Research on Dual-Loop Control of Three-Phase Grid-Connected Inverter with LCL Filter Based on PCI Control

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***Abstract*—According to the defects of traditional PI control, the paper presents a new method which is Proportional Complex Integral (PCI) control to implement the control of three-phase grid-connected inverter with LCL filter. Conventional PI control has infinite gain in the two-phase rotating reference frame, but can not achieve the zero error tracking in the two-phase stationary reference frame, which is used in the system to eliminate coupling. However, the PCI control has infinite gain at fundamental frequency in the two phase stationary frame. Finally, the simulation result shows that the new method is correct and effective.**

***Index Terms*—PCI control, conventional PI control, two-phase stationary frame**

I. Introduction

Nowadays, with the development of economy and the increasing consumption of energy, to take renewable energy like wind and solar energy as substitute to traditional energy, such as thermal power and hydroelectric power, is an urgent and important mission [1]. The wind energy and solar energy is prevailing and can be used widely. So the problem is how to use it efficiently and effectively. And the inverter control technology is one of the most important techniques to take advantage of new energy.

Actually, there are three types of filter, which are L filter, LC filter and LCL filter. And they have their own advantages and disadvantages [2]. The L filter has a simple structure and is easy to be achieved. But its filtering performance is not as good as LCL filter. The LC filter is usually used in the two modes of grid-connected and stand-alone mode, and the capacitance is just like local load in the grid-connected mode. Then the filtering performance is just like L filter. In the grid-connected mode, the most prevailing filter is LCL filter, which has better filtering performance than L filter and LC filter. The defect of it is also obvious. Due to the high order system, the control system has resonant peak at the resonant frequency, which leads to the instability of system.

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Therefore, the design of control system is very important, which should not only guarantee the stability of the system, but also help the system satisfy the characteristic requirements. In general, three-phase inverter has two control modes to inhibit resonant peak, which are active damping control and passive damping control, respectively [3]. The passive damping control is that the capacitance C is cascaded or paralleled with resistance to increase the system damping. However, the new resistance will increase the energy consumption and decrease the efficiency. The active damping control, which adopts the dual-loop control including grid-connected current and capacitance current, can not only inhibit the resonant peak, but also have more efficient effects than the passive damping control [4].

The paper employs two-phase stationary reference frame to avoid coupling and implements the separating control of two axes, basing on the traditional dual-loop current control. Because of the PI control unable to achieve zero tracking of alternating signals, therefore, the paper adopts PCI control to get infinite gain at the fundamental frequency. And the inner circle adopts proportional control to enhance the response speed.

II. The System Structure

In the paper, the inverter's source is DC source which is equivalent to the output voltage of new energy [5]. The whole grid-connected system and its control structure are shown in Fig. 1. Compared with the feedback of grid-connected current and reference current, the value which has passed PCI controller, is designed to be as reference value of inner capacitance current. After passing the P controller, the output is modulation wave. The paper adopts sinusoidal pulse width modulation and the modulation frequency is 10kHz. The choice of LCL filter parameters is not the point of this paper, so the filter parameters is given directly, and the L_1 is 3mH which is equivalent to L_2, the capacitance C is 2uF. The u_a, u_b and u_c are designed as grid voltage and its valid value is 220V. The Fig. 2 shows the mathematical model of the system with LCL filter in two-phase stationary reference frame, and i_2 is grid current, u_g is grid voltage and u_{inv} is the output voltage of inverter [6].

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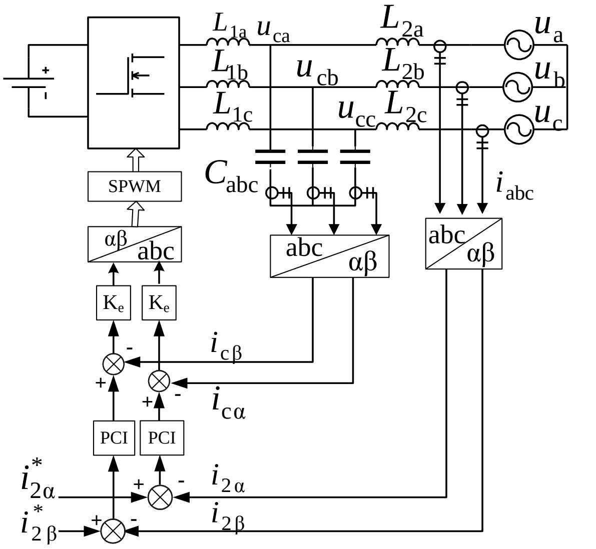

Figure 1. The control structure of system.

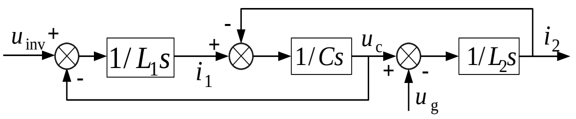

Figure 2. The mathematical model diagram of LCL filter.

III. The Analysis of Control System

According to the Fig. 2, the transfer function of LCL filter can be gotten, which is:

$$G_1(s)=\frac{i_2(s)}{u_{\mathrm{inv}}(s)}=\frac{1}{L_1L_2Cs^3+(L_1+L_2)s} \tag{1}$$

The mathematical model of PCI control is as follows:

$$G(s)=K_{\mathrm{p}}+\frac{K_{\mathrm{i}}}{s-j\omega} \tag{2}$$

In the equation, K_{p} and K_{i} are proportional coefficient and integral coefficient, respectively [7]. And the mathematical model of whole system is shown in Fig. 3.

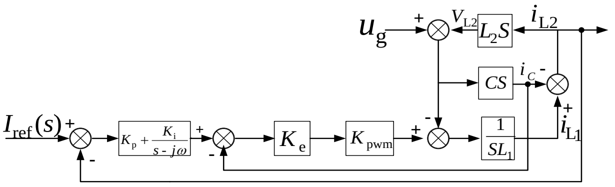

Figure 3. The diagram of control system.

Then the closed-loop transfer function of system can be gained as:

$$G_{\mathrm{c}}(s)=\frac{A_1s+A_0}{B_4s^4+B_3s^3+B_2s^2+B_1s+B} \tag{3}$$

$$A_1=K_{\mathrm{p}}K_{\mathrm{e}}K_{\mathrm{pwm}}$$

$$A_0=K_{\mathrm{e}}K_{\mathrm{pwm}}(K_{\mathrm{i}}+\mathrm{j}\omega_0K_{\mathrm{p}})$$

$$B_4=L_1L_2C$$

$$B_3=K_{\mathrm{e}}K_{\mathrm{pwm}}L_2C-\mathrm{j}L_1L_2C\omega_0$$

$$B_2=L_1+L_2-jK_{\mathrm{e}}K_{\mathrm{pwm}}L_2C\omega_0$$

$$B_1=K_{\mathrm{p}}K_{\mathrm{e}}K_{\mathrm{pwm}}-\mathrm{j}\omega_0(L_1+L_2)$$

$$B_0=K_{\mathrm{e}}K_{\mathrm{pwm}}(K_{\mathrm{i}}+\mathrm{j}\omega_0K_{\mathrm{p}})$$

The parameters are designed as follows: K_{p}=0.5, $K_{\mathrm{e}}K_{\mathrm{pwm}}$=22, K_{i}=500, and ω_0 is 314rad/s.

Then, the coefficients are:

A_1=11, A_0=11000+j3454, B_4=1.8*10^{-11},

B_3=1.32*10^{-7}-j5.65*10^{-9}, B_2=0.006-j4.41*10^{-5},

B_1=11-j1.884, B_0=11000+j3454.

The bode diagram of closed-loop control system is shown in Fig. 4.

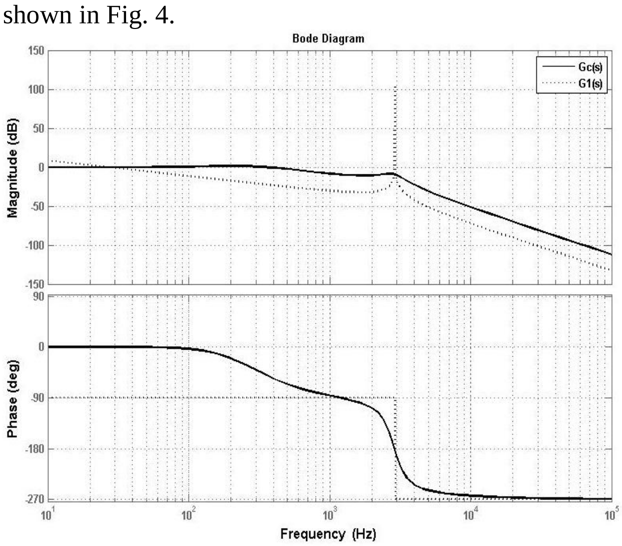

Figure 4. The bode diagram of closed-loop control system.

In the picture, the solid line represents the bode diagram of system, and the dashed line the bode diagram of LCL filter. From the diagram, the LCL filter system of three-order has resonant peak at the resonant frequency, which may lead to instability of system easily and enhance the harmonic content of system around the resonant frequency. Implementing the PCI of dual-loop control can implement the zero error tracking of magnitude and phase of system fundamental frequency, and eliminate the resonant peak. Therefore, it proves that the PCI control can increase the system damping as well as improve the system stability.

For there is complex in the controller, so the implementation of control is not easy to achieve. According to the (4), then the Fig. 5 can be obtained.

$$K_{\mathrm{p}}+\frac{K_{\mathrm{i}}}{s-j\omega_0}=K_{\mathrm{p}}+\frac{\frac{K_{\mathrm{i}}}{s}}{1-j\frac{K_{\mathrm{i}}}{s}\times\frac{\omega_0}{K_{\mathrm{i}}}} \tag{4}$$

The $\alpha\beta$ stationary frame has an inherent feature of 90 shift, then the (5) can be obtained.

$$\begin{cases} jm_{\beta}=m_{\alpha} \\ jm_{\alpha}=-m_{\beta} \end{cases} \tag{5}$$

Based on the Fig. 5, a simplified diagram can be deduced shown in Fig. 6. Therefore, the PCI controller is easy to be implemented.

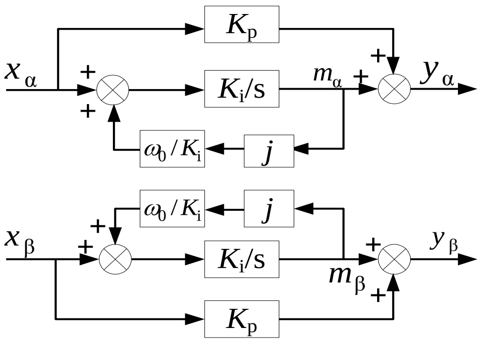

Figure 5. The structure design of PCI control.

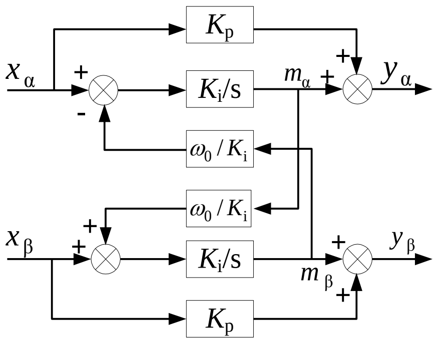

Figure 6. The implement of PCI control structure.

IV. THE ANALYSIS OF SIMULATION

According to the above design, the control system is simulated on the platform of Simulink and the parameters are same as the analysis above, and DC source is 700V. In order to have better comparison with the two control modes, the proportional coefficient and integral coefficient of each control is identical, and K_p is 0.5, K_i is 500 and K_e is 0.22. The grid current and grid voltage are shown in Fig. 7 and the reference current value is 30A. The current value shown in the picture has been enlarged two times.

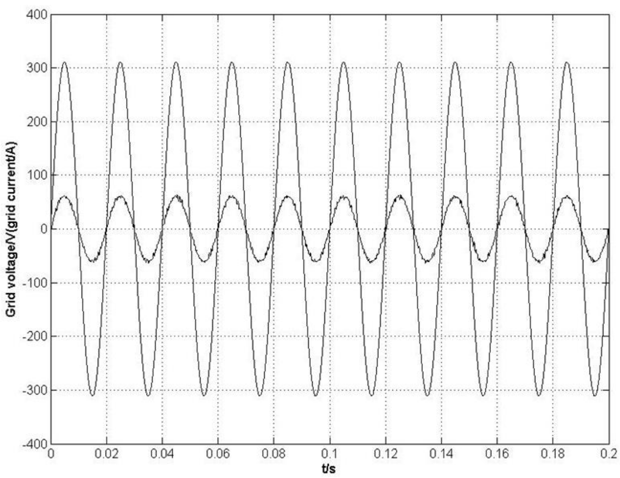

Figure 7. The grid current and grid voltage.

From the picture, the grid current achieves the goal of unit power factor and has better tracking performance. The Fig. 8 shows the total harmonic distortion of grid current under PCI control and PI control.

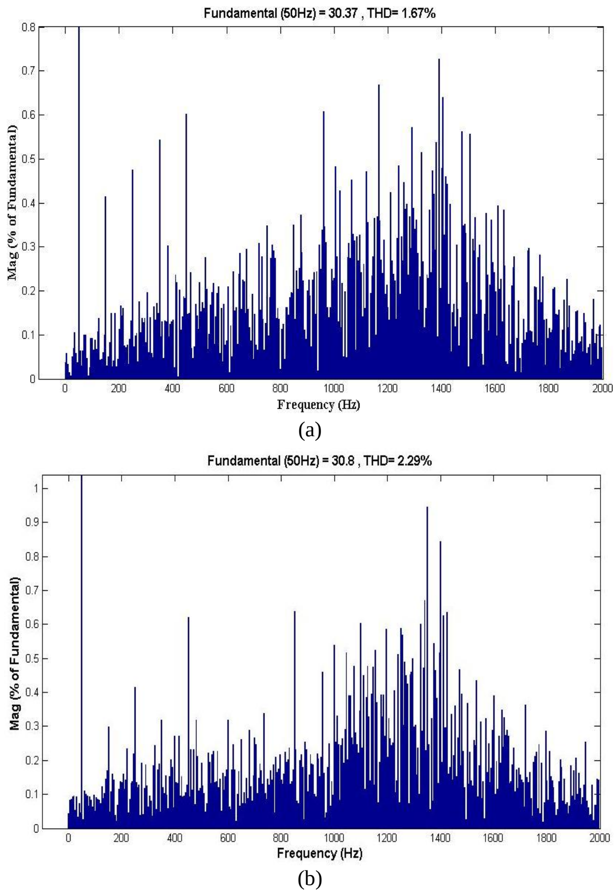

Figure 8. (a) The current THD value under PCI control (b) the current THD value under PI control.

Under the same conditions, the current THD value of PCI control is 1.67%, while the current THD value of PI control is 2.29%. Obviously, the former is better than the latter, which certifies that the performance of PCI control is more excellent than PI control. And the current value of fundamental frequency under PCI control is 30.37A, while the current value of PI control is 30.8A. Therefore, the tracking error of PI control is greater than PCI control, evidently.

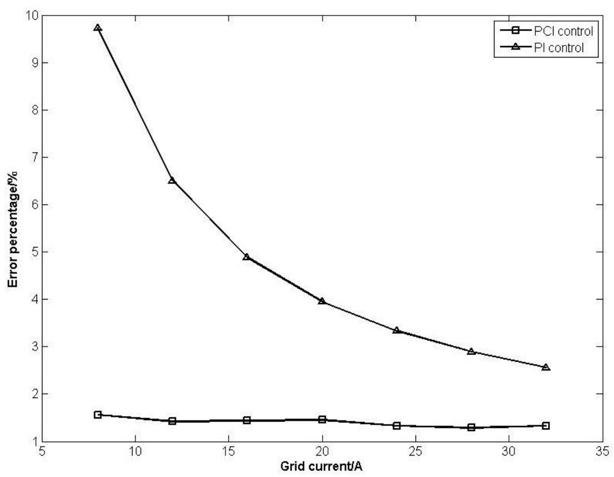

Figure 9. The current steady-state error under PCI control and PI control.

The Fig. 9 shows the steady-state error of grid current under PCI control and PI control. From the picture, when the parameters are identical, the steady-state error of grid current under PCI control is much smaller than current error under PI control. In addition, when the reference current value is smaller, the steady-state error of grid current under PI control is bigger. However, under the PCI control, the value of reference current has small impacts on the steady-state, which is conducive to the stability of system.

The Fig. 10 shows the change of grid current when reference current values changes suddenly. The changing time is at 0.125s and the reference value is changing from 15A to 30A and the current waveform has been enlarged five times. From the picture, what can be obtained is that the grid current has almost no overshoot and can track the reference value rapidly. So the new strategy is proved to be effective and correct.

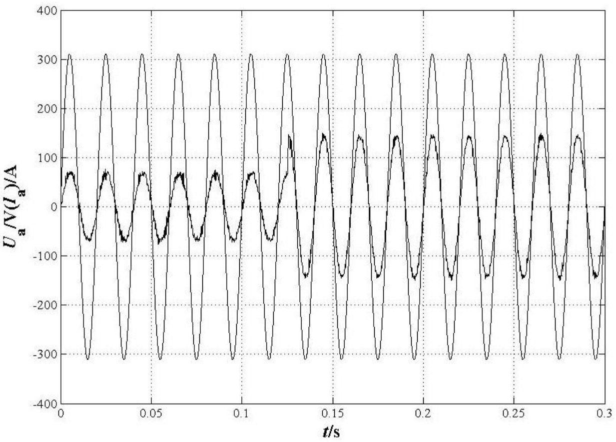

Figure 10. The waveform of grid current as the reference current changes.

V. CONCLUSION

Basing on the traditional dual-loop control of grid-connected inverter, the paper takes PCI control in the outer loop and proportional control on the inner loop. For the reference current is sinusoidal alternating signal, the PCI control has more accurate tracking performance at the fundamental frequency compared with traditional PI control. For the system is unstable easily to implement LCL filter, so the paper had chosen appropriate parameters to guarantee the stability of system first, then compared with the system performance of two control modes under the same parameters and external conditions. And the simulation results show that, the PCI control help the system to get lower grid current THD value and have better current quality. Moreover, under the condition of different reference current, the steady-state error of PCI control is smaller and the tracking performance is more accurate.

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REFERENCES

[1] X. Q. Guo and W. Y. Wu, "Improved current regulation of three-phase grid-connected voltage-source inverters for distributed generation systems," *IET Renew. Power Gener.*, vol. 4, no. 2, pp. 101-115, Apr. 2010.

[2] Y. Jia, J. Zhao, and X. Fu, "Direct grid current control of LCL-filtered grid-connected inverter mitigating grid voltage disturbance," *IEEE Trans. Power Electron.*, vol. 29, no. 3, pp. 1532-1541, 2014.

[3] G. Shen, X. Zhu, J. Zhang, *et al.*, "A new feedback method for PR current control of LCL-filter-based grid-connected inverter," *IEEE Trans. Ind. Electron.*, vol. 57, no. 6, pp. 2033-2041, Jun. 2010.

[4] G. Q. Shen, *et al.*, "An improved control strategy for grid-connected voltage source inverters with an LCL filter," *IEEE Trans. Power Electron.*, vol. 23, no. 4, pp. 1899-1906, Jul. 2008.

[5] M. Xue, Y. Zhang, Y. Kang, Y. Yi, S. Li, and F. Liu, "Full feedforward of grid voltage for discrete state feedback controlled grid-connected inverter with LCL filter," *IEEE Trans. Power Electron.*, vol. 27, no. 10, pp. 4234-4247, Oct. 2012.

[6] M. Liserre, R. Teodorescu, and F. Blaabjerg, "Stability of photovoltaic and wind turbine grid-connected inverters for a large set of grid impedance values," *IEEE Trans. Power Electron*., vol. 21, no. 1, pp. 263-272, Jun. 2006.

[7] W. W. Li, *et al.*, "Full-Feedforward schemes of grid voltages for a three-phase-type grid-connected inverter," *IEEE Trans. Ind. Electron*., vol. 60, no. 6, pp. 2237-2250, Jun. 2013.

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