A dc-link startup pre-charging control strategy for modular multilevel converter

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ABSTRACT

- This paper presents a dc-link startup pre-charging control strategy for modular multilevel converter.
- In order to achieve a soft-startup performance of MMC, this paper presents a dc-link startup pre-charging control strategy which contains three stages.
- The first stage is pre-charging with current-limiting resistors based on the principle of half-bridge MMC. The second stage is bypassing the current-limiting resistors sequentially. The mathematical model of bypassing resistors sequentially is established, and the optimal bypassing times are achieved to minimize the inrush current during the uncontrolled startup stage. In the last controllable charging stage, constant current charging is adopted to reduce the inrush current effectively.
- Finally, the performance of the proposed method is verified by the simulations.

INTRODUCTION

MMC is not only widely applied in DC power transmission, but also in motor drive, battery energy storage, etc. Currently, the common sub-module (SM) in MMC is the half-bridge structure. To avoid the large inrush current during MMC startup stage, the pre-charging strategy is required.

Moreover, there is few literatures that cover the detail theoretical analysis on the calculation and limitation of inrush current in the uncontrolled pre-charging stage, and the dynamic characteristics of startup still needs to be optimized.

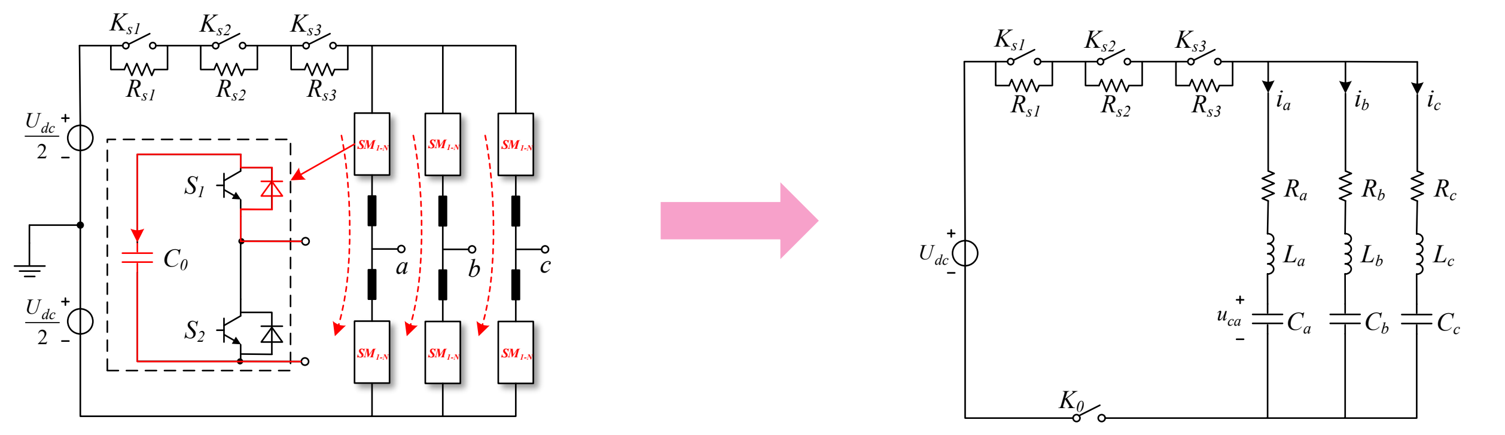
Therefore, this paper proposes a fast dc-link startup control method for three-phase half-bridge MMC.

The proposed dc-link startup pre-charge procedure is mainly divided into three stages: the uncontrolled charging stage with current-limiting resistors, the uncontrolled charging stage with current-limiting resistors bypassed, and the controllable charging stage with constant current.

METHODS

Stage 1: Uncontrolled pre-charging with current-limiting resistors

Circuit diagram of the proposed method can be expressed:



Taking phase A as an example, the following expression can be deduced:

$$\frac{d^2u_{ca}}{dt^2}+\frac{3R_s+R_a}{L_a}\frac{du_{ca}}{dt}+\frac{1}{L_aC_a}u_{ca}=\frac{U_{\rm dc}}{L_aC_a} \Rightarrow \begin{cases} u_{ca(t)}=U_{\rm dc}+\dfrac{U_{\rm dc}}{\lambda_1-\lambda_2}\left(\lambda_2e^{\lambda_1t}-\lambda_1e^{\lambda_2t}\right) \\ i_{a(t)}=C_a\dfrac{du_{C_a}}{d_t}=\dfrac{\lambda_1\lambda_2C_aU_{\rm dc}}{\lambda_1-\lambda_2}\left(e^{\lambda_1t}-e^{\lambda_2t}\right)\end{cases}\left(0<t\le t_1\right)$$

where $\lambda_{1,2}=\frac{1}{2L_a}\left[-(3R_s+R_a)\pm\sqrt{\frac{1}{C_a}\left[(3R_s+R_a)^2C_a-4L_a\right]}\right]$

Stage 2: Uncontrolled pre-charging with current-limiting resistors bypassed sequentially

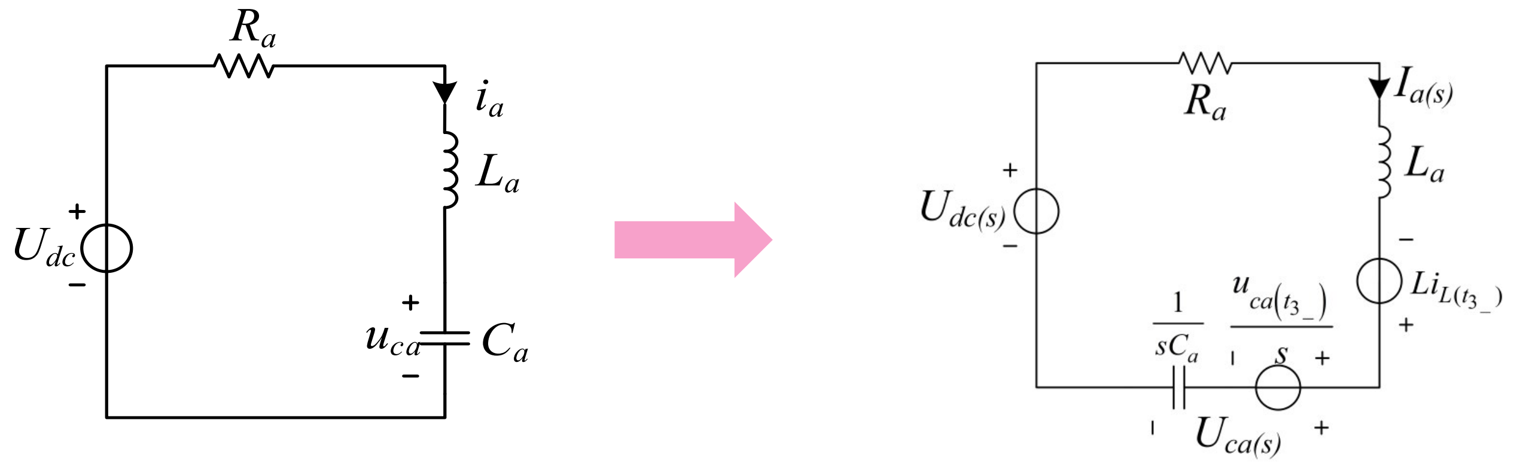
Then, the voltage of equivalent capacitor C_a is $u_{ca(t)}$, and the circulating current $i_{a(t)}$ can be deduced:

$$u_{ca(t)}=\begin{cases}U_{\rm dc}+\dfrac{U_{\rm dc}}{\lambda_1-\lambda_2}\left(\lambda_2e^{\lambda_1t}-\lambda_1e^{\lambda_2t}\right)\left(0<t\le t_1\right)\\ U_{\rm dc}+\dfrac{U_{\rm dc}}{\lambda_1'-\lambda_2'}\left(\lambda_2'e^{\lambda_1'(t-t_1)}-\lambda_1'e^{\lambda_2'(t-t_1)}\right)\left(t_1<t\le t_2\right)\\ U_{\rm dc}+\dfrac{U_{\rm dc}}{\lambda_1''-\lambda_2''}\left(\lambda_2''e^{\lambda_1''(t-t_2)}-\lambda_1''e^{\lambda_2''(t-t_2)}\right)\left(t_2<t\le t_3\right)\end{cases} \quad i_{a(t)}=C_a\frac{du_{C_a}}{d_t}=\begin{cases}\dfrac{\lambda_1\lambda_2C_aU_{\rm dc}}{\lambda_1'-\lambda_2'}\left(e^{\lambda_1t}-e^{\lambda_2t}\right)\left(0<t\le t_1\right)\\ \dfrac{\lambda_1'\lambda_2'C_aU_{\rm dc}}{\lambda_1'-\lambda_2'}\left(e^{\lambda_1'(t-t_1)}-e^{\lambda_2'(t-t_1)}\right)\left(t_1<t\le t_2\right)\\ \dfrac{\lambda_1''\lambda_2''C_aU_{\rm dc}}{\lambda_1''-\lambda_2''}\left(e^{\lambda_1''(t-t_2)}-e^{\lambda_2''(t-t_2)}\right)\left(t_2<t\le t_3\right)\end{cases}$$

where

$$\begin{cases}\lambda_{1,2}=\dfrac{1}{2L_a}\left[-(3R_s+R_a)\pm\sqrt{\dfrac{1}{C_a}\left[(3R_s+R_a)^2C_a-4L_a\right]}\right],\ R_s=R_{s1}+R_{s2}+R_{s3}\left(0<t\le t_1\right)\\ \lambda_{1,2}'=\dfrac{1}{2L_a}\left[-(3R_s'+R_a)\pm\sqrt{\dfrac{1}{C_a}\left[(3R_s'+R_a)^2C_a-4L_a\right]}\right],\ R_s'=R_{s2}+R_{s3}\left(t_1<t\le t_2\right)\\ \lambda_{1,2}''=\dfrac{1}{2L_a}\left[-(3R_s''+R_a)\pm\sqrt{\dfrac{1}{C_a}\left[(3R_s''+R_a)^2C_a-4L_a\right]}\right],\ R_s''=R_{s3}\left(t_2<t\le t_3\right)\end{cases}$$

In order to simplify the calculation, the time-domain analysis of the circuit needs to be converted to the frequency-domain analysis when all current-limiting resistors are bypassed.

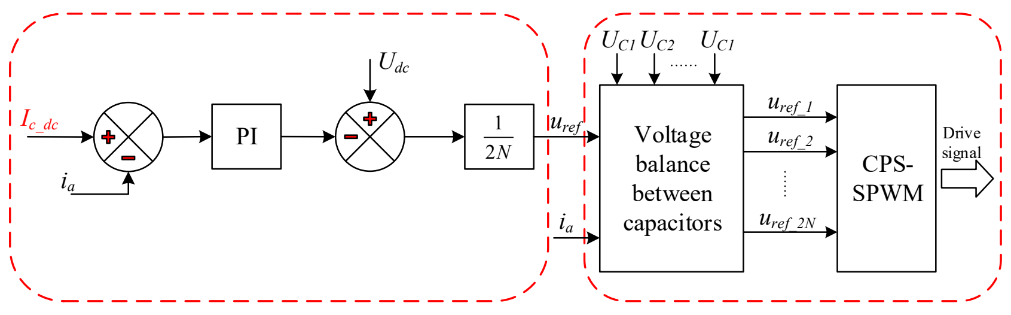


$$\left(R_a+sL_a+\frac{1}{sC_a}\right)I_{a(s)}-L_ai_{a(t_{3\_})}+\frac{u_{ca(t_{3\_})}}{s}=U_{{\rm dc}(s)}$$

$$\begin{cases}u_{ca(t_{3\_})}=U_{\rm dc}+\dfrac{U_{\rm dc}}{\lambda_1''-\lambda_2''}\left(\lambda_2''e^{\lambda_1''(t_3-t_2)}-\lambda_1''e^{\lambda_2''(t_3-t_2)}\right)\\ i_{a(t_{3\_})}=\dfrac{\lambda_1''\lambda_2''C_aU_{\rm dc}}{\lambda_1''-\lambda_2''}\left(e^{\lambda_1''(t_3-t_2)}-e^{\lambda_2''(t_3-t_2)}\right)\end{cases} \Rightarrow \begin{cases}u_{ca(t)}={\rm L}^{-1}\left[U_{ca(s)}\right]={\rm L}^{-1}\left[\dfrac{U_{{\rm dc}(s)}+L_ai_{a(t_{3\_})}-\dfrac{u_{ca(t_{3\_})}}{s}}{s^2L_aC_a+sC_aR+1}+\dfrac{u_{ca(t_{3\_})}}{s}\right]\\ i_{a(t)}={\rm L}^{-1}\left[I_{a(s)}\right]={\rm L}^{-1}\left[\dfrac{U_{{\rm dc}(s)}+L_ai_{a(t_{3\_})}-\dfrac{u_{ca(t_{3\_})}}{s}}{R+sL_a+\dfrac{1}{sC_a}}\right]\end{cases}\left(t_3<t\le t_4\right)$$

Stage 3: Pre-charging with constant current

It is only half of the rated SM capacitor voltage $U_{C(rate)}$, thus further current control is needed.



Finally, the switching signal of each SM is obtained by CPS-SPWM scheme.

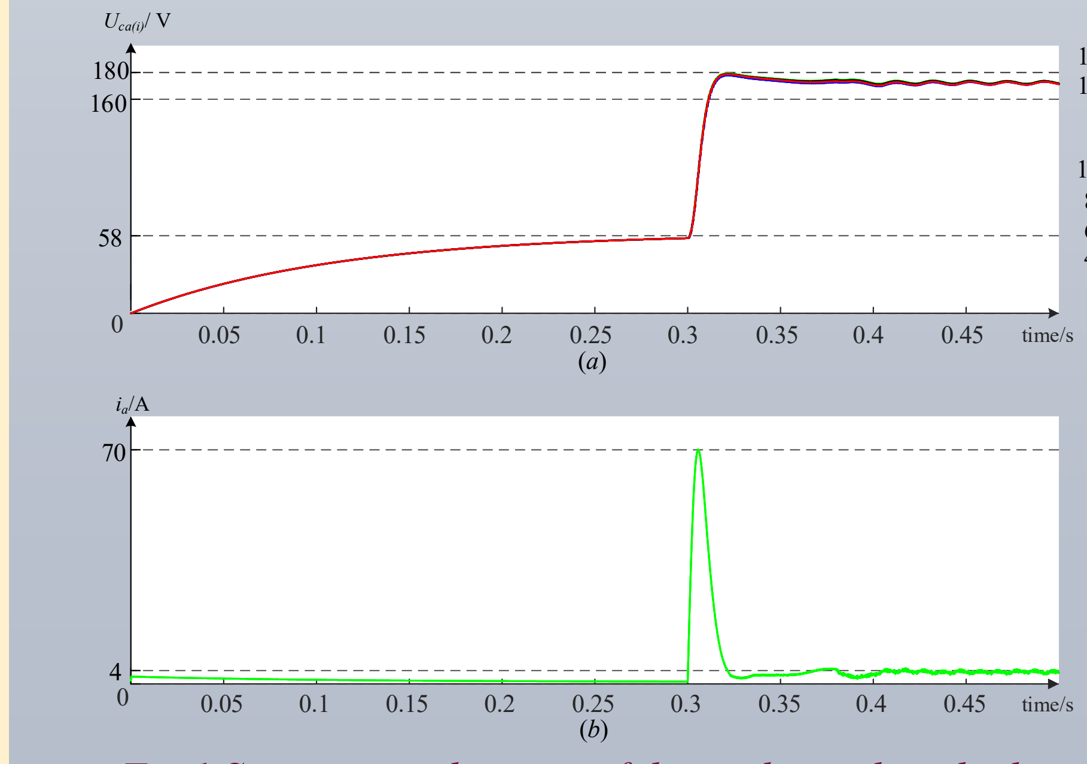


Fig.1 Startup pre-charging of the traditional method
(a)voltage waveform of the SM capacitor
(b)circulation current waveform of phase A.

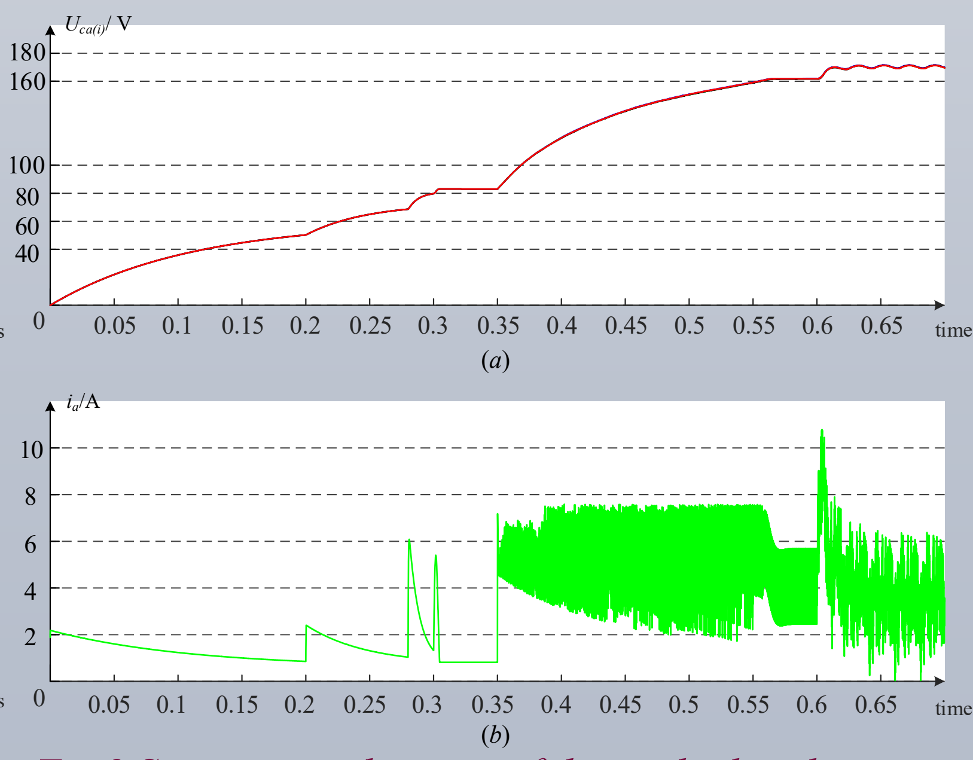


Fig.2 Startup pre-charging of the proposed method in this paper
(a)voltage waveform of the SM capacitor
(b)circulation current wave-form of phase A.

RESULTS

To verify the proposed dc-link startup pre-charging method, simulations are conducted in a MATLAB/Simulink environment.

In Fig.1, it shows the waveform of the traditional startup pre-charging. It can be seen that the inrush current is very large in phase A. When the only current-limiting resistor is bypassed, it is easy to cause damage to the power devices in the actual process.

Fig.2 shows the waveform of SM capacitor voltage of the upper arm of phase A and phase circulation current of the proposed method. The dc-link startup is divided into three stages:

Stage 1: 0~0.2s is the uncontrolled pre-charging stage with current-limiting resistors.

Stage 2: The uncontrolled pre-charging stage of bypassing current-limiting resistor: 0.2s, 0.28s and 0.3s are the bypass times for current-limiting resistors R_{s1}, R_{s2} and R_{s3}, respectively. 0.3~0.35s is the uncontrolled charging stage after all current-limiting resistors are bypassed.

Stage 3: constant current pre-charging stage of 0.35~0.6s, and stable operation stage after 0.6s.

It minimizes the inrush current effectively during the startup pre-charging.

CONCLUSIONS

This paper mainly analyzes the problem of startup and mathematical modeling analysis of the dc-link startup stage. In the uncontrolled charging stage, the method of bypassing the current-limiting resistor by stage is adopted. In the controllable charging stage, the SM capacitor is charged to the rated capacitor voltage at constant current by closed-loop control. According to the proposed method, the following conclusions can be drawn:

(1) It can minimize the inrush current by achieving bypass times during uncontrolled pre-charging stage.

(2) Moreover, it can reduce startup time and eliminate the inrush current during controlled pre-charging stage.