Simulation of LLCL filter based on active damping weighted current control strategy

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Abstract. Grid-connected inverters is the core component of distributed generation system, and the filter is the core component of the inverters. When the inverter works, the filter can effectively filter and suppress the high-frequency harmonics in the output current of the inverter side, so as to ensure the stability of the power grid and improve the working effect of the whole grid connected inverter system. The filter is a high order underdamped system, and the LLCL Filter also has a resonance peak. In this paper, a weighted current method based on active damping is used. In this method, the output current of the inverter side and the current of the grid side are weighted with a reasonable proportion as the feedback quantity, the weighted current feedback is the outer loop, and the LC series branch current feedback is the inner loop. The system is reduced to the first order theoretically, which makes up for the under damping problem of the system and suppresses the resonance peak of the system. Through the simulation experiment, the feasibility of the active damping weighted current method is verified.

1 Introduction

As the main means to solve the problems of traditional power industry, new energy power generation mainly includes grid connected operation, island operation and multi energy complementary power generation.[1] Based on the solar energy, wind energy and other renewable energy power generation, there are advantages such as no pollution, rich storage, etc., and the proportion in the power grid is increasing. However, photovoltaic and wind power generation often need to be connected with AC power grid through an energy conversion device, i.e. grid connected inverter.[2-3] Grid connected inverter is the bridge between new energy and AC power grid. If there are a lot of distorted harmonics in its output current, it will have an impact on the electrical equipment at the point of common coupling. Therefore, it is necessary to add a filtering device between the grid connected inverter and the grid to attenuate the switching harmonics caused by PWM and meet the grid connected standard.[4]

There are four types of output filters for photovoltaic inverter: L-type, LC type, LCL and LLCL type. L-type output filter is a first-order system, although the control is simple, but it has a bad effect on the suppression of high-frequency harmonics. LC type filter can effectively filter out high frequency harmonics in independent operation mode, but it does

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not play a filtering role in grid connection mode, which is equivalent to load. LCL type output filter is a third-order system, which has a strong ability to suppress high-frequency harmonics. However, the high-frequency harmonics in the output current of the grid side of the inverter are mainly concentrated at the switching frequency of the system, and the filtering ability of LCL type filter at the switching frequency is insufficient. Compared with the traditional LCL filter, the LLCL Filter has better ability to filter current harmonics at the switching frequency and better dynamic response performance. At the same time, the filter inductance at the grid side is smaller, which can improve the resonance frequency of the system. However, the LLCL Filter is composed of four energy storage elements,which have fixed resonance points.

In order to solve the above problems, a weighted current method based on active damping is proposed in this paper, which can make up for the under damping problem and suppress the resonance peak of the system.

2 Analysis and design of LLCL filter

The structure diagram of three-phase LLCL Filter grid connected inverter is shown in Figure 1.

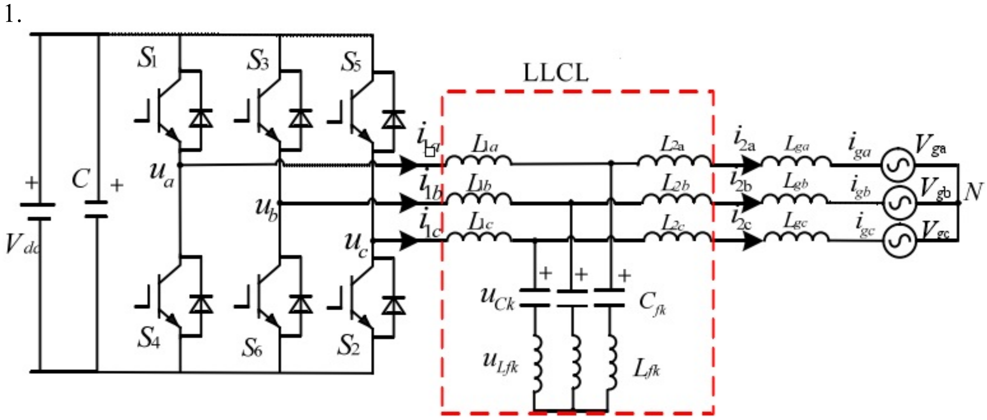

Fig. 1. Structure diagram of three-phase LLCL Filter grid connected inverter.

The inductance at the inverter side is L1k, the filter capacitance is Cfk, the filter inductance is Lfk, the inductance at the grid side is L2k, the current at the inverter side is i1k, the output current of the filter is i2k, the grid side current is igk, The output voltage of the inverter is uik, the capacitance voltage is uCk, the inductive voltage is uLfk, the grid impedance is Lgk, the grid voltage is ugk. k=(a,b,c).

For the parameter setting of LLCL filter, many factors need to be considered. On the premise of considering the filtering effect, the restriction requirements of relevant regulations, as well as the weight, cost and volume of the filter itself and other factors need to be considered.[5]

1) Design of Inductor on Inverter Side

The magnitude of the inductance at the inverter side affects the ripple of the output current at the inverter side. If the ripple current is too large, the components will be damaged and the stability of the system will be affected. Therefore, when calculating the side inductance, the current ripple coefficient should be controlled within 40%.

$$\frac{\Delta \mathrm{I}}{\mathrm{I}_{\max}} = \frac{\mathrm{U_d}}{4\mathrm{L_1 f_s I_{ref}}} \leq 40\% \tag{1}$$

where, Δ I is the output current L1 ripple at the inverter side, and Iref is the reference current.

2) Design of filter capacitor

By setting the resonant frequency of LC series resonant branch at the switching frequency, LLCL Filter can effectively filter out the harmonics at the switching frequency. In the case of fixed switching frequency, the value of filter capacitance is inversely proportional to the value of filter inductance. If the filter capacitance is too large, the reactive power of the filter will be increased and the working efficiency of the system will be reduced. Therefore, when designing the filter capacitor of llcl filter, the reactive power absorbed by the capacitor should not exceed 5% of the rated power. The value range of filter capacitance is:

$$C \leq \frac{5\%P_c}{U_0^2 W0} \tag{2}$$

where, Pc is the rated power of grid connected inverter and U_0^2 is the fundamental voltage of grid.

3) Design of filter inductor

On the premise of good filtering effect, the filtering electric induction system can not only keep the system fast, but also ensure the system has good tracking effect.[6-7] The constraints are as follows:

$$f = \frac{1}{2\pi\sqrt{L_f C}} \tag{3}$$

Therefore, the calculation formula of filter inductance is:

$$L = \frac{1}{4\pi f^2 C} \tag{4}$$

4) Design of inductor on grid side

Because LLCL Filter has a good ability of restraining harmonic at switching frequency, the current harmonic at twice switching frequency of the designed grid side inductance L meets the following formula:

$$\frac{U_d/\pi \times \max(|J_1(2\pi\alpha)|,|J_3(2\pi\alpha)|,|J_5(2\pi\alpha)|) \times |G_{u-i}(j2w)|}{I_{ref}} \leq 0.3\% \tag{5}$$

where, $J_1(2\pi\alpha)$, $J_3(2\pi\alpha)$, $J_5(2\pi\alpha)$ are the corresponding sideband harmonics at frequencies 2W+W0, 2W + 3w0, 2W+5w0, respectively.

5) Design of resonance frequency

Because the output current of the inverter mainly contains the harmonics near the fundamental and switching frequency, and the switching frequency is much higher than the fundamental frequency, the relationship among the fundamental frequency, the switching frequency and the resonance frequency of the filter can be reasonably constrained to avoid the occurrence of resonance to the greatest extent.

When designing the resonant frequency of the filter, it should be noted that its size should not be less than 10 times of the fundamental frequency and not more than 1/2 of the switching frequency.[8]

$$10f_1 \leq f_r = \frac{1}{2\pi\sqrt{[(\frac{L_1 L_2}{L_1+L_2}+L_f)]C_f}} \leq 0.5f \tag{6}$$

where, F1 is the fundamental frequency and the value is 50 Hz.

6) Design quality factor of series branch

When designing LC series branch of LLCL filter, we should not only ensure that the series branch resonates at the switching frequency, but also control the quality factor Q of resonance branch not less than 10 and not more than 50.

$$Q = \frac{1}{R_f}\sqrt{\frac{L_f}{C_f}} \tag{7}$$

3 Active damping weighted current method

The current at the inverter side and the current at the grid side are weighted and summed by the weighted current method, the weighted current is the feedback of the system.In this way, the current error can be reduced, the power factor can be increased, and the system stability can also be improved; However, at the resonance frequency, the weighted current method can not effectively reduce the order of the system, and will affect the quality of the incoming current, which will cause interference to the stability of the system.

In view of the resonance component in the weighted current method, combined with the effectiveness of the active damping method to suppress resonance, this paper adds the active damping strategy on the basis of the weighted current method, and adopts the double closed-loop current control strategy with the weighted current feedback as the outer loop and the LC series branch current feedback as the inner loop. The control block diagram is shown in Figure 2.

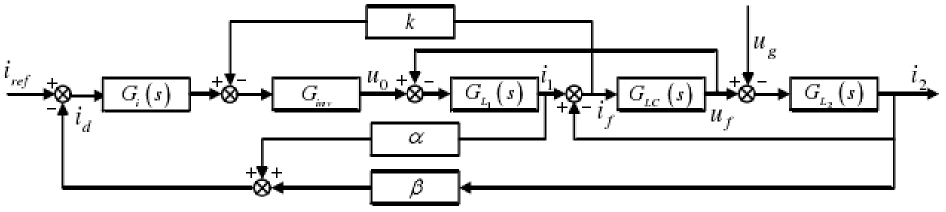

Fig. 2. Improved weighted current feedback strategy.

Open loop transfer function of the system:

$$G(s) = \frac{i_d(s)}{i_{ref}(s) - i_d(s)} = \frac{G_i(s)G_{inv}((\alpha+\beta)(L_fC_fs^2+1)+\alpha L_2C_fs^2)}{(L_1L_2C_f+L_fC_f(L_1+L_2))s^3+KG_{inv}L_2C_fs^2+(L_1+L_2)s} \quad (8)$$

After the active damping strategy is introduced, a new damping term appears in the open-loop transfer function of the system, which increases the damping of the system and realizes the suppression of resonance.

4 Simulation verification

On the MATLAB/Simulink platform, the structure model of grid connected inverter system based on llcl filter is built, and the simulation and FFT analysis are carried out. Figure 3 shows the simulation waveform of the output current at the grid side when using the weighted current method. From the FFT analysis chart, it can be seen that the THD of the output current at the grid side is 4.26%.

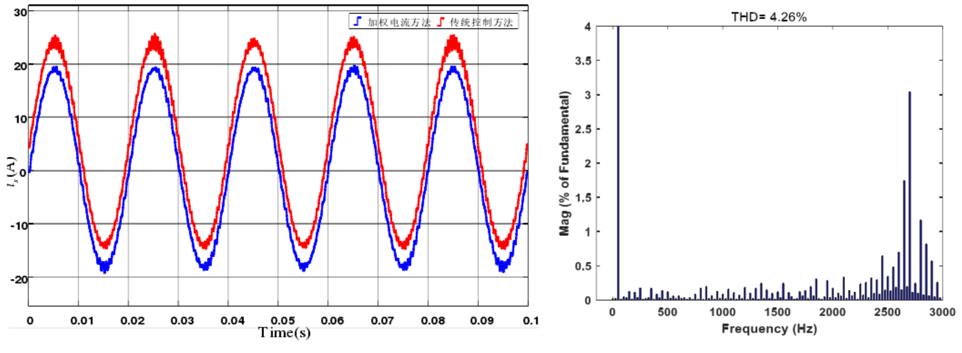

Fig. 3. Simulation diagram using weighted current method.

Figure 4 is the simulation diagram of output current at grid side after adding active damping. From the waveform, it can be seen that the quality of output current at grid side is improved, and THD of output current at grid side is reduced to 3.64%. It is proved that this method can effectively reduce the order of the system to the first order system, thus improving the stability of the system.

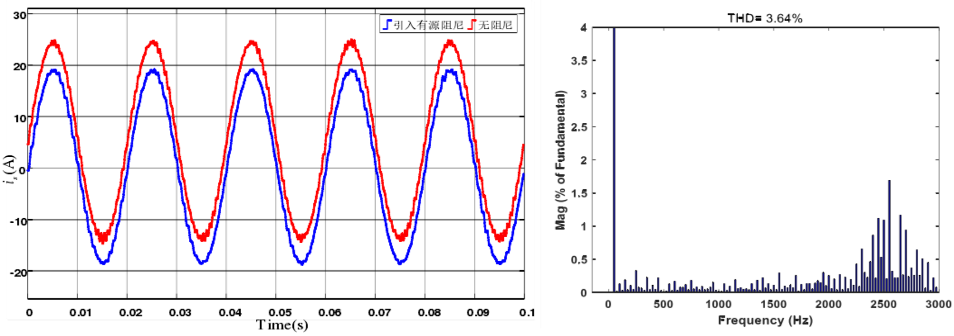

Fig. 4. Simulation diagram with active damping strategy.

5 Conclusion

In this paper, the resonance suppression of LLCL grid connected inverter is studied, and the design method and principle of each parameter of LLCL filter are analyzed. In this paper, the weighted current method based on the active damping method is used. The inverter side current and the grid side current are used to form the weighted current with a reasonable proportion as the feedback quantity. In theory, the system is reduced to the first order and the system resonance is effectively suppressed. The simulation results show that the THD of the system is suppressed, and the system is stable.

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