Research on LCL-type three-phase photovoltaic grid-connected inverter based on passive damping

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Abstract: The traditional LCL filter has resonance phenomenon in the working process of three-phase photovoltaic grid-connected inverter system. Based on the analysis of the frequency characteristics of LCL filter equivalent circuit before and after the introduction of passive damping resistor, it is concluded that the resonance of the system can be suppressed after the introduction of passive damping resistor. In the meantime, the current double closed-loop control strategy used in the system is introduced in detail. Finally, the simulation model is built by Matlab / Simulink simulation platform to verify the feasibility of the research method of LCL-type three-phase photovoltaic grid-connected inverter based on passive damping.

1. Introduction

With the increasing scarcity of traditional energy sources such as oil and coal, and the increasing pollution of the natural environment, solar photovoltaic power generation has gradually attracted the attention of the state and society[1]. Three-phase photovoltaic grid-connected inverter is generally controlled by pulse width modulation technology. The harmonic current generated by the frequent switching of power devices will cause harmonic pollution [2], which is generally filtered by L, LC or LCL filter, and the LCL filter has better filtering effect[3]. However, The LCL filter itself is a third-order system without damping, and there is a resonance phenomenon in the working process of the system [4], which reduces the stability of the system.

In this paper, the design method of LCL filter in series with passive damping resistor in capacitor branch is proposed, which can effectively suppress the generation of resonance phenomenon. At the same time, a current double closed loop control strategy to achieve direct control of grid-connected current is presented[5-6]. The internal loop controls the capacitor current by P proportional controller, and the external loop controls the grid-connected current by PI controller, which can effectively maintain the accuracy and stability of the system[7-8]. Finally, the feasibility of LCL-type three-phase photovoltaic grid-connected inverter based on passive damping is verified by Matlab / Simulink simulation platform.

2. System composition

Figure 1 is the composition of LCL three-phase photovoltaic grid-connected system. PV is the output of the pre-stage photovoltaic system, which is replaced later by a DC power supply. It is connected by a capacitor to an inverter made up of IGBTs, which is then connected to an LCL filter and finally conveyed to the grid. The capacitive current and grid-connected current are collected, and the current controller is adjusted by the current double closed-loop control strategy to reduce the harmonic component of the...
grid-connected current, so as to maintain the stability of the system.

![Figure 1: The composition of LCL three-phase photovoltaic grid-connected system](image)

### 3. Equivalent Circuit Analysis of LCL Filter

#### 3.1 Traditional LCL filter

For the traditional LCL filter, its equivalent circuit is shown in figure 2.

![Figure 2: The equivalent circuit of traditional LCL filter](image)

In figure 2, \( L_1 \) and \( L_2 \) are inverter side inductance and grid side inductance respectively, \( I_a \) and \( I_s \) are inverter side current and grid-connected current respectively, \( V_a, V_c \) and \( V_s \) are inverter output voltage, capacitor branch voltage and grid voltage respectively. The equivalent circuit equation in three-phase stationary coordinate system is obtained by Kirchhoff’s law.

\[
\begin{align*}
L_1 \frac{dI_a}{dt} &= V_a - V_c \\
L_2 \frac{dI_s}{dt} &= V_c - V_s \\
C \frac{dV_c}{dt} &= I_a - I_s
\end{align*}
\]  

(1)

The Transfer function of grid-connected current to inverter output voltage can be obtained by formula (1).

\[
G(s) = \frac{I_c(s)}{V_a(s)} = \frac{1}{s^3L_1L_2C + S(L_1 + L_2)}
\]

(2)

Its resonant frequency \( \omega \) is expressed as follows.
According to formula (2), taking the experimental parameters $L_1 = 0.3$ mH, $L_2 = 0.2$ mH, $C = 20$ μF, the Bode diagram is shown in figure 3.

![Bode Diagram of Traditional LCL Filter](image)

Figure 3. The Bode diagram of traditional LCL filter

The resonance point of LCL filter appears at $\omega = 20400$ rad/s, which affects the stability of the system. Therefore, passive damping resistors are often introduced into the capacitor branch in engineering. When the damping resistor is paralleled with the capacitor branch, the voltage of the two ends of the damping resistor is close to the grid voltage, the loss is great and the heating of the device is more serious. So the damping resistor is connected in series into the capacitor branch.

### 3.2 LCL filter with series passive damping resistor

The equivalent circuit of LCL filter with series resistor is shown in figure 4.

![Equivalent Circuit of LCL Filter with Series Resistor](image)

Figure 4. The equivalent circuit of LCL filter with series resistor

According to Kirchhoff’s law, the following equation is obtained.
The Transfer function of grid-connected current to inverter output voltage can be obtained by formula (4).

\[
G(s) = \frac{1 + SRC}{S^3 L_1 L_2 C + S^2 RC(L_1 + L_2) + S(L_1 + L_2)}
\]  

Taking the experimental parameters \(L_1 = 0.3\ \text{mH}, L_2 = 0.2\ \text{mH}, C = 20\ \mu\text{F}, R=1\Omega\), the Bode diagram of the traditional LCL filter and the LCL filter with series damping resistor is shown in figure 5.

Figure 5. The Bode diagram of the traditional LCL filter and the LCL filter with series damping resistor.

In figure 5, the resonance phenomenon of the LCL filter disappears, and the attenuation capability of the high-frequency harmonics is maintained. However, the introduction of passive damping resistor will increase the additional loss of the system and require the special heat dissipation devices to solve the problem of device heating.

4. Current double closed-loop control strategy

Figure 6 is the current double closed-loop control strategy block diagram of three phase photovoltaic grid connected system. Directly using grid-connected current \(I_s\) as external loop control variable to realize fast tracking response to actual grid-connected current output. At the same time, in order to restrain the increase of damping, the capacitor current \(I_c\) feedforward is introduced as the internal loop control variable. Since the PI controller cannot achieve static-free control of three-phase AC currents, \(I_s\) and \(I_c\) are converted from a three-phase static coordinate system to a two-phase synchronous rotating coordinate system by performing the abc/dq coordinate system conversion. In the case of three-phase symmetrical load, the transformed two-phase direct flow \(I_{sd}\) and \(I_{sq}\) are compared with \(I_{sd}^*\) and \(I_{sq}^*\). \(I_{sd}^*\) is the setting value of active component of grid-connected current, and \(I_{sq}^*\) is the setting value of reactive component of grid-connected current. The result of the comparison is compensated by the PI controller and then transformed by the dq/abc coordinates from two-phase direct flow to three-phase alternating flow. In the meantime, through the detection of the grid voltage, the phase value of the grid voltage is
provided by the phase-locked loop (PLL) technology for the coordinate transformation, so as to achieve the grid-connected current in phase with the grid voltage. Finally, the driving signals of three-phase bridge inverter circuit are generated by pulse width modulation (PWM) technology.

![Current double closed-loop control strategy block diagram of grid-connected system](image)

Figure 6. Current double closed-loop control strategy block diagram of grid-connected system

The closed loop transfer function of grid-connected current \( I_s \) to the set value of grid-connected current amplitude \( I_{sd}^* \)

\[
G_i(s) = \frac{X_0 S + X_1}{Y_0 S^4 + Y_1 S^3 + Y_2 S^2 + (Y_3 + X_0) S + X_1} \quad (6)
\]

Among them, \( X_0 = P_1 P_2 \); \( X_1 = I_1 P_2 \); \( Y_0 = L_1 L_2 C \); \( Y_1 = L_2 R_1 C + L_1 R_2 C + L_2 P_2 C \); \( Y_2 = L_1 + L_2 + R_1 R_2 C + R_2 P_2 C \); \( Y_3 = R_1 + R_2 \). \( R_1 \) is the internal resistance of the filter inductance \( L_1 \) and the loss caused by the locked dead zone of the upper and lower arms of each phase. \( R_2 \) is the internal resistance of the filter inductance \( L_2 \). \( P_1 \) and \( I_1 \) are control parameters of PI controller, \( P_2 \) is control parameters of PI proportional controller.

5. Parameter design for filter

Set the phase voltage \( V_s = 220 \text{V} \), the input voltage \( V_{dc} = 800 \text{V} \) on the DC side, the switching frequency \( f = 10 \text{KHz} \) and the rated value of active power \( P_N = 25 \text{KW} \) for a three-phase grid-connected system.

5.1 The value of inverter side inductance \( L_1 \)

The value of \( L_1 \) is affected by the current ripple. In general, the current ripple is 15% – 25% of the rated current. The proportion is taken as 20%.

\[
\Delta i = \frac{V_{dc}}{8L_1 f} \leq 0.2 I_N \quad (7)
\]

The rated current \( I_N = \frac{P_N}{3V_S} \). By formula (7), when the left and right are equal, the relevant parameters are substituted, and \( L_1 = 1.32 \text{mH} \).

5.2 The value of grid side inductance \( L_2 \)

The value of inductance \( L_2 \) will not only affect the dynamic response of the system, but also affect the overall loss of the system. The relationship between \( L_2 \) and \( L_1 \) is \( L_2 = K \times L_1 \), and \( K \) is the proportional
coefficient. Generally, when $K = 0.25$, the system has better performance and smaller loss, so $L_2 = 0.33$ mH.

5.3 The value of filter capacitor $C$

If the value of capacitance $C$ is too small, it will affect the inductance voltage drop in the system. If the value is too large, it will reduce the power factor of the system and generate more reactive power. In general, the filter capacitor $C$ is taken under the condition that the reactive power generated by the capacitor $C$ is less than $15\%$ of the rated power of the system.

$$C \leq 0.15 \times \frac{P_N}{3 \times 2\pi f_0 \times V_s^2}$$  \hspace{1cm} (8)

$f_0$ is basic frequency $50$Hz. According to formula (8), when the ratio is $5\%$, $C = 9.13 \mu F$. The filter capacitor $C$ is selected as $10\mu F$.

5.4 The value of damping resistor $R$

The value of damping resistor is generally $1/3$ of the capacitive reactance of resonant frequency, and the formula of resistor $R$ is as follows.

$$R = \frac{1}{3} \times \omega C$$  \hspace{1cm} (9)

Substituting the inverter side inductance $L_1$, the grid side inductance $L_2$ and the filter capacitor $C$ into formula (3), $\omega = 19462$ rad/s. According to formula (9), $R = 0.065\Omega$.

6. Simulation analysis

According to formula (6), the closed-loop poles of the double closed-loop system are configured by using the control system with limited degrees of freedom. Through the calculation method of zero-pole cancellation and the introduction of natural frequency $\omega$ as an additional variable, $P_1 = 1.029$, $I_1 = 5.311$, $P_2 = 80.276$ are obtained. Because the rated current $I_N = \frac{P_N}{3V_S}$, so the active component of grid-connected current $I_{sd^*} = 37A$. Reactive component $I_{sq^*}$ is set to 0 in order to achieve unit power into the grid. The simulation model of three-phase grid-connected system is constructed in Matlab / simulink, as shown in figure 7.

![Figure 7. The simulation model of three-phase grid-connected system](image-url)
The control module is shown in figure 8.

![Internal diagram of control module](image)

**Figure 8. Internal diagram of control module**

The specific simulation parameters are shown in table 1.

| Simulation parameter          | Setting value | Simulation parameter          | Setting value |
|-------------------------------|---------------|-------------------------------|---------------|
| Input voltage                 | 800V          | Switching frequency           | 10KHz         |
| Basic frequency               | 50Hz          | Inductance L₁                 | 1.32mH        |
| Inductance L₂                 | 0.33mH        | Filter capacitor C            | 10μF          |
| Damping resistor R            | 0.065Ω        | P₁                            | 1.029         |
| I₁                            | 5.311         | P₂                            | 80.276        |
| Active component Isd*         | 37A           | Reactive component Isq*       | 0A            |

Figure 9 shows the three-phase grid-connected voltage and current waveforms, which are standard sine waves, and the voltage and current are successfully consistent in phase and frequency through phase-locked loop (PLL) technology.

![Three-phase grid-connected voltage and current waveforms](image)

**Figure 9. Three-phase grid-connected voltage and current waveforms**

Figure 10 is the total harmonic distortion rate analysis of C-phase grid-connected current. The total harmonic distortion rate (THD) is only 0.21 %, and the harmonic content of each order is below 0.15 %, which meets the grid-connected requirements.
Figure 10. C-phase grid-connected current total harmonic distortion rate analysis

Figure 11 is the output current waveform of LCL filter before and after adding damping. $I_{s1}$ represents adding damping resistance, and $I_{s2}$ represents not adding damping. At the resonant frequency, the resonant degree of $I_{s2}$ is significantly higher than that of $I_{s1}$, which verifies that the resonant phenomenon of the system can be suppressed by the introduction of passive damping resistor.

Figure 11. LCL filter output current waveforms before and after adding damping resistor

Figure 12 shows the corresponding waveform of the dynamic experiment of the system. At 0.3 s, the setting value of the active component of the grid-connected current $I_{sd}$ changes from 37 A to 30 A, and the C-phase grid-connected current can be stabilized within one cycle and maintained at 30 A under control, so the system has good dynamic response ability.
7. Conclusion

By comparing and analyzing the frequency characteristics of traditional LCL filter and LCL filter with series passive damping resistor, the influence of series passive damping resistor on the stability of the system is summarized.

At the same time, the current double closed-loop control strategy is analyzed and the relevant parameters are designed. Finally, the feasibility of LCL-type three-phase photovoltaic grid-connected inverter based on passive damping is verified by Matlab / Simulink simulation platform.

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