Research on LLCL Filtering Grid - Connected inverter under the Control of PFI

Ren-qing Li, Ke-yong Zong, Yan-ping Wang, Yang Li, Jing zhang
School of Information Science and Engineering, Dalian Polytechnic University, Dalian 116034, China
1835025107@qq.com.

Abstract. This passage puts forward a kind of LLCL inverter which is based on the proportional feedback integral(PFI) control so as so satisfy the request of the grid-current outputed by the renewable energy generation system. The passage builds the topological graph of grid-connected inverter and makes an analysis of principle of linear superposition aims to reveal the essence of the problem of steady-state error that exists in proportional integral control. We use LLCL filter and the method of passive damping to solve the problem of resonant peak. We make simulation of the grid system with the software named MATLAB/Simulink. The result shows that the grid current enters steady state quickly and in the same time,which has the identical phase and frequency of grid-voltage. The harmonic content in grid current satisfies the request of grid standard.

1. Introduction

With the shortage of traditional fossil fuels and problem of the environmental pollution, it is urgent to develop and utilize renewable clean energy [1]. The new energy power generation equipment needs to convert the electrical energy to the voltage level required for the local load, or transmit it to the power grid. Whether it is a photovoltaic unit, a wind power unit or a fuel cell unit, an inverter is necessary to be used as a grid connection to achieve power transmission to the grid [2][3]. The output of inverter is directly related to the quality of the output power of the generation system. Thus, improving the control performance of grid connected inverter has become one of the focuses of research [4].

The Grid connected inverter usually controls the grid connected current directly or indirectly to achieve the unity power factor operation [5]. Traditional grid connected inverters usually adopt PI control to realize the adjustment of grid connected current. But it is difficult to control the grid current accurately and quickly because the PI control has steady error [6]. In the document [7], proportional resonance control is adopted to solve the stable error of output-current. However, the DC power supply bias problem can not be effectively suppressed. This paper introduces a proportional feedback integral control to reach zero steady-state error control of the tracked grid-current. At the same time, the grid connected inverter needs to connect with the grid through the filter to prevent current harmonics from entering the power grid [8][9].

In the paper, a LLCL grid-inverter which is suitable for network side current feedback is studied. Then proposing a passive damping control strategy nor only realize the zero steady-state error control of grid-current but also guarantee good stability of the inverter. The simulation results proved the accuracy of the proposed strategy.
2. Introduction of Proportional Feedback Integral Control

The paper studies the single phase grid-inverter so as to facilitate the analysis. The diagram of a typical grid-inverter control system is displayed in Fig.1. \( i_{\text{ref}} \) is the grid connected output reference current. \( U_g \) is the grid-voltage. \( i_2 \) is the grid-current outputed the inverter. \( G(S) \) is the controller. \( P(S) \) is the filter.

The expression for the system output \( i_2 \) can be derived according to figure 1.

\[
i_2 = \frac{G(s)P(s)}{1 + G(s)P(s)} i_{\text{ref}} - \frac{P(s)}{1 + G(s)P(s)} u_g
\]  

(1)

![Fig.1 PI control closed-loop system](image)

![Fig.2 PFI control closed-loop system](image)

The superposition principle is used to discuss separately in frequency domain for studying the influence of the reference-current which is \( i_{\text{ref}} \) and the grid-voltage which is \( u_g \) on the output grid. First of all, \( u_g \) is valued at 0. Then the amplitude frequency characteristics of formula (1) can be obtained as it is show in formula (2).

\[
\left| \frac{i_2(s)}{i_{\text{ref}}(s)} \right| = \left| \frac{G(s)P(s)}{1 + G(s)P(s)} \right|
\]  

(2)

In order to realize the zero steady-state amplitude error output of grid connected current, the formula (3) should be satisfied.

\[
\left| G(S)P(S) \right|_{j\omega} = \left| 1 + G(S)P(S) \right|_{j\omega} = 1
\]  

(3)

\( P(S) \) is a finite value, so the formula (4) must be satisfied.

\[
\left| G(S) \right|_{j\omega} = \infty
\]  

(4)

In the same way, the phase frequency characteristic of formula (1) is displayed as follow:

\[
\varphi(\omega) = -\angle \frac{G(s)P(s)}{1 + G(s)P(s)}
\]  

(5)

If the value of \( \varphi(\omega) \) is 0, it is necessary to satisfy the formula (4). Then the zero steady-state error control of the grid-current \( i_2 \) which is at the fundamental angular frequency can be achieved. Making \( i_{\text{ref}} \) value at 0, as long as satisfy the formula (4), the attenuation of grid voltage’s disturbance can be realized according to the analysis of frequency domain.

In the fundamental frequency, the gain of the traditional PI controller is \( \sqrt{k_p^2 + k_i^2 / \omega^2} \).

It can be seen from the expression that it has no infinite gain characteristic, so it is impossible to realize the zero steady-state error control of the outputed-current \( i_2 \).

As shown in Figure 2, the PFI control that based on the PI control form a feedback link in the integration process.

The formula of the the grid-current \( i_2 \) which is under the PFI control is as follow:

\[
i_2 = \frac{k_pP(s)s}{s + k_pP(s)s + k_iP(s)} i_{\text{ref}} - \frac{P(s)s}{s + k_pP(s)s + k_iP(s)} u_g
\]  

(6)

When \( u_g \) is 0, \( k_v = -\omega j / P(j\omega) \), the amplitude frequency characteristic of formula (2) is 1, and the phase frequency characteristic of formula (2) is 0. Similarly, when considering the influence of the grid voltage \( u_g \) on the output current, \( j\omega = -P(j\omega)k_v \), \( i_2 = (1/k_v)u_g \).

As seen that under PFI control, the disturbance of grid-voltage to grid connected current is attenuated by \( K_v \) at the fundamental angular frequency. It shows that the disturbance of grid voltage will bring steady error to the output of grid connected current.
3. System Control Scheme

The topology of the single grid-inverter system with the LLCL filter is displayed in Figure 3. The input voltage $U_{dc}$ is supplied by the new energy source through the boost circuit. $i_1$ is the output current. $i_f$ is the LC resonant circuit current. $i_2$ is grid connected current.

The equivalent control mould of the inverter with a LLCL filter is displayed in Figure 3. The closed loop transfer function can be obtained by Figure 4.

$$\frac{i_2(s)}{u_0(s)} = \frac{L_C a^2 + 1}{(L_L L_f + (L_L + L_f) s^2) + (L_f + L_L) s}$$  \hspace{1cm} (7)

This Potter diagram of the open-loop transfer function of the system is displayed in Figure 5.

According Figure 5, the current on line side $I_2$ can be attenuated at the switching frequency and its vicinity higher harmonics as long as the frequency of LC series is set at the switching frequency of the filter.

Also, according Figure 5, the structure of LLCL filter has the identical resonance peak problem as the structure of LCL filter. It leads to the instability of the system when harmonic amplification occurs. Therefore, the resonant spike must be suppressed to ameliorate the stability of the inverter. Currently, there are two main methods to solve this problem, passive damping method and active damping method. Passive damping is that putting the series resistance in the filter resonant circuit. Active damping is that forming the virtual resistance through multiple loops and feedback. The virtual resistance can attenuate the resonance. According to the literature [10][11][12], the active damping method is easily affected by the system parameters and the nonideal factors of the controller, but the passive damping method is less affected by these factors.

This paper adopts the network side current outer loop control and the passive damping control. At the same time, introducing the grid-voltage feed-forward control strategy for avoid the grid-voltage
fluctuation or disturbance to grid connected system. The system control block diagram is shown in Figure 6. 

\[ i_{\text{ref}} = \frac{C \cdot k_p \cdot k_{\text{PWM}} \cdot L_1 s^3 + C \cdot k_p \cdot k_{\text{PWM}} \cdot R s^2 + k_p \cdot k_{\text{PWM}} \cdot s}{D(s)} \]

The closed loop transfer function of the system can be obtained by Figure 6.

\[ D(s) = (C \cdot L_1 \cdot L_2 + C \cdot L_1 \cdot L_1 + C \cdot L_2 \cdot L_1) s^4 + (C \cdot L_1 \cdot R_1 + C \cdot L_2 \cdot R_2 + C \cdot k_p \cdot k_{\text{PWM}} \cdot L_1) s^3 + (L_1 + L_2 + C \cdot k_p \cdot k_{\text{PWM}} \cdot L_1 + C \cdot k_p \cdot k_{\text{PWM}} \cdot R_2) s + k_p \cdot k_{\text{PWM}} \]

4. Simulation Experiment

The paper build a simulation model with the software named MATLAB/Simulink to verify the proper of the theoretical analysis. The model is as PFI control basis on the grid-inverter. The simulation model includes DC bus, inverter, LLCL filter, power grid and its control system. The main parameters which in the simulation model are list out in Table 1.

| parameter | L_1/mH | L_2/mH | C/mF | L_3/mH | kp   | ki    |
|-----------|--------|--------|------|--------|------|-------|
| number    | 4      | 2      | 0.01 | 1      | 0.002| 187   |

When the system model is running, the waveform of grid-voltage and grid-current are shown in Figure 7. Waveform of grid-current and reference current are shown in Figure 8. AS shown from Figure 7 that the grid-voltage amplitude is 311V and the frequency is 50Hz. The current and voltage are the same phase as the frequency, so as to achieve grid connection requirements. Also we can see from Figure 8 that the output-current of the grid-connected get into steady state soon. It is shown that the proportional delay feedback integral control can keep the output current closely following the change of the reference current. That is to say, the PFI control can reach zero steady-state error over the output current i_2.

The Fourier analysis of the grid current harmonic distortion is shown in Figure 9. It can be seen from the diagram that under the dual function of PFI control, the total harmonic distortion rate of the grid-connected output current is reduced to 0.14% which is far less than the grid connected requirements 5%.

Fig.10 is the reference current and simulation waveform of the LLCL inverter under the PI control. Fig.11 is Fourier analysis of total harmonic distortion of grid connected output current. It can be seen from Fig.10 that there is a phase difference of 1.2 degrees between the output current and the reference current Iref. It is unable to achieve accurate tracking control of grid current. We can see that when the output-current is the same, the total current harmonic distortion rate rises to 0.27% which is greater than 0.14% under the PFI control from Fig.11.
5. Conclusion

In the paper, PFI control strategy is used to ameliorate the grid-connected output current. The zero steady-state error control is realized by introducing a feedback link on the basis of PI control. It makes the grid-connected current and the grid-voltage have the identical frequency and phase in order to satisfy the grid connection requirement. The LLCL filtering structure is used to filter the single grid connected inverter. It can greatly attenuate the higher harmonics at the switching frequency. The paper also adopts the passive damping method to solve the problem of inherent resonance spike which exists in LLCL structure so as to enhance the stability of the inverter. The results of simulation prove the correctness and feasibility of the theoretical analysis.

Reference

[1] Zeng Zheng, Yang Huan, Zhao Rong-xiang, ET al. Overview of multi-functional grid-connected inverters [J]. Electric Power Automation Equipment, 2012, 32(8): 5-15(in Chinese).

[2] Cui Hong-fen, Wang Chun, Ye Jilei, ET al. Research of interaction of distributed PV system with multiple access points and distribution network [J]. Power System Protection and Control, 2015, 43(10): 91-97(in Chinese).

[3] Xie Shao-jun, Ji Lin, Xu Jin-ming. Review of grid impedance estimation for grid-connected inverter [J]. Power System Automation Technology, 2015, 39(2): 320-326(in Chinese).

[4] HAN X, AI X, SYN Y. Research on large-scale dispatchable grid-connected PV systems [J]. Journal of Modern Power Systems and Clean Energy, 2014,2(1): 69-76.

[5] Xu Jing-ming, Xie Shao-jun, ET al. An adaptive current control for grid-connected LCL-filtered inverters in weak grid case [J]. Proceedings of the CSEE, 2014,34(24):4031-4039(in Chinese).

[6] Guo Xiao-qiang, Jia Xiao-yu, Wang Huai-bao, ET al. Analysis and online transfer of stationary frame zero steady-state error current control for three-phase grid-connected inverters [J].Transactions of China Electrotechnical Society, 2015,30(4):8-14(in Chinese).

[7] Meng Jian-hui, Shi Xin-chun, ET al. Optimal control of photovoltaic grid-connected current based on PR control [J]. Electric Power Automation Equipment, 2014,34(2):42-47(in Chinese).

[8] Wu W, He Y, Blaabjerg F. An LLCL power filter for single-phase grid-tied inverter[J].IEEE Transactions on Power Electronics, 2012,27(2):782-789.

[9] Xu De-zhi, Wang Fei, Ruan Yi, ET al. Topology deduction and analysis of grid-interfacing filters [J]. Transactions of China Electrotechnical Society, 2015,30(4):15-25(in Chinese).

[10] LEI Yi, ZHAO Zheng-ming, YUAN Li-qiang, ET al. Factors contributing to damping of grid-connected photovoltaic inverter with LCL filter [J]. Automation of Electric Power Systems, 2012,36(21):36-40(in Chinese).

[11] Wang Hai-song, Wang Han, Zhang Jian-wen, ET al. S L dipaciator passive damping control for LCL grid-connected inverter [J]. Power System Technology, 2014,38(4):895-902(in Chinese).

[12] Jin Liang-liang, Zhou Li-dan, Yao Gang, ET al. A novel LCL filter adopted in grid-connected inverter [J]. Power System Protection and Control, 2016,44(11):2-8(in Chinese).