Research of Influence of Grid Voltage and Harmonics on Output Current Quality of Grid Connected Inverter and Improved Control Strategy

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ABSTRACT: Considering the background harmonics of common coupling point voltage in renewable generation system, the equivalent circuit model of grid-connected inverter is established. The mechanism of the influence of voltage background harmonics at common coupling point on the output current of grid-connected inverter is analyzed. A multi-resonant controller is introduced into the control loop to improve the output power quality of grid-connected inverter. A parameter design method of multi-resonant controller is suggested. Finally, the model of renewable energy generation system and distribution network is built in the simulation software, and the background harmonic parameters are set. The simulation experiments of the control strategy with or without multi-resonance controller are carried out respectively. The experimental results verify the correctness and feasibility of the control strategy used in this paper.

1. Introduction

The development of society is increasingly demanding energy, and the use of fossil energy such as coal, oil and natural gas has caused serious environmental pollution. On the other hand, the fossil energy reserves are limited, and human beings are facing the dilemma of energy depletion\textsuperscript{[1]}. Replacing fossil energy with renewable energy represented by wind and solar energy is an effective way to solve the above problems. At present, the method of large-scale use of renewable energy is a distributed generation system based on renewable energy (DGS-BRE)\textsuperscript{[2]}. Grid-connected inverter is the key equipment in DGS-BRE, which plays an important role in connecting renewable energy power generation units and distribution networks, and converting DC power into power frequency AC power, its performance directly determines the quality of DGS-BRE incoming power. The grid-connected inverter controls the switching device of the bridge inverter circuit to be turned on or off by the pulse-width modulation (PWM) strategy, and inverts DC power into the power frequency AC power. In order to filter the AC side PWM switching frequency (including the sideband frequency) current and its harmonics, a filter needs to be introduced between the inverter bridge and the grid. And LCL type filter is widely used because of its small size, low cost and good filtering performance.

In this paper, the three-phase LCL grid-connected inverter is taken as the research object. Considering the background harmonic of the common coupling point voltage, the mathematical model of the three-phase LCL grid-connected inverter is derived. A simplified grid-connected system admittance model is established to analyze the mechanism of grid-connected current harmonic
generation. Then a resonant controller is introduced into grid-connected inverter control loop, reduces the equivalent output admittance at the harmonic frequency of the grid-connected inverter, improves the output power quality of the grid-connected inverter, and the design method of resonant controller parameters are given. Finally, the grid-connected system model is built in MATLAB/Simulink, and the feasibility and effectiveness of the adopted control strategy are verified by comparative experiments.

2. Mathematical Model of Inverter and Mechanism Analysis of Grid-connected Current Harmonic Generation

The circuit topology and control strategy of the three-phase LCL grid-connected inverter system are shown in Fig.1. In Fig.1, \( U_{dc} \) is the DC side voltage of the inverter, \( i_{dc} \) is the DC side current; \( u_a, u_b, u_c \) is the three-phase output voltage of the inverter, \( L_1 \) is the inverter side inductance, \( L_2 \) is the grid side inductance, \( U_{ga}, U_{gb}, U_{gc} \) is the three-phase voltage of the grid, \( C \) is the filter capacitor, and \( I^* \) is the given current amplitude. The inverter system adopts a double closed-loop control structure, the outer ring is a grid-connected current control loop, and the inner ring is a capacitive current active damping ring for damping the resonance peak of the LCL filter. The grid phase information obtained by the phase-locked loop (PLL) is combined with the current setpoint to form a given current reference value in the two-phase stationary coordinate system. Then, after the outer loop feedback, the grid-connected current is converted to the command current by the coordinate transformation. This current is subtracted from the capacitive branch feedback active damping current by the current controller, the difference and output voltage of the inverter is used as modulation signal. Finally the switching transistor is turned on or off.

Fig. 1 three-phase inverter system

The CLARKE transformation is performed on the state space expression of the grid-connected system in the three-phase natural coordinate system to obtain the mathematical model of the grid-connected system in the two-phase stationary coordinate system. Due to the two-phase state variables are decoupled and symmetric in the two-phase stationary coordinate system, it is possible to study one of the phases \(^2, 3\).
Fig. 2 is a control block diagram of one of the two-phase systems in a stationary coordinate system. When power voltage is not considered, that is $U_g = 0$, the input current $i_2$ is taken as the output, and the command current $i^*$ is taken as the input, according to the control block diagram of the system, the open loop transfer function of the system is

$$G(s) = \frac{G_{PR}}{L_1 L_2 C^3 s^3 + KL_2 C^2 s^2 + (L_1 + L_2)s}$$  \hspace{1cm} (1)$$

Then the closed-loop transfer function is

$$G_i(s) = \frac{i_2}{i^*} = \frac{G_{PR}}{L_1 L_2 C^3 s^3 + KL_2 C^2 s^2 + (L_1 + L_2)s + G_{PR}}$$  \hspace{1cm} (2)$$

When the grid voltage disturbance $U_g$ is considered, the closed-loop transfer function is

$$G_i(s) = \frac{i_2}{U_g} = \frac{L_1 C s^2 + C s + 1}{L_1 L_2 C^3 s^3 + KL_2 C^2 s^2 + (L_1 + L_2)s + G_{PR}}$$  \hspace{1cm} (3)$$

According to the two transfer functions shown in equations (2) and (3), using the superposition principle, the functional relationship of the input current is

$$i_2 = G_i(s)i^* + G_i(s)U_g$$  \hspace{1cm} (4)$$

It can be seen in equation (4) that the input current $i_2$ is determined by $i^*$ and $U_g$. Therefore, when the grid voltage is distorted, since $G_{v}(s)$ is not zero, the input current is affected that a part of the distortion current is introduced, resulting in the reduction of input power quality. To reduce the interference of the background harmonics of the power grid, the gain of the grid voltage at the harmonic frequency is approaching zero, that is, the denominator is infinite, and other parameters are fixed, so as long as the $G_{PR}$ is infinite, the grid voltage gain tends to be zero, the command current gain tends to be 1, which can well weaken the influence of grid background harmonics, and better track the command current. The amplitude-frequency characteristic of the resonant controller is shown in Fig.3. Infinite amplitude gain can be generated at a specified frequency\cite{4, 5}, so it can be introduced into the control loop to suppress the influence of voltage background harmonic on output current of grid-connected inverter.

![Fig. 3 control block diagram of grid connected system](image-url)

![Fig. 3 amplitude frequency characteristics of quasi resonant controller](image-url)
3. Multi-resonance controller parameter design method

The grid background voltage is not always a standard sinusoidal voltage. Due to the presence of a non-linear load, a non-fundamental sinusoidal voltage drop is generated, causing the grid voltage to be distorted. The background harmonics of the power grid are mostly low-order harmonics. Therefore, we need to add the corresponding multi-resonant controller as a harmonic compensator to minimize the influence of grid background harmonics on the input current. After introducing the multi-resonant controller, the current controller expression is

$$G_{PR} = k_p + \frac{2k_r \omega_1 s}{s^2 + 2\omega_1 s + \omega_1^2} + \frac{2k_r \omega_5 s}{s^2 + 2\omega_5 s + \omega_5^2} + \frac{2k_r \omega_7 s}{s^2 + 2\omega_7 s + \omega_7^2}$$  \hspace{1cm} (5)

Among them, $\omega_1$, $\omega_5$, and $\omega_7$ are the angular frequency of fundamental wave, the 5th harmonic, and the 7th harmonic, respectively.

![Bode Diagram](image)

Fig. 4 Bode diagram of multi-resonant controller

It is not difficult to see in Fig.4 that the amplitude gain of the controller at a given number of harmonics is much greater than the gain at other frequencies. According to the expression of the input current $i_2$, the gain is larger, the gain to the command current is closer to 1, and the gain to the grid voltage is closer to 0, so that the influence of the grid voltage on the input current can be greatly weakened, track command currents quickly and improve the power level of the network.

Ignore the grid background voltage, there is

$$G(s) = \frac{i_2}{i_1} = \frac{G_{PR}}{L_1L_2Cs^3 + KL_2Cs^2 + (L_1 + L_2)s + G_{PR}}$$  \hspace{1cm} (6)

Among them,

$$G_{PR} = k_p + \frac{2k_r \omega_1 s}{s^2 + 2\omega_1 s + \omega_1^2} + \frac{2k_r \omega_5 s}{s^2 + 2\omega_5 s + \omega_5^2} + \frac{2k_r \omega_7 s}{s^2 + 2\omega_7 s + \omega_7^2}$$  \hspace{1cm} (7)

It can be seen from the above transfer function that the unknown parameters of the system are mainly the capacitive current feedback coefficient $K$, the $k_p$ of the multi-resonant controller and $k_{r1}$, $k_{r5}$, $k_{r7}$ and $\omega_c$. These parameters play an important role in the performance of the grid-connected inverter.

The premise of the selection of these parameters is to ensure the stability of the system. On this basis, the dynamic performance of the system is as good as possible. Of course, the small steady-state error is also crucial. According to the definition of the root locus: the characteristic root of the closed-loop transfer function changes with the variable parameters to leave a series of paths on the s-plane. So changing the parameters of the closed-loop transfer function, the resulting pole map is the required root locus. According to the root locus, the effect of each parameter on the dynamic and
steady-state performance of the system can be seen, which facilitates the selection and optimization of the parameters. Therefore, the choice of parameters in this paper is mainly to judge the stability of the system through the root locus, and then study the stability margin according to the Bode diagram.

For the tuning of system parameters, the appropriate parameters are selected mainly by Bode diagram of the system, phase angle margin, amplitude margin and pole-zero distribution of the system. From the perspective of transfer function, $K$ and $k_p$ are closely related, so it is best not to study the influence of a variable on the stability of the system separately, but to change these two parameters at the same time to find out the relationship between the two parameters, which is convenient for selection and optimization of parameter.

4. Simulation
In fact, there are some low-order harmonics in the grid voltage, mainly the 5th and 7th harmonics. Therefore, simulations are mainly performed for non-ideal grid voltages. Table 1 shows the parameter settings of the inverter. For the grid voltage, the 5th and 7th harmonics are set to be 10% each, and the introduction time is 0.2s.

| Parameters                        | Symbol and value |
|-----------------------------------|------------------|
| DC voltage (V)                    | $U_{dc}$=650     |
| Grid phase voltage (V)            | $U_g$=220        |
| Grid frequency (Hz)               | $f_g$=50         |
| Inverter switching frequency (Hz) | $f_{sw}$=25k     |
| Rated power (kW)                  | $P$=12           |
| Inverter side inductance (H)      | $L_1$=0.002      |
| Grid side inductance (H)          | $L_2$=0.001      |
| Filter capacitor (f)              | $C$=10μf         |
| Capacitance current feedback coefficient | $K$=60                |
| Multiple resonant controller parameters | $k_{r1}=k_{r5}=k_{r7}$=1000, $k_p$=30, $\omega_c$=1.5 |
| Network current distortion rate    | THD<2.5%         |

The multi-resonant controller is selected as the harmonic compensator, and the compensator parameters are set to be $k_{r1}=k_{r5}=k_{r7}$=1000, $K$=60, $k_p$=30, $\omega_c$=1.5. It can be seen from the simulation results shown in Fig. 5, when the grid voltage is distorted and there are no 5th and 7th resonance controllers, the distortion rate of the grid-connected current is very large, and the harmonic requirements of the input current cannot be reached. Fig. 6 is the FFT analysis of the grid current when the grid voltage is distorted but the controller contains 5th and 7th resonance controllers. The grid current distortion rate is very small. Therefore, the multi-resonant controller can well reduce the influence of the harmonics of the grid voltage on the input current.
Fig. 5 FFT analysis of grid current in power grid containing harmonic voltage

Fig. 6 FFT analysis of harmonic current and harmonic current in Grid

5. Conclusion
The output power quality of the grid-connected inverter is affected by the voltage quality of the grid-connected point. The background harmonics of grid-connected point form the grid-connected inverter output current harmonics on the equivalent impedance of the grid-connected inverter, make the grid-connected inverter become a harmonic source and further deteriorate the power quality of the grid, eventually the output power of the grid-connected inverter cannot meet the industry standard and has to be cut off, which in turn affects the power flow of the distribution network, and reduces the reliability of power supply and the efficiency of renewable energy generation. Introducing the multi-resonant controller into the grid-connected inverter control loop can effectively improve the loop gain at the harmonic frequency and reduce the influence of the grid voltage disturbance on the grid-connected output current. The simulation results prove the effectiveness of the adopted control strategy, and it can be promoted for use.

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