Research on LCL-filtered Grid-Connected Inverter Based on Fractional Order PI Controller

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Abstract. With the high attention paid to new energy sources, grid-connected inverters with LCL filter have been widely used. In order to maintain the steady state operation of the system and reduce the resonance, the current double closed loop control decision with a PI controller is often adopted. However, the PI controller has only two adjustable parameters, Kp and Ki, and the adjustment accuracy is limited. This paper focuses on the simulation of the lightning interference and humid environment that inverters may face after being put into use in outdoor open space, such as solar power stations and so on. Since the fractional-order PI controller has three adjustable parameters, it can effectively improve the system performance and make the output more in line with the actual application requirements. Therefore, this paper selects the fractional-order PI controller and compares with the control performance of the traditional PI controller. Finally, the conclusion comes out that the system based on fractional order PI controller has stronger anti-interference ability and better robustness.

1. Introduction

Nowadays, the application of solar panels and small wind turbines has attracted people's attention[1]. Scholars are committed to researching on the application of grid-connected inverters in some DC voltage sources and grid connections. In order to reduce the harmonic components in the input grid current and ensure the reliable operation of the grid, a better filter is needed. At present, because the LCL filter has strong capability of reducing high-frequency harmonic attenuation, it is widely used to suppress the harmonic attenuation in the output current of grid-connected inverts. However, since the grid-connected inverter with LCL filter is often used in outdoor environments such as solar power stations, it is susceptible to lightning, humid environment and other factors, causing disturbance signals or changes in component performance. In recent years, the research of fractional-order PID controllers has received extensive attention. Because of its many adjustable parameters, it can effectively improve the structure and performance of the system. Therefore, this paper studies the system performance of LCL grid-connected inverter under traditional PI control and fractional PI control.

2. The structure of LCL-filtered grid-connected inverter

Figure.1 shows the structure of a single-phase LCL-filtered grid-connected inverter[3] based on double-closed loop control decision. It includes a DC voltage \( V_d \), which is generated by a renewable energy power generation system; an inverter bridge composed of four IGBTs; a filter composed of \( L_1 \), \( C \), and \( L_2 \); \( U_b \) is the AC voltage output from the inverter; \( i_{L1} \) inverter bridge output current; \( i_{L2} \) inverter grid-connected current; \( U_i \) is the grid voltage.
3. The design of fractional order PI controller

3.1 A mathematical model based on traditional PI controller

Traditional PID control has been widely used in a large number of systems. Considering that the differential control D is very sensitive to the noise of the system, and it is easy to cause oscillation of the system control process and reduce the adjustment quality. Therefore, the PI controller is used in the LCL filtered grid-connected inverter.

Compared to the single closed-loop current control cell, the double closed-loop control strategy can effectively suppress the resonance. The block diagram of the grid-connected current double-loop control strategy of the inverter with LCL filter based on PI control is shown in Figure. 2. The closed-loop transfer function of the control system is obtained from Figure. 2:

$$\frac{i_L(s)}{i(s)} = \frac{K_{PWM}}{s^3L_1L_2C + s^2KL_2C + s(K_{PWM}L_2C)}$$

(3.1)

Fig 2. Block diagram of LCL-filtered grid-connected inverter

Based on current double loop control strategy

In the figure, Kp is the proportional gain and Ki is the integral gain. Kpwm is the equivalent gain of the inverter, and its size is the ratio of the input DC voltage to the carrier voltage amplitude.

3.2 The mathematical model based on traditional PI controller

The traditional PID control is widely used in the control system, and it has three control parameters: Kp, Kc, and Kd. Compared to conventional PID control, the fractional-order PID controller has two more adjustable parameters λ and μ. Since the λ and μ values are allowed to be scored, the fractional-order controller has more flexibility in controlling the controlled object in order to obtain a better control effect.

The fractional-order PID controller can also be abbreviated as PI^λ D^μ controller. Its transfer function is as follows:

$$G_c(s) = K_p + \frac{K_i}{s^\lambda} + K_ds^\mu, \quad \lambda, \mu > 0$$

(3.2)

If the amplitude margin A(m) and the phase margin φ(m) are known, the fractional-order controller of the controlled object can be designed to meet the performance requirements of the system. Note that the transfer function of the controlled object is Gp (s), and the transfer function of the controller is Gc (s), then the calculation formula of the amplitude margin and the phase margin is obtained:
\[
\varphi_m = \arctan\left[\frac{G_c(j\omega_c)G_p(j\omega_c)}{\omega_c^2 G_c(j\omega_c)G_p(j\omega_c)}\right] + \pi
\]

\[A_m = \frac{1}{\left|G_c(j\omega_c)G_p(j\omega_c)\right|}\]  

In the formulate, \(w_e\) is satisfied:

\[G_c(j\omega_c)G_p(j\omega_c) = 1\]  

While \(w_c\) is satisfied:

\[\arctan\left[\frac{G_c(j\omega_c)G_p(j\omega_c)}{\omega_c^2 G_c(j\omega_c)G_p(j\omega_c)}\right] = -\pi\]  

Substituting \(G_c(s)\) with Equation 4.1 gives the following relationships:

\[K_p + K_t \frac{\cos \frac{\pi \lambda}{\omega_c^2}}{\omega_c^2} + K_D \frac{\cos \frac{\pi \mu}{2 \omega_c^2}}{\omega_c^2} = R_{mc}\]  

\[K_p + K_t \frac{\cos \frac{\pi \lambda}{\omega_c^2}}{\omega_c^2} + K_D \frac{\cos \frac{\pi \mu}{2 \omega_c^2}}{\omega_c^2} = R_{mx}\]  

\[-K_t \frac{\sin \frac{\pi \lambda}{\omega_c^2}}{\omega_c^2} + K_D \sin \frac{\pi \mu}{2 \omega_c^2} = I_{mc}\]  

\[-K_t \frac{\sin \frac{\pi \lambda}{\omega_c^2}}{\omega_c^2} + K_D \sin \frac{\pi \mu}{2 \omega_c^2} = I_{mx}\]  

At the same time, \(w_c\) and \(w_e\) meet the following formula:

\[-\frac{1}{\omega_c^2 G_p(j\omega_c)} = R_{mc} + jI_{mc}\]  

\[-\frac{\cos \varphi_m - j\sin \varphi_m}{G_p(j\omega_c)} = R_{mx} + jI_{mx}\]  

Since the phase margin \(A(m)\) and the amplitude \(\varphi(m)\) margin are known, Equation (3.10) and (3.11) are actually four equations, thus there are 8 equations and 11 variables \((\omega_s, \omega_c, \lambda, \mu, K_P, K_I, K_D, R_{mc}, R_{mx}, I_{mc}, I_{mx})\), the other three parameters can be determined by minimizing the square of the difference:

\[J = \int_0^\infty e^2(t)dt\]  

The above formula can approximately figure out all the parameters of the controller\(^{[9]}\). However, the differential control \(D\) is sensitive to noise and causes oscillation of the system. In this system, only the fractional-order PI controller can be used for control.

4. Simulation

In order to compare the performance of LCL-filtered grid-connected inverters under traditional PI controllers and fractional-order controllers, the simulation verification comparisons were carried out in Matlab/simulink. The system parameters are: rated power \(P_n=10kW\), rated voltage \(V_n=220V\), DC voltage \(V_d=400V\), filter inductor \(L_1=3mH\), filter capacitor \(C=8uF\), filter inductor \(L_2=1.8mH\), switching frequency \(20Hz^{[9]}\).

4.1 Comparison of Tracking Performance

The traditional PI controller needs to adjust the two parameters of \(K_P\) and \(K_I\). For the proportional link, increasing the gain \(K_P\) of the controller can reduce the steady-state error of the system, thereby improving the control precision of the system and speeding up the effect speed, but at the same time reducing the relative stability of the system. For the integral link, the introduction of the integral link is beneficial to eliminate the steady-state error, but it will bring a large overshoot, the adjustment time becomes longer, and the stability of the system will be worse. Based on this, the parameters of the traditional PI controller are set to \(K_P=0.4\), \(K_I=82\). As for the parameters of the fractional PI controller, we figure out the \(K_P\) and \(K_I\) values\(^{[6]}\) and debug them in the vicinity, it obtains better control results when \(K_P=0.6\), \(K_I=43.7\), and \(\lambda=0.9\). The simulation results of the LCL filter grid-connected inverter based on the fractional-order PI controller are showed in Figure.3, and compared with the step response curve under the traditional PI control:

\[\begin{align*}
\varphi_m &= \arctan\left[\frac{G_c(j\omega_c)G_p(j\omega_c)}{\omega_c^2 G_c(j\omega_c)G_p(j\omega_c)}\right] + \pi \\
A_m &= \frac{1}{\left|G_c(j\omega_c)G_p(j\omega_c)\right|}
\end{align*}\]
In order to see the differences between them clearly, we compare the dynamic performance of the two controllers, including overshoot $\sigma\%$, rise time $tr$, peak time $tp$, and adjustment time $ts$. The results are shown in Table 1:

| Controller       | $\sigma\%$ | $tr$/ms | $tp$/ms | $ts$/ms |
|------------------|------------|---------|---------|---------|
| Traditional PI   | 32.0       | 32.189  | 48.715  | 102.252 |
| Fractional PI    | 1.2        | 22.800  | 25.397  | 72.509  |

From Table 1, we can clearly see that compared with the traditional PI control, the fractional-order PI control has the advantages of small overshoot and rapid response. The only shortcoming is that the adjustment time is relatively long, but the overall advantage outweighs the disadvantages.

Harmonics entering the network will affect the normal use of various electrical equipment under the power grid system, increase the harmonic losses, and reduce the efficiency of power transmission and power consumption. GB/T19935-2005 grid connection technical requirements clearly stated that the total harmonic distortion rate THD shall not exceed 5%, and the grid-connected current and the grid-connected voltage are required to be in the same direction and have the same frequency\(^{(8)}\). We compare the grid-connected current-grid voltage waveform and the total harmonic distortion rate of the two, and obtain the following simulation results in Figure 4 and Figure 5:

Both of them meet the requirements of grid-connected current and grid voltage in the same frequency and same direction. In addition, we need to analyze and compare the harmonic components, and get the following results from Figure 5 and Figure 6: The harmonic components of the grid-connected current based on the fractional-order PI control are significantly reduced, which is beneficial to the control of the incoming current harmonics in the grid-connected system.
4.2 Performance study of two controllers in practical applications

4.2.1 Performance comparison of systems under disturbance signals
Considering that LCL-type grid-connected inverters are mostly used for solar power generation, which are mostly built on an open area, easily affected by environmental factors such as lightning. Here, we will add a single pulse perturbation between the controller and the controlled object. The signal is used for simulation, and the performance difference of the LCL filtering grid-connected system based on the two controllers is compared. The following conclusions are obtained from the figure 8 and Fig. 9:

Comparing the above two figures, it can be seen that when the LCL-type grid-connected inverter circuit is subjected to pulse perturbation under fractional PI control, the overshoot is smaller than that of the conventional PI control, and the speed of restoring the stable state is faster than that of the conventional PI control. In general, the system with fractional PI as the control is less affected, more anti-interference, and more applicable in the field.
4.2.2 The impact of component performance changes on the system

Considering that the LCL filter grid-connected inverter circuit uses the system for a long time, the parameters of the inductance and capacitance may change, which causes the transfer function of the system to change. Since the system is outdoors, the influence of the humid environment causes the capacitor to be damp and the charge is not accumulated, so the capacitance value becomes larger when the voltage is constant. When the electricity feels the tide, it will lead to an increase in core loss and a decrease in the inductance. In this paper, it is assumed that the C capacitance value in the circuit increases by 10%, and the L1 and L2 inductance values decrease by 10%. The simulation results are shown in the Figure.11:

![Figure.10 Unit step response of the system when component parameters change](image)

It can be seen from the above simulation results that when the LCL-type grid-connected inverter is used in outdoor humid conditions, the change of component parameters has a greater impact on the traditional PI-controlled system, and the system output response overshoot is large, while the system under fractional-order PI control is less affected. In this regard, we can know that the fractional-order PI controller has better robustness and still has good performance after the LCL filter parameters changed.

5. Conclusion

In this paper, we research the LCL-filtered grid-connected inverter system. The performances based on traditional PI control and fractional-order PI control are compared in many aspects. The conclusions are as follows: When the fractional-order PI controller is used in the system, and the component parameters are changed, in the case of poor conditions, it still has better performance, stronger robustness and stronger anti-interference ability. Compared with the traditional PI controller, the fractional-order PI controller can adjust the fractional order $\lambda$ in addition to the adjustable $K_p$ and $K_i$. It can effectively improve the structure of the system and can be applied to the LCL-filtered grid-connected inverter system.

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