Quasi Proportional Resonant Controller Based MMC Grid Side Harmonic Suppression Research

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***Abstract*—High-voltage direct current transmission based on modular multi-level converter (MMC-HVDC) has developed rapidly in recent years due to its advantages such as high efficiency, small size, no commutation failure, and the ability to supply power to passive AC systems. It has become a hot spot in the field of high-voltage direct current transmission. Many high-voltage direct current transmission projects based on modular multi-level converter have been successively built and put into operation all over the world. However, there are also some problems to be solved in MMC-HVDC project. For example, the high harmonic content at the network side of the converter leads to the serious voltage distortion at the common connection point (PCC), which leads to the maloperation of the protection of modular multi-level converter (MMC). The problem of harmonic pollution at the network side of the modular multi-level converter has affected the safe and stable operation of the MMC-HVDC project. However, there is less analysis on this problem in the existing literature, so it is very necessary to further study this problem. Aiming at the problem of harmonic suppression on the network side of modular multi-level converter, a harmonic suppression strategy based on quasi proportional resonance controller (QPR) is proposed in this paper. The principle of this strategy is simple and easy to implement. The proposed harmonic suppression strategy has a certain reference value for solving the related problems in the actual MMC-HVDC project. The harmonic suppression strategy is simulated in PSCAD, and the simulation results show that the proposed harmonic suppression strategy has good harmonic suppression effect.**

Keywords—MMC-HVDC, harmonic suppression, quasi proportional resonance control

I. INTRODUCTION

In order to meet the demand of clean energy transmission and power supply in load centers, high-voltage direct current transmission technology is widely used in the world to realize long-distance and large-capacity transmission of energy resources [1]. In the field of high-voltage direct current transmission, the high-voltage direct current transmission based on modular multi-level converter (MMC-HVDC) has developed rapidly in recent years because of its remarkable advantages, such as high efficiency, small size, no commutation failure, and the ability to supply power to passive AC system. Many high-voltage direct current transmission projects based on modular multi-level converter have been successively built and put into operation all over the world. However, there are also some problems to be solved in MMC-HVDC project. For example, the high harmonic content at the network side of the converter leads to the serious voltage distortion at the common connection point (PCC), which leads to the maloperation of the protection of modular multi-level converter (MMC). Although the network side harmonics generated by MMC when it adopts the nearest level approximation modulation are small, for weak active systems or occasions with large load harmonics, flexible DC systems are still required to provide certain harmonic suppression capability [2]. The problem of harmonic pollution on the grid side of multi-level converter has affected the safe and stable operation of MMC-HVDC project, but there is less analysis of this problem in the existing literature, so it is necessary to further study this problem.

In the published literature, there have been many studies on harmonic analysis and suppression [2-13]. In the harmonic suppression of converter, the proportional resonance controller has the advantages of infinite gain at the resonance point and zero steady-state error tracking ability, so it has become a good choice for harmonic control. In terms of harmonic suppression of converter, in [2], for the harmonic suppression at the grid side of MMC-HVDC, the proportional resonance control and harmonic compensation control scheme is adopted in the current inner loop to realize the tracking control for specific harmonics, but the harmonic suppression effect of this method is limited. In [7], a harmonic suppression method based on resonance control is proposed to solve the problem of insufficient harmonic suppression ability of the current distributed inverter. The virtual harmonic impedance is synthesized quickly and accurately through the second-order generalized integrator, and the virtual harmonic impedance is introduced into the inverter current control link to realize the compensation of harmonic voltage. Reference [8] aimed at the harmonic current pollution problem in MMC-HVDC, based on the flexible direct inner loop PI controller and the proportional resonance controller, the zero static error tracking of harmonic current was realized, and a closed-loop control strategy of network side current of modular multi-level converter in distribution network was proposed, which realized the effective suppression of network side harmonic current. Reference [9] proposes a novel inverter voltage source grid connection scheme based on harmonic voltage repetitive control. The voltage harmonics at both ends of the grid connected reactance are detected by fast harmonic detection algorithm, and the corresponding harmonic voltage is sent by repetitive control to compensate for the harmonic impact of the grid, reduce the harmonic voltage difference on the grid connected reactance, and achieve the purpose of reducing the overall harmonic distortion rate of the grid connected current. Reference [10-11] studies the harmonic suppression of permanent magnet fan side converter. Reference [12] proposed a current harmonic suppression method based on coordinate transformation to solve the problems of grid connected current distortion and high low-order harmonic content of cascaded H-bridge photovoltaic inverter. Reference [13] proposed an adaptive harmonic droop control strategy for low-voltage microgrid inverter.

In this paper, a harmonic suppression strategy based on quasi proportional resonance (QPR) controller is proposed. Based on the flexible DC inner loop controller, the quasi proportional resonance controller is used to generate additional harmonic voltage to form a closed-loop control structure of network side current, so as to realize the suppression of network side harmonic current. PSCAD is used to simulate the proposed harmonic suppression strategy, and the results show that the harmonic suppression strategy has good harmonic control effect.

II. Harmonic Suppression Strategy

A. Control Strategy of MMC-HVDC System

The topology of three-phase MMC is shown in Fig. 1. The bridge arm of modular multilevel converter adopts the mode of sub module cascade, and each bridge arm is composed of N sub modules and a series reactor.

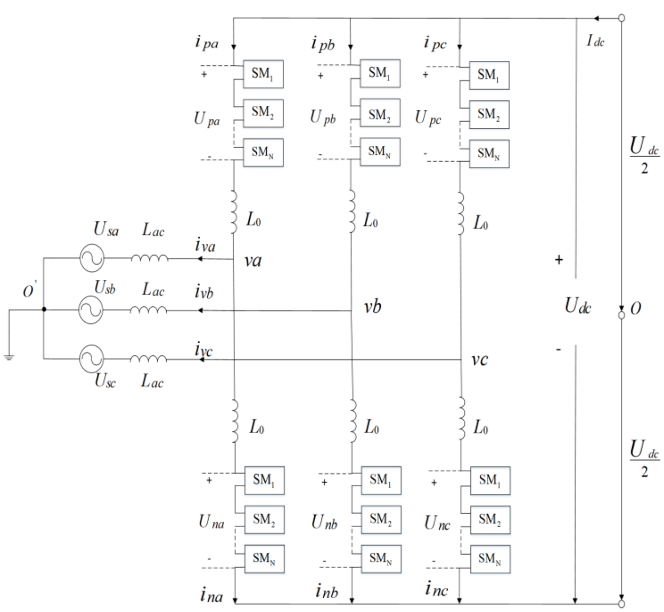

Fig. 1. Modular multilevel converter model diagram

In Fig. 1, U_{sj} is the voltage on line side, i_{vj} is the current on valve side, U_{vj} is the voltage at the inverter outlet, i_{pj} and i_{nj} is the upper bridge arm current and lower bridge arm current respectively, U_{pj} and U_{nj} is the upper bridge arm voltage and lower bridge arm voltage respectively, L_{ac} is the AC system equivalent reactance, L_0 is the bridge arm reactance, the bridge arm resistance is ignored. According to Fig. 1, Kirchhoff voltage equation is established:

$$U_{sj} + L_{ac}\frac{di_{vj}}{dt} + U_{pj} + L_0\frac{di_{pj}}{dt} = U_{oo'} + \frac{U_{dc}}{2} \quad (1)$$

$$U_{sj} + L_{ac}\frac{di_{vj}}{dt} - U_{nj} - L_0\frac{di_{nj}}{dt} = U_{oo'} - \frac{U_{dc}}{2} \quad (2)$$

where, $U_{oo'}$ is the voltage difference with the point O and O′, U_{dc} is the DC side voltage.

Define the differential mode voltage of the upper and lower bridge arms as U_{diffj}, and the common mode voltage of the upper and lower bridge arms as U_{comj}, and the expressions are as follows:

$$U_{diffj} = \frac{1}{2}(U_{nj} - U_{pj}) \quad (3)$$

$$U_{comj} = \frac{1}{2}(U_{nj} + U_{pj}) \quad (4)$$

where, the differential mode voltage U_{diffj} is consistent with the voltage at the outlet of the converter U_{vj}. Defined L_1 as equivalent reactance, $L_1 = L_{ac} + \frac{L_0}{2}$.

From (1)-(4), it can be deduced that:

$$L_1\frac{di_{vj}}{dt} = U_{oo'} - U_{sj} + U_{vj} \quad (5)$$

Under the condition that the AC system is symmetrical, the fundamental component of $U_{oo'}$ is 0, while in the controller design of MMC, the AC side only pays attention to the fundamental component. Therefore, (5) can be simplified as:

$$L_1\frac{di_{vj}}{dt} = U_{vj} - U_{sj} \quad (6)$$

The frequency domain form of the fundamental frequency dynamic equation of MMC in dq coordinate system can be obtained by performing pike transform and Laplace transform on (6):

$$L_1 s i_{vd}(s) = -U_{sd}(s) + U_{vd}(s) + \omega L_1 i_{vq}(s) \quad (7)$$

$$L_1 s i_{vq}(s) = -U_{sq}(s) + U_{vq}(s) - \omega L_1 i_{vd}(s) \quad (8)$$

where, $i_{vd}(s)$ and $i_{vq}(s)$ are the d and q axis components of the valve side current, $U_{vd}(s)$ and $U_{vq}(s)$ are the d and q axis components of the voltage at the outlet of the converter, $U_{sd}(s)$ and $U_{sq}(s)$ are the d and q axis components of the grid side voltage, and ω are the angular frequency.

According to (7) and (8), the control block diagram of the flexible DC inner loop current controller is shown in Fig. 2.

The physical quantity controlled by the flexible DC outer loop power controller is an active power physical quantity and a reactive power physical quantity. Among them, the active power physical quantity is one of the AC side active power, DC side voltage and AC system frequency, and the reactive power physical quantity is one of the AC side reactive power and AC side voltage. Because this paper does not involve the improvement of the flexible DC outer loop power controller, therefore, the outer loop power controller of flexible DC will not be described in detail here.

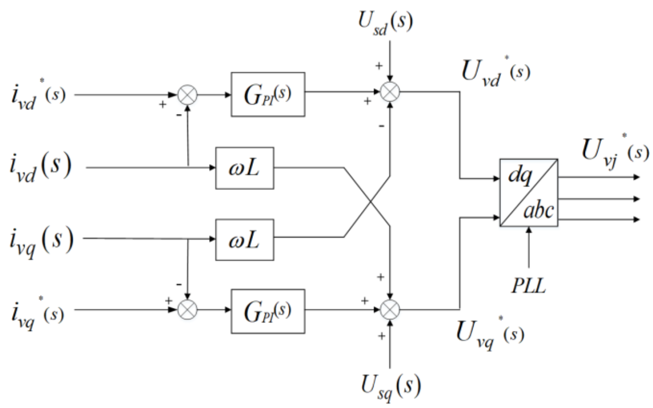

Fig. 2. Control block diagram of flexible DC inner loop current controller

B. *Quasi Proportional Resonance (QPR) Controller*

The proportional resonance controller (PR controller) has infinite gain at the resonance point and can track the harmonic current without static error. It is a good choice for harmonic control. The general expression of the ideal resonance controller is shown in (9) [14]:

$$G_R = \frac{K_r s}{s^2 + \omega_r^2} \tag{9}$$

Because the ideal resonant controller does not contain damping term, its frequency band at the resonant frequency is very narrow, and the gain outside the resonant frequency point drops rapidly, making the system extremely sensitive to the parameters in the circuit and grid fluctuations [14-15]. Therefore, many literatures have studied how to improve the ideal resonant controller, and the quasi resonant controller is widely used to replace the ideal resonant controller. The bandwidth of the quasi resonant controller at the resonant frequency increases, which reduces the sensitivity to the system and is conducive to enhancing the stability of the system [14]. The transfer function of the quasi resonant controller is shown in (10), in which ω_r is the resonant frequency, that is, the harmonic frequency to be eliminated. The comparison of Bode diagram between quasi resonant controller and ideal resonant controller is shown in Fig. 3. The solid line in Fig. 3 is the Bode diagram of quasi resonant controller, and the dotted line is the Bode diagram of ideal resonant controller.

$$G_{QR} = \frac{2\omega_c K_r s}{s^2 + 2\omega_c s + \omega_r^2} \tag{10}$$

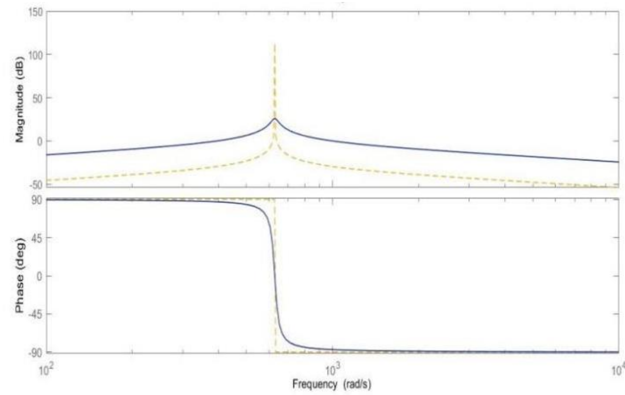

Fig. 3. Bode diagram of quasi resonant controller and ideal resonant controller

The proportional resonance controller (PR controller) composed of quasi resonance controller is called quasi proportional resonance controller (QPR controller). The transfer function of quasi proportional resonance controller is shown in (11). The Bode diagram of the quasi proportional resonance controller used in this paper is shown in Fig. 4.

$$G_{QPR} = K_p + \frac{2\omega_c K_r s}{s^2 + 2\omega_c s + \omega_r^2} \tag{11}$$

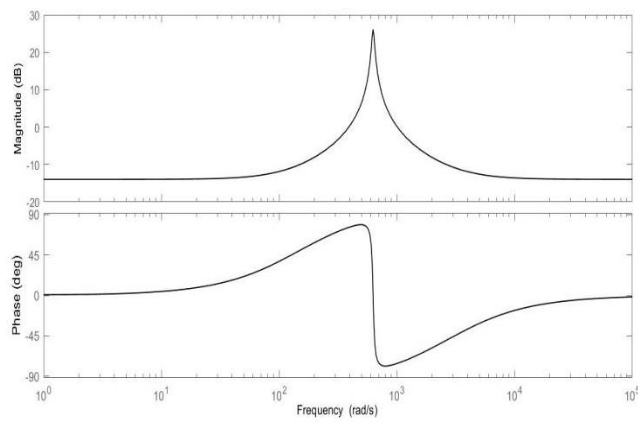

Fig. 4. Bode diagram of quasi proportional resonant controller

C. *The Proposed Harmonic Suppression Strategy on the Network Side*

The proportional integral (PI) controller has good performance in tracking direct flow, but there must be steady-state error in tracking AC flow. Therefore, if only the traditional current loop d-axis and q-axis proportional integral control method is adopted, it can not track harmonic current without static error, while the quasi proportional resonance controller can track harmonic current without static error and has good ability to resist external disturbance.

In this paper, aiming at the problem of harmonic pollution on the network side of modular multi-level converter, a harmonic suppression strategy is proposed. The proposed harmonic suppression strategy superimposes the harmonic suppression link composed of bandpass filter and quasi proportional resonance controller in the flexible DC inner loop current controller to realize the extraction and suppression of harmonic current on the network side. The control block diagram of the harmonic suppression strategy is shown in Fig. 5, in which $G_{QPR}(s)$ is the transfer function of the quasi proportional resonance controller and $G_{BPF}(s)$ is the transfer function of the bandpass filter.

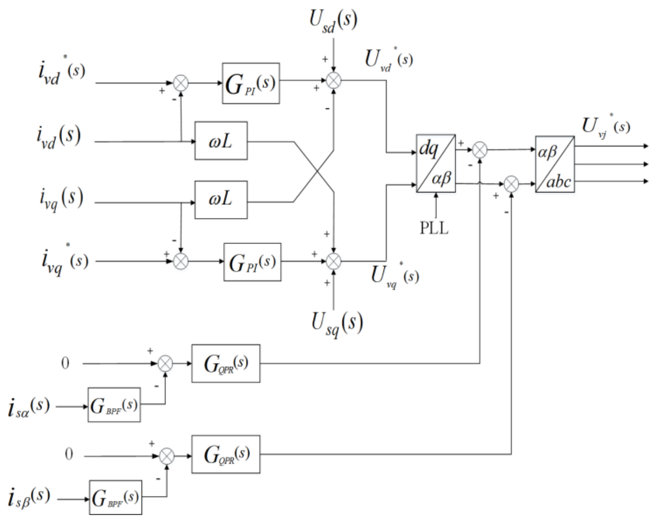

Fig. 5. Block diagram of harmonic suppression strategy at network side

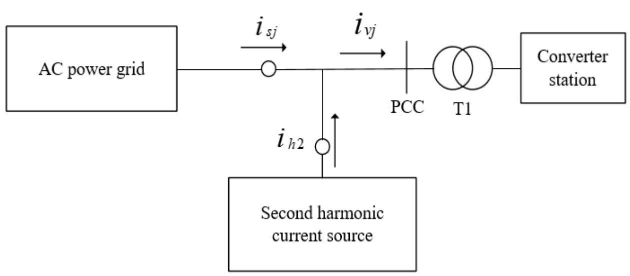

Fig. 6. Schematic diagram of the relationship between network side current i_s and valve side current i_v

In order to more clearly illustrate the effect of the proposed harmonic suppression strategy, the relationship between network side current i_s and valve side current i_v is illustrated, as shown in Fig. 6, in which, i_{h2} is the second harmonic current generated by nonlinear devices.

The principle of the proposed harmonic suppression strategy is as follows. The second harmonic component of the network side AC current is obtained through the band-pass filter. Take the difference between the second harmonic component of the network side current i_s and 0 as the input of the quasi proportional resonance (QPR) controller, and add the output of the quasi proportional resonance controller to the voltage reference value at the inverter outlet in the αβ coordinate system, as an additional voltage. In this way, a closed-loop control structure of the network side current will be formed. When there is a second harmonic component in the network side current i_s, QPR controller can infinitely enlarge the difference between the second harmonic component in the network side current and 0. Due to the formation of a closed-loop control structure, the second harmonic component in i_s will gradually approach 0 under the action of negative feedback, so as to achieve the effect of harmonic current suppression at the network side.

The harmonic suppression strategy proposed in this paper carries out harmonic control in the αβ static coordinate system, and the positive sequence harmonic and negative sequence harmonic can be controlled simultaneously by the quasi proportional resonance controller. The harmonic suppression strategy is simple and easy to implement. The simulation experiments in PSCAD verify the effectiveness of the harmonic suppression strategy proposed in this paper.

III. SIMULATION VERIFICATION

In PSCAD, the simulation model of AC power grid connected to MMC converter station as shown in Fig. 6 is built to verify the governance effect of the proposed harmonic suppression strategy on the second harmonic current at the grid side. In order to be closer to the actual situation, the AC power grid adopts the equivalent model of a part of the actual power grid. The simulation time is 10 seconds in total. The proposed harmonic suppression strategy is input in the first 5 seconds and not input in the last 5 seconds. The simulation results are as follows.

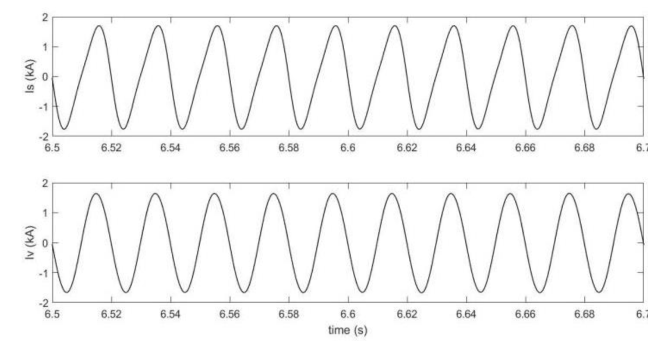

Fig. 7. Waveform diagram of network side current i_s and valve side current i_v without harmonic suppression strategy

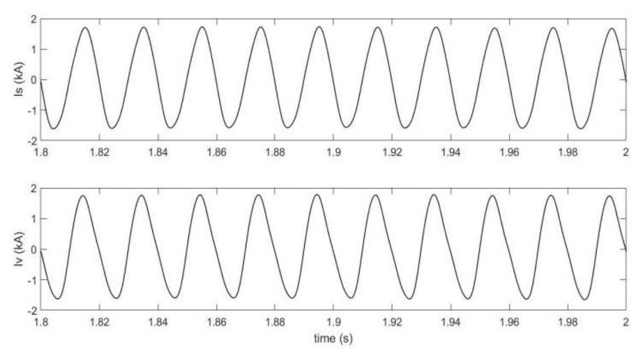

Fig. 8. Waveform diagram of network side current i_s and valve side current i_v when adding harmonic suppression strategy

It can be seen from Fig. 7 that when the harmonic suppression strategy is not added, the waveform distortion of the network side current i_s is relatively serious, while the waveform of the valve side current i_v is similar to the sine wave. Compared with Fig. 7 and Fig. 8, it can be seen that when the harmonic suppression strategy is added, the waveform of the network side current i_s has been significantly improved. When the proposed harmonic suppression strategy is added, the waveform of the network side current i_s is similar to the sine wave.

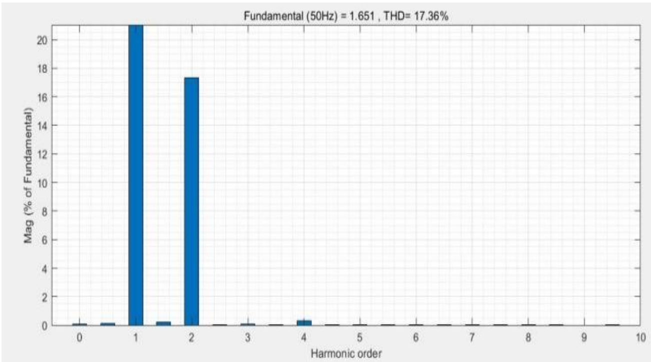

Fig. 9. Frequency analysis of network side current i_s without harmonic suppression strategy

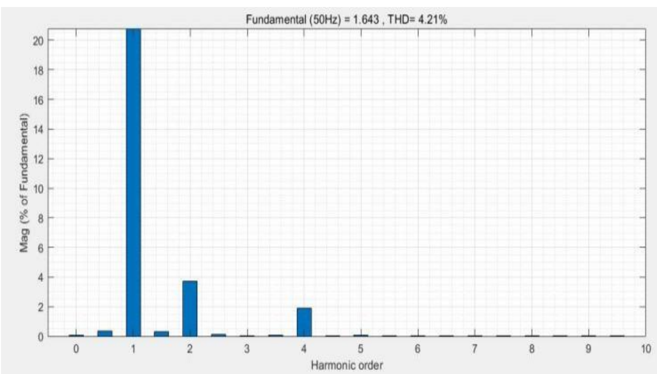

Fig. 10. Frequency analysis of network side current i_s with harmonic suppression strategy

Fig. 9 and Fig. 10 show the frequency analysis of the simulated network side current i_s. It can be seen from the figure that when the harmonic suppression strategy is added, the amplitude of the second harmonic component in the network side current i_s is significantly reduced, from 17.36% when the harmonic suppression strategy is not added to 3.73%, and the harmonic distortion rate (THD) of the network side current i_s is also reduced from 17.36% when the harmonic suppression strategy is not added to 4.21%. Calculate the harmonic suppression of the network side current i_s, as shown in Table I. It can be seen that the proposed harmonic suppression strategy has a good harmonic suppression effect on the network side current i_s.

TABLE I. STATISTICS OF HARMONIC SUPPRESSION DATA OF NETWORK SIDE CURRENT i_s

	Uncompensated/%	*Compensated/%*	*Inhibition ratio/%*
Second harmonic	17.36	3.73	78.51
THD	17.36	4.21	75.75

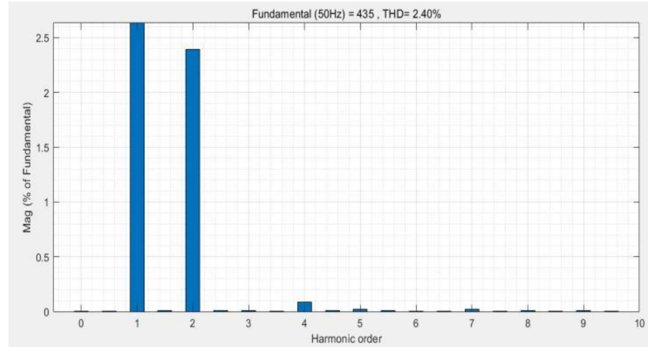

Fig. 11. Frequency analysis of voltage at the outlet of converter U_v without harmonic suppression strategy

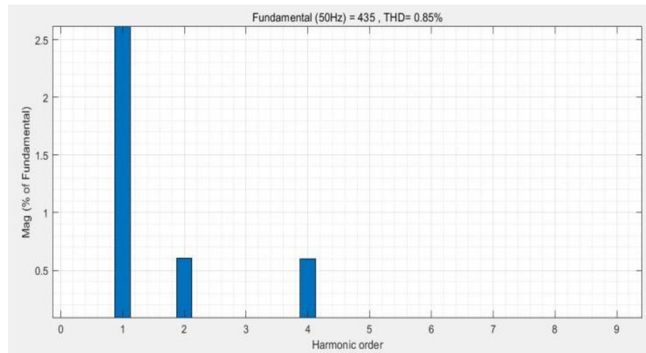

Fig. 12. Frequency analysis of voltage at the outlet of converter U_v with harmonic suppression strategy

It can be seen from Fig. 11 and Fig. 12 that when the harmonic suppression strategy is added to the network side current i_s, the harmonic content in the voltage at the outlet of the converter U_v also decreases, the second harmonic content in the voltage at the outlet of the converter U_v decreases from 2.39% to 0.60%, the suppression ratio is 74.9%, the harmonic distortion rate (THD) of the voltage at the outlet of the converter U_v decreases from 2.40% to 0.85%, and the suppression ratio of harmonic distortion rate is 64.58%. When the harmonic suppression strategy is added, the harmonic content in the voltage at the outlet of the converter U_v decreases, and the THD of the voltage at the outlet of the converter decreases, so it will be less likely to cause the maloperation of the flexible DC related protection, which is conducive to the safe and stable operation of the flexible DC system.

IV. CONCLUSION

Aiming at the problem of harmonic suppression on the grid side of modular multi-level converter, a harmonic suppression strategy based on quasi proportional resonance controller (QPR) is proposed in this paper. This strategy carries out harmonic control in the αβ static coordinate system. The principle is simple and easy to implement. The proposed harmonic suppression strategy has a certain reference value for solving the related problems in the actual flexible direct current engineering. The effectiveness of the proposed harmonic suppression strategy is verified by simulation experiments in PSCAD.

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