Grid-Connected Resonance Suppression Of Group-Series Photovoltaic Cluster Inverters Based On Hybrid Damping

Shengqing Li\textsuperscript{1,2,a}, Zhijian Wang\textsuperscript{1,2*}

\textsuperscript{1}School of Electrical and Information Engineering, Hunan University of Technology, Zhuzhou City, Hunan Province, China, 412007

\textsuperscript{2}Photovoltaic micro-grid intelligent control technology Hunan Engineering Research Center, Zhuzhou, Hunan, China, 412007

\textsuperscript{a}lsq1961@hut.edu.cn

\textsuperscript{*}Corresponding author’s e-mail: 1079913679@qq.com

Abstract. Grid-connected group-series photovoltaic cluster inverter system will cause resonance, which will adversely affect the system. To suppress grid-connected resonance, the mathematical model, resonance mechanism and resonance characteristics of the cluster inverters are analyzed, and a global resonance suppression strategy based on hybrid damping is proposed. In the current loop of the inverter, capacitive current feedback and parallel voltage proportional feed-forward are introduced as active dampers to reduce the harmonics of the parallel current. On this basis, RLC type second-order resonance suppression circuit is added as passive damping to suppress system resonance, so that the output current of the inverters can meet the grid-connected conditions when the cluster is connected to the grid. The simulation and experimental results show that the total harmonic distortion of the grid-connected current decreases from 10.54\% to 1.97\% after three series photovoltaic cluster inverters adopt this strategy, which effectively suppresses the grid-connected resonance.

1. Introduction
Resonance caused by clusters of string photovoltaic inverters connected in parallel to the distribution network has an adverse effect on the operation of the grid and the quality of power. Scholars at home and abroad have carried out many studies on the suppression of photovoltaic grid-connected resonance. A control strategy based on active damping is proposed\cite{1}. When performing harmonic compensation, a parallel active filter is used to suppress system resonance. An active damping control strategy based on the combination of capacitor voltage and current feedback is proposed\cite{2}. Although this method has a good resonance suppression effect, it increases the complexity of the system. An active harmonic conductance method that suppresses the harmonic current of the inverter without changing the hardware topology or adding sensors is proposed to suppress system resonance\cite{3}. However, it only uses analog noise as a harmonic source for resonance reproduction, and has not been fully verified by simulation. The
above-mentioned documents are all verified on a single grid-connected inverter, and have not verified the feasibility of the method from the perspective of multiple units. By analyzing the impedance model of a single inverter, and deriving the impedance of multiple inverters in parallel, a notch control strategy based on active damping is proposed[4]. Although this method can effectively suppress parallel resonance, it ignores the influence of grid impedance on system stability. In summary, it is necessary to study the parallel resonance suppression strategy of string photovoltaic cluster inverters.

This paper takes the string photovoltaic cluster as the research object, establishes the mathematical model of the parallel system of the string photovoltaic cluster inverter, and uses the transfer function and frequency domain analysis method to analyze the resonance mechanism and resonance characteristics of the cluster grid-connected inverter parallel system. After analysis, a global resonance suppression strategy based on hybrid damping is proposed. Taking three string photovoltaic grid-connected systems as an example, the resonance point in the system is suppressed, and the resonance suppression effect is analyzed. Finally, simulations and experiments prove the correctness and effectiveness of the proposed control strategy.

2. Cluster topology

The string-type photovoltaic cluster system is composed of string-type photovoltaic grid-connected inverters in parallel. The output current of the inverter is collected and flows into the grid at a public grid-connected point through an LCL filter. The cluster system of string photovoltaic inverters is shown in Figure 1.

![Figure 1. Structure of string type photovoltaic cluster inverter system](image)

In Figure 1, each photovoltaic grid-connected system includes photovoltaic panels, booster circuits, inverters, LCL filters and weak grids; PV\(_i\) is the i string photovoltaic array; MPPT is the maximum power point tracking module of the photovoltaic array, which is composed of a DC/DC converter and a DC/AC converter composed of a DC-side inductor \( L_{dc} \), a stabilized capacitor \( C_{dc} \), a diode, and a transistor. A two-stage converter is connected to the weak grid through an LCL filter; \( u_i \) is the
output voltage of the i inverter; $i_{p1}$ is the grid-connected current of the i inverter; $u_{PCC}$ is the voltage at the common coupling point; $C_{cpv1}$ is the parasitic capacitance of the i photovoltaic panel to ground; weak grid impedance $Z_g$ and grid voltage $u_{g}$, $i_{1l1}$, $i_{2l1}$, and $i_{l}$ are the inverter-side inductor current, grid-side inductor current, and grid-connected current respectively; $R_{l11}$ and $R_{l21}$ are the parasitic resistance of the filter inductor; $C_i$ is the filter capacitor, and $u_c$ is the capacitor voltage, where $i=1, 2, 3...n$.

3. Resonance mechanism and characteristic analysis

3.1. Resonance mechanism analysis

Taking the first three grid-connected inverters in Figure 1 as a cluster, the mechanism of cluster resonance is analyzed. The resistance element in the weak current network can increase the damping of the system and improve the stability of the system[5]. To verify the suppression ability of the proposed control method under the most severe system resonance, it is assumed that the weak current network is purely inductive, that is, the impedance only contains $L_g$. The mathematical model of the grid-connected system of string photovoltaic cluster inverters is

In the dq axis, the apparent power $S_{dq}$ is expressed as follows

$$
\begin{aligned}
\begin{cases}
  u_i &= L_{1i} \frac{di_{1i}}{dt} + u_c \\
  C_i \frac{du_c}{dt} &= i_{1i} - i_{p1} \\
  u_c &= L_{2i} \frac{di_2}{dt} + L_s \frac{di_s}{dt} + u_x \\
  i_s &= i_{p1} + i_{p2} + i_{p3}
\end{cases}
\end{aligned}
$$

(1)

Where $u_i$ is the voltage on the output side of the inverter, $L_{1i}$ and $i_{1i}$ are the filter inductor and the current flowing through the inductor on the output side of the first inverter, $u_c$ is the voltage of the filter capacitor, $C_i$ is the filter capacitor of the first inverter, and $L_{2i}$ is The grid-connected filter inductance of the first inverter, $L_s$ is the grid inductance, $u_{g}$ is the grid voltage, $i_{l}$ is the grid-connected current of the cluster system, $i_{p1}$, $i_{p2}$, and $i_{p3}$ are the first, second, and third grid-connected inverters respectively Grid-connected current.

From equation (1), the transfer function from $u_i$ to grid-connected current $i_{p1}$ is

$$
G(s) = \frac{G_{21}(s)G_{22}(s)G_c(s)}{G_p(s)+1}
$$

(2)

Where

$$
\begin{align*}
  G_{21}(s) &= \frac{1}{sL_{11}}, G_c(s) = \frac{1}{sC_i}, G_p(s) = \frac{1}{sL_s}, G_{22}(s) = \frac{1}{sL_{21}}; \\
  G_g(s) &= G_{21}(s)G_c(s) + G_{22}(s)G_c(s) + G_{21}(s)G_{22}(s)G_c(s) + \\
  G_{21}(s)G_{22}(s)G_g(s) + G_{22}(s)G_g(s) + G_{21}(s)G_{22}(s)G_g(s)
\end{align*}
$$

According to formula (2), the system has two resonance points, namely
Table 1 shows the cluster system parameters, and Figure 2 shows the frequency characteristics of the cluster. Combining equation (3) and Figure 2, it can be seen that the system has two resonance peaks: one is $f_{\text{LCL}} (1980 \text{Hz})$, which is related to the number of parallel units $n$ and the size of the grid impedance; the other is $f_{\text{LCL}} (4590 \text{Hz})$, its value is not affected by the grid impedance and the number of parallel units $n$.

Table 1. Cluster system parameters

| Parameter                  | Value | Parameter                  | Value |
|----------------------------|-------|----------------------------|-------|
| DC side voltage $U_d$/V    | 700   | Grid side inductance $L_2$/mH | 0.2   |
| Grid-voltage frequency $f$/Hz | 50    | Grid voltage $U_s$/V        | 380   |
| Inverter-side-inductance $L_1$/mH | 1.5   | Grid impedance $L_g$/mH     | 1.2   |
| Filter capacitor $C$/μF    | 6.8   | Switching-frequency $f_{gw}$/kHz | 10   |

Figure 2. Cluster frequency characteristics

3.2. Resonance characteristics analysis

If the system parameters and working conditions of $n$ grid-connected inverters in the parallel system are the same, the grid impedance connected to each grid-connected inverter will be amplified by $n$ times [6,7]. Therefore, the resonance frequency generated by the grid-connected PV cluster is

$$f_{\text{LCL}} = \frac{1}{2\pi} \sqrt{\frac{L_{11} + L_{21}}{L_1 L_2 C_1}}$$

$$f_{\text{LCLg}} = \frac{1}{2\pi} \sqrt{\frac{L_{11} + L_{21} + 2L_g}{L_1 (L_{21} + 2L_g) C_1}}$$

(3)
The grid-connected resonance frequency characteristics of multiple inverters are shown in Figure 4. It can be seen from Figure 4 that as the number of inverters in the cluster system increases, the resonance point generated by the cluster grid connection gradually shifts to a low frequency band, and the resonance point generated by the LCL inverter itself remains unchanged.

Figure 3. Frequency characteristics of parallel inverters

4. Cluster resonance suppression strategy

4.1. Active damping strategy

This paper proposes a control strategy of grid-connected voltage proportional feedforward and capacitive current feedback, which effectively improves the stability of the inverter control system and suppresses resonance. And effectively reduce the hardware cost and power consumption, the control block diagram is shown in Figure 4.

Figure 4. Capacitor current feedback and grid voltage proportional feed-forward control block diagram

In Figure 4, the input current i*, the output current i_{in}. The capacitive current i_{c} compensates the system through feedback and eliminates the current caused by grid connection. The inverter equivalent gain K_{PWM}=1.K_{d} is the active damping coefficient, G_{f} is the proportional feedback coefficient, and G_{PR}(s) is the quasi-PR current controller. The harmonic compensation link is added to the PR controller to suppress harmonics caused by grid fluctuations. The form of the PR controller is as follows

\[ G_{PR} = k_p + \sum_{b=1,5,7} \frac{2\omega_k s}{s^2 + 2\omega_k s + (\omega_k)^2} \]  

In the formula, k_{p}, k_{i}, \omega_{1}, \omega_{c} respectively represent the proportional gain, generalized integral coefficient, resonance angle frequency and controller bandwidth of the quasi-PR current controller.

The open-loop transfer function of the system is
According to the parameters in Table 1, the frequency characteristic curve and root locus of the system are shown in Figure 7. In Figure 7(a), the comparison before and after adding the strategy found that the peak value of the current resonance point decreased from 109dB to -2.09dB, indicating that the capacitive current feedback and grid voltage feedforward control strategy can effectively suppress the system resonance; in Figure 7(b), The root locus of the system is distributed on the left half plane of the complex plane, which theoretically proves that the control strategy is feasible.

Figure 5. Frequency characteristics and root locus distribution of system under control strategy

4.2. Global resonance suppression strategy based on hybrid damping

Aiming at the system-level resonance caused by the parallel connection of cluster inverters, an improved global resonance suppression control strategy is proposed. In this paper, a parallel RLC-type second-order resonance suppression circuit is designed at the PCC point. The principle of the second-order RLC resonance suppression circuit is shown in Figure 8.

In Figure 6, the second-order RLC type resonance suppression circuit is used to reduce the high-frequency harmonic signal as much as possible, minimize the impact on the low-frequency compensation signal, and minimize the resonance peak. \( R_d \) increases the damping of the system and reduces the resonance spikes caused by the harmonics of the grid-connected current; the role of \( C_d \) is to reduce the system loss; \( u_d \) is the terminal voltage of the grid-connected current; and \( i_d \) is the current of the RLC resonance suppression circuit.

From equation (4), the resonance frequency of the resonance suppression circuit is

\[
\omega_s = \frac{1}{2\pi LC} = \frac{1}{2\pi} \sqrt{\frac{L_i + L_2 + nL_y}{L_1 (L_2 + nL_y) C_i}}
\]

Combining formula (8), the constraint conditions of \( L, C \) and \( R \) are derived as [7,8]

\[
\begin{cases}
C = \frac{1000\sqrt{5} \omega_s}{2\pi U_s} \\
L < \frac{R}{10\omega} \\
RLC = \sqrt{\frac{L_1 (L_2 + nL_y) C_i}{L_1 + L_2 + nL_y}}
\end{cases}
\]
In the formula, $f=50\text{Hz}$, $\omega=2\pi f$.

The control block diagram of the global resonance suppression strategy is shown in Figure 7. In the figure, $G_d(s)$ is the Laplace transform of the equivalent impedance of the second-order RLC resonance suppression circuit. $G_d(s) = \frac{1}{sC + \frac{sL}{sL + R}}$.

Figure 8 shows the frequency characteristic curve of the cluster. In Figure 8, before adding the control strategy, the resonance peak of the inverter is 109dB, and the resonance peak of the
The grid-connected cluster system is 131dB; after adding the global resonance suppression strategy control, the resonance peak of the inverter is reduced to -48dB, and the cluster system is parallel. The peak value of the network resonance drops to -19.8dB. Therefore, in theory, the strategy proposed in this article is correct and feasible.

Figure 9. Contrast bird diagram with or without control strategy when impedance changes. Figure 9 shows the change curve of the system equivalent open loop under different grid impedances. It can be seen from Figure 9(a) that when the resonance suppression strategy is not added, as the grid equivalent impedance \( L_g \) increases, the cut-off frequency and phase margin of the system gradually decrease, and the dynamic performance of the system gradually deteriorates. However, compared with the Bode diagram shown in Figure 9(b) with the added resonance suppression strategy, the system has been in a stable state, indicating that the stability of the system has been improved after adding the global resonance suppression strategy based on hybrid damping.

Figure 10. Schematic diagram of grid connected control of series photovoltaic cluster.
5. Simulation Results and Analysis

5.1. Simulation verification
In order to verify the correctness and effectiveness of the proposed strategy, a simulation model of a parallel cluster of three string photovoltaic inverters was built in Matlab/Simulink. The control principle is shown in Figure 10, and the parameters involved in the system are shown in Table 1. The parameters and control strategy of each inverter are the same.

1) Comparative analysis with or without strategies
The parameters of the PR current regulator are shown in Table 2. R=50 Ω, L=0.1mH, C=0.4 μF, and the grid-connected current FFT harmonic analysis is shown in Figure 14.

| Parameter | Value | Parameter | Value |
|-----------|-------|-----------|-------|
| K_p       | 163.5 | K_r5      | 150   |
| ω_c       | 6.28  | K_r7      | 10    |
| K_r1      | 360   | K_r9      | 10    |
| K_r3      | 210   | K_r11     | 10    |

(a) Harmonic analysis of grid-connected current without strategy
It can be seen from Figure 11(a) that the current waveform has been distorted, and the total harmonic distortion (THD) of the grid-connected current is 10.54%, of which the 39th harmonic (cluster grid-connected resonance) and the 92nd harmonic (inverter) The self-resonance of the device is very high, and the THD is 3.2% and 3.6% respectively. It can be seen from Figure 11(b) that the THD of the grid-connected current is 1.97%. Compared with THD without the resonance suppression strategy, the decrease is as high as 81.3%. Therefore, the THD is significantly suppressed, of which the 92nd harmonic and the 39th harmonic The waves are 0.05% and 0.03%, respectively. Compared with THD without the resonance suppression strategy, the reduction degrees are 98.44% and 99.17%, respectively, indicating that this strategy can effectively suppress the resonance caused by the parallel connection of the string photovoltaic cluster inverters.

2) Change of grid impedance

In order to verify the stability of the system under the strength of the power grid, the simulation results of the system under the change of the power grid impedance are shown in Table 3. The data in Table 3 shows that the system can operate stably in the range of 0~1.2mH grid impedance. Compared with the methods in literature [6,7], the control strategy proposed in this paper can effectively improve the stability of the cluster grid-connected system under weak grids, which proves the effectiveness of the strategy.

| Grid impedance Lg/mH | Without strategy THD Lg/% | With strategy THD Lg/% | THD Degree of decline |
|----------------------|---------------------------|------------------------|----------------------|
| 1.2                  | 10.54                     | 1.97                   | 81.3%                |
| 0.8                  | 11.66                     | 1.59                   | 86.4%                |
| 0.1                  | 12.84                     | 2.90                   | 77.4%                |
| 0                    | 13.41                     | 2.52                   | 81.2%                |

5.2. Experimental verification
To verify the effectiveness of the resonance suppression strategy proposed in this paper, a cluster system composed of three string photovoltaic inverters was built in the laboratory. The inverter parameters in the experiment are the same as those shown in Table 1. The grid-connected current waveform diagram before and after the control strategy is added is shown in Figure 12.

Comparing the results of the current waveform before and after adding the global resonance suppression strategy in Figure 12, it can be seen that the strategy proposed in this paper effectively suppresses the harmonics near the resonance point and significantly reduces the current distortion rate. The effectiveness of the resonance suppression strategy proposed in this paper is verified.

6. Conclusion
Aiming at the grid-connected resonance problem of the string-type photovoltaic cluster inverter parallel system, this paper analyzes the resonance generation mechanism and proposes a hybrid damping-based string-type photovoltaic cluster inverter grid-connected global resonance suppression strategy. And carry out simulation verification, get the following conclusions:
1)The control method of capacitive current feedback and grid voltage proportional feedforward can effectively suppress the resonance of the LCL inverter, effectively improve the stability of the inverter control system, and suppress the occurrence of resonance. There is no need to install additional hardware equipment, which is highly feasible and can replace passive damping, effectively reducing hardware costs and power consumption.
2)Compared with the first-order RLC suppression circuit, the second-order RLC suppression circuit has the advantages of low fundamental wave loss and good suppression effect. On the basis of capacitive current feedback and grid-connected voltage proportional feedforward, an RLC-type
global second-order resonance suppression circuit is added, which can effectively suppress the resonance caused by the parallel connection of series photovoltaic cluster inverters.  

3) The global resonance suppression strategy proposed in this paper effectively suppresses the output of harmonic currents. Simulation and experimental results show that the THD of the grid-connected current waveform drops from 10.54% to 1.97% after adding the global resonance suppression strategy, thereby avoiding the occurrence of resonance phenomena, Verifying the correctness and effectiveness of the strategy.

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