

PAPER • OPEN ACCESS

## Grid-connected Inverter Control Strategy Based on Capacitor Voltage Error Inertia Feedback

To cite this article: Ning Xing *et al* 2020 *IOP Conf. Ser.: Earth Environ. Sci.* **558** 052072

View the [article online](#) for updates and enhancements.

You may also like

- [Research on Control Strategy of Z-source Photovoltaic Grid-connected Inverter Based on Sliding Mode Control](#)  
Yunhong Zheng, Qingquan Zhang and Xumin Huang
- [Vulnerability of high-speed rail grid-connected system on branch potential energy transfer entropy](#)  
Wen-Li Fan, Ye-Qi Xiao, Xiao-Feng He et al.
- [Control strategy of grid-connected inverter droop based on GMPPT method](#)  
Xuyang Zhang, Jun Teng, Pengqiao Zhang et al.



**ECS**  
The  
Electrochemical  
Society  
Advancing solid state &  
electrochemical science & technology

**DISCOVER**  
how sustainability  
intersects with  
electrochemistry & solid  
state science research

# Grid-connected Inverter Control Strategy Based on Capacitor Voltage Error Inertia Feedback

Ning Xing<sup>a</sup>, Hongquan Huang<sup>\*</sup>, Yanming Chen<sup>b</sup>

School of Electrical Engineering, Guangxi University, Nanning 530004, China

<sup>\*</sup>Corresponding author e-mail: hhq5839@163.com, <sup>a</sup>2207565363@qq.com,

<sup>b</sup>yanming.chen@126.com

**Abstract.** Firstly, the mathematical model of single-phase grid connected inverter is established. Then, the mathematical derivation is carried out according to the state space model, and the control strategy of grid-connected inverter based on capacitor voltage error inertia feedback is proposed. In this strategy, the first-order inertial feedback of capacitor voltage error is adopted to suppress the resonance peak of LCL filter, the feedforward of capacitor reference voltage is adopted to improve the tracking performance of the system, and the proportional feedforward of grid-connected voltage is used to suppress the harmonic of power grid. In addition, Simulation verifies the feasibility and effectiveness of the proposed control strategy.

## 1. Introduction

Renewable energy, represented by solar energy and wind energy, has become the focus of energy development in various countries due to its abundant reserves and no pollution. Renewable energy generates electricity through distributed generation system. The principle is to change renewable energy sources into direct current power through power generation equipment, then the grid-connected inverter is used to change direct current (DC) power to alternating current (AC) power and transmit it to the grid. Therefore, grid connected inverter is core device of whole distributed generation system. In order to enable the distributed generation system to deliver high quality current to the power grid stably and efficiently, a good control strategy is needed to control the grid-connected inverter. Therefore, it has very important meaning to study the strategy of grid-connected inverter.

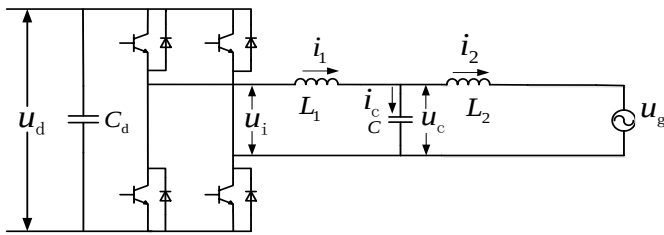
At present, for the sake of reducing high frequency harmonic components in the grid-connected current and obtain high-quality output current, LCL filter is usually selected to filter out harmonics[1]. However, LCL filter is a high-order system. Its high-order characteristics will make the system produce undamped resonance, and reduce the stability of the system. In addition, PI controllers[2]-[3] and PR controllers[4] are commonly used at present. However, PI control will have some tracking errors when tracking the AC signal, the AC signal can be converted to the DC signal through coordinate transformation to overcome the shortcoming that PI controller cannot track AC signal accurately. However, the application of this technology in single-phase inverter not only makes the controller design complex, but also reduces the transient performance of the system. Therefore, a new control strategy for grid-connected inverter based on capacitive voltage error inertial feedback is proposed. The proposed control strategy is not simply to use the filter capacitor voltage and inverter side current for direct feedback. Instead, the error of the filter capacitance current and its reference



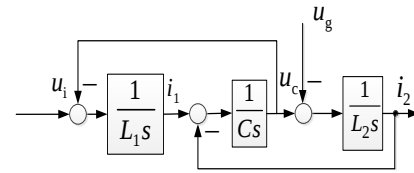
current is combined with the first order inertial controller as the inner loop feedback, and the error of the invert side current and its reference current is combined with the proportional controller as the feedback of the outer loop, through this to improve the robustness of the system. The proposed control strategy makes the grid-connected system have good grid-connected current quality, good tracking performance, good dynamic performance. At the same time, it has strong robustness to the fluctuation of grid voltage.

## 2. Mathematical Derivation of the Control Strategy

Figure1 is structure diagram of grid-connected inverter. Because the parasitic resistances of the inductor and capacitor is beneficial to the stability of system, and these resistances are relatively small. Therefore, in order to simulate the worst operating conditions of the system, the parasitic resistance of capacitance and inductance was ignored in this study[5].



**Figure 1.**structure diagram of inverter



**Figure 2.**Control diagram of LCL

$C_d$  is the DC-side capacitor,  $L_1$  is the inverter-side inductor,  $i_1$  is the inverte-side current,  $i_c$  is the capacitor current,  $C$  is the filter capacitor,  $L_2$  is the grid-side inductor,  $u_g$  is the grid voltage,  $u_d$  is the DC-side voltage,  $u_c$  is the capacitor voltage,  $u_i$  is output voltage of inverter,  $i_2$  is the grid-connected current.

According to figure 1, the LCL model structure figure 2 can be obtained. According to figure 2, the transfer function expression from  $u_i$  to  $i_2$  in the LCL control diagram can be geted as follows:

$$\frac{I_2(s)}{U_i(s)} = \frac{1}{L_1 L_2 C s^3 + (L_1 + L_2)s} \quad (1)$$

According to figure 1, the differential equation of the inverter can be written as equation (2).

$$\begin{cases} \frac{di_1}{dt} = \frac{1}{L_1} u_i - \frac{1}{L_1} u_c \\ \frac{du_c}{dt} = \frac{i_c}{C} \\ \frac{di_2}{dt} = \frac{u_c}{L_2} - \frac{u_g}{L_2} \end{cases} \quad (2)$$

Where  $u_i = \lambda u_d$ ,  $\lambda$  is the switch function,  $u_i$  is the control input of the inverter.

In this control strategy, the error of the filter capacitance current and its reference current is combined with the first order inertial controller as the inner loop feedback, and the error of the invert side current and its reference current is combined with the proportional controller as the feedback of the outer loop. So, define the state variables as (3).

$$x_1 = i_1 - i_{1r}, \quad x_2 = u_c - u_{cr} \quad (3)$$

Where  $i_{1r}$  are the reference current of  $i_1$ , and  $u_{cr}$  is the reference voltage of  $u_c$ . Making use of equation (3) can be get(4).

$$\dot{x}_1 = \dot{i}_1 - \dot{i}_{1r} = \dot{i}_1 - \dot{i}_{cr} - \dot{i}_{2r} \quad (4)$$

Substitute the first formula in (2) into (4) to get(5).

$$\dot{x}_1 = \frac{1}{L_1}u_i - \frac{1}{L_1}u_c - \dot{i}_{cr} - \dot{i}_{2r} \quad (5)$$

Making use of  $u_c = x_2 + u_{cr}$ , equation (5) can be written as equation (6).

$$\dot{x}_1 = \frac{1}{L_1}u_i - \frac{1}{L_1}x_2 - \frac{1}{L_1}u_{cr} - \dot{i}_{2r} - \dot{i}_{cr} \quad (6)$$

In order to minimize the error energy of the system, we only need to set the right side of equation (6) as 0, so it can get the following.

$$u_i = x_2 + u_{cr} + L_1\dot{i}_{2r} + L_1\dot{i}_{cr} \quad (7)$$

By introducing the intermediate input variable  $u_{i1}$  into equation (7), equation (7) can be written as equation (8).

$$u_i = u_{i1} + u_{cr} + L_1\dot{i}_{2r} + L_1\dot{i}_{cr} \quad (8)$$

In order to accelerate  $x_1$  convergence,  $u_{i1}$  introduces the state feedback gain  $k_1$ ,  $u_{i1}$  can be written as equation (9).

$$u_{i1} = u_{i2} - k_1x_1 \quad (9)$$

$u_{i2}$  introduces the state feedback gain  $k_2$ ,  $u_{i2}$  can be written as equation (10).

$$u_{i2} = -k_2x_2 \quad (10)$$

Substitute equation(10) and (9) into (8), we can get (11).

$$u_i = -k_1x_1 - k_2x_2 + u_{cr} + L_1\dot{i}_{2r} + L_1\dot{i}_{cr} \quad (11)$$

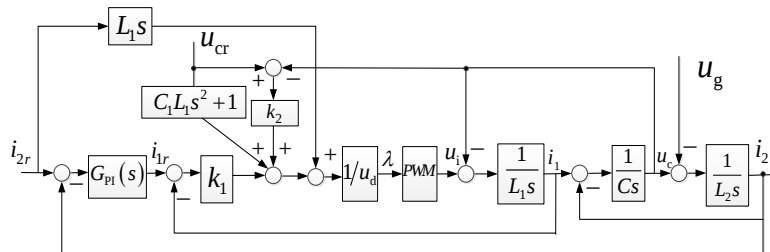
Then, making use of  $i_{cr} = C(du_{cr}/dt)$  and  $u_i = \lambda u_d$ , the control duty cycle can be obtained as (12).

$$\lambda = \frac{1}{u_d} \left[ -k_1x_1 - k_2x_2 + u_{cr} + L_1C \frac{d^2u_{cr}}{dt^2} + L_1 \frac{di_{2r}}{dt} \right] \quad (12)$$

In this design, PI controller is used to generate the reference current  $i_{1r}$  of current  $i_1$ . The transfer function of PI is shown in (13).

$$G_{PI}(s) = k_p + k_i / s \quad (13)$$

According to formula (12), the control structure diagram 3 of the system can be obtained.



**Figure 3.** Control structure of grid-connected system

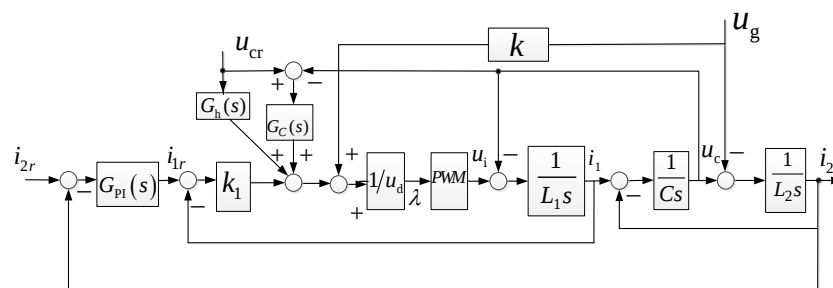
It can be known from Figure.3 that the second order differential is contained in the capacitor reference voltage feedforward control. In practical engineering applications, the differential link is easier to introduce noise[6]. In this study, low-pass filter  $1/(\tau s + 1)$  is introduced into the capacitor reference voltage feedforward in order to suppress noise, where  $\tau$  is time constant. Moreover, due to the large number of harmonics in the power grid, they will be harmful to the quality of grid-connected current, and feedforward of grid-connected voltage is widely used due to the good effect of suppressing the harmonics. Therefore, this paper adopts grid-connected voltage proportional feedforward to suppress power grid harmonics. At the same time, in order to suppress the resonance of LCL filter, the first-order inertia link  $1/(\tau s + 1)$  is introduced into the capacitor voltage error feedback[7].

So, the improved grid-connected inverter system control duty cycle can be written as equation (14).

$$\lambda = \frac{1}{u_d} \left[ -k_1 x_1 - k_2 \tau^{-1} e^{-t/\tau} x_2 + \tau^{-1} e^{-t/\tau} (u_{cr} + L_1 C \frac{d^2 u_{cr}}{dt^2}) + k u_g \right] \quad (14)$$

Where  $\tau^{-1}e^{-t/\tau}$  is the inverse Laplace transform of  $1/(\tau s+1)$ .

According to formula (14), the improved control structure diagram 4 of the system can be obtained.



**Figure 4.** improved control structure of the grid-connected system

Where  $u_{cr}=L_2s i_{2r}+u_g$ , PWM is the inverter link,  $G_h(s)=\frac{1}{\tau s+1}$ ,  $G_c(s)=k_2\frac{1}{\tau s+1}$ .

It is obvious that the system control structure in figure 4 is mainly composed of five controllers .

1)  $ku_g$  is the grid-connected voltage proportional feedforward controller, which can suppress the influence of harmonics on the system.

2)  $[1/(\tau s+1)](CL_1s^2+1)u_{cr}$  is the capacitor reference voltage feedforward controller. It can reduce the phase difference between  $i_2$  and  $u_g$ , improve the tracking performance of the system.

3)  $k_2[1/(\tau s+1)]x_2$  is the first-order inertial feedback controller of capacitance voltage error, which can provide some active damping for the system, and can suppress the resonance peak of LCL filter.

4)  $k_1x_1$  is the traditional P controller.

5)  $G_{PI}(s)(i_{2r}-i_2)$  is the PI controller to generate reference current of inverter side, which can improve the performance of system.

### 3. The influence of inertial feedback on system resonance

By substituting equation (14) into equation (2), and then carrying out Laplace transform and simplification, the closed-loop transfer function between  $i_2$  and its reference current  $i_{2r}$  of the system can be obtained as (15).

$$\frac{I_2}{I_{2r}} = \frac{A_4s^4 + A_2s^2 + A_1s + A_0}{B_5s^5 + B_4s^4 + B_3s^3 + B_2s^2 + B_1s + B_0} \quad (15)$$

$$B_5=L_2L_1C\tau, B_4=L_2(L_1C+k_1C\tau), B_3=L_1\tau+k_1CL_2+\tau L_2, B_2=k_1\tau+L_1+k_1\tau k_p+k_2L_2+L_2,$$

$$B_1=k_1+k_1k_p+k_1k_1\tau, B_0=k_1k_i, A_4=L_1CL_2, A_2=k_1\tau k_p+k_2L_2+L_2, A_1=k_1k_p+k_1\tau k_i, A_0=k_1k_i$$

Then, the open-loop transfer function (16) of system can be obtained.

$$G_1 = \frac{I_2(s)}{I_{2r}(s) - I_2(s)} = \frac{A_4s^4 + A_2s^2 + A_1s + A_0}{C_5s^5 + C_4s^4 + C_3s^3 + C_2s^2 + C_1s + C_0} \quad (16)$$

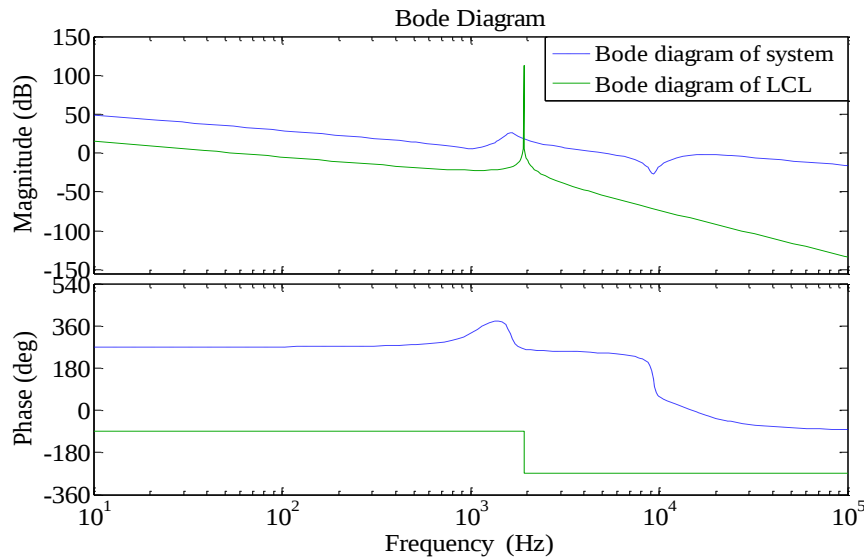
$$\text{Where } C_5=B_5, C_4=B_4-A_4, C_3=B_3, C_2=B_2-A_2, C_1=B_1-A_1, C_0=B_0-A_0.$$

According to equations (1) and (16), the bode diagram of transfer function from  $u_i$  to  $i_2$  in LCL model and the bode diagram of the system's open-loop can be drawn respectively, this is shown in Figure 5. As can be seen from the figure, the bode diagram curve of LCL model has a resonance peak. However, the bode diagram curve of the system designed has no obvious resonance peak.

### 4. Simulation and result analysis

In order to make further verify the effectiveness and feasibility of the control strategy proposed in this paper, simulink is used for simulation[8]. The simulation model is built in Simulink according to the

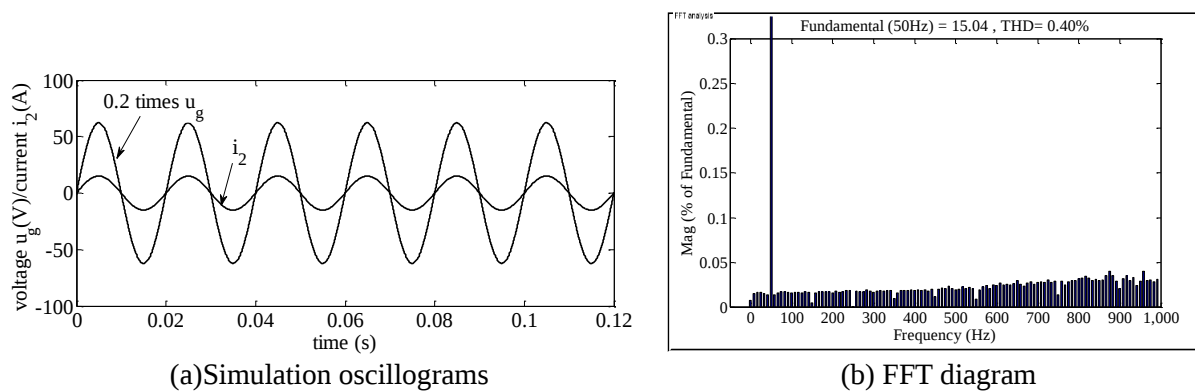
Figure 4. The simulation results are shown in Figure 6-9. Set the given value of grid-connected current as  $i_{2r}=15\sin(\omega t)$ , the effective value of grid voltage is 220V. In order to ensure a good visual effect and facilitate observation, the grid-connected voltage is reduced to its 0.2 times before entering the oscilloscope. The parameters as: fundamental frequency  $f_0=50\text{Hz}$ , switching frequency  $f_{sw}=20000\text{Hz}$ ,  $u_d=400\text{V}$ ,  $L_1=2\text{mH}$ ,  $C=12\mu\text{F}$ ,  $L_2=0.8\text{mH}$ ,  $k_1=170$ ,  $k_2=80$ ,  $k=1$ ,  $k_i=18000$ ,  $k_p=1$ ,  $\omega=314\text{rad/s}$ ,  $\tau=0.01\text{ms}$



**Figure 5.** Bode diagram of transfer function of LCL model and

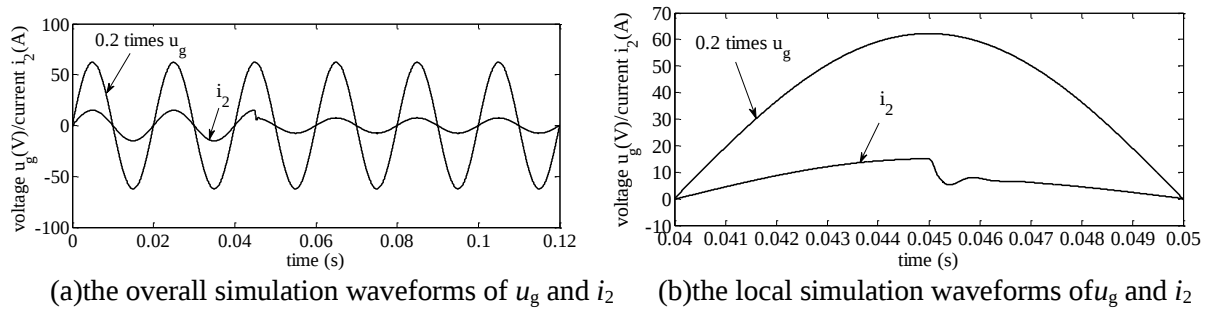
open-loop transfer function of grid connected system

Figure 6 shows the simulation oscillograms of the grid-connection voltage  $u_g$  and grid-connected current  $i_2$  and the fast Fourier transform(FFT) analysis diagram of grid-connected current  $i_2$  for the system. In figure 6, the simulation waveforms of  $u_g$  and  $i_2$  are all relatively smooth sinusoidal waveforms. The total harmonic distortion rate (THD) of  $i_2$  is only 0.40%, which is far less than the international standard 5%. The simulation peak value of grid-connected current  $i_2$  is about 15.05, almost equal to the given value 15. According to the simulation in figure 6, the proposed control strategy enables the system to have good grid-connected current quality and good tracking performance.



**Figure 6.** The simulation oscillograms of  $u_g$  and  $i_2$  for the system

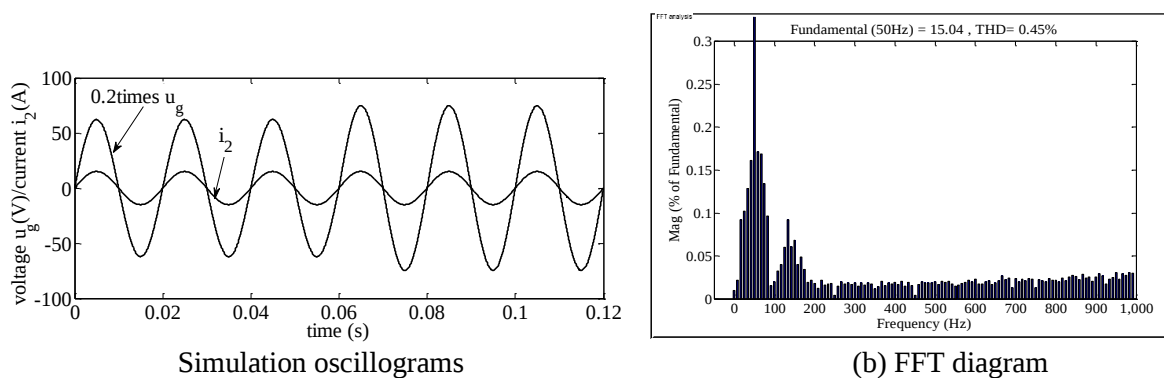
Figure 7 is simulation oscillograms of  $u_g$  and  $i_2$  for the system with sudden change of reference current setting value. Where, (a) is the overall simulation oscillograms of  $u_g$  and  $i_2$  of the reference current given value mutation, and (b) is the local simulation oscillograms of  $u_g$  and  $i_2$  of the reference current given value mutation. That can know from (a), when reference current  $i_{2r}$  decreases from 15A to 7.5A at  $t=0.045s$ , the simulation curves of  $u_g$  and  $i_2$  can track the change of reference current  $i_{2r}$ . As can be seen from figure (b), When the grid-connected reference current  $i_{2r}$  changes, the grid-connected current quickly tracks the reference current after experiencing a short fluctuation of 0.7ms. The above analysis shows that the system has better dynamic performance.



**Figure 7.** the simulation waveforms of  $u_g$  and  $i_2$  with sudden

change of reference current setting value.

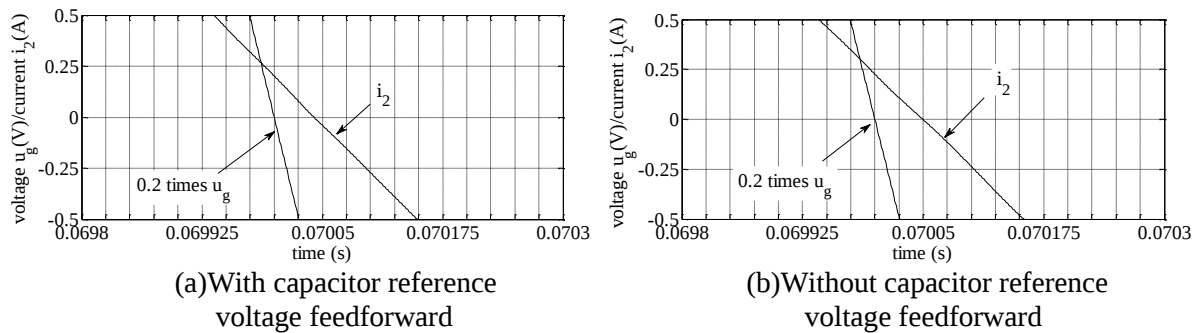
Figure 8 is simulation oscillograms of  $u_g$  and  $i_2$  and FFT diagram of  $i_2$  for the system when the grid voltage surges. Where (a) is the simulation oscillogram and (b) is the FFT diagram. That can know from (a), the grid voltage increases by 20% at  $t=0.06s$ , that is, it increases from the original 311V to 373.2V, the grid-connected current can remain stable. In addition, that can know from (b) that the THD of the system is 0.45% when the grid voltage is increased by 20%, which is far less than the international standard of 5%. These show that the system has strong robustness to the fluctuation of power grid voltage.



**Figure 8.**the simulation oscillograms of  $u_g$  and  $i_2$  and FFT diagram of  $i_2$

When the grid voltage increases by 20%

Figure 9 show that the simulation oscillograms of  $u_g$  and  $i_2$  of the system under with and without capacitor reference voltage feedforward, respectively. As can be seen from Fig 9, the phase difference of  $u_g$  and  $i_2$  with capacitor reference voltage feedforward is smaller than that of  $u_g$  and  $i_2$  without capacitor reference voltage feedforward. This shows that the capacitor reference voltage feedforward is helpful to improve the tracking accuracy of the system. The grid power of system connection is improved.



**Figure9** the simulation oscillograms of  $u_g$  and  $i_2$  of the system

## 5. Conclusion

The mathematical derivation is carried out accord to the state space model of the system the control strategy of grid-connected inverter based on capacitance voltage error inertia feedback is obtained. The control strategy consists of five controllers, which respectively the first-order inertial feedback controller of capacitor voltage error to suppress resonance, and the capacitor reference voltage feedforward controller to improve the tracking performance of the system, and the grid-connected voltage proportional feedforward controller to suppress the influence of grid harmonics on the system, and the PI controller to generate reference current of inverter-side current, and the traditional P controller. Simulation results show that the proposed control strategy makes the grid-connected system have good grid-connected current quality, good tracking performance, good dynamic performance. At the same time, it has strong robustness to the fluctuation of grid voltage.

## Acknowledgments

This work was financially supported by National Natural Science Foundation of China (51567004).

## References

- [1] Wang Ying, Zhou Leming. Optimized Design Method of Grid Current Feedback Active Damping for LCL-type Grid-connected Inverter [J]. Proceedings of the CSU-EPSCA, 2017,29 (10):130-137.
- [2] Wang Jibiao, Chen Qihong, Zhang Liyan, Zhou Keliang. Internal Model Principle Based Dual-Mode PI Control for Grid-Tied Inverters [J]. Transactions of China Electrotechnical Society, 2018, 33 (23): 5484-5495.
- [3] Wang Yifei, Zhu Jing, LI Xia, Wei Quan. Composite Control Scheme of Grid-connecting Converter Based on PI and Repetitive Controllers [J]. High Voltage Apparatus, 2015, 51 (07):87-91.
- [4] X.Wang, P.C.Loh, F.Blaabjerg. Stability Analysis and Controller Synthesis for Single-Loop Voltage-Controlled VSIs, IEEE Trans[J]. Power Electron, 2017, 32 (2):7394-7404.
- [5] Zhang Linfeng. Application of The passivity-based control Theory in LCL-type Grid-Connected Inverter [D]. Guangxi University, 2019.
- [6] Zhang Benben. Research on Control Methods of Grid Connected Inverter Based on LCL filter in Distrubuted Energy System [D]. Zhejiang University of Technology, 2017.
- [7] Gao Xuanjie, Miao Hong, Zeng Chengbi. Xiong Zhengyong. Impedance phase angle compensation control for improving stability of photovoltaic grid-connected inverter in weak grid[J]. Electrical Measurement & Instrumentation, 2019, 56 (22):1-6.
- [8] Li Ming, Zhang Xing, Yang Ying, Zhao Wenguang. Grid Voltage Feedforward Control Strategy Based on Weighting Coefficient in Weak Grid [J]. Journal of Power Supply 2017, 15 (06): 10-18.