A Design of Three-level Inverter Based on PCI Control

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Abstract. To solve the problem that the PI-controlled three-level inverter can't achieve zero steady-state error on AC, a closed-loop control scheme using the PCI controller is proposed. The voltage and current double closed-loop control scheme is adopted. The circuit of diode-clamped three-level inverter is selected as the controlled object. And the PCI controller is designed. The zero steady-state error of three-level inverter based on the PCI control is analyzed in detail. Finally, the closed-loop control system of three-level inverter is simulated on the MATLAB/Simulink platform. The results show that the PCI control has good dynamic response ability and can accurately track various sudden loads. And then the correctness of theoretical analysis is verified.

1. Introduction

The three-level inverter is one of the most widely used multilevel inverters, it is one of the effective ways to realize high voltage and high power conversion. It has been widely used in motor frequency control system, static var compensation, active filter and UPS [1]. However, the open-loop inverter can not achieve good tracking and dynamic response, so the closed-loop control method has become the focus of research.

At present, the control methods of inverter mainly include deadbeat control [2], repetitive control, variable structure control of synovium, etc. Because the PI control algorithm is simple and mature, it has been widely used in the field of inverter control. But the PI can't achieve the zero steady-state error control of AC. Therefore, these control methods have certain limitations [3].

Based on the frequency domain analysis, the PI controller is improved. And the proportional complex integral (PCI) controller is proposed [4]. It can not only realize the error-free tracking of AC, but also can be directly applied to the abc coordinate system, omitting the coordinate transformation link and meets the requirements of the inverter performance index [5].

2. The design of closed-loop control system for three-level inverter

Figure 1 is the principle block diagram of closed-loop control for three-phase three-level inverter. The control process is that the given reference voltages \(u_a^*, u_b^*, u_c^*\) respectively subtract the voltages \(u_a, u_b, u_c\) at both ends of the filter capacitor \(C\) to get the voltage error signals \(e_a, e_b, e_c\). The given current signals are obtained by the PCI voltage controller, which compared with the currents flowing through the filter inductor \(L\). The output signals \(y_a, y_b, y_c\) are sent to the SVPWM pulse width modulation generator, Then, the duty cycle control signals drive the opening and closing of 12 switches of the three-level inverter. So the closed-loop control of the inverter can be realized [6].

To eliminate the harmonic of the output voltage, LC filter is selected. Compared with LCL filter, its control is simple and the output effect is better.
2.1. The design of the diode-clamped three-level inverter circuit

The diode-clamped three-level inverter is composed of a DC power supply $E$, two DC voltage-dividing capacitors $C_1$ and $C_2$, and three-phase three-level inverter bridges. Each bridge arm includes four power switches $S_{x1}$-$S_{x4}$, four continuous-current diodes $D_{x1}$-$D_{x4}$ and two clamping diodes, where $x$ represents three phases $a$, $b$ and $c$. The schematic diagram of three-level inverter circuit is shown in figure 2.

2.2. Principle and parameter design of the PCI controller

This paper presents a proportional complex integral (PCI) controller, whose transfer function is in equation (1).

$$G(s) = k_p + \frac{k_i}{s - j\omega_0}$$  (1)

Where: $k_p$ is the proportional coefficient, $k_i$ is the integral coefficient, $\omega_0$ and is the given AC frequency.

Because the transfer function of the PCI controller contains complex $j$, it is more difficult to realize the controller. According to the phase difference of 120 degrees between three phases in abc coordinate system, the $m_a$ clockwise shifting 90 degrees is obtained by $m_b$ minus $m_c$, but the amplitude is increased $\sqrt{3}$ times, namely $m_b-m_c=j\sqrt{3}m_a$ [8]. In the same way, the vector $m_b$ and $m_c$ can be obtained. From the above analysis, the corresponding principle diagram of the PCI controller is shown in figure 3.
Figure 3. The principle diagram of the PCI controller

To ensure fast response speed and avoid amplifying noise, the system bandwidth range is generally selected to be 10 times higher than the fundamental frequency and lower than 1/5 of the switching frequency. According to the definition of bandwidth, when the amplitude of closed-loop amplitude frequency characteristic of the system is reduced to -3dB, the corresponding frequency is $\omega_b$, and the frequency range of $0-\omega_b$ is called the bandwidth of the system. Considering the influence of $k_p$ and $k_i$ on the closed-loop amplitude frequency characteristic, the bandwidth $\omega_b=4500\text{rad/s}$ is selected in this paper. Therefore, $k_p$ and $k_i$ are determined for this system, that is, $k_p=0.15$, $k_i=25$.

3. Zero-steady-state error analysis of three-level inverter controlled by the PCI controller

For the convenience of analysis, the control block diagram of three-level inverter can be simplified, shown in figure 4. Following is a detailed analysis of the three-level inverter controlled by the proportional complex integrator controller.

Figure 4. The system block diagram of closed-loop control for three-level inverter

Where $U_a(s)$ is a given voltage signal of a-phase, $G_a(s)$ and $G_i(s)$ are the transfer functions of the PCI controller of the voltage loop and the current loop respectively, $K$ is the equivalent gain of three-level inverter bridge, $T$ is the switching period of the inverter, $U_d(s)$ is the output voltage signal of a-phase filter capacitor [9].

The closed-loop transfer function of the output relative to the reference input can be obtained from figure 4 in equation (2).

$$U_a(s) = \frac{G_i(s)G(s)K}{[(Ts+1)(Ls+r)+G_i(s)K]sC+G_i(s)G(s)K}U_a^*(s)$$

(2)

The transfer function of the PCI controller in equation (3).

$$G(s) = \frac{k_p s + k_i - j k_i \omega_0}{s - j \omega_0} = \frac{N(s)}{s - j \omega_0}$$

(3)

Then the transfer functions of controllers for the voltage and current loops are expressed in equation (4) and (5), respectively.
\[ G_v(s) = \frac{N_1(s)}{s - j\omega_0} \quad (4) \]
\[ G_i(s) = \frac{N_2(s)}{s - j\omega_0} \quad (5) \]

By substituting \( G_v(s) \) and \( G_i(s) \) in equation (4) and (5) into equation (2), we obtain equation (6):
\[ U_v(s) = \frac{N_1(s)N_2(s)K}{[(s - j\omega_0)^2(Ts + 1)(Ts + r) + N_1(s)(s - j\omega_0)K] \cdot sC + N_1(s)N_2(s)K} U_v^*(s) \quad (6) \]

For further analysis, \( s = j\omega \) is substituted into equation (6), which can be expressed as:
\[ U_v(j\omega) = \frac{N_1(j\omega)N_2(j\omega)KU_v^*(j\omega)}{[(j\omega - j\omega_0)^2(j\omega T + 1)(j\omega L + r) + N_1(j\omega)(j\omega - j\omega_0)K] \cdot j\omega C + N_1(j\omega)N_2(j\omega)K} \quad (7) \]

In equation (7), when \( \omega = \omega_0 \), \( U_v(s) = U_v^*(s) \), the output is completely independent of the disturbance signal and can accurately track the real-time change of the input. Therefore, the PCI controller can achieve accurate control of the controlled object, and achieve zero steady-state error control for DC and AC [10].

4. Simulation and result analysis

4.1. Application analysis of the PCI control method in specific system

The simulation model of three-level inverter is built in Simulink. The DC side voltage is 600V, the filter capacitance is 30\( \mu \)F, the filter inductance is 0.18mH and switching frequency is 2kHz. To verify the correctness of the PCI control algorithm and the effect of output waveforms of three-level inverter under different loads, simulation is carried out under resistive load, inductive load and capacitive load, respectively. The waveforms are shown in figure 5.

Figure 5. (a) the voltage waveform at \( R=10\Omega \)

Figure 5. (b) the voltage waveform at \( L=0.2H \)
Figure 5. The voltage waveforms under resistive, inductive and capacitive loads

Shown in Figure 5, the designed PCI double closed-loop control has good voltage output waveforms under different loads, and can achieve stable output in a quarter cycle. The correctness of the PCI controller is verified.

To better verify that PCI double closed-loop controller not only has good effect under different loads, but also has good dynamic response under sudden changes of loads. Therefore, the simulation is carried out under various sudden changes of load and voltage, respectively. The simulation waveforms are shown in Figure 6 and Figure 7.

Figure 6. (a) the voltage abrupt waveform Figure 6. (b) the current abrupt waveform

Figure 6. The load voltage and current waveforms changed from inductive to capacitive at \( t=0.03s \)

Figure 6 shows the waveforms of load voltage and current when the load changes from inductive to capacitive. It can be seen from that the load voltage fluctuates slightly at 0.03s, almost to normal state, and the current has a small mutation, but it can still resume stable operation quickly in less than half a cycle. Furthermore, the PCI control method can effectively overcome the disturbance caused by the mutual conversion between different types of loads, and the response speed is fast.

Figure 7. (a) the voltage abrupt waveform Figure 7. (b) the current abrupt waveform

Figure 7. The load voltage and current waveforms when a given voltage changes from 30V to 60V and then to 90V

Figure 7 shows the waveforms of load voltage and current when the given voltage amplitude varies at 0.04s and 0.08s, respectively. It is obvious that the dynamic response of voltage and current waveforms is almost the same, they can track the change of the given value quickly and can also restore stable operation in a very short time.
Through the analysis of the above three operating conditions, it is verified that the PCI control method can effectively solve the impact of various sudden changes on the system, which reflects the advantages of the PCI control method.

4.2. Contrastive analysis of the PCI and PI control methods
To show the PCI has better control effect, PCI and PI controllers are respectively used for simulation with same parameters. The simulation voltage waveforms of the a-phase voltage is shown in figure 8.

![Figure 8](image)

**Figure 8.** The a-phase voltage diagram of the PI and PCI control

From figure 8, it can be seen that when the controller is PI, the tracking effect is not ideal, there are differences in amplitude and phase angle, and zero steady-state error control of AC can't be realized. However, when the PCI controller is used, zero error tracking can be achieved in about half a cycle without the phase difference. Using the spectrum analysis function of powergui module, the harmonic content of output waveform is detected under two control modes. As shown in figure 9, the harmonic content of output voltage waveform controlled by the PCI controller is lower. Therefore, the PCI controller has a better effect on AC control.

![Figure 9](image)

**Figure 9.** The contrast chart of harmonic content controlled by the PI and PCI controllers

5. Conclusion
By adopting the double closed-loop control scheme of voltage and current of the PCI controller, the PCI controller is designed, and the complex theory is applied to practical application. The simulation results show that PCI control has good dynamic response ability, and can achieve accurate tracking under various situations of the load mutation. It solves the disadvantage that traditional PI can't achieve error-free tracking of AC, and has exploratory significance.
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References
[1] Zeng J, Yang L, Huang J C and Qiu G B 2019 Discontinuous modulation of three-level inverter based on dynamic space vector Transactions of China Electrotechnical Society 34 377-86.
[2] Jiang W D, Li L B, Wang J P, Zhai F and Li J S 2018 Improved discontinuous pulse width modulation strategy for neutral point clamped three-level inverter Automation of Electric Power Systems 42 127-34.
[3] Wang C 2017 Study of three-level inverter based on pci control Harbin University of Science and Technology 1-47
[4] Xia Y G and Zheng E R 2018 Study of steady-state control strategy for mmc-hvdc system based on pci controller Electric Drive 48 29-34
[5] Xiang C Q, Chen C Y, Han D and Cheng S 2018 VSPWM for npc three-level inverter with neutral point potential unbalance degree feedback Electric Machines and Control 22 50-58
[6] Feng T, Kang L Y, Hu B H and Feng Y B 2018 A neutral point potential balancing strategy for three-level t-type inverter based on deadbeat control Transactions of China Electrotechnical Society 33 1827-34.
[7] Manoranjan S and Sivakumar K 2017 A three level lc-switching based voltage boost npc inverter IEEE Transactions on Industrial Electronics 64 2876-83.
[8] Chen X, Tang B, Cai W H, Mao H F and Yu F 2019 Design of proportional complex integral current control strategy for active power filter Power Capacitor and Reactive Power Compensation 40 35-40
[9] Gu X, Liu C, Zhang G Z, Shi T N and Xia C L 2019 Space-vector based synchronous discontinuous pwm for three-level inverter with output current optimization Transactions of China Electrotechnical Society 34 924-33.
[10] Liao Z P, Liu Z Y and Xi R X 2018 Harmonic suppression method for grid connected photovoltaic inverter Electric Drive 48 28-33