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High Frequency Resonance Damping Method for Voltage Source Converter Based on Voltage Feedforward Control

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Abstract: High frequency resonance (HFR) is a subsistent problem which affects the operation of the voltage source converter (VSC) connected to the parallel compensated grid. The appearance of HFR introduces a significant high frequency component in the grid voltage, thereby the operation of VSC system will be seriously affected. For enhancing the operation capability of VSC system, an HFR damping method based on the voltage feedforward control is proposed in this paper, which can reshape the VSC system impedance effectively in a wideband range. Besides, different with the existing HFR damping methods, the proposed method introduces a correction factor instead of the series virtual impedance with fixed value, so that the effect of impedance reshaping is irrelevant to the parameters of controlled object. In addition, this paper analyzes the fundamental control performance of VSC system after equipping the proposed method, for verifying that the proposed method will not worsen the fundamental control. Experimental results are given to validate the effectiveness of the proposed damping method.

Keywords: damping control; high frequency resonance; parallel compensated grid; voltage source converter

1. Introduction

As an essential grid-connected device, voltage source converter has been widely used in the renewable power generation systems and the distributed power grids. However, due to rapid development of power system and transmission technique, the power networks with comparatively large impedance are replacing the conventional stiff grids to connect with VSC systems [1–6], which means that the impedance of grid should be considered seriously.

As indicated by the impedance stability theory [7,8], resonance occurs if the phase angle difference between the grid impedance and the impedance of VSC has insufficient phase margin at the intersection of impedance magnitude. The existing researches have pointed out that, the grid-connected VSC system has the issue of high frequency resonance (HFR) when it connects to the grid with parallel compensation [9–12], since the impedance of parallel compensation grid behaves as the capacitance characteristic [7,8], while the impedance of VSC system tends to be an inductance in high frequency [11–13]. When HFR occurs, voltage of the point of common coupling (PCC) will be deteriorated significantly by the resonance component, thereby the performance of VSC system cannot satisfy the grid connection standard. In practice, the filter inductance is essential for VSC system to suppress current harmonics, meanwhile the effective control bandwidth of current controller is limited within 500 Hz since the switching frequency in the grid-connected VSC for the renewable power generation system is relatively low. Thus, the issue of HFR cannot be avoided in the grid-connected

VSC system by choosing the proper physical and control parameters, which means the improved control strategy have to be involved in VSC system for avoiding HFR. Therefore, it is essential to regulate the phase of VSC impedance, for the sake of guaranteeing that the grid-connected VSC system have sufficient phase margin.

The existing damping solutions can be divided into passive damping [14,15] and active damping [16–21], while the latter is more widely used. For the grid-connected VSC, according to the different instability mechanisms, the existing damping methods can be achieved by the optimizing of PLL (Phase locked loop) [16,17] and current feedback [18,19]. For the stability issue which caused by PLL, the optimizing of PLL parameters [16] and the improved PLL structure [17] are the effective methods for damping resonance, while it cannot be used for HFR damping, due to the reason that the bandwidth of PLL is much lower than the frequency range of HFR [9–15]. The damping methods based on current feedback [18,19] introduce a series impedance which can effectively achieve impedance reshaping at a fixed frequency point [18] or in a wide frequency range [19], thus they have been widely employed in the application of HFR damping [12–15].

As of now, the researches about HFR have made some process [9–13,22,23]. The simplified impedance model for VSC which can be employed to analyze the mechanism of HFR was derived in [10,11], thereby the HFR damping control based on the resonator was proposed in [12,13]. However, the controller based on resonator has a narrow bandwidth, usually 20 Hz to 50 Hz, so that the damping control is only effective on the condition that the HFR frequency can be detected accurately and provided to the resonator. To obtain the accurate frequency of HFR, the frequency locked loop based on adaptive notch filter (ANF-FLL) is commonly employed to obtain the resonance frequency [10–12], but when the HFR frequency changes, the dynamic delay of frequency detection component [24,25] will degrade the effectiveness of the HFR damping, so that when parallel compensation degree changes, the performance of HFR damping is undesirable. For overcoming this issue, [22] mitigates the performance degrade of HFR damping control by extending the bandwidth of damping control based on resonant regulator, but the essential issue which caused by frequency detection was not solved, since the frequency detection component still be employed. For liberating the frequency detection component, [23] introduced a virtual impedance which is effective within the wideband range, so that the impedance phase of VSC can be reshaped in a wide frequency, the stability of VSC can be guaranteed well during the transient process of compensation degree changes. However, the implementation of the wideband virtual impedance contains several differential elements, which can severely reduce the practicability [26,27] since the designed differential components should be modified to be causal.

Besides, all the existing HFR damping solutions are achieved by the current feedback control as of now. The current feedback control introduces a virtual impedance of which value is fixed [28], the virtual impedance can effectively reshape the output impedance phase of VSC, thereby to provide a sufficient phase margin between the VSC system and the weak grid. However, if the damping controller is not redesigned, the value of the virtual impedance is fixed [28], when the parameters of VSC systems change, the original impedance of VSC system changes as well, the impedance reshaping may not work properly, since the virtual impedance may not match the original impedance of VSC system [9–13,28]. Therefore, the existing damping controller have to be redesigned to obtain the optimal performance when the controlled object changes.

For the purpose of phase amendment for the VSC system impedance more effectively and practicably, thereby improve stability of VSC system, this paper develops an HFR damping method based on the voltage feedforward (VFF) control, which can be universal for different VSC systems without parameters redesigning. On the one hand, the proposed damping control is effective within the wideband range where HFR may occurs so that the defect caused by the HFR frequency detection will be avoided. The more important point is that the proposed voltage feedforward control generates a correction factor instead of a fixed value virtual impedance on the original impedance of VSC, thus

the phase amendment effect is irrelevant to the parameters of VSC system, so that is why the proposed damping control is universal for different VSC systems.

In this paper, Section 2 analyzes the phenomenon and mechanism of HFR, then the shortcoming of existing HFR damping control will be investigated, Section 3 deduces the VSC system impedance with proposed voltage feedforward, and gives the schematic diagram of the proposed method. In Section 3, the performance evaluation for HFR damping control and the fundamental control will be given. The experimental verifications in Section 5 verify the effectiveness and the practicability of the proposed voltage feedforward. Section 6 summarizes conclusions for this paper.

2. Mechanism of HFR and Analysis for the Existing Damping Control

Figure 1 gives the structure of current-controlled VSC under parallel compensated grid, in which VSC system connects the parallel compensation grid via an LCL filter. V_{dc} represents the DC voltage, V_{PCC} is the voltage at PCC, V_g represents grid voltage, i_g represents output current of VSC system, u_o represents the output voltage of VSC. C_f , R_f , L_{lf} and L_{gf} represent the filter capacitance, filter resistance, inner filter inductance and outer filter inductance respectively. As to the grid parameters, L_g and R_g represent the equivalent impedance of grid, C_g is used to describe the parallel compensation capacitance. The different parallel compensation capacitance can provide different reactive power, the parallel compensation degree is defined as the ratio of the reactive power and the rated capacity of the VSC system. The fundamental frequency of grid is noted as ω_g . The mathematical model of VSC in dq frame can be expressed as (1)

$$\begin{cases} u_{od} = -(R + Lp)i_{gd} + V_{PCCd} + \omega_g L i_{gq} \\ u_{oq} = -(R + Lp)i_{gq} + V_{PCCq} + \omega_g L i_{gd} \end{cases} \quad (1)$$

where the subscript d, q represent dq -axis components in the dq frame; p represents differential operator, $p = d/dt$. The parameters of the 1 kW VSC system can be referred in Table 1, the modulation method of VSC in this paper is space vector modulation (SVM), the switching frequency in the following simulations and experiments both are 5 kHz.

Figure 1. LCL based VSC system under parallel compensated grid.

Table 1. kW voltage source converter (VSC) System.

P_n	1 kW	L_{lf}	3 mH
V_g	110 V	C_f	3 μ F
V_{dc}	250 V	R_f	1 Ω
T_d	150 μ s	L_{gf}	0.8 mH

Since the impedance expressions of VSC and the grid have been derived and verified in [9–13], the impedance of VSC is irrelevant to the modulation method, the expressions of VSC impedance Z_{vsc} and grid impedance Z_{grid} are given directly here,

$$Z_{vsc} = \frac{Z_C[H_i(s)G_d(s) + Z_{lf}] + (Z_C + Z_{lf})Z_{gf}}{Z_C + Z_{lf}} \quad (2)$$

$$Z_{grid} = \frac{sL_g + R_g}{s^2L_gC_g + sL_gR_g + 1} \quad (3)$$

The impedance model for Equation (2) is correct in high frequency while invalid at fundamental frequency. [9–13] have developed the accurate impedance model for VSC system, which is valid in any frequency range. It is indicated that the fundamental control loop, outer control loop, decoupling component, especially the phase locked loop (PLL) [7,8] should be considered in the impedance model for guaranteeing the validity of impedance expression around fundamental frequency. Since the frequency of HFR is much higher than fundamental frequency, usually higher than 500 Hz, the influence of PLL, outer control loop and decoupling component are small enough due to the limited bandwidth [9–11] indicates that the impedance model for the issue of HFR can be simplified by ignoring the effect of PLL, outer control loop and decoupling component.

Figure 2 gives the bode diagrams of the VSC impedance and the grid impedance, of which parameters can be referred in Table 1. As seen in Figure 2, when the VSC system connects to the parallel compensation grid with 20.5% compensation degree, there are two intersections of impedance magnitude, P_1 and P_2 , in which the phase difference between Z_{vsc} and Z_{grid} is 176° at P_2 (990 Hz), which indicates that the VSC system connects to parallel compensation grid suffers the harm of HFR.

Figure 2. Bode diagram of VSC impedance and grid impedance.

In fact, in the range where higher than 300 Hz and lower than 1500 Hz, the impedance of filter inductance Z_{lf} is much smaller than the impedance of filter capacitance Z_C , which causes that Z_{vsc} is close to 90° [10,11] in this region. Once grid impedance and VSC impedance intersect in this region, HFR will occur, thus this region is called a potential unstable region, which can be seen in Figure 2. It can be concluded that the core of HFR damping is to achieve phase amendment for Z_{vsc} in the potential unstable region to avoid the appearance of the unstable impedance intersections.

2.1. Analysis for the Existing HFR Damping Control

The existing HFR damping methods introduce a fixed value impedance on the basis of original impedance as can be described in Figure 3, which are achieved by the current feedback control, so that the phase of VSC impedance can be reshaped. Meanwhile the impedance reshaping effect is relevant to the HFR damping controller and the parameters of controlled object. The phase amendment effect $\Delta\theta_{CF}$ can be described as (4), thus it can be concluded as,

- (1) The introduction of the virtual impedance with fixed value can reshape the impedance of VSC system effectively, so that HFR can be damped for a certain VSC system with the appropriate current feedback controller.
- (2) If the phase amendment effect is expected to be maintained when VSC parameters change, the value of virtual impedance has to be redesigned, since the original impedance of VSC has influence on the phase amendment effect as well.

$$\Delta\theta_{CF}(s) = \frac{Z_{vsc_re}}{Z_{vsc}} = \angle\left(1 + \frac{Z_{virtual}}{Z_{vsc}}\right) \quad (4)$$

Figure 3. Equivalent circuit of VSC system after impedance reshaping.

For illustrating the effect of damping and general shortcoming of the existing HFR damping control more intuitively, the wideband impedance reshaping method in [23] will be applied in the two VSC systems with the different parameters since the method in [23] overcomes the issue of performance decline which exist in the methods of [9,10].

2.1.1. Case 1, Analysis for 1 kW VSC System

In Figure 2, the blue curve is the reshaped impedance of VSC system with the HFR damping control of [23], in which the controller is designed in advance. After introducing the HFR damping method, the VSC impedance can be effectively reshaped as $Z_{vsc_re_CF}$. The intersections between $Z_{vsc_re_CF}$ and Z_{grid} shift to P_3 and P_4 , of which the phase difference between $Z_{vsc_re_CF}$ and Z_{grid} are 66.5° and 109.2° respectively, which indicates that the HFR can be damped effectively. The corresponding simulation is given in Figure 4a, the VSC suffers from a 1000 Hz HFR before 0.1s, in which the components of resonance in V_{PCC} and output current i_g are 88.4% and 8.99% respectively, after enabling the damping control at 0.1s, the components of resonance in V_{PCC} and output current i_g can be damped to 1.21% and 0.17% respectively.

Figure 4. High frequency resonance (HFR) damping control based on wideband virtual impedance for VSC systems.

The analysis above indicates that the existing HFR damping control strategy is effectively for a certain VSC system indeed.

2.1.2. Case 2, Analysis for the 1 kW VSC System When Parameter Changes

However, as is shown in Figure 5, if the controlled object becomes case 2, the inductance of 1 kW VSC system changes to 5 mH, and the HFR damping controller in case 1 cannot amend the phase of VSC impedance effectively, since the controller in case 1 is not inappropriate for case 2. Before introducing the HFR damping control, there is an unstable frequency point P_2 (985 Hz) where the phase different between Z_{vsc} and Z_{grid} is 176° . After intruding the HFR damping controller, the phase difference cannot be decreased effectively, which illustrates that the damping controller in case 1 cannot be applied for case 2 directly.

Figure 5. HFR damping controller without re-designing parameters for 1 kW VSC system when filter inductance changes.

The corresponding simulation is illustrated in Figure 4b. The 1 kW VSC system suffers the 985 Hz HFR before 0.1 s, in which the components of resonance in V_{PCC} and output current i_g are 37.8% and 6.8% respectively, though HFR damping controller is enabled at 0.1 s, the resonance still exists, the components of resonance in V_{PCC} and output current i_g are 10.8% and 5.2% respectively

Thus, it can be concluded that the existing HFR damping control cannot adapt the changing of controlled object well, though it can be effective for a certain system with the pre-designed controller.

3. The HFR Damping Control Strategy Based on Voltage Feedforward

3.1. Description for the Proposed HFR Damping Control Strategy

According to the discussions above, the core of HFR damping is phase amendment, while the phase amendment capability of existing HFR damping methods is relevant to VSC parameters. So, it is significative to investigates a novel HFR damping control method of which phase amendment effect is irrelevant to VSC parameters thus once the HFR damping controller is designed, it can be universal for different VSC systems.

The implementation of the proposed voltage feedforward control for VSC system is illustrated in Figure 6. The vector control based on PI controller is employed since it guarantees that the output current i_{gdq} can track the reference i_{gdq}^* accurately, in which the reference can be calculated by the power reference [29,30],

$$i_{gdq}^* = \frac{P^* + jQ^*}{1.5V_{PCCd}} \quad (5)$$

where P^* and Q^* represent the reference of active power and reactive power respectively.

Figure 6. Implementation of VSC system with the proposed voltage feedforward control.

HFR damping control is realized by the voltage of PCC feedforward, in which the feedforward path contains a high-pass filter and a proportional controller, the former component is responsible for keeping fundamental control away from the influence which caused by the damping control. It should be pointed that the high-pass filter should have barely influence on HFR damping control, but has the capability of isolating the fundamental control and high frequency damping control effectively. The latter component regulates the effect of voltage feedforward, of which function will be analyzed detailly later.

Besides the output of PI controller and HFR damping controller, the decoupling component $E_{dq} = -ji_g\omega_g L_{lf}$ was concluded in the voltage reference as well, which can counteract the coupling of VSC control in dq frame [29–31].

3.2. Impedance Expression of VSC System with the Proposed Control Strategy

Impedance expression of VSC with the proposed feedforward control should be deduced firstly, since it is the basis of the stability analysis. As indicated by the existing researches [9–12], outer power loop, phase locked loop (PLL) and the decoupling component have barely influence on the impedance of VSC due to the narrow bandwidth, thereby the impedance expression of the VSC with the proposed voltage feedforward control can be obtained by the control block in Figure 7. Thus, the expression of reshaped VSC impedance is written as follows,

$$Z_{vsc_re} = -\frac{V_{PCC}}{i_g} = \frac{Z_C[H_i(s)H_d(s) + Z_{lf}] + (Z_C + Z_{lf})Z_{gf}}{Z_C(1 - KG_h(s)G_d(s)) + Z_{lf}} \quad (6)$$

Figure 7. Control block of VSC system with the PCC voltage feedforward.

With the expression of reshaped impedance, the impedance reshaping effect can be expressed as the ratio of reshaped impedance and original impedance, meanwhile it can be noticed that the reshaped impedance equals to the original impedance when $K = 0$. Thus, the effect of phase amendment can be defined as $\Delta\theta_{VFF}$, as can be seen in (7), of which physical significance is phase variations of after impedance reshaping.

$$\Delta\theta_{VFF}(s) = \frac{Z_{vsc_re}}{Z_{vsc_re}|_{K=0}} \quad (7)$$

As indicated by the existing researches [9–12], the potential HFR frequency range can be obtained within the frequency range where $Z_{lf} \ll Z_C$, since in this region the impedance of VSC system is mainly depended on the filter inductance, which results in an inductive characteristic for the impedance of VSC system. In addition, considering that high-pass filter can isolate the HFR damping control and fundamental control so that the high-pass filter has barely influence on HFR damping control, $\Delta\theta_{VFF}$ can be further described as,

$$\begin{aligned} \Delta\theta_{VFF}(s) &= \frac{Z_{vsc_re}}{Z_{vsc_re}|_{K=0}} \\ &= \angle \frac{1+Z_{lf}(s)/Z_C(s)}{1+Z_{lf}(s)/Z_C(s)-KG_h(s)G_d(s)} \approx \angle \frac{1}{1-KG_d(s)} \end{aligned} \quad (8)$$

According to (8), the conclusions for the VSC system with the proposed damping method based on voltage feedforward can be summarized as,

- (1) The phase amendment effect of the damping method based on voltage feedforward control can be adjusted by the coefficient of proportional controller, which indicates that the proposed HFR damping control can be effective on the premise that K is suitable.
- (2) The impedance reshaping effect of the proposed damping method is irrelevant to the parameters of VSC system, which indicates that when the time delay and K are fixed, the phase amendment effect can be maintained for different VSC systems.

3.3. Voltage Feedforward Control Design Procedure

The design procedure for PI controller has been investigated in [31,32], so the design procedure for the voltage feedforward control will be detailedly given in this section.

Firstly, the high-pass filter can be designed according its role of isolating the HFR damping control and fundamental control. A Chebyshev filter is used, since its stop zone is narrow, which can well guarantee the isolation between HFR damping control and fundamental control [33]. In view of the unstable potential region is 300 Hz to 1500 Hz, the cut-off frequency is ought to lower than 300 Hz [23], while the orders of the high-pass filter should not be over-high to avoid the complicated discretization [33], thus the high-pass filter is selected as a five order Chebyshev filter, while the cut-off frequency is 50 Hz, the expression can be written as,

$$G_h(s) = \frac{\bar{s}^5}{\bar{s}^5 + 4.20\bar{s}^4 + 7.32\bar{s}^3 + 10.83\bar{s}^2 + 6.55\bar{s} + 5.59} \quad (9)$$

Since the impedance reshaping effect is only related to the coefficient K , for assigning a suitable value for the proportional coefficient, the impedance reshaping effect of VSC system with different K ought to be analyzed.

As illustrated in Figure 8, when K is negative, the phase of Z_{vsc_re} will be increased in the potential unstable region so that HFR cannot be damped effectively, thus the proportional coefficient ought to be positive. While for the positive coefficient, the phase of VSC impedance can be amended effectively to avoid HFR in the potential unstable region. As is shown in Figure 8, the phase amendment is more effective with the larger K . However, the voltage feedforward control can generate influences in the frequency where higher than the potential unstable region as well, so that over-high coefficient can cause Z_{vsc_re} be less than -90° in the region out of the unstable regions, which is marked as unexpected unstable region in Figure 8. Thus, it is vital to balance the trade-off between the potential unstable region and the unexpected unstable region by assigning the suitable proportional coefficient for voltage feedforward control. In this paper, $K = 0.5$ is selected, on this occasion, the phase of VSC impedance

can be regulated to range of $[-63^\circ, 58^\circ]$, while the unexpected unstable region can be avoided, which means the proposed voltage feedforward control can damp HFR reliably at this condition.

Figure 8. Reshaped impedance of VSC when different voltage feedforward coefficients are applied.

4. Performance Evaluation for VSC with the Proposed Voltage Feedforward Control

The design procedure of the proposed control strategy for 1kW VSC system has been given in Section 3, but the evaluation for different VSC systems still needs be investigated, to reveal the merit of the proposed control strategy. In view of the HFR damping performance for 1kW VSC system has been analyzed in last section, this section analyzes the adaptability of the proposed HFR damping method for the VSC system firstly when the filter inductance changes, to verify the conclusion that the proposed damping control can be universal for different VSC systems, then the fundamental control performance of the VSC system with the proposed method will be discussed as well, for proving that the proposed damping method has no influence on the operation of fundamental control.

4.1. Adaptability of the Proposed Method for the Different VSC Systems

In Figure 9, the impedance curve of the 1 kW VSC system with different 5mH filter inductance is given. It can be seen that, different with the existing HFR damping method, the proposed control method can reshape impedance of the VSC system effectively, the phase difference between $Z_{vsc_re_VFF}$ and Z_{grid} at the unstable intersection point P_2 can be amended to 136° . The corresponding simulation is illustrated in Figure 10. After enabling the proposed HFR damping control at 0.1 s, the 985Hz resonance components in V_{PCC} and output current i_g can be damped to 0.7% and 0.4% from 37.8% and 6.8% respectively, which indicates that impedance reshaping effect of proposed control strategy can be maintained when VSC system changes.

Figure 9. Impedance reshaping effect for 1 kW VSC system with different parameters.

Figure 10. The proposed control strategy for the 1 kW VSC system with different parameters.

4.2. The Fundamental Performance Analysis for VSC with the Proposed Voltage Feedforward Control

The analysis above indicates that the VSC with the proposed voltage feedforward control has a reliable performance for damping HFR, while the evaluation for the performance of fundamental control is indispensable as well, since the introduction of voltage feedforward control may generate influence on the fundamental control.

The performance of fundamental control can be revealed by the transfer function from output current to the reference [22,23], of which expression $H_{fc}(s)$ can be derived by Figure 7.

$$\begin{cases} H_{fc}(s) = \frac{i_g}{i_g^*} = \frac{H_i(s)G_d(s)}{\Delta} \\ \Delta = (Z_{grid} + Z_f)(1 + \frac{Z_{lf}}{Z_C}) - Z_{grid}KG_d(s) + Z_{lf} + H_i(s)G_d(s) \end{cases} \quad (10)$$

With obtaining the expression of $H_{fc}(s)$, the bode diagrams of $H_{fc}(s)$ with and without the voltage feedforward control can be illustrated in Figure 11. Before employing the voltage feedforward control, the characteristic of $H_{fc}(s)$ is unity gain and zero phase in low frequency, which means the tracking accuracy of the current reference can be guaranteed. While after introducing the proposed voltage feedforward control, the characteristic of $H_{fc}(s)$ in the low frequency can be maintained, which indicates that the introduction of the proposed voltage feedforward control will not affect the steady-state performance of fundamental control. Meanwhile the cut-off frequency of $H_{fc}(s)$ will be extended from 112 Hz to 165 Hz after employing the proposed damping control, which means that the dynamic response capability of VSC system will be improved.

Figure 11. The bode diagrams of $H_{fc}(s)$.

Hence, it can be summarized that the steady-state performance of fundamental control will not be worsen by the proposed voltage feedforward control, while dynamic response capability of VSC system can be enhanced simultaneously.

4.3. Performance of the Proposed HFR Damping Method for Multiple Parallel Units

For the grid-connected system contains multiple parallel units, the admittance can be described as,

$$Y_{vsc} = Y_{vsc1} + Y_{vsc2} + \dots + Y_{vscn} \quad (11)$$

where, Y_{vsc} represents the admittance of the overall system, Y_{vsc1} , Y_{vsc2} ... Y_{vscn} represent the admittance of different single VSC system.

Before applying HFR damping control, the impedance characteristic of every single VSC in the frequency where HFR may occur is inductive so that the characteristic of Y_{vsc} is inductive as well. As analyzed in the Section 3, impedance reshaping effect of the proposed voltage feedforward control is irrelevant to the control object, thus when the proposed HFR damping control is employed, a correction factor β which is only decided by the feedforward controller will be generated on the impedance of every single VSC system, of which expression can be derived by (8).

$$\beta = \frac{Z_{vsc_re}|_{K=0}}{Z_{vsc_re}} = 1 - KG_d(s) \quad (12)$$

Thereby, the reshaped impedance of the multiple parallel units with same time delay can be expressed as,

$$Y_{vsc_re} = \beta Y_{vsc1} + \beta Y_{vsc2} + \dots + \beta Y_{vscn} = \beta Y_{vsc} \quad (13)$$

It can be found that that the admittance of multiple parallel units can be effectively reshaped by the proposed control as well.

In order to verify the conclusion above, a grid-connected system which contains two VSC systems is analyzed as an example, of which structure can be described as Figure 12. The parameters of VSC system are corresponding to the parameters in Table 1.

Figure 12. Structure of the multiple parallel units.

Figure 13 illustrates the admittance of grid-connected system and parallel compensation grid. After employing the proposed voltage feedforward control method, the phase of Y_{vsc} can be effectively regulated in the potential unstable region, which indicates that the proposed method is effective for the integral system as well.

Figure 13. Bode diagram of integral system.

5. Experimental Verification

Experimental verifications for a 1 kW VSC system to validate the effectiveness of the proposed voltage feedforward control are given in this section, as shown in Figure 14. The parameters of VSC system is shown in the Table 1, as mentioned in Section 2, space vector modulation was employed, the switching frequency in the digital control was s 5 kHz. The inductance and resistance of the parallel compensated grid were 2 mH and 0.2 Ω respectively, the degree of parallel compensation was set as 20.5%, the corresponding capacitor was 12 μ F. AC source is implemented by the three-phase programmed source Chroma 61704, the DC bus of VSC system was achieved by a DC voltage source. The control system was realized by DSP TMS320F28335.

Figure 14. The structure of the experimental platform.

As illustrated in Figure 15, when the proposed control strategy was disabled, a 1005Hz HFR occurs in the VSC system, which is corresponding to the analysis of Figure 2. The appearance of HFR results in the unsatisfactory waveform of three-phase voltage V_{abc} and current I_{abc} , of which THD were 6.3% and 3.1% respectively, in which the HFR components of V_{abc} and I_{abc} were 5.6% and 2.5% respectively, thereby the output power of VSC were distorted as well, of which ripple components were 4.9% and 6.0% respectively. After the time when enabling the voltage feedforward control, HFR was damped effectively, meanwhile the THD of V_{abc} and I_{abc} was reduced to 0.9% and 0.9%. Meanwhile the ripples of active power and reactive power could be mitigated to 0.9% and 1.1%.

Figure 15. HFR damping for the VSC system ① V_{sabc} (100 V/div), ② I_{abc} (8 A/div), ③ P (1.5 kW/div), ④ Q (1.5 kVar/div).

Figure 16 exhibits the operation of VSC when the degree of parallel compensation was changed to 10.0%, the stability of VSC could be maintained in this process, while the THD of V_{abc} and I_{abc} were 0.9% and 0.7% respectively after the regulation of compensation degree, which illustrates that the voltage feedforward control can cope well with the change of parallel compensation degree.

Figure 16. HFR damping for the VSC system.

The experimental results of power regulation are shown in Figure 17 to reveal the fundamental control performance. When the power reference was regulated from 0.5 kW to 1 kW, the regulation of power could be accurately achieved within 5 ms, while VSC system kept stable.

Figure 17. HFR damping for the VSC system.

For illustrating the adaptivity of the voltage feedforward control, Figure 18 exhibits the operation of VSC when the parameters of VSC change. When the inner inductance was changed to 5 mH, the

VSC system with proposed voltage feedforward control could damp HFR effectively as well, the THD of V_{abc} and I_{abc} could be reduced to 0.9% and 0.8% from 6.1% and 3.0% respectively, which verifies the conclusion that control effect of voltage feedforward can be maintained when VSC parameters vary.

Figure 18. HFR damping for the VSC system with different parameters.

For verifying the analysis of Section 4.3, the experimental result for the integral system is given as Figure 19. Figure 19 illustrates the operation of grid-connected system which contained two VSC, in which VSC I output 500 W and VSC II output 1 kW. Before enabling the proposed control, a 1005 Hz HFR existed in the grid-connected system, which can introduce a 6.4% distortion in V_{PCC} , while the HFR components in output current of VSC I I_{VSCI} and VSC II I_{VSCII} were 4.0% and 4.4% respectively, the THD of I_{VSCI} and I_{VSCII} were 4.4% and 4.7%. With the enabling of the voltage feedforward control, HFR could be damped effectively, the HFR component of V_{PCC} , I_{VSCI} and I_{VSCII} could be reduced to 1.0%, 0.6%, 0.8% respectively, while the THD of I_{VSCI} and I_{VSCII} could be decreased to 0.8% and 0.9%. Thus, the experimental results and the corresponding analysis indicates that the proposed control can be effective for the operation of multiple parallel units.

Figure 19. HFR damping for integral system ① V_{abc} (100 V/div), ② I_{VSCI} (8 A/div), ③ I_{VSCII} (8 A/div), ④ P_t (1.5 kW/div), ⑤ Q_t (1.5 kVar/div).

6. Conclusions

In this paper, the shortcomings of the existing HFR damping control are analyzed, then an HFR damping control based on voltage feedforward control is proposed, the merits of the voltage feedforward control can be presented as follows,

- (1) The voltage feedforward control can effectively reshape VSC impedance in the range where HFR may occurs, so that the disadvantage of existing HFR damping control which caused by the frequency detection can be avoided.

- (2) The effect of the voltage feedforward control will be kept when the parameters of VSC system vary, which is superior to all the existing HFR damping methods based on current feedback.
- (3) Meanwhile, the proposed control method is effective for the integral system with multiple parallel units as well.

The experimental results which are carried on a 1 kW VSC system verify the correctness and effectiveness of analytical analysis. What can be concluded is that the VSC system with the proposed voltage feedforward control has a good performance under the grid with parallel compensation grid.

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