Active Damper Frequency Division Control Method for Cluster Resonance of Photovoltaic Inverters

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Abstract. Aiming at the harmonic resonance problem of photovoltaic inverter cluster system when it is incorporated into weak power grid, an active damper frequency division control method is proposed to suppress the harmonic resonance. Firstly, the voltage signal measured by the voltage transformer is separated according to the frequency, and then the harmonic conductance value of the frequency band is controlled respectively according to the harmonic voltage. Finally, the output current is feedback controlled by the generalized integral PI controller, so as to realize the impedance remodeling of the photovoltaic inverter cluster system. This method can adjust the value of virtual conductance in different frequency band adaptively according to the harmonic voltage, so as to suppress the harmonic resonance problem of photovoltaic inverter cluster more effectively. The simulation results of Matlab/Simulink demonstrate the correctness and effectiveness of the proposed frequency division control method.

1. Introduction
When a cluster of photovoltaic inverters is connected in parallel to the weak power grid, a complex high-order network will be formed by the coupling between multiple photovoltaic inverters and the power grid. When the output harmonic current frequency and resonance frequency of the photovoltaic inverter are the same, harmonic resonance will occur in the photovoltaic inverter cluster system, which will cause adverse effects on the stability of the power grid [1-3]. Active damper (AP) is a kind of power electronic device which can change the impedance characteristics of power network. The active damper can be equivalent to connecting a virtual conductance in parallel in the resonant frequency band of the system to provide sufficient damping for the system to suppress the generation of resonance.

Literature [4] designed an LCL type active damping control method based on bandpass filter. When the resonance frequency of the system is variable, this method can effectively suppress the resonance problem. However, this method focuses on the resonance suppression of single inverter, and its effect on the resonance suppression of photovoltaic inverter cluster is limited. Literature [5]
proposed a centralized resonance suppression strategy based on active dampers, which can effectively suppress high-frequency resonance without changing the original system topology and control strategy. However, the feedback control can only be applied to the fixed frequency signal, and the resonance suppression effect will decrease due to the variation of resonance frequency. Literature [6], the harmonic voltage and harmonic current on the common nodes are extracted by the notch filter, and the harmonic impedance characteristics of the system are reconstructed by the control algorithm, so as to suppress the harmonic resonance of the system. However, in this paper, the inverter is only equivalent to the harmonic current source when constructing the harmonic network, and the influence of the output impedance of the inverter on the system is ignored, which makes the conclusion more ideal. Literature [7] proposed a kind of active damper, which, through the feedback control of harmonic current and harmonic voltage at the parallel node, is equivalent to parallel access of harmonic conductance at the parallel node. However, this method adopts the same virtual conductivity parameters for different frequency harmonic signals in the control loop. In order to achieve better resonance suppression effect, it is often necessary to set a larger virtual conductivity parameter, which will increase the power consumed by the active damper. In reference [8], active dampers and LC filters are connected to common nodes in series. The filter can withstand part of the grid voltage and reduce the active damper operating voltage, thus reducing the operating cost. But this structure has poor harmonic suppression effect. Literature [9] proposed a current decoupling control strategy, which transformed the positive sequence and negative sequence components of each harmonic signal into DC components, and then detected and controlled each harmonic respectively. However, this control strategy requires a large amount of computer storage space and processor resources. When the traditional frequency division control is adopted, coordinate transformation and low-pass filtering for the D-axis component and Q-axis component of different sub-harmonics in the filter and the load current are needed for many times, which is a complicated process. Using this control strategy requires larger storage space and faster computing speed. In Literature [10], the number of coordinate transformation and low-pass filter in the control loop is reduced to half of that in the traditional frequency division control by tracking error current. By modifying the anti-rotation matrix to compensate the phase of each harmonic, the control effect of the higher harmonic is improved. Literature [11] proposed a harmonic compensation method based on VPI controller. This method can effectively filter out the unbalance harmonic components in the grid-connected current, and because of its relatively simple structure, it is more convenient to adjust the parameters and occupies less processor resources. In Literature [12], harmonic frequency division control is realized in parallel in the way of pure hardware circuit, which improves the real-time performance of the system. Inverter feedforward control and step size optimization are used to reduce the adverse effect of delay in digital control and voltage sampling on harmonic voltage suppression. However, this method does not change the impedance characteristics of the original system, and the system still has the risk of resonance.

The resonance of photovoltaic inverter cluster system can be suppressed by adding active damper. In order to increase the resonance suppression effect, an active damper frequency division control method is proposed. The virtual conductance values in different frequency bands can be adjusted adaptively according to harmonic voltage at the bus so as to suppress system resonance more effectively.
2. Analysis of cluster resonance mechanism of photovoltaic inverters based on frequency characteristics

The grid-connected model of a single photovoltaic inverter is shown in Figure 1, and the LCL filter on its AC side will form a third-order circuit.

![Figure 1. Grid-connected model of photovoltaic inverter](image)

The current-voltage relationship on the AC side of the photovoltaic inverter can be expressed as:

\[
\begin{align*}
    u_c &= L_i \frac{di}{dt} + u_c \\
    C \frac{du}{dt} &= i_1 - i_2 \\
    u_c &= u_g + L_2 \frac{di_2}{dt} + L_g \frac{di_s}{dt}
\end{align*}
\]

(1)

Laplace transform of Equation (1) is obtained as follows:

\[
\begin{align*}
    u_i(s) &= sL_i i_1(s) + u(s) \\
    sCu_c(s) &= i_1(s) - i_2(s) \\
    u_c(s) &= u_g(s) + sL_2i_2(s) + L_g i_s(s)
\end{align*}
\]

(2)

Its control block diagram is shown in Fig. 2.

![Figure 2. Equivalent block diagram of LCL inverter](image)

Usually the LCL filter capacitor is connected in series with a small resistor to increase system damping. In case of series resistance on capacitor side, the transfer function between grid-connected current Ig and input voltage UI is:

\[
G(s) = \frac{RCs + 1}{L_i L_c s^3 + (L_i + L_g)RCs^2 + (L_i + L_g)s}
\]

(3)

The LCL inverter itself has a resonance peak. A resistor in series in the capacitor branch can increase the photovoltaic inverter damping and thus suppress the resonance problem of a single inverter. However, the frequency characteristics of photovoltaic inverter cluster system are very different from that of single photovoltaic inverter. The cluster system of photovoltaic inverters
usually includes several photovoltaic inverters, which are connected to the large power grid after connecting to the common connection points in parallel. The structure diagram of photovoltaic inverter cluster system is shown in Figure 3.

![Figure 3. Structure diagram of photovoltaic inverter cluster system](image)

Taking two photovoltaic inverters connected to the grid as an example, the control block diagram is shown in Figure 4.

![Figure 4. Equivalent block diagram of photovoltaic inverter cluster grid-connection](image)

The $G_1(s) = 1/L_1\omega_0$; The $G_2(s) = 1/L_2\omega_0$; $G_3(s) = 1/L_3\omega_0$. Then the transfer function of the output current of the photovoltaic inverter cluster to the reference voltage is:

$$G_p(s) = \frac{G_1(s)G_2(s)G_3(s)}{G_1(s)+1}\quad (4)$$

Where $G_1(s)=G_1(s)G_2(s)+G_2(s)G_3(s)+G_3(s)G_1(s)+G_2(s)G_2(s)+G_3(s)G_3(s)+G_1(s)G_3(s)+G_2(s)G_1(s)G_3(s)G_2(s)$. According to Equation (4), the system has two resonant frequencies. The resonant frequencies are:

$$\begin{align*}
  f_1 &= \frac{1}{2\pi} \sqrt{\frac{L_1 + L_2}{L_1C_1L_2}} \\
  f_2 &= \frac{1}{2\pi} \sqrt{\frac{L_3 + L_4 + L_5}{L_1C_1(L_2 + L_3)}}
\end{align*}\quad (5)$$

It can be seen from Equation (5) that there are two resonant frequencies in the system, wherein $f_1$ is the resonance generated by the LCL type inverter itself, and $f_2$ is the coupling between the
photovoltaic inverter cluster system and the power grid impedance $L_g$. With the increase of the number of parallel photovoltaic inverters, the equivalent output resistance of photovoltaic inverter cluster will gradually decrease, which is equivalent to the gradual increase of the grid impedance when converted to a single inverter. The resonant frequency generated by the coupling between the photovoltaic cluster system and the grid impedance $L_g$ will vary. At this point, the frequency characteristics of photovoltaic inverter cluster are shown in Figure 5. The resonant frequency generated by cluster grid-connected inverters will decrease with the increase of the number of grid-connected inverters, while the resonant frequency of photovoltaic inverters will remain unchanged.

![Figure 5. Grid-connected frequency characteristic diagram of photovoltaic inverter cluster](image)

3. Frequency division control method of active damper

When the photovoltaic inverter cluster system is grid-connected, the current flowing through the equivalent impedance of the grid will increase with the increase of the number of grid-connected inverters. At this time, the wide range variation of the grid impedance will change the impedance characteristics of the photovoltaic inverter cluster system. Even the photovoltaic inverter cluster system which originally operated in a stable state may lose its stability due to harmonic resonance. Therefore, reshaping the output impedance of photovoltaic inverter cluster system is an effective method to suppress the harmonic resonance of photovoltaic inverter cluster system. Through the feedback control of the inverter, the external characteristics of the impedance can be simulated in a specific frequency band, and the harmonic resonance can be suppressed by connecting the virtual impedance in parallel to the common connection point.

Active dampers work in a similar way to active power filters. Active dampers control the external characteristics of the simulated impedance by feedback to the output current so as to reconstruct the impedance characteristics of the system. A cluster structure of photovoltaic inverters including active dampers is shown in Figure 6. In the figure, $n$ photovoltaic inverters are connected to a common node with an active damper. Common nodes are connected to the large grid through line impedance $Z_g$. $Z_{inv,i}$ is the output impedance of the inverter; $U_g$ is the power grid voltage; $R_v$ and $G_v$ are virtual resistance and virtual conductance, respectively.
The traditional active damper control method is shown in Figure 7. The control method needs to extract the harmonic components of voltage and current. The harmonic component can be obtained by filtering the 50Hz signal in the control loop with a notch filter. There are also harmonic detection methods based on the theory of instantaneous reactive power. After the harmonic component of the inverter output AC current is obtained, the output current of the inverter can be calculated by the algorithm. The external characteristics of virtual impedance can be simulated by feedback control.

Because the switching devices in the inverter need to consume energy when running. Therefore, in the process of operation, the control system should absorb the grid side energy to maintain the stable operation of the inverter. This process can be realized by feedback control of the capacitor voltage on the DC side of the inverter.

An active damper connected in parallel at the common connection points can increase the damping of the photovoltaic inverter cluster, thus reducing the harmonic voltage at the common connection points and suppressing the resonance of the system. The active damping adaptive control method proposed in this paper is shown in Figure 8.
The active damper control algorithm makes the output current approach the reference value and realizes the simulation of the external impedance characteristics. The energy required for damping resonance is obtained from the common connection points. The DC side capacitance voltage is controlled by feedback, and the DC side capacitance voltage is stabilized at about 700V, which can maintain the stable operation of the active damper.

The traditional active damper control algorithm usually sets the virtual resistance as a fixed value. Generally, $R_v$ needs to be set to a smaller value to adapt to different conditions. However, when the virtual resistance is small, there will be a large power loss, which is not conducive to the economic operation of the system. Therefore, an adaptive regulation method is designed according to the drooping characteristics of the harmonic virtual impedance, which can adjust the virtual conductance. According to the droop relationship between the virtual resistance and the harmonic voltage of the common bus, the numerical expression of the virtual resistance simulated by the active damper is:

$$R_v = R_{ref} - k(U^2_{pcc} - U^2_{imp})$$  \hspace{1cm} (6)

The adaptive adjustment method of virtual resistance in the active damping control is shown in Figure 9. The algorithm can adjust the value of virtual resistance adaptively according to the harmonic voltage content. When the harmonic voltage content is small, the virtual resistance value adaptively increases and the power loss of the device decreases. When the content of harmonic voltage is large, the value of virtual resistance adaptively decreases and the system damping increases.

When the system is resonant, there will be a large harmonic voltage in a specific frequency band. Parallel virtual resistors at the resonant frequency can suppress the harmonic resonance problem of photovoltaic inverter cluster. Therefore, the virtual resistance in the active damper can be controlled by frequency division. In order to divide the frequency and control the harmonic
resistance of different frequency bands, it is necessary to separate the signals of different frequencies in the measured voltage. The specified sub-harmonic voltage separation strategy is shown in Figure 10. The strategy can separate the harmonic voltage signals of different frequencies from the measured ABC three-phase voltage.

Figure 10. Specifies the sub-harmonic voltage separation strategy

According to the internal mode principle, in a linear time-invariant system, if the reference signal of any form is to be tracked without static error, the feedback loop must contain a dynamic model that is the same as the reference signal. In order to realize the non-static control of different frequency signals, the generalized integral PI controller is adopted in the current controller. The controller transfer function is:

$$G_n(s) = K_p + \frac{2K_r \omega_n s}{s^2 + 2\omega_n s + (n\omega_0)^2}$$

Where, $K_p$ is the proportional control coefficient; $K_r$ is the resonance integral control coefficient; $\omega_0$ is the fundamental wave frequency of the power grid; $\omega_c$ can affect the bandwidth of the controller.

The control block diagram of the current controller is shown in Figure 11. The controller has a higher gain at a specific subharmonic frequency, which can realize the feedback control of the output current at different frequencies. In the figure, $n=1,2,...$ Considering that the harmonic voltage at the common connection point of the photovoltaic inverter cluster system mainly appears in the form of odd harmonics, $n$ only takes an odd value in the controller.
Figure 11. Frequency division current controller

The Bode diagram of frequency division control current controller is shown in Figure 12. It can be seen that the controller has a higher gain at the characteristic harmonic frequency, which can realize the tracking control of the current at this frequency.

Figure 12. Bode diagram of the controller

4. Simulation and result analysis

In order to verify the suppression effect of the active damper designed in this paper on the harmonic resonance of the photovoltaic inverter cluster system, a photovoltaic inverter cluster system model with active damper was built on the Matlab/Simulink simulation platform, and its analysis and verification were carried out. In this paper, the effect of active dampers on the harmonic resonance suppression of photovoltaic inverter cluster system is verified respectively under the grid impedance environment. Firstly, the grid impedance of photovoltaic inverter cluster system is $R_g=1.1\Omega$; $L_g=1.1mH$, the power generation is connected to the grid. The voltage waveform of the common connection point is shown in Figure 12. As can be seen from Figure 12, when the grid impedance $R_g=1.1\Omega$; $L_g=1.1mH$, the harmonic content of UPCC of the common connection voltage is larger. There is an obvious harmonic resonance problem in photovoltaic inverter cluster system. This will have a bad effect on the power quality of the photovoltaic inverter cluster system.
Figure 13. Transient process after the addition of active damper

In the simulation, an active damper is set to connect to the common connection point in parallel at 0.2s. When the active damper is connected to the common connection point in parallel, the voltage waveform of the photovoltaic inverter cluster system is significantly improved. It can be seen from the figure 13 that the active damper can enter a stable state in half a period, and the transient process is short, and the speed of the control loop is good.

The voltage harmonic distortion rate without active damper is shown in Figure 14. There are obvious harmonic components in the common connection points of optical inverter cluster system. Odd-order harmonics are the main harmonics, even harmonic content is less, the total harmonic distortion rate reached 9.73%. Odd harmonics mainly occur around 650Hz frequency. It can be judged that the harmonic resonance problem occurred in the photovoltaic inverter cluster system near 650Hz frequency. The power quality of photovoltaic inverter cluster system is poor.

Figure 14. Voltage harmonic distortion rate without active damper

The voltage harmonic distortion rate after the addition of active damper is shown in Figure 15. It can be seen that the power quality is improved obviously with the addition of active damper. The total harmonic distortion rate decreased from 9.73% to 1.57% before adding active damper. The harmonic resonance problem of photovoltaic inverter cluster system has been improved obviously.

Figure 15. Voltage harmonic distortion rate after adding active damper
When the grid impedance $R_g = 0.9\Omega$ and $L_g = 0.9\text{mH}$, the voltage waveform of the common connection voltage $U_{PCC}$ is shown in Figure 16. The active damper can quickly enter the stable state and provide sufficient damping for the system to suppress the harmonic resonance problem.

![Figure 16. Transient process after active damper addition](image)

It can be seen from Figure 17 and Figure 18. The total harmonic distortion rate decreases from 6.29% to 1.16% before adding active damper. The harmonic content at 650Hz decreased from 4.8% to 0.33% before the active damper was added. The harmonic resonance problem of photovoltaic inverter cluster system has been solved, and the power quality has been significantly improved.

![Figure 17. Voltage harmonic distortion rate without active damper](image)

![Figure 18. Voltage harmonic distortion rate after adding active damper](image)
5. Conclusion
In this paper, an active damper frequency division control strategy is proposed to solve the harmonic resonance problem of photovoltaic clusters. The active damper can adjust the value of virtual resistance in different frequency band adaptively according to the harmonic voltage signal so as to effectively suppress the resonance problem of the system. The simulation is carried out and the following conclusions are obtained:
(1) Under the premise of not changing the original system structure and control strategy of photovoltaic inverter, connecting the active damper to the common connection point of photovoltaic inverter cluster system can effectively suppress the generation of system cluster resonance.
(2) The proposed frequency division control method of active damper can adjust the virtual resistance values in different frequency bands according to the harmonic content, so as to effectively suppress the resonance of the system.

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