Advances in Engineering Research (AER), volume 131
3rd Annual International Conference on Electronics, Electrical Engineering and Information Science (EEEIS 2017)

Modeling and Control of Single-Phase LCL-type Grid-connected Inverter in Discrete Domain

Jing-Hua ZHOU[1,a], Qi-Hang WANG[2,b,*], Ya-Ai CHEN[3,c] and Xiao-Wei ZHANG[4,d]

[1,2,3,4]North China University of Technology, Shijingshan District, Beijing, China

[a]zjh@ncut.edu.cn, [b]597201580@qq.com, [c]cya@ncut.edu.cn, [d]zxw@ncut.edu.cn

*Qi-Hang WANG

Keywords: Discrete, Model, Stability, Control parameter.

Abstract. The power electronics control system can be designed in the discrete domain or continuous domain. In consideration of the digitally control and delay of actual system, it is more accurate to design the system control parameters in discrete domain. This paper firstly establishes the discrete domain model of the system, then analyzes stability of the system in the discrete domain, specifically designs the control parameters. After that verifies the correctness of the discrete domain design scheme through simulation in MATLAB. With relatively universal adaptability, the design process of control parameters researched in this paper provides reference for designing of the controller of the grid-connected inverter in discrete domain.

1 Introduction

As the interface of power electronic equipment and power grid, single phase grid-connected inverter is widely used and continuously concerned and researched in recent years. The digital signal processor is commonly used, as its performance is greatly improved. And it's easier to achieve complex algorithm. However, the introduction of sample & hold into the digital control will inevitably defer the control system to some extent. this will reduce stability margin of the system and worsen the control performance [1]. Therefore, it's very necessary to analyze the model and control algorithm of the system in the discrete domain.

Firstly, the paper establishes the mathematical model of discrete domain for the single phase LCL grid-connected inverter, and obtains the open-loop pulse transfer function of the system. Secondly, the text further analyzes stability of the system through Nyquist stability criterion, and designs the specific controller parameter of the system through the Bode diagram method. Finally, the text establishes the discrete domain simulation model in MATLAB, simulates by the controller parameter designed in the continuous domain and the discrete domain respectively in this model.The simulation result verifies the effectiveness of the design of the controller in discrete domain through contrastively analysis .

2 Discrete Domain Model

The circuit of the single phase LCL-filter grid-connected inverter is as shown in Figure 1.

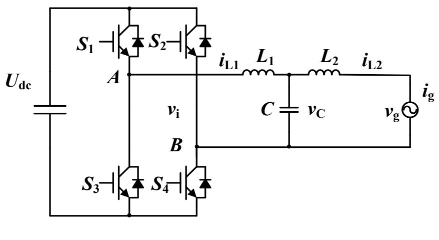
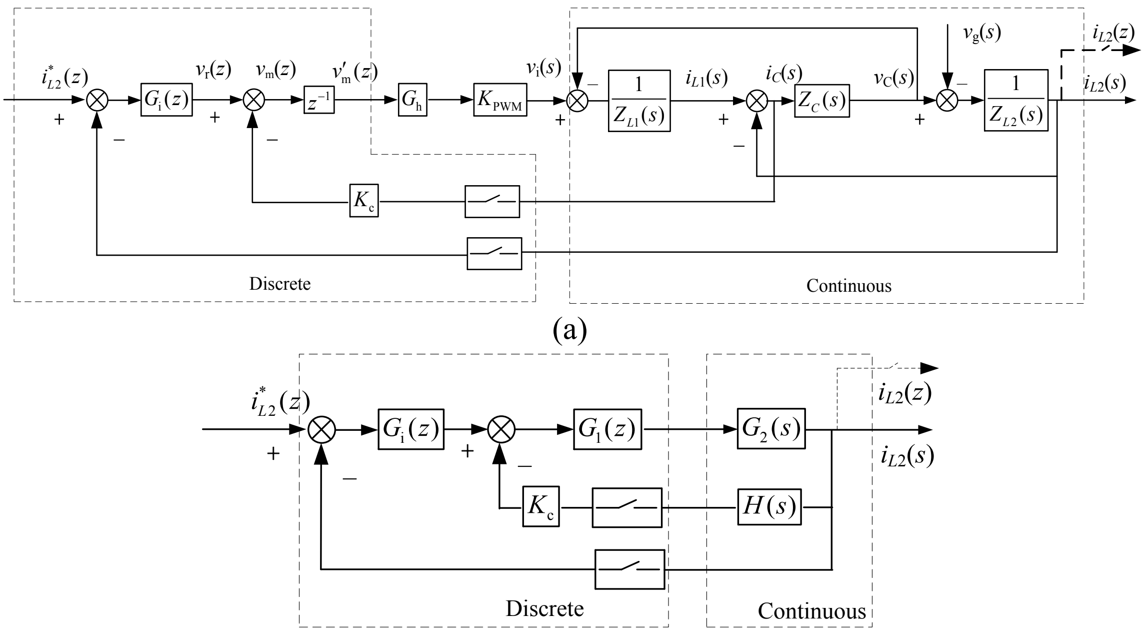


Figure 1 Circuit of Grid-connected Inverter

It shall firstly establish the discrete domain model of the system. Grid-connected inverter adopts dual current control scheme. The inner loop adopts capacitive current active damping[2] and the outer loop adopts grid-connected current control . $G_i(z)$ is the outer loop regulator. The system control block diagram is as shown in Figure 2(a).



(a)

(b)

Figure 2 System Control Block Diagram

In Figure 2(a), the system is composed of continuous part and discrete part. Digital control system is discrete system, and the controlled object is continuous system. The zero-order holder (G_h) transfers the digital pulse sequence into continuous signal. The sampling switch transfers continuous system into discrete system. The discrete domain model of the whole system can be established through z-domain transfer. In Figure 2, z^{-1} is one-beat computation delay of the digital controller to show the modulation characteristic of PWM.

The simplified Figure 2(b) can be obtained by Figure 2(a), then the open-loop pulse transfer function can be expressed as

$$G_o(z) = G_i(z)\frac{G_1(z)G_2(z)}{1+K_c G_1(z)G_2 H(z)} \tag{1}$$

Transfer the function of s-domain to z-domain and simplify the transfer function, it can get the open-loop pulse transfer function in z-domain as formula (2).

$$G_o(z) = \frac{G_i(z)K_{PWM}}{\omega_r(L_1+L_2)} \frac{\omega_r T_s(z^2-2z\cos\omega_r T_s+1)-(z-1)^2\sin\omega_r T_s}{(z-1)[z(z^2-2z\cos\omega_r T_s+1)+(z-1)\dfrac{K_c K_{PWM}}{\omega_r L_1}\sin\omega_r T_s]} \tag{2}$$

According to Nyquist criterion, the stability of the closed-loop system can be judged by analyzing the distribution of poles of open-loop transfer function. Therefore, it shall analyze stability of the discrete system and design the control parameter based on the open-loop transfer function formula (2).

3 Design of Controller Parameters

During analysis on the stability of the closed-loop system according to Nyquist stability criterion, it shall firstly know the number of open-loop right poles of the system. When quasi PR regulator is selected as the outer loop current regulator, it can be seen from formula (2) that the open-loop pulse transfer function of the system has 6 poles. Wherein, anti-frequency distortion bilinear transformation method [3] is adopted for z-domain transfer mode of quasi PR regulator. Characteristics of this transfer method: If the continuous system is stable, the discrete system is also stable. Therefore, it shall firstly analyze stability of active damping based on the discrete domain model of the system, and then design specific system control parameters through Bode diagram analysis method.

3.1 Analysis on the Stability of Active Damping

The system of 10kW grid-connected inverter is designed in the text.It can refer to literature [4] to design the parameter of LCL filter. The parameters of the inverter was listed in Table 1 .

Table 1 Circuit Parameters of System

L_1	C	L_2	f_{sw}	U_g	U_{dc}	f_0	K_{PWM}
0.4mH	8μF	0.15mH	10kHz	220V	360V	50Hz	1

It can be seen from formula (2) that the number of right poles of the open-loop pulse transfer function of the system will be determined by formula (3).

$$z(z^2-2z\cos\omega_r T_s+1)+(z-1)\frac{K_c K_{PWM}}{\omega_r L_1}\sin\omega_r T_s=0 \tag{3}$$

w transfer method can be used to transfer formula (3) from *z* domain to *w* domain.

$$a_0 w^3+a_1 w^2+a_2 w+a_3=0 \tag{4}$$

Various coefficients in formula (4) are shown in formula (5). Substitute parameters in Table 1 into formula (5), it can get the coefficient expression relevant to variable K_c of active damping.

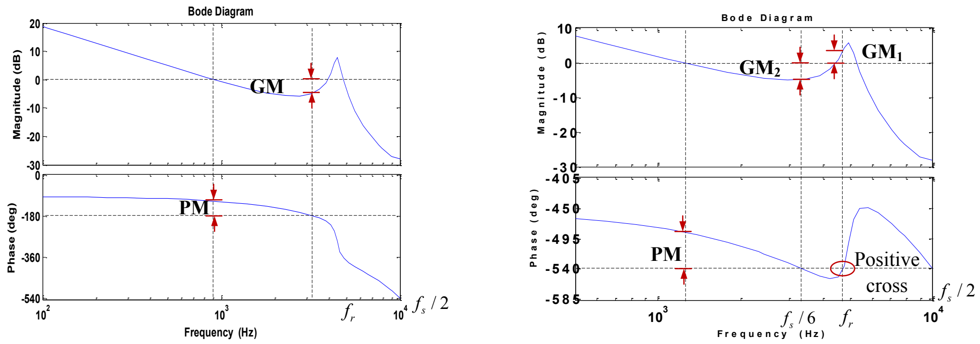
$$\begin{cases} a_0=1+\cos\omega_r T_s+\dfrac{K_c K_{PWM}}{\omega_r L_1}\sin\omega_r T_s \\ a_1=1+\cos\omega_r T_s-2\dfrac{K_c K_{PWM}}{\omega_r L_1}\sin\omega_r T_s \\ a_2=1-\cos\omega_r T_s+\dfrac{K_c K_{PWM}}{\omega_r L_1}\sin\omega_r T_s \\ a_3=1-\cos\omega_r T_s \end{cases} \Rightarrow \begin{cases} a_0=0.87+0.073K_c \\ a_1=0.87-0.146K_c \\ a_2=1.13+0.073K_c \\ a_3=1.13 \end{cases} \tag{5}$$

It can be analyzed that the number of right poles of the open-loop system through Routh method. When different values of active damping coefficient K_c are taken, symbols of the first-column coefficients of the Routh array are shown in Table 2.

Table 2 Routh Symbols

	l_0	l_1	l_2	l_3
$0<K_c<6.0$	+	+	-	+
$-11.9<K_c<0$	+	+	+	+

In consideration of high frequency oscillation of capacitive current, it shall value K_c near zero only, as it is easy to introduce high-frequency harmonic into the system due to too large feedback coefficient. From Table 2, when the active damping coefficient K_c is more than 0, the first column of the Routh Table has two times of sign change. As a result, the system has two open-loop right poles, and open loop of the system is unstable; when K_c is more than -11.9 but less than 0, there is no sign change in the first column of the Routh Table, the system has no open-loop right pole, and open loop of the system is stable. According to the Nyquist stability criterion, stability of the system can be analyzed through the Nyquist curves under the condition of knowing the number of open-loop right poles of the system. But it shall not limit the specific stability margin of the system.Therefore, it may analyze the stability and stability margin of the system in the Bode diagram[5]. Considering no outer-loop compensation measure (current regulator $G_i(z)$=1), draw the Bode diagrams with the different values of K_c.



(a) K_c <0 (b) K_c >0

Figure 3 Bode Diagram of Open Loop of Zero Current Regulator

From Figure 3(a), the system with predicted dynamic and static performance can be designed directly by limiting the magnitude margin and phase margin. From the analysis in Table 2, if K_c is more than 0, the open-loop transfer function has two right poles. Therefore, one time of positive cross in the open-loop Bode diagram of the system shall be designed as Figure 3(b). Stable system can also be designed by limiting the two amplitude margins and one phase margin.

3.2 Design of Control Parameters

Open-loop gain of the whole system meanwhile influences the high and low frequency characteristics of the system. Therefore, the current regulator and active damping control parameters shall be designed together. When quasi PR regulator is selected as the current regulator, anti-frequency distortion bilinear z-domain transfer is adopted to get the z-domain expression of PR regulator

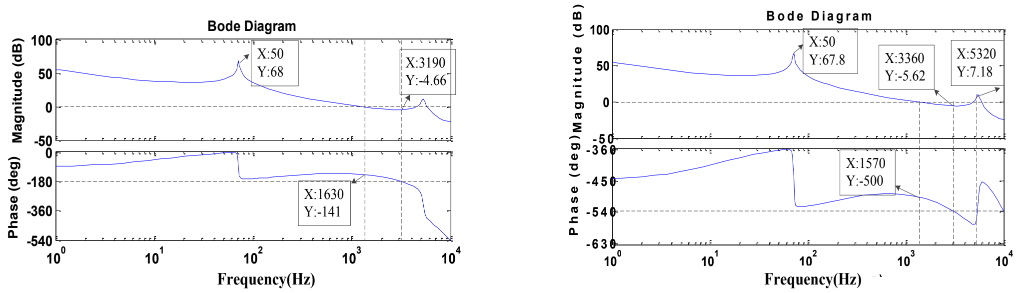
$$G_{\mathrm{PR}}(z)=\frac{\left[K_{\mathrm{p}}\omega_0+(K_{\mathrm{p}}+K_{\mathrm{r}})\omega_{\mathrm{c}}\sin\omega_0 T_s\right]z^2-\left(2K_{\mathrm{p}}\omega_0\cos\omega_0 T_s\right)z+K_{\mathrm{p}}\omega_0-(K_{\mathrm{p}}+K_{\mathrm{r}})\omega_{\mathrm{c}}\sin\omega_0 T_s}{\left(\omega_0+\omega_{\mathrm{c}}\sin\omega_0 T_s\right)z^2-\left(2\omega_0\cos\omega_0 T_s\right)z+\omega_0-\omega_{\mathrm{c}}\sin\omega_0 T_s} \tag{6}$$

It can get the complete open-loop transfer function of the discrete domain system by substituting the expression of the current regulator into formula (2). The magnitude margin can be calculated through the transfer function as well as the phase margin and fundamental frequency gain of the system. It is able to design the dynamic and static performance of the system through restricting magnitude margin and phase margin, and design the steady-state error of the system through restricting fundamental frequency gain. The control parameters designed in accordance with the actual circuit in this topic are as shown in Table 3.

Table 3 Control Parameters

K_p	K_c	K_r
4.15	±1	600

From the parameters shown in Table 3, The bode diagram of the open-loop transfer function of the system will be finalized. The simulation diagrams are as shown in Figure 4.



(a) K_c =−1 (b) K_c =1

Figure 4 Bode Diagram of Open-loop System

From Figure 4, all the amplitude margins are more than 3dB, and phase margins are more than 40°. These satisfy a stable system constraint condition. It is large enough for fundamental frequency gain (nearly 70dB) to guarantee the fundamental frequency signal tracking of the system.

4 Discrete Domain Simulation of the System

set up the discrete domain simulation model in MATLAB as shown in Figure 5.

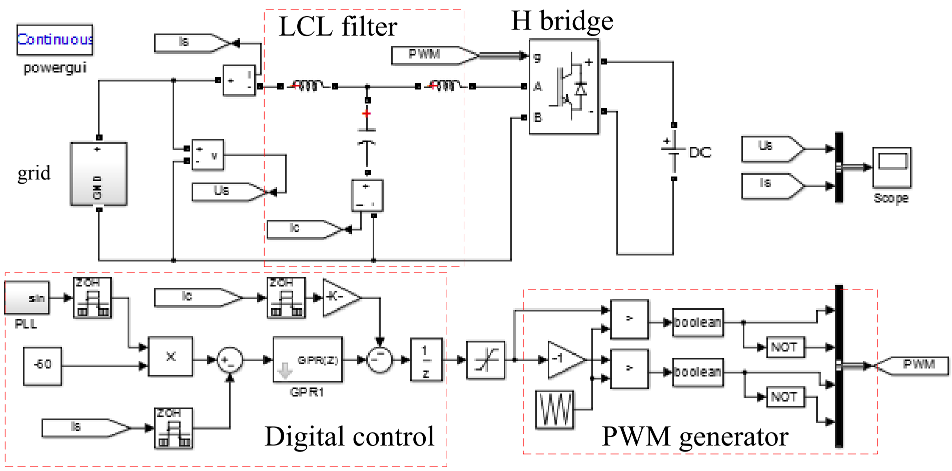


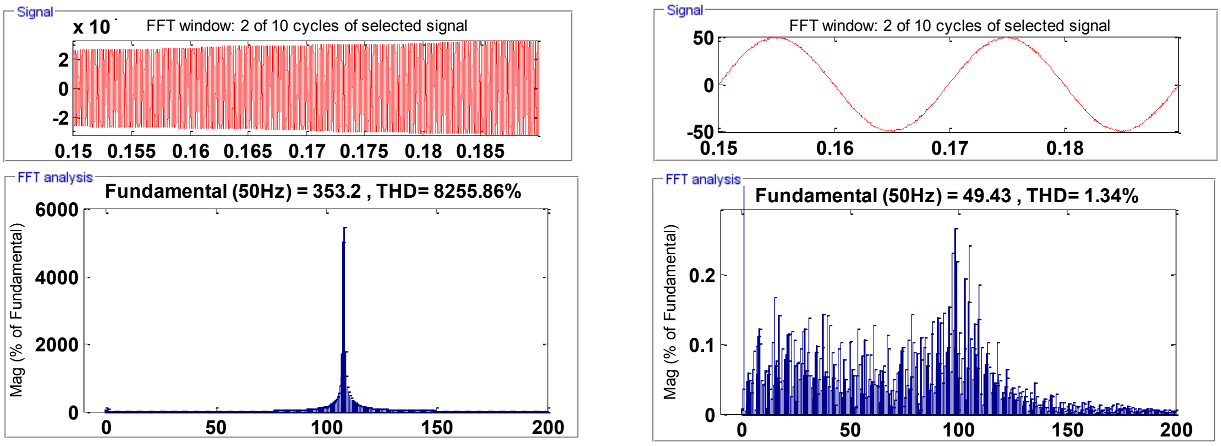
Figure 5 MATLAB Simulation Diagram of Discrete Domain of the System

Design control parameters of the system can be calculated in the continuous domain through the Bode diagram analysis method the same as the preceding part .They are shown in Table 4.

Table 4 Control Parameters of Continuous Domain

K_p	K_c	K_r
6.9	10	960

The continuous domain control parameters in Table 4 can achieve very good grid-connected current wave in the continuous domain simulate system. Substitute the control parameters in Table 3 and Table 4 respectively into the discrete domain simulation system in Figure 5, to get the grid-connected current wave in Figure 6. From FFT analysis of current waveform, when the control parameters designed in the continuous domain are used in the discrete domain, grid-connected current has a lot of resonant frequency waves, and the system is gradually diverged; and the system parameters designed in the discrete domain result in 1.34% THD of the grid-connected current, which is able to meet the requirements of grid connection of the system properly. Therefore, the control system parameters obtained in the continuous domain cannot be directly used in the actual control system, and the parameters should be re-designed in the discrete domain.



(a) continuous domain parameters (b) discrete domain parameters

Figure 6 FFT Analysis of Grid-connected Current

5 Conclusions

The text firstly builds the mathematical model of grid-connected inverter with LCL filter in discrete domain, and analyzes the stability of the control system. Based on the mathematical model, obtain the open-loop pulse transfer function of the system through reasonable equivalent simplification and z-transform mode. Then provide detailed steps of controller parameter design. The simulation results verify the feasibility of the designed parameters. The text have good engineering practicality and reference value.

References

[1] Zou C, Liu B, Duan S, et al. Influence of delay on system stability and delay optimization of grid-connected inverters with LCL filter[J]. IEEE Trans. on Industrial Electronics, 2014, 10(3):1775-1784.

[2] Xu Jinming, Xie Shaojun, Xiao Huafeng. Research on control mechanism of active damping for LCL filters[J]. Proceedings of the CSEE, 2012, 32(9):15-20.

[3] Yepes A G, Freijedo F D, Doval-Gandoy J, et al. Effects of Discretization Methods on the Performance of Resonant Controllers[J]. IEEE Transactions on Power Electronics, 2010,25(7):1692-1712.

[4] alili K, Bernet S. Design of LCL filters of active-front-end two-level voltage-source converters[J]. IEEE Trans. on Industrial Electronics, 2009, 56(5):1674-1689.

[5] Dannehl J, Wessels C, Fuchs F. Limitations of voltage-oriented PI current control of grid-connected PWM rectifiers with LCL filters[J]. IEEE Trans. On Industrial Electronics, 2009, 56(2):380-388.