A Photo-Voltaic Invert-er Cluster Resonance Suppression Method Based on Capacitor Voltage Feed-Forward

Shengqing Li\textsuperscript{1a}, Xin Yao\textsuperscript{1b}, Ziran Peng\textsuperscript{1*}, Zhichao Shen\textsuperscript{1c}

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

\textsuperscript{a}lsq1961@sohu.com; \textsuperscript{b}lsq1961@hut.edu.com; \textsuperscript{c}1987984368@qq.com; \textsuperscript{d}605199020@qq.com

*Corresponding author's e-mail:pengziran@163.com

Abstract. Photo-voltaic inverts usually use LCL filter for filtering, and LCL filter will bring resonance problems to the system. This paper focuses on invert-er side current feedback control (invert-er side current feedback, ICF). This paper proposes a method for suppressing resonance of photo-voltaic invert-er clusters based on capacitor voltage feed-forward. First, establish the ICF mathematical model based on HPF and CVF under the weak grid, qualitatively analyze the resonance mechanism of the cluster invert-er, then analyze the system control structure and stability according to the proposed method, and finally verify the effectiveness of the proposed method through simulation and experiment.

1. Introduction

Due to its simple and convenient access to the power grid, new energy power generation is more and more widely used in China \cite{1, 2}, including relatively decentralized small-scale distributed power generation and highly centralized medium and large-scale power generation. Power plant \cite{3, 4}. Due to the relatively scattered location of renewable energy power generation, it is necessary to use long-distance transmission lines to connect the system to the public power grid \cite{5, 6}. Therefore, the public power grid is a weak current grid. The energy of renewable energy is mainly collected into the power grid through grid connected inverter \cite{7}, but it will produce high-frequency harmonics that make the system fluctuate. The most widely used method of active damping is to suppress the LCL resonance peak through the cascade caused by the inverter, which usually requires a filter. LCL filter has smaller volume and stronger high-frequency harmonic attenuation ability, and the frequency of simple 1 filter decreases gradually. Therefore, when considering cost and performance, the latter has advantages. However, without proper damping, the self resonance of LCL filter will threaten the stability of the system.

At present, many experts and scholars have proposed various passive or active damping schemes to suppress LCL self resonance. The former increases the power loss, especially in high-power...
applications [8], [9], while the latter simplifies the system structure and reduces the cost of digital filter and current regulator [10], but its parameters need to be synchronized with the corresponding parameters of the system. Another active damping law involves the feedback of filter variables. Through the combination of different filter variables or other variables, the damping performance can be effectively realized. For example, reference [11] proposes inverter side current feedback using a first-order high pass filter, which can suppress the resonance peak through a small resonance frequency offset while maintaining high power quality. Reference [12] proposed a quadrature second-order generalized integrator to achieve more accurate resonant frequency and stronger noise suppression ability. A time delay compensation method based on second-order generalized integrator is proposed in reference [14], which is used to expand the stability region of double loop power grid current feedback control system.

Based on the above problems, this paper proposes a method for suppressing resonance of photovoltaic inverter clusters based on capacitor voltage feed-forward. First, establish the ICF mathematical model based on HPF and CVF under the weak grid, qualitatively analyze the resonance mechanism of the cluster inverter, then analyze the system control structure and stability according to the proposed method, and finally verify the effectiveness of the proposed method through simulation and experiment.

2. String photo-voltaic cluster Grid connected system

2.1. System structure

The structure of photovoltaic inverter cluster system is shown in Figure 1.

![Figure 1. Structure of photo-voltaic cluster inverter system](image-url)

In Figure 1, photo-voltaic Grid connected system includes five parts: Photo-voltaic panels, booster circuits, inverters, LCL filters and weak grids. \( P_{VI} \) is a string photo-voltaic array. The DC/DC converter and the DC/AC converter composed of the DC-side induct-or \( L_{dc} \), the stabilized capacitor \( C_{dc} \), diodes. The weak grid includes impedance \( R_g \), \( L_g \) and grid voltage \( u_g \). \( i_{L1n}, i_{L2n}, \) and \( i_g \) are the invert-er-side induct-or current, grid-side induct-or current, and Grid connected current, respectively. When the photovoltaic panel is illuminated, DC is generated, which is
converted into AC after passing through the inverter, filtered by LCL, gathered at the PCC at the common point, and finally to the power grid.

2.2. Mathematical model of a single invert-er

The Grid connected system with a single invert-er connected to the LCL filter is shown in Figure 2, where L1, L2, Cf and Lg are the invert-er-side inductance, grid-side inductance and capacitance, and grid impedance of the LCL filter, respectively.

The parameters of the Grid connected invert-er are shown in Table 1. This article uses single sampling. In this paper, the invert-er side current is sampled for feedback control, and the sampling capacitor voltage is used for feed-forward and grid voltage phase synchronization.

![Figure 2. Single invert-er grid connected system](image)

**Table 1. Grid connected invert-er parameters**

| parameter                          | value |
|------------------------------------|-------|
| Grid frequency f0/H z              | 50    |
| invert-er side inductance L1/μ H   | 400   |
| Filter capacitor Cf/μ F            | 30    |
| Grid side inductance L2/μ H        | 190   |
| Sampling frequency f s/k H Z       | 12    |
| Operating frequency f s w/ k H Z   | 12    |

Therefore, the frequency domain analysis of Fig. 2 is carried out, and the parasitic inductance is ignored. The mathematical model of the system can be expressed as:

\[
\begin{align*}
    v_{i_{abc}}(s) &= sL_1i_{abc}(s) + v_{C_{abc}}(s) \\
    v_{C_{abc}}(s) &= sL_2i_{g_{abc}}(s) + v_{g_{abc}}(s) \\
    i_{i_{abc}}(s) &= sC_f v_{C_{abc}}(s) + i_{g_{abc}}(s) \\
    L_e &= L_1 + L_2
\end{align*}
\]

(1)

In the formula, \(v_{i_{abc}}\) is the output phase voltage, \(i_{i_{abc}}\) is the current of the invert-er; \(v_{g_{abc}}\) is the grid phase voltage, \(i_{g_{abc}}\) is current; \(v_{C_{abc}}\) and \(i_{C_{abc}}\) are the voltage and current of Cf, respectively. This article uses a stationary \(\alpha \beta\) coordinate system.

\[
\begin{align*}
    v_{1_{\alpha\beta}}(s) &= sL_1i_{1_{\alpha\beta}}(s) + v_{C_{\alpha\beta}}(s) \\
    v_{C_{\alpha\beta}}(s) &= sL_2i_{g_{\alpha\beta}}(s) + v_{g_{\alpha\beta}}(s) \\
    i_{i_{\alpha\beta}}(s) &= sC_f v_{C_{\alpha\beta}}(s) + i_{g_{\alpha\beta}}(s)
\end{align*}
\]

(2)

Therefore, the ICF control structure block diagram using CVF is shown in Figure 3, where \(G_{C_{\alpha}}(z)\) is a discrete invert-er-side current controller. \(G_{ef}(z)\) is a function of the CVF part; \(z-1\) is the
calculation of the digital delay in one cycle; the zero-order keeper (ZOH) is PWM modulation, the grid voltage \( v_g \) in Fig. 3.

![Diagram](image)

**Figure 3.** Transfer function diagram of system

GVF (z) = 1 is the most common form of CVF, which is called unit voltage feedforward. However, as mentioned in the introduction, the dynamic performance of unit CVF in weak current network and the ability to suppress low-frequency harmonics are weak. Therefore, in order to improve the dynamic performance and low-frequency harmonic capability of CVF, HPF is added to CVF loop, and its expression is shown in (3).

\[
G_{sf}(s) = \frac{H_s}{s + \omega_c} \tag{3}
\]

According to the Austin discrimination method, the discretion expression of formula (3) is (4), where \( T_s \) is the control period.

\[
G_{sf}(z) = \frac{2H(z-1)}{(\omega_c T_s + 2)z + (\omega_c T_s - 2)} \tag{4}
\]

3. Stability analysis

The transfer function of Figure 3 is shown in Figure 4.

![Diagram](image)

**Figure 4.** Simplified transfer function graph in discrete domain

Through the z-transform method, the continuous part of the ZOH-based hybrid system can be discretion accurately. Therefore, from GII (z) and GVC (z) in Figure 4

\[
G_{ii}(z) = \frac{T_s}{(L_1 + L_2)(z-1)}
\]

\[
+ \frac{L_x}{\omega_{res} L_4 (L_1 + L_2)} \left( \frac{(z-1) \sin(\omega_{res} T_s)}{z^2 - 2z \cos(\omega_{res} T_s) + 1} \right) \tag{5}
\]

\[
G_{ic}(z) = \frac{L_x (z+1) \left[ 1 - \cos(\omega_{res} T_s) \right]}{(L_1 + L_2) \left[ z^2 - 2z \cos(\omega_{res} T_s) + 1 \right]} \tag{6}
\]

Among them, \( \omega_{res} \) is the resonant angular frequency of LCL filter, and its expression is:
\[ \omega_{res} = 2\pi f_{res} = \sqrt{\frac{L_1 + L_x}{L_1 L_x C_f}} \] (7)

Equations (8) and (9) are derived from the open-loop and closed-loop transfer functions of Fig. 4, respectively:

\[ T_{ol}(z) = \frac{z^{-1} G_c(z) G_{lf}(z)}{1 - z^{-1} G_{lf}(z) G_{vc}(z)} \] (8)

\[ T_c(z) = \frac{T_{ol}(z)}{1 + T_{ol}(z)} \] (9)

In order to analyze the stability of the system, the ICF pole diagram is drawn according to the parameters in Table 1, as shown in Figure 5. Two different forms of CVF polar coordinates are drawn in Fig. 5. GC (z) remains unchanged at 1.85, and the gate inductance LG changes from 0 to 2000 \( \mu \)H. In Fig. 5, (a) represents the case without CVF (GVF (z) = 0), and (b) represents the case of unit CVF (GVF (z) = 1).

**Figure 5.** ICF pole diagram. (a) no CVF, (b) unit CVF

As can be seen from Fig. 5 (a), the poles of the output current of the inverter are concentrated at the center of the circle in the low frequency band and on the circumference in the high frequency band, so the current is stable in the low frequency band and unstable in the high frequency band; After adding CVF, the poles in the high frequency band begin to move closer to the center, indicating that the current instability in the high frequency band has been improved, but it is not enough. In order to further stabilize the high frequency current, HPF is added to the CVF circuit. According to the parameters in Table 1, LG is assumed \( \text{max}=800 \mu \text{H} \), \( \omega \) C can be determined as 6280 rad / s

\[ 0.5 \omega_{res\_min} \leq \omega_c \leq 0.7 \omega_{res\_min} \] (10)

\[ \omega_{res\_min} = \sqrt{\frac{L_1 + (L_1 + L_{\text{max}})}{L_1 (L_1 + L_{\text{max}}) C_f}} \] (11)

It can be obtained from table 1 and equations (10) and (11) \( \omega \) The value of C is 6280 rad / s. The parameter H appearing in equations (4) and (5) has an important influence on the stability of low frequency and high frequency of the system. Therefore, the final value of H can be determined by the pole diagram under the actual parameters.
When HPF and CVF are used, different H values are adopted on the basis of Fig. 5, and the extreme value diagram of TCL (z) is shown in Fig. 6.

![Figure 6](image)

**Figure 6.** Add HPF pole diagram (a) H = 1, (b) H = 0.75, (c) H = 0.5, (d) H = 0.25.

As can be seen from Figure 6, when h is taken as 1, the extreme point in the high-frequency region is close to the circumference, while the extreme point in the low-frequency region is close to the center of the circle. However, when h is taken as 0.25, the extreme point in the high-frequency region is close to the circumference again, and the high-frequency current becomes unstable again. Therefore, in conclusion, the best value of H is 0.5; At the same time, it can be seen from figures 5 and 6 that HPF and CVF not only make the resonance suppression effect better, but also maintain the stability of the system when the system frequency changes.

4. Resonance suppression method of photovoltaic inverter cluster based on capacitor voltage feed-forward

For the above time domain analysis, Fig. 3 can be simplified to Fig. 7. Suppose I_{ref}=0, and the transfer function G_d(s) in Fig. 7 represents the calculation and ZOH delay, which cannot be ignored. Otherwise, a derivation error will occur. G_d(s) can be obtained according to the Pader approximation:

\[
G_d(s) \approx \frac{1 - \frac{T_d s}{2} + \left(\frac{T_d s}{2}\right)^2}{1 + \frac{T_d s}{2} + \left(\frac{T_d s}{2}\right)^2}
\]

Where T_d=1.5 Ts.
Figure 7. Transfer function diagram of system in frequency domain when $I_{ref} = 0$

From Figure 4-6, the transfer function $G_{vgig}(s)$ from $v_g$ to $i_g$ can be derived as:

$$G_{vgig}(s) = \frac{i_g(s)}{v_g(s)} = \frac{1}{\frac{G_{ef}(s)G_{g}(s)-1}{sL_T} - sC_f}$$

(13)

Since this article uses a fixed $\alpha$ $\beta$ reference system, the quasi-proportional resonant current controller is the first choice. The QPR controller function used to control the inverter side current is:

$$G_{c}(s) = K_p + \frac{2K_r \omega_0 s}{s^2 + 2\omega_0 s + \omega_0^2}$$

$$+ K_{rh} \sum_{k=5,7} \frac{s \cos(\omega k) - h \omega k \sin(\omega k)}{s^2 + 2\omega_0 s + (h \omega k)^2}$$

(14)

In the formula, $K_p$ is the overall gain of $G_c(s)$; $K_r$ is the fundamental frequency gain; $\omega_0$ is the angular frequency of the grid. In fact, the grid frequency $f_i$ usually fluctuates within 0.5 Hz relative to the standard value, so $\omega i = 2\pi f_i$. According to the parameters in Table 1, all the parameters in (14) $G_c(s)$ are shown in Table 2.

Table 2. Current controller parameters

| parameter                  | value          |
|----------------------------|----------------|
| Overall gain $K_p$         | 1.85           |
| Fundamental frequency gain $K_r$ | 60             |
| Harmonic frequency gain $K_{rh}$ | 150           |
| 5th compensation phase angle $\phi_5$ | 0.87rad/s     |
| 7th compensation phase angle $\phi_7$ | 0.87rad/s     |

When HPF is added to CVF circuit, it can not only suppress current harmonics, but also help to suppress voltage harmonics. The principle of this method is relatively simple, but its performance is excellent. List the relevant parameters in Table 2, and then synthesize the parameters in Table 1 to obtain the baud diagram of $gvgig$, as shown in Figure 8.
In Fig. 8, different inductance values and CVF under different conditions are considered respectively. It can be seen from the figure that HPF and CVF have weak suppression effect in low frequency band and strong suppression effect in high frequency band, especially for 5th-19th harmonic. When \( L_g = 800 \mu \text{H} \), when the unit CVF method is adopted, the ability of \( G_{v_{gig}}(s) \) to suppress harmonics of the grid voltage becomes weaker. It can be seen from Figure 4-7 that the resonance peak value of \( G_{v_{gig}}(s) \) drops to 550Hz. What is more serious is that the unit CVF has basically no ability to suppress the harmonics of the grid voltage, and may even amplify the harmonics of the grid voltage. However, even in the case of large grid inductance, the HPF and CVF-based methods also show a stable grid voltage harmonic suppression capability.

Figure 9 compares the pole diagrams of the ICF control closed-loop transfer function under HPF, CVF, and CVF changing grid inductance. As can be seen from Figure 9, when the inductance increases, the poles of CVF gradually diverge and spread around the unit circle, indicating that the stability of the whole system is decreasing, so CVF is only suitable for power grids with low inductance.

**Figure 9.** ICF control pole diagram (a) HPF and CVF (b) CVF

5. Simulation verification

In this paper, the simulation is carried out on MATLAB. In order to further illustrate the effectiveness of capacitor voltage feedforward, figure 10 shows the starting current waveform of
the inverter. Figure 10 (a) shows the waveform without capacitor voltage feedforward. Fig. 10 (b) shows the waveform of adding capacitor voltage feedforward.

![Image of waveforms](image.png)

**Figure 10. Inverter starting current waveform when \( L_g = 0 \mu H \) (a) without capacitor voltage feedforward (b) adding capacitor voltage feedforward**

As can be seen from Figure 10, when there is no capacitive current feedforward, the inverter starts in 0.02 seconds, and the maximum current at startup is nearly 80A, which will have a great impact on the electrical appliances of the power grid; When feedforward is adopted, the maximum current of the inverter is reduced to about 30a, and the current is reduced by 62.5%.

In order to verify the grid voltage harmonic suppression capability of the proposed method, in Figure 11, the grid voltage \( v_g \) adds 1% of the 5th and 11th harmonic voltages.

![Image of waveforms](image.png)

**Figure 11. When \( L_g = 800 \mu H \), the current waveform on the grid side (a) without HPF (b) add HPF**

It can be clearly seen from Figure 11 that when HPF is added at 0.05 seconds, the whole current curve becomes smooth, the waveform distortion is improved, and the degree of waveform distortion is greatly reduced. Similarly, FFT analysis with or without HPF is performed for the same CVF control with or without hpf. The analysis results are shown in Figure 12.
It can be seen from Figure 12 that when CVF and HPF are not added, the 11th harmonic proportion of grid side current is 50%. When CVF and HPF are added, the proportion of 11th harmonic decreases to about 15%, and the decrease range is about 70%; Other harmonics also have an obvious downward trend. Therefore, the combination of HPF and CVF can effectively improve the power grid voltage harmonic suppression ability controlled by ICF.

6. Conclusion
This paper proposes a method for suppressing resonance of photo-voltaic invert-er clusters based on capacitor voltage feed-forward. First, establish the ICF mathematical model based on HPF and CVF under the weak grid, qualitatively analyze the resonance mechanism of the cluster invert-er, then analyze the system control structure and stability according to the proposed method, and the simulation results verify the effectiveness of the proposed method through simulation and experiment sexuality and correctness.

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