

# MMC circulating current suppression strategy based on improved quasi-PR control

Guangjie Fu \*, Zhiwei Lu

School of Electrical Information Engineering, Northeast Petroleum University, Daqing, China

\* Corresponding author: Guangjie Fu (Email: fgjmhw@163.com)

**Abstract:** The internal circulation of modularized multilevel converter will affect waveform quality and increase system loss. In this paper, the basic principle and topological structure of MMC as well as the causes of the internal circulation are briefly analyzed. A method of harmonic component extraction based on the second-order generalized integrator and the suppression strategy of MMC circulation based on feedforward compensation quasi-proportional resonant control are proposed. The feasibility of this strategy is verified in MATLAB/Simulink, and the simulation results show that the circulation and capacitor voltage fluctuation are controlled within a reasonable range.

**Keywords:** MMC circulating current suppression strategy; Improved quasi-PR control.

## 1. Introduction

With the rapid development of power electronics technology, modular multilevel converter MMC has become the mainstream high-voltage flexible DC transmission topology [1-2]. With the characteristics of modularization, low harmonics and low loss, MMC can independently control active power and reactive power and is widely used in photovoltaic, wind power grid-connected and isolated island power supply [3-5]. However, the partial pressure of submodules is not balanced during operation, which will generate interphase circulation between the three phase bridge arms. Interphase circulation will distort the current waveform of the bridge arm, reduce the operating efficiency of the converter, increase the system loss, and even affect the operating stability of the system. Therefore, effective circulation suppression strategies must be adopted to eliminate circulation.

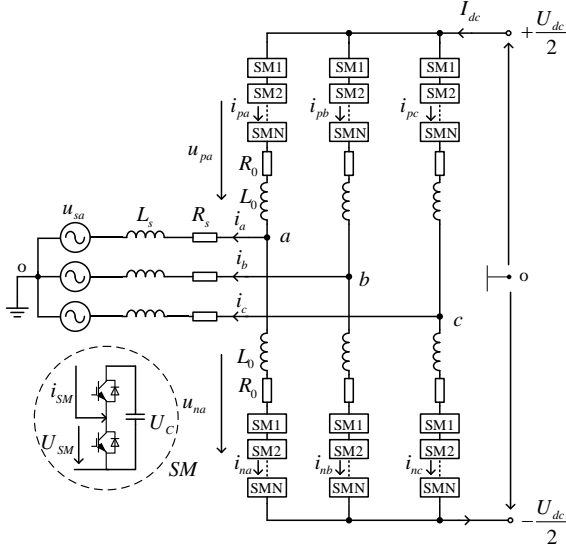
At present, circulation suppression strategies are mainly divided into passive circulation suppression and active circulation suppression. The passive circulation suppression strategy mainly reduces the amplitude of the circulation by increasing the series reactance value of the bridge arm. However, the circulation suppression effect of this method is limited, and the frequency response speed of the system will be reduced. Active circulation suppression is mainly to add additional controllers to the circulation equivalent model, and use feedback to track the given reference value to achieve the suppression of harmonic components [6]. The circulation controller based on PI control is proposed in literature [7]. This control strategy has been widely used in the field of flexible DC transmission, but this method requires phase-to-phase decoupling and coordinate transformation, and the control system design is complex, and only applies to three-phase systems. Literature [8] proposes a circulation suppression strategy based on the combination of multiple PR controllers, which overcomes the shortcoming that a single PR controller cannot suppress higher order even harmonics. However, the bandwidth of the controller is narrow, and the resonant frequency is easily offset, which affects the stability of the system. Literature [9] proposes a harmonic suppression strategy of quasi-PR controller, which increases the phase

Angle margin and bandwidth, but fails to suppress higher-order even harmonics. To solve these problems, this paper proposes an improved quasi-PR control MMC circulation suppression strategy, which does not require phase decoupling and coordinate transformation, and simplifies the control system design. In addition, this strategy can suppress not only the double frequency component in the circulation, but also the higher order even harmonic component.

## 2. Topology and mathematical model of MMC

The simplified topology of MMC is shown in Figure 1. Each phase is composed of two identical upper and lower bridge arms, and a single bridge arm is cascaded by  $N$  identical submodules.  $L_0$  is the equivalent inductance of the bridge arm,  $L_s$  is the current limiting inductance, and  $R$  is the equivalent resistance of the line.  $u_{pj}$ ,  $i_{pj}$ ,  $u_{nj}$ ,  $i_{nj}$  ( $j=a, b, c$ ) are the voltage and current instantaneous values of the upper and lower bridge arms in each phase, respectively.  $u_{sj}$  and  $i_{sj}$  are grid side voltage and current, respectively.  $u_{dc}$  Indicates the DC side voltage.

The common submodule is usually the half-bridge submodule, which consists of 2 IGBTs, 2 diodes in reverse parallel, and DC capacitance. The module has three working states: input, excision and lock. By controlling the trigger pulse, the input or removal of the submodule is realized, so that the output voltage of the submodule is the capacitor voltage  $U_c$  or 0. By controlling the number of submodules input into the upper and lower bridge arm, the output of level  $N+1$  is realized.



**Figure 1.** MMC single-ended simplified equivalent circuit

According to the simplified topology of MMC, Kirchhoff's voltage law can be obtained:

$$\begin{cases} \frac{1}{2}U_{dc} = u_{pj} + u_{jo} + L_0 \frac{di_{pj}}{dt} + R_0 i_{pj} \\ \frac{1}{2}U_{dc} = u_{nj} - u_{jo} + L_0 \frac{di_{nj}}{dt} + R_0 i_{nj} \end{cases} \quad (1)$$

In the formula,  $u_{jo}$  is the AC side voltage of each phase output; Add the two formulas in Formula (1) to obtain:

$$\frac{U_{dc}}{2} - \frac{u_{pj} + u_{nj}}{2} = \frac{L_0}{2} \left( \frac{di_{pj}}{dt} + \frac{di_{nj}}{dt} \right) + R \frac{i_{pj} + i_{nj}}{2} \quad (2)$$

According to Kirchhoff's current law, the upper and lower bridge arm currents of each phase are:

$$\begin{cases} i_{pj} = i_{zj} + \frac{i_{sj}}{2} \\ i_{nj} = i_{zj} - \frac{i_{sj}}{2} \end{cases} \quad (3)$$

In the formula,  $i_{zj}$  is the j phase circulation; From Formula (3), the expression of j phase interphase circulation can be deduced as follows:

$$i_{zj} = \frac{i_{pj} + i_{nj}}{2} \quad (4)$$

By substituting formula (2) into formula (4), we can get:

$$\frac{U_{dc}}{2} - \frac{u_{pj} + u_{nj}}{2} = L_0 \frac{di_{zj}}{dt} + R i_{zj} \quad (5)$$

As can be seen from formula (5), the size of circulation is determined by the difference between the sum of DC voltage and the voltage of the upper and lower bridge arms.

## 2.1. Circulation suppression

There is a difference between the DC voltage and the sum of the upper and lower bridge arm voltage, which is fundamentally due to the unbalanced voltage equalization of the submodules, resulting in the circulation inside the MMC. When the MMC operates in an ideal condition, the voltage of each phase submodule remains balanced at all times, and the capacitor voltage of each submodule is  $U_c = U_{dc}/N$ . However, in actual operating conditions, due to the impossibility of completely consistent bridge arm parameters and the slight difference in the turn-on time of each IGBT, the capacitor

voltage value of each sub-module has a certain deviation, and the DC voltage generated by each phase unit is difficult to keep consistent, so there is a circulation between each phase unit. Literature[10] obtained the expression of internal circulation according to energy conservation on both sides of the system:

$$\begin{cases} i_{za} \approx \frac{I_{dc}}{3} + I_{2f} \sin(2\omega t + \varphi) \\ i_{zb} \approx \frac{I_{dc}}{3} + I_{2f} \sin\left[2\left(\omega t - \frac{2}{3}\pi\right) + \varphi\right] \\ i_{zc} \approx \frac{I_{dc}}{3} + I_{2f} \sin\left[2\left(\omega t + \frac{2}{3}\pi\right) + \varphi\right] \end{cases} \quad (6)$$

In the formula,  $I_{dc}$  is the DC current component;  $I_{2f}$  is the peak value of double frequency circulation.  $\varphi$  is the phase Angle of circulation?

According to formula (6), the circulation components mainly contain DC components and frequency-double negative sequence components. In addition, the circulation also contains a small amount of higher-order even wave components. The DC component of the circulation is used to exchange active power between the submodule and the system. Ac even harmonic component increases the circulation amplitude and directly affects the energy storage of submodules. Therefore, the double frequency and higher order even harmonic components in the circulation need to be eliminated by reasonable control methods.

## 2.2. Harmonic extraction method based on second order generalized integrator

### 2.2.1. Harmonic extraction method based on second order generalized integrator.

In this paper, the harmonic component of circulation is extracted based on the combination of second order generalized integrator and DC integrator. As shown in Figure 2, the double frequency angular frequency of  $\omega_h$  is  $200\pi$ . The generalized second-order integrator is analyzed:

$$\frac{\omega_h / s}{1 - (\omega_h / s)^2} = \frac{s\omega_h}{s^2 - \omega_h^2} \quad (7)$$

When  $s = \omega_0 = 200\pi$ , the double frequency component in formula (2) is infinite after the circulation  $i_{zj}$  passes through the second order generalized integrator, so the double frequency component can be extracted from the circulation because the energy of double frequency is large. Then, by making the difference between the double frequency component and the circulation through the negative feedback, the DC component and the higher order even harmonic component are obtained. Then through the DC integrator, because the DC integrator can only pass through the DC component, other high-order even harmonic components are filtered out; After a negative feedback difference with the original loop flow, the double frequency and higher order even harmonic components  $i_{2zj}$  in the loop are obtained.

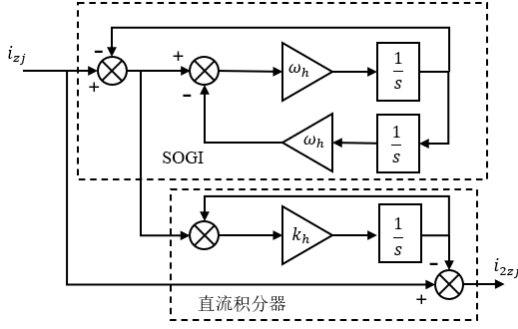


Figure 2. Extraction method of circulating harmonic components

### 2.2.2. Quasi-pr controller design

Compared with PI controller, ideal PR controller does not need phase decoupling and coordinate transformation, can track AC signal without static error, and has almost no attenuation at the resonant point. However, the ideal PR controller has narrow bandwidth, poor resistance to frequency changes, poor stability and low robustness. In this paper, a quasi-PR controller with better performance is adopted, which enlarges the bandwidth and improves the performance against frequency disturbance while maintaining high gain of resonant points. It is suitable for both single-phase and three-phase MMCS. Its transfer function is:

$$G(s) = k_p + \frac{2k_r\omega_c s}{s^2 + 2\omega_c s + \omega_0^2} \quad (8)$$

In the formula,  $k_p$  and  $k_r$  are proportionality coefficient and resonance coefficient respectively;  $\omega_0$  and  $\omega_c$  are resonant frequency and cutoff frequency respectively.

Different from PR controller, the gain of quasi-PR controller at resonant point is no longer infinite, and the size is  $k_p + k_r$ . The design of  $k_p$  and  $k_r$  has an important impact on the dynamic performance and stability of the system [11]. Therefore, an MMC circulation suppression structure based on PR controller can be designed, as shown in Figure 3.

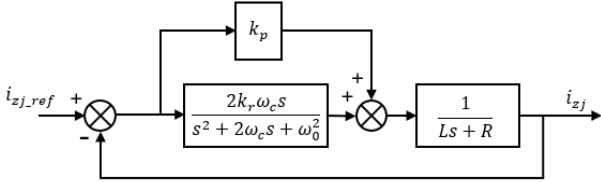


Figure 3. Structure block diagram of quasi-PR controller

### 2.2.3. Design of quasi-PR controller with feedforward compensation

In addition to a large number of double frequency components, there are also a small number of higher orders even harmonic components. A single quasi-PR controller can only suppress the double frequency component; Although the combination of multiple quasi-PR controllers can suppress some even harmonic components of higher order, the control is relatively complicated. In this paper, a quasi-PR controller with feedforward compensation is adopted to eliminate the influence of submodule capacitance voltage on system disturbance from the source. Figure 4 shows the structure of a quasi-PR controller with feedforward compensation.

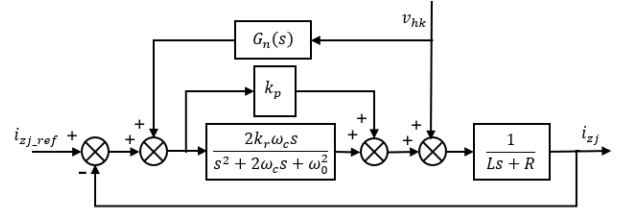


Figure 4. Structure block diagram of quasi-PR controller with feed-forward compensation

According to Figure 4, the output transfer function under disturbed  $v_{hk}$  can be obtained:

$$G_n(s) = \frac{G_1(s)[1 + G_{PR}(s)G_n(s)]}{1 + G_{PR}(s)G_n(s)} N(s) \quad (9)$$

In the formula,  $G_1(s) = 1/(Ls + 1)$ ;  $G_{PR}(s)$  is quasi PR controller;  $G_n(s)$  is feedforward compensation;  $N(s)$  is the perturbed part. The error under disturbance is expressed as:

$$E(s) = -G_n(s) \quad (10)$$

In order to eliminate the influence of perturbation,  $E(s) = 0$  is required, and it can be concluded that:

$$G_n(s) = -\frac{s^2 + 2\omega_c s + \omega_0^2}{k_p s^2 + 2(k_p + k_r)\omega_c s + k_p \omega_0^2} \quad (11)$$

In order to simplify calculation, steady-state analysis of disturbance is carried out. At this time, it is advisable to:

$$G_n(s) = -\frac{1}{k_p} \quad (12)$$

## 3. Simulation verification

In order to verify the effectiveness of the circulation suppression method, a simulation model of 11-level modular multilevel converter was built on the MATLAB/Simulink simulation platform, and the nearest level approximation modulation strategy was adopted. The main simulation parameters are shown in Table 1.

Table 1. Simulation parameters

Parameter name	Numerical value
MMC Number of submodules of the bridge arm	10
Submodule capacitance value /mF	2.5
Bridge arm inductance value /mH	3
Submodule capacitor voltage initial value /V	2000
Frequency /Hz	50
DC side voltage /kV	20

Taking the A-phase of the MMC model as an example, Figure 5 shows the A-phase circulation before and after the circulation suppression. Before the circulation suppression, the circulation stabilized around -320~720A, and after the circulation suppression was put in for 0.05s, the circulation stabilized around 180A with small fluctuations. It can be seen that the circulation inhibition effect is obvious.

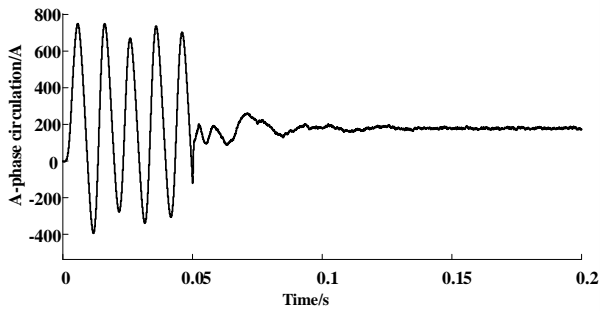


Figure 5. A-phase circulation before and after circulation suppression

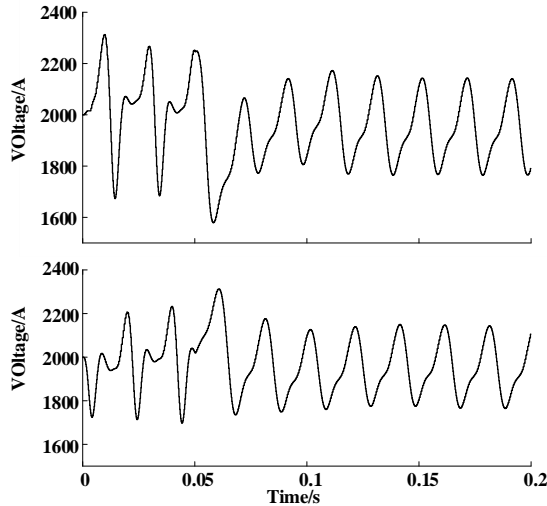


Figure 6. The circulation suppresses the front and rear A-phase bridge arm currents

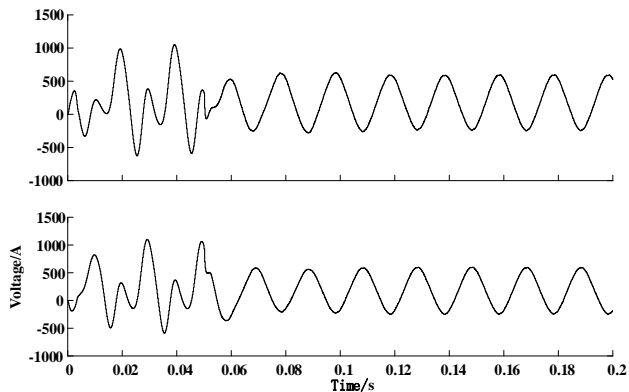


Figure 7. A-phase upper and lower bridge arm submodules

Figure. 6 and Figure. 7 show the upper and lower bridge arm current and submodule capacitor voltage waveforms of phase A respectively. There are obvious double frequency distortion before adding circulation suppression. Figure. 8 and Figure. 9 respectively show the current harmonic analysis of the upper and lower A-phase bridge arms before and after circulation suppression. The waveform distortion rate decreases from 125.69% to 2.68%, and the double frequency component and even harmonic component significantly decrease.

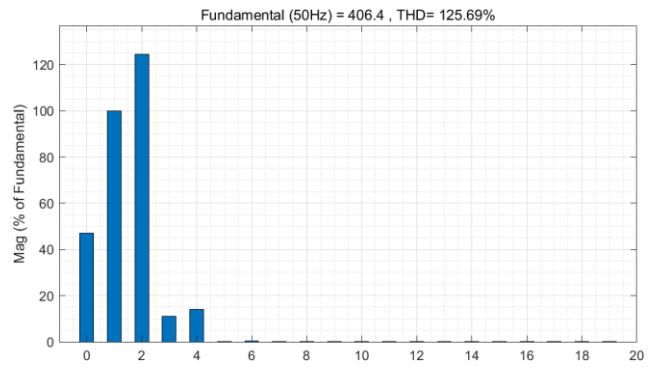


Figure 8. Harmonic analysis of upper bridge arm current before circulation suppression

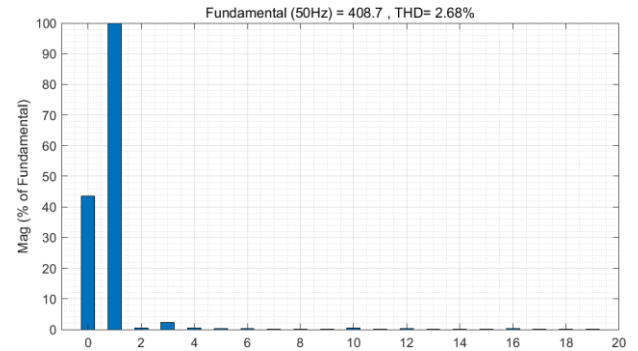


Figure 9. Harmonic analysis of upper bridge arm current in A phase after circulation suppression

## 4. Conclusion

Aiming at the interphase circulation caused by the voltage unbalance of MMC submodules, this paper proposes a method to extract harmonic components based on the combination of generalized integrator and DC integrator, which solves the problem that the harmonic components obtained by indirect calculation are not accurate enough. A feedforward link is added to the quasi-PR controller to solve the problem that a single quasi-PR controller cannot suppress the high order even harmonics and the complex control system of multiple quasi-PR controllers. The correctness and effectiveness of the proposed control strategy are verified by simulation.

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