AC- and DC-Side Start-Up Strategies for Half-/Full-Bridge Hybrid Modular Multilevel Converter

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***Abstract*—The hybrid modular multilevel converter (MMC) composed of half-bridge submodules (HBSMs) and full-bridge submodules (FBSMs) is considered as a promising topology to deal with dc fault in high-voltage direct-current (HVDC) transmission systems. Compared with conventional HB-MMC, start-up process in hybrid MMC is different due to SMs topology difference. For ac-side start-up, the voltages of HBSM capacitors and FBSM capacitors are unbalanced after uncontrolled pre-charge process. For dc-side start-up, applying current-limiting resistor to restrict the inrush current can be costly. Aiming to charge the SMs capacitors to rated value smoothly, start-up strategies are proposed in this paper. The proposed ac start-up method can eliminate the unbalance voltage during closed loop pre-charge control stage. The dc start-up method without current-limiting resistor is proposed by regulating dc-link voltage. Simulation in PSCAD/EMTDC is implemented to verify the feasibility and validity of the proposed start-up strategies.**

Keywords—Hybrid; Modular Multilevel Converter; Closed loop Pre-charge Control

I. INTRODUCTION

The modular multilevel converter (MMC) is the most attractive topology for high-power high-voltage applications [1-3] due to its modular structure and low harmonic distortion of the output waveforms. Considering the issues of dc fault, the arm of hybrid MMC composed of full-bridge submodules (FBSMs) and half-bridge submodules (HBSMs) is proposed [4][5]. The hybrid MMC not only has dc fault ride-through capability but also suffers lower losses than FB-MMC [6], which is supposed to be the main configuration of next generation MMC.

Pre-charging the submodules (SM) capacitors to their rated values smoothly is the prerequisite of steady state operation for MMC-HVDC. The existing start-up methods can be classified into ac-side pre-charge and dc-side pre-charge according to energy sources. One start-up scheme adopts an additional dc source that possess the rated capacitor voltage to charge submodules one by one [7], which requires a dc circuit breaker. When the MMC consists of a large number of submodules, this method is not cost-effective. To address the issue, many start-up schemes are proposed to charge those SM capacitors by the dc-link. The capacitors will get further charged by changing the number of blocked SMs in arms [2]. Since these methods are not developed based on closed loop control, the charging current is uncontrollable during whole pre-charge process. Closed loop start-up control methods are introduced in [8], [9]. The charging current is regulated at a constant to charge all capacitors by feedback control [8]. The small signal model of closed loop pre-charge during start-up is derived and an averaging capacitor voltage control is introduced [9]. SM capacitors can be charged through the grid side (ac-side), resistors and breakers are placed in MMC arms in [10], which reduces the system reliability. However, without considering the different characteristics of various SM circuits, the aforementioned methods are mainly based on HB-MMC. Focusing on the start-up issue for a clamp-double submodule (CDSM) MMC, a grouping sequentially start-up method is introduced in [11], while the deviation among the capacitor voltages should be concerned. As for hybrid MMC, specific trigger signals are given to every FBSMs in the whole pre-charge process in reference [12], by which those closed loop control start-up for HB-MMC can be applied to hybrid MMC. Since devices in SMs are not controllable during uncontrolled pre-charge process and capacitors absorb energy from ac-side or dc-side voltage automatically, that method needs additional control signal generator, which results in high-cost implement.

In this paper, a start-up method for hybrid MMC is proposed to charge the capacitors to nominal voltage. This paper analyzes the unequal uncontrolled charging process of capacitors for FBSMs and HBSMs from ac-side main voltage. Based on that, closed loop pre-charge control strategies will take over to further charge capacitors as well as eliminate the imbalance voltage between different SMs. The start-up scheme of hybrid MMC under dc-side is also introduced. The capacitors are pre-charged by dc-link, which means the direction of charging current is certain. Furthermore, the overall start-up scheme for two-terminal MMC-HVDC is brought out.

II. OPERATION PRINCIPLES OF HYBRID MMC

The topology of a half-/full-bridge hybrid MMC is shown in Fig. 1. Each phase comprises upper and lower two symmetrical arms, with two arm inductors L_0 attached. Each arm consists of N identical power cells with H HBSMs and F FBSMs. U_{dc}, U_{sm} represent the dc-link voltage and the output

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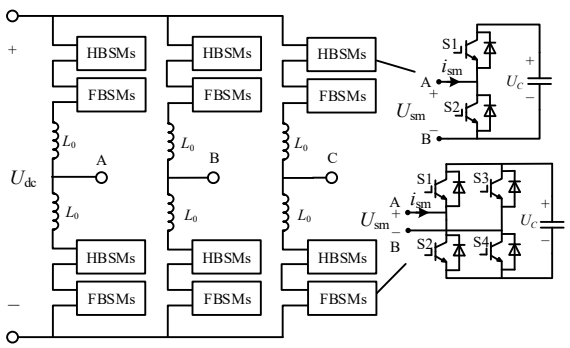


Fig. 1. Topology of half-/full-bridge hybrid MMC

TABLE I. SWITCHING STATES OF FBSM

MODE	S1	S2	S3	S4	U_{sm}	U_C
postive	on	off	off	on	U_C	charging(i_{sm}>0) discharging(i_{sm}<0)
bypass	off	on	off	on	0	constant
bypass	on	off	on	off	0	constant
negative	off	on	on	off	$-U_C$	discharging(i_{sm}>0) charging(i_{sm}<0)
block	off	off	off	off	U_C $-U_C$	charging(i_{sm}>0) charging(i_{sm}<0)

voltage of SM. The switching states of FBSM is shown in Tab. I., which can generate an extra negative voltage state $-U_C$. Based on that, compared with conventional steady-state operation, MMC that contains FBSMs can operate under over modulation aiming to increase ac-side voltage [13].

If a maximum number of M SMs are allowed to operate at the $-U_C$ state in each arm ($M \le F$), the rated dc-link voltage U_{dcr}, rated capacitor voltage U_{cr}, peak phase voltage U_p and modulation index m are given as

$$U_{dcr} = (N - M)U_{cr} \tag{1}$$

$$U_p = \frac{N+M}{2}U_{cr} \tag{2}$$

$$m = \frac{2U_p}{U_{dcr}} = \frac{N+M}{N-M} \tag{3}$$

III. ANALYSIS OF PRE-CHARGE PROCESS

A. Ac uncontrolled pre-charge process

1) Circuit Operation Analysis

Since FBSMs and HBSMs are blocked in the uncontrolled pre-charge stage, the capacitors in FBSMs are charged all the time regardless of current direction. However, capacitors get charged only if the current i_{sm} is positive for HBSMs, which indicates that there is an unequal pre-charge between HBSMs and FBSMs.

Taking the upper arm of phase A and B as an example, the charging loop and the equivalent circuits are shown in Fig. 2(a) and (b), respectively. L_s is the equivalent system inductance and R_{lim} is the current-limiting resistor. It can be seen that when the current flows from phase A to phase B (i.e., the line voltage $U_{ab} > 0$), all the capacitors of FBSMs get charged. On the contrary, the capacitors of HBSMs in phase B are charged while in phase A, the rest HBSM are bypassed and voltage of capacitors is constant. Once the current reverses, the charging process for all the FBSM capacitors continues, while the state of HBSM capacitors is changed. HBSM capacitors in phase A get charged and the rest HBSM capacitors are bypassed. As for the lower arms, the process is completely symmetrical. The analysis indicates that the charging time of FBSM capacitors is twice the HBSM capacitors. Because of identical capacitors both in FBSMs and HBSMs, FBSM capacitors voltage is quite twice that of HBSM capacitors and an unbalance voltage occurs. When the sum of the output voltage of all the SMs between two phases reaches the ac line voltage peak, the uncontrolled pre-charge process comes to an end, given by

$$U_F = 2U_H \tag{4}$$

$$2FU_F + (N - F)U_H = \sqrt{3}U_p \tag{5}$$

Then the voltages of FBSM capacitors and HBSM capacitors after uncontrolled pre-charge stage can be solved as

$$U_F = \frac{2\sqrt{3}}{N+3F}U_p \tag{6}$$

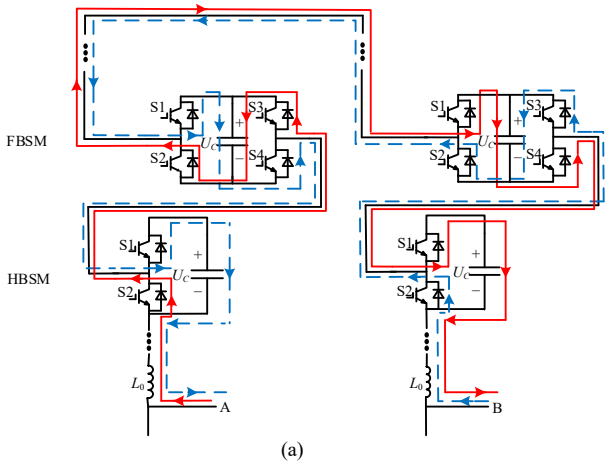
$$U_H = \frac{\sqrt{3}}{N+3F}U_p \tag{7}$$

Considering the requirement of capacitor voltage balance, M should be less than $N/3$ [4]. According to (2), the rated capacitor voltage is

$$U_{cr} = \frac{2U_p}{N+M}, \quad \frac{U_F}{U_{cr}} = \frac{\sqrt{3}(N+M)}{N+3F} \le \frac{8\sqrt{3}}{15} < 1 \tag{8}$$

As shown in (8), even the higher FBSM capacitors voltage is less than the rated voltage, which means all SMs should be controlled to get further charged. Since FBSM can generate negative output even when all switches blocked. The final dc-link voltage U_{dcf} after this process is

$$U_{dcf} = -FU_F + FU_F + HU_H = HU_H \tag{9}$$



(a)

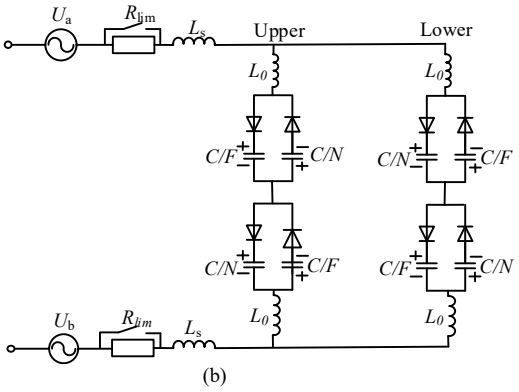


Fig. 2. Ac uncontrolled pre-charge of hybrid MMC (a) charging loop (b) equivalent circuit

2) Current-limiting Resistor Selection

The current-limiting resistor is applied to avoid inrush current and ensure safe operation of power device during uncontrolled pre-charge process. As shown in Fig. 2(b), the equivalent capacitance of each arm varies with the direction of current. Note that when the first time the ac line voltage reaches its peak, the maximum charging current occurs. Though the whole uncontrolled pre-charge process is difficult to accurately described by equations, it can be considered as the over-damped zero-state response of second order circuit in first charging cycle. The maximum charging current i_{cm} can be acquired as follows

$$i_{cm} \approx \frac{\sqrt{3}U_p}{\sqrt{4R_{lim}^2+\left[\omega\left(2L_s+L_0\right)-\frac{N+F}{2\omega C}\right]^2}} \tag{10}$$

The current-limiting resistor is selected to keep the arm current below the maximum allowable current I_{max} of devices. Therefore, R_{lim} is selected based on

$$R_{lim} \geq \frac{1}{2}\sqrt{\frac{3U_p^2}{I_{max}^2}-\left[\omega\left(2L_S+L_0\right)-\frac{N+F}{2\omega C}\right]^2} \tag{11}$$

B. Ac closed loop pre-charge control

In order to charge capacitors to nominal value, closed loop pre-charge control method is taken, as shown in Fig. 3. Two important targets are eliminating the unbalanced voltage caused by uncontrolled pre-charge process and building dc-link voltage. Since the dc-link voltage is supposed to raise gradually, which will be explained in following section, a dc-link voltage control is introduced. The reference of dc-link voltage is set to a value that slopes up to the rated voltage. The outer loop controller regulates dc-link voltage, and the reference of inner loop controller gets reference from it. Based on Clark transform, a decoupling current loop structure is derived. i_d, i_q represents the d-axis and q-axis component of ac-side current, respectively. Aiming at lower reactive power, the q-axis current reference is set to zero. The output u_d^* and u_q^* denote expected d-axis and q-axis component of ac-side voltage. However, as (6), (7) indicates that an unbalance voltage exists after uncontrolled pre-charge process, the HBSM capacitors

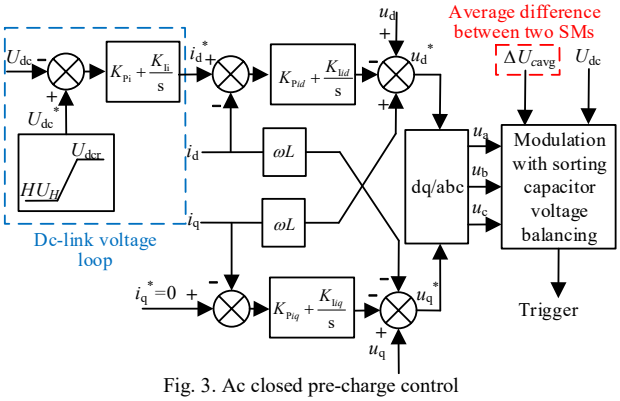


Fig. 3. Ac closed pre-charge control

should be charged preferentially to eliminate voltage difference. The conventional modulation scheme combined with sorting capacitor voltage balancing algorithm [14] is inappropriate here because of MMC operating under over modulation, which means modulation wave is not always above zero, FBSMs will be inserted before imbalance eliminated and the voltage balancing process will be complex. In addition, part of FBSMs will get uncharged applying this modulation scheme and the start-up process is time consuming. To tackle this problem, the modulation wave generation is modified. The modulation wave of upper and lower arms can be expressed as

$$v_{xp} = \frac{u_{dcr}}{2} - u_x\left(1-\frac{\Delta U_{Cavg}}{U_H}\right) \quad (x = a,\ b,\ c) \tag{12}$$

$$v_{xn} = \frac{u_{dcr}}{2} + u_x\left(1-\frac{\Delta U_{Cavg}}{U_H}\right) \quad (x = a,\ b,\ c) \tag{13}$$

where ΔU_{Cavg} is the difference between FBSM and HBSM capacitors averaging voltage. In this way, the modulation wave can be achieved by HBSMs, which means HBSMs are selected preferentially to get charged. As ΔU_{Cavg} gets smaller and smaller, the modulation waves are gradually restored. Once ΔU_{Cavg} is reduced to zero, that is, imbalance voltage is eliminated, then all the SMs are alternately charged to nominal value. Note that when the proposed method is applied, the ac output v_x of converter can be insufficient at first and devices are under the risk of inrush current. In response, the current-limiting resistors will be bypassed until ΔU_{Cavg} reaches zero. After that the over modulation operation can obtain a higher v_x than normal operation and the charging current can be well restricted.

Besides, the sorting capacitor voltage balancing method functions in the whole stage.

C. Dc uncontrolled pre-charge process

For a MMC-HVDC system with two terminals, each MMC can be pre-charged by ac grid as presented above. If the MMC inverter supplies passive load, the passive side MMC should get charged by dc-link provided through the active side MMC. Under this condition, the direction of charging current is constant (i.e., $i_{sm} > 0$). For all the SMs are blocked during uncontrolled pre-charge process, FBSM capacitors and HBSM capacitors are charged together. Fig. 4 depicts the equivalent

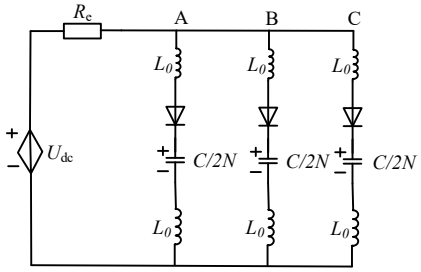


Fig. 4. Equivalent circuit of dc uncontrolled pre-charge process

circuit of charging loop. The voltages of different SM capacitors are raised synchronously. Similarly, when the sum of the output voltage of one phase SMs reaches the rated value of dc-link voltage, the uncontrolled pre-charge process comes to an end. The final voltage of each capacitor after this process can be obtained as

$$U_F = U_H = \frac{U_{\text{dcr}}}{2N} \tag{14}$$

Aiming at avoiding inrush current during this process, a current-limiting resistor is applied generally. Since the current-limiting resistor is set in dc-link, which requires a matching dc breaker, the configuration can be costly and complicated. To overcome these drawbacks, a start-up strategy is introduced. As shown in Fig. 4, considering the value of equivalent system resistance R_e is normally small, the equivalent circuit is under-damped without current-limiting resistor. For all SMs are blocked and capacitors in them are not able to release power, the oscillation process will end when the equivalent system capacitor reaches its peak value, which indicates there exists an overvoltage. According to the proposed ac closed loop pre-charge control method, the voltage of dc-link is regulated to slope up. Therefore, for a two terminals MMC system, selecting an appropriate slope k can limit the charging current during dc uncontrolled pre-charge process. The voltage of equivalent system capacitor u_{ce} can be obtained as

$$u_{\text{ce}}(t) = k\left[t - \frac{2\zeta}{\omega_{\text{n}}} + \frac{e^{-\zeta\omega_n t}}{\omega_{\text{n}}}\left(2\zeta\cos\omega_{\text{d}}t + \frac{2\zeta^2-1}{\sqrt{1-\zeta^2}}\sin\omega_{\text{d}}t\right)\right]$$

$$\omega_{\text{d}} = \sqrt{\frac{1}{2L_0C_{\text{e}}} - \left(\frac{R_{\text{e}}}{4L_0}\right)^2} = \sqrt{\omega_{\text{n}} - \left(\frac{R_{\text{e}}}{4L_0}\right)^2},\quad \zeta = \frac{R_{\text{e}}}{4}\sqrt{\frac{C}{NL_0}} \tag{15}$$

In order to avoid the overvoltage occurs, assuming the maximum allowable overvoltage is 1.05 U_{dcr}, the slope k can be limited as

$$U_{\text{cem}} = U_{dcr} + \frac{k\cdot e^{-\frac{\zeta\omega_{\text{n}}U_{\text{dcr}}}{k}}}{\omega_{\text{n}}}\left(2\zeta\cos\frac{\omega_{\text{d}}U_{\text{dcr}}}{k} + \frac{2\zeta^2-1}{\sqrt{1-\zeta^2}}\sin\frac{\omega_{\text{d}}U_{\text{dcr}}}{k}\right) \le 1.05U_{\text{dcr}} \tag{16}$$

Moreover, the slope k is selected to keep the arm current below the maximum allowable current I_{max} of devices, given as

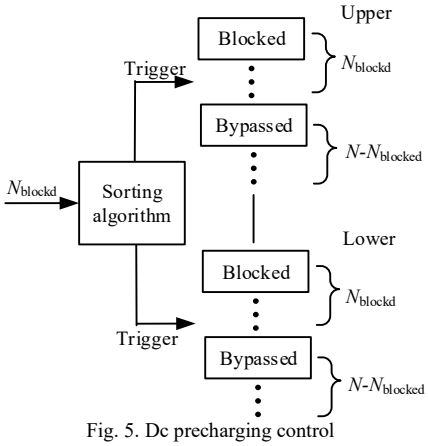


Fig. 5. Dc precharging control

$$i_{\text{m}} = \frac{C}{2N}k\left(1-2\zeta^2 + \frac{2\zeta^2-1}{\sqrt{1-\zeta^2}}\right) \le I_{\text{max}} \tag{17}$$

D. Dc pre-charge control

In this stage, dc-link voltage reaches rated value, the voltage of each SM capacitor should be charged from $U_{\text{dcr}}/2N$ to $U_{\text{dcr}}/(N\text{-}M)$. Note that the direction of charging current is still constant, the proposed pre-charge control method change the number of blocked SM and bypass the rest SM. When a HBSM is blocked, it gets charged. On the contrary, the voltages of bypassed HBSM capacitors maintain constant. When a FBSM is blocked, whether it generates a positive output or a negative output, the capacitor gets charged while the voltages of bypassed FBSM capacitors are unchanged. Since the initial voltages of FBSM capacitors and HBSM capacitors are identical, all SMs can be treated equally. As shown in Fig. 5, part of SMs are in blocked alternately, with the rest SMs are bypassed. The number of blocked SMs reduces gradually to avoid inrush current, given as

$$N_{\text{blocked}} = N - \frac{N+M}{2(t_1 - t_0)}(t - t_0) \tag{18}$$

where t_0 represents the moment when uncontrolled pre-charge stage ends and t_1 represents the desired moment that controlled pre-charge stage ends. Note that every time the number of blocked SMs changes, there exists an overvoltage in next charging period. The amplitude of overvoltage diminishes as the number of submodules N increases.

Considering the requirement of capacitor voltage balance,, the general sorting capacitor voltage balancing algorithm is also applied here.

IV. Simulation Results

In order to verify the start-up method proposed in this paper, a two-terminal hybrid MMC simulation model established in PSCAD/EMTDC is shown in Fig. 6. MMC rectifier utilizes ac pre-charge method while dc pre-charge method is applied to the MMC inverter.

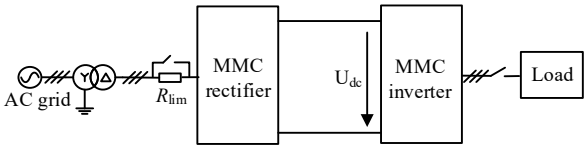


Fig. 6. Two-terminal MMC-HVDC system

TABLE II. SYSTEM PARAMETERS

System parameters	Value
Ac voltage (phase to ground peak) U_p/kV	12
Dc voltage U_{dcr}/kV	16
Rated capacitor voltage U_{cr}/kV	2
SMs per arm N	10
HBSMs per arm H	5
Negative output FBSMs per arm M	2
Arm inductor L_0/mH	12
SM capacitance C/mF	5
Current-limiting resistor R_{lim}/Ω	21

The system parameters of the hybrid MMC-HVDC are shown in Tab. II. The equivalent inductor of the ac grid source and the impedance of transmission are neglected. Assuming that the allowing maximum current of devices is I_{max}=500A, the current-limiting resistor can be chosen as R_{lim}=20.8Ω, which is acquired by (10). In this paper, R_{lim} is selected 21Ω for simulation. The number of negative output FBSMs per arm is M=2 and the number of SMs per arm is N=10, which indicates that the MMC-HVDC operates in over modulation state with m=1.5. The two MMC are exactly the same but operates at opposite condition.

A. Ac-side pre-charge process

The proposed ac-side start-up strategy is applied in the MMC rectifier apply. Fig. 7 presents the simulation results. During ac uncontrolled pre-charge process (before t=0.5 s), the voltage of HBSM capacitor is lower than FBSM capacitor and voltage unbalance is established. The final voltage of FBSM capacitor is about 1.6kV while HBSM capacitor is half, which is compliant to the formulas (6), (7). The ac closed loop pre-charge controller operates at t=0.5s, the HBSM capacitor is charged preferentially to eliminate voltage difference. As the voltage difference reduces and the reference of dc voltage slopes up, FBSM is inserted to support dc voltage and capacitor gets charged. With sorting capacitor voltage balancing method, the unbalance voltage is eliminated at t=0.72s, the current-limiting resistor is bypassed at meantime. Then all the capacitors get charged to the rated voltage and the dc voltage is raised to rated value at t=0.8s. Note that a voltage drop occurs due to that averaging HBSM capacitors voltage is less than averaging SM capacitors voltage and the inserted HBSMs are not able to build enough dc voltage. Since the inner current loop functions after current-limiting resistor is bypassed, the inrush current is limited.

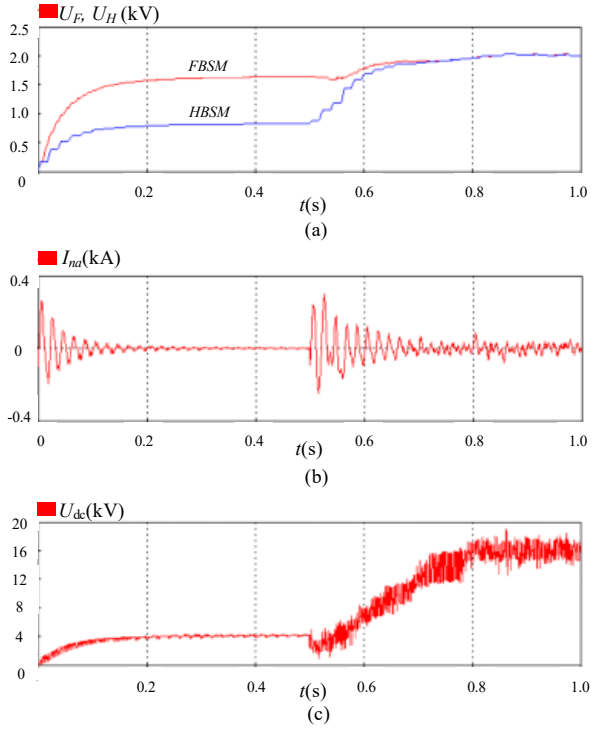


Fig. 7. Ac-side start-up: (a) FBSM and HBSM capacitor voltage; (b) arm current during start-up; (c) dc voltage

B. Dc-side pre-charge process

Fig. 8 presents the simulation results of the dc-side start-up process, and the MMC inverter is charged through dc-link voltage.

The uncontrolled pre-charging ends at t=0.8s, all the FBSM capacitors and HBSM capacitors do have the equal voltage. Then dc pre-charge control begins, SMs are blocked alternately to get further charged. At t=1.4s, the voltages of

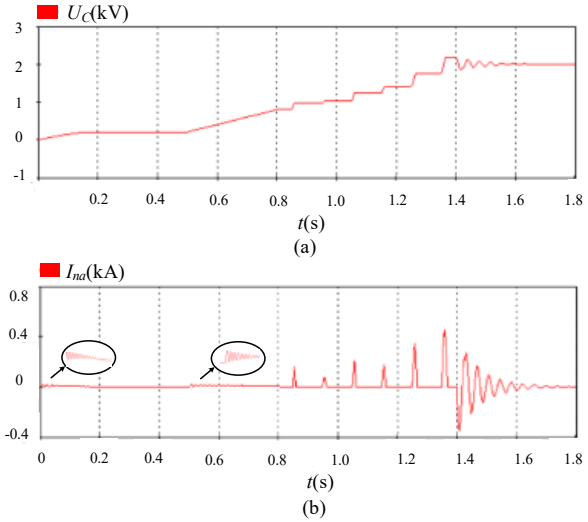


Fig. 8. Dc-side start-up: (a) FBSM and HBSM capacitor voltage; (b) arm current during start-up

capacitors exceed the rated value and SMs are no more blocked but inserted to get discharged. Finally, all capacitors are balanced at rated voltage at about t=1.6s. The inrush charging current is restricted in the whole start-up process.

V. Conclusion

In this paper, start-up strategies are proposed for the hybrid MMC under ac- and dc-side conditions. The unbalance capacitor voltages between HBSMs and FBSMs during ac start-up process are analyzed. The ac pre-charge control scheme can eliminate the imbalance as well as regulate dc-link voltage. Based on that, the dc pre-charge control method without dc-side current-limiting resistor is studied and the slope of raising dc-link voltage is selected. Effectiveness of the proposed strategies are verified through building a two-terminal MMC-HVDC simulation in the PSCAD/EMTDC. The simulation results demonstrate the proposed strategies can pre-charge the SM capacitors with keeping capacitor voltage balanced and limit the charging current during the start-up process under different conditions.

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