Control of Circulating Current in Modular Multilevel Converter under Unbalanced Voltage using Proportional-Resonant Controller

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Abstract

The circulating current control within the phase legs is one of the main control objectives in a modular multilevel converter (MMC) under different operating conditions. This paper proposes a control strategy of circulating currents in the MMC under unbalanced voltage by using a proportional-resonant (PR) controller. Under the unbalanced voltage, the circulating currents in the MMC consists of three components such as positive-sequence, negative-sequence, and zero-sequence circulating currents. With the PR controller, all components of the circulating current will be directly controlled in the stationary reference frame without decomposing into positive- and negative-sequence components. Thus, the ripples in the circulating currents and the DC current are suppressed under the unbalanced voltage. The effectiveness of the proposed method is verified by simulation results based on PSCAD/EMTDC simulation program.

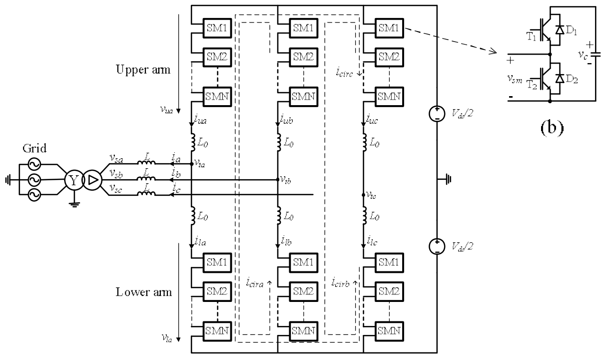
Key words: Circulating current, Modular multilevel converter, Proportional-resonant controller, Positive-sequence, Negative-sequence, Zero-sequence.

1. Introduction

Recently, the modular multilevel converter (MMC) has become a promising voltage source converter (VSC) topology for medium and high voltage applications. The control of the MMC has been researched by many authors [1]. In the MMC, one of the most important control strategies is the control of the circulating currents that only flow within the phase legs. Although the circulating currents don't affect to the AC-side currents of the MMC, they can cause power losses in the arms and increase the magnitude of the submodule capacitor votlage ripple. Under the unbalanced votlage, the circulating current contains three components such as positive-sequence, negative-sequence, and zero-sequence components. The positive- and zero-sequence components cause an unbalance in the circulating currents and then lead to the ripple in the DC current. In [2], the authors have presented a control strategy of circulating currents under the balanced voltage implemented in the double frequency rotating reference frame. However, this control strategy cannot eliminate the positive-and zero-sequence components under the unbalanced voltage. To improve this problem, the authors in [3] have proposed a proportional-integral-resonant (PIR) controller for suppressing the circulating currents under the unbalanced votlage. This method has disadvantage because of the calculation of three gain parameters. Besides, the reference DC current was calculated by ignoring the power losses in the converter. Thus, this paper proposes a control strategy of the circulating currents in the MMC under the unbalanced voltage by using the PR controller. In this control strategy, all components of the circulating currents will be directly controlled in the stationary reference frame (αβ-frame) without decomposing into positive- and negative-sequence components. The reference values of the circulating currents are set to zero. Thus, the ripples in the circulating currents and the DC current are suppressed under the unbalanced voltage.

2. Main subject

2.1 Configuration of the modular multilevel converter



(a)

Fig. 1 Configuration of the modular multilevel converter.
(a) Circuit diagram, (b) Submodule

The configuration of the MMC is shown in Fig. 1. The circulating currents only flow within phase legs and do not affact to the AC side of the MMC. The upper and lower arm currents can be calculated as

$$i_{uj} = \frac{i_j}{2} + i_{diffj} \tag{1}$$

$$i_{lj} = -\frac{i_j}{2} + i_{diffj} \tag{2}$$

where $j = a, b, c$ denotes the phase A, B, and C. i_j is the output current of phase j. i_{diffj} is the inner difference current of phase j that flows through both the upper and lower arms, and it is given by

$$i_{diffj} = \frac{i_{uj} + i_{lj}}{2} = \frac{i_{dc}}{3} + i_{cirj} \tag{3}$$

where i_{cirj} is the circulating current of phase j, i_{dc} is the DC current.

Under the balanced voltage, the circulating currents only contain a negative-sequence double frequency component, $i_{cirj} = i_{cirj}^{-}$, and the sum of three-phase circulating currents is zero. However, the circulating currents will contain three components under the unbalanced votlage as

$$i_{cirj} = i_{cirj}^{+} + i_{cirj}^{-} + i_{cirj}^{0} \tag{4}$$

where i_{cirj}^{+}, i_{cirj}^{-}, and i_{cirj}^{0} are the positive-, negative-, and zero-sequence components of the circulating currents.

The DC current under the unbalanced voltage is calculated as

$$i_{dc1} = \sum_{j=a,b,c} i_{diffj} = i_{dc} + \sum_{j=a,b,c} i_{cirj}^{+} + \sum_{j=a,b,c} i_{cirj}^{-} + \sum_{j=a,b,c} i_{cirj}^{0} \tag{5}$$

The second and third terms in (5) are zero while the fourth term in (5) is not zero. There will be a zero-sequence circulating currents flowing into the DC side and cause a ripple in the DC current. Thus, a full control strategy of the MMC under the unbalanced voltage conditions is the suppression of all components of the circulating currents, namely positive-, negative-, and zero-sequence components. This can be done by using the PR controller in the αβ-frame. In this case, the circulating currents will be controlled directly in the αβ-frame, a decomposition of the circulating current into the positive- and negative-sequence components is not necessary. Besides, the output currents of the MMC are also contain the positive-, negative-, and zero-sequence components. Thus, the PR controller is also applied to control the output currents of the MMC. The transfer function of the PR controller is expressed as

$$G_{PR} = K_p + \frac{K_i s}{s^2 + \omega^2} \tag{6}$$

where K_p is the proportional gain that is adjusted as the same way for a PI controller, K_i can be tuned for shifting the magnitude response vertically.

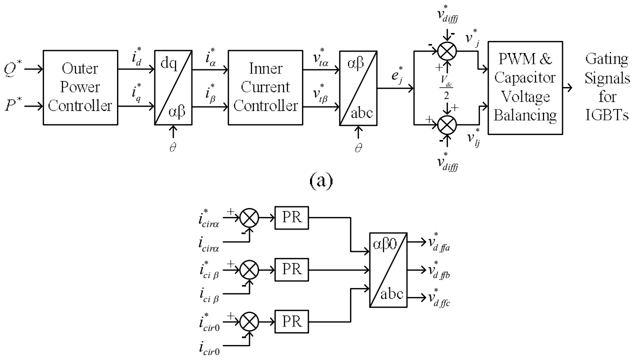
The control strategy of the circulating currents and the MMC is given in Fig. 2.

2.2 Simulation results

In order to verify the effectiveness of the proposed control strategy, the simulation results are performed in two cases with the same line-to-ground fault and the same control strategy of the output currents. The first case is the control strategy of the circulating currents with the PI controller in the synchronous rotating reference frame (Fig. 3). The second case is the proposed control strategy of the circulating currents (Fig. 4). The parameters of the MMC are given in Table I. The simulation results are shown in Fig. 3 and Fig. 4. The line-to-ground fault occurs from 1 s to 1.2 s as shown in Fig. 3(a). The three-phase output currents are balanced during faulting time as seen in Fig. 3(b). With the PI controller and without controlling the positive- and zero-sequence components, there are the ripples in the inner difference currents and the DC current as shown in Figs. 3(c) and (d). With the PR controller, the ripples in the inner difference currents and the DC current are removed completely as illustrated in Figs. 4(a) and (b).

3. Conclusion

This paper has proposed a control strategy of the circulating currents in the MMC under the unbalanced voltage by using the PR controller. The simulation results have demonstrated that the ripples in the inner difference currents or the circulating currents and the DC current are removed under the unbalanced voltage with the proposed control strategy. It means that the positive-, negative, and zero-sequence components in the circulating currents are suppressed completely. This confirms the effectiveness of the proposed control strategy.



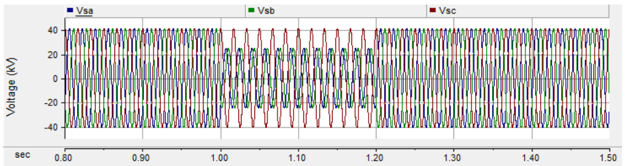
(a)

(b)

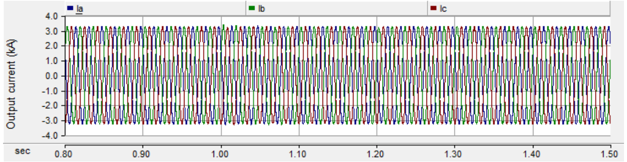
Fig. 2 Control strategies. (a) Control strategy of the MMC, (b) Proposed control strategy of the circulating currents

TABLE I. THE PARAMETERS OF MMC

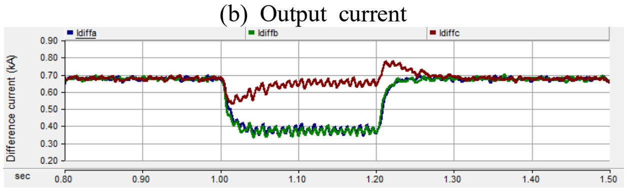
Rated power	200 MW
AC system voltage	154 kV
Nominal frequency	60 Hz
Transformer ratio	154 kV/50 kV
Dc-link voltage	±50 kV
Number of SMs per arm	20



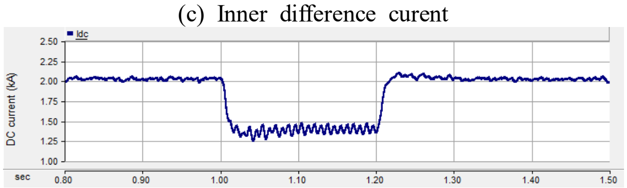
(a) Grid voltage



(b) Output current

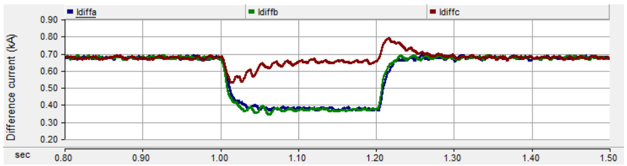


(c) Inner difference curent

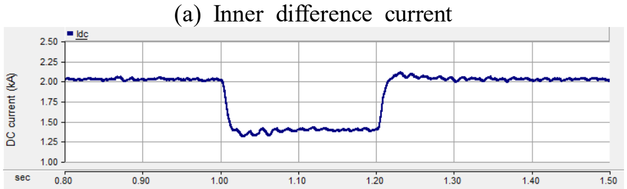


(d) DC current

Fig. 3 Control strategy of circulating currents with the PI controller under the unbalanced voltage



(a) Inner difference current



(b) DC current

Fig. 4 Control strategy of circulating currents with the PR controller under the unbalanced voltage

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