{line, max}}=14.14$ kV. $V_{\text{dc, nom}}=20$ kV, $N=20$. $V_{\text{cap, ref}}=V_{\text{dc, nom}} / N=1$ kV. The SM capacitance $C=20$ mF. The branch inductance $L=6$ mH. The charging resistor $R=25$ Ω. The sampling/control frequency is $f_s=10$ kHz. The PI parameters of the capacitor voltage controller is $K_p=5$, $K_i=5/f_s$. The PI parameters of the current controller is $K_p=10$, $K_i=100/f_s$. The start-up of MMC has four stages with the proposed method. At 0.5 s, $S_1$ (see Figure 1) is closed, and the MMC starts uncontrolled charging. At 1.5 s, $S_2$ (see Figure 1) is closed, and the charging resistor is bypassed. The active charging process begins at 2.0 s and ends at 2.5 s, during which period the MMC is unlocked. The start-up process ends at 3.0 s. The detailed simulation results are shown in Figure 6.

As can be seen from Figure 6, the arm average capacitor voltages increase gradually during the uncontrolled pre-charging stage 1 and stage 2. The grid currents are suppressed by the pre-charging resistor. After the MMC is unlocked at 2.0 s, the arm average capacitor voltages are well balanced and raise rapidly from about 630 V to 1050 V during the stage 3, and converges quickly to the nominal reference 1 kV during the stage 4. The grid currents are well regulated during stage 3 and stage 4. The peak value of the grid currents is about 380 A.

For comparison, the grid current waveforms of the MMC when adopting the conventional methods are presented in Figure 7. As can be seen, the inrush current’s peak value is about 2 kA if no inrush current limiting method is applied. By adopting the method in [12], the inrush current’s peak value is reduced to about 800 A, which is still higher than the result obtained by the proposed method. Concluded from the simulation results, the proposed start-up strategy can effectively suppress the inrush current during active charging process, and is more advantageous than the existing methods.
4. Conclusion
Firstly, the cause of inrush current during the MMC’s active charging process is analysed in detail. Based on the analysis, a novel start-up strategy of the MMC for dc distribution system is proposed. The start-up strategy adaptively adjusts the dc voltage reference to achieve the maximum output ac voltage according to the real-time total capacitor voltage, and uses the average capacitor voltage to calculate the inserted SM number for compensation of the arm output voltage error. In addition, zero-sequence voltage is also applied to further enlarge the output ac voltage of the MMC. By taking these methods together, the output ac voltage’s amplitude of the MMC is increased and be equal to the ac grid voltage’s amplitude. Therefore, the inrush current can be effectively suppressed. The feasibility and advantages of the proposed strategy are verified by the simulation results.

5. References
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