OPAL-RT Tutorial

DCE&S, TU Delft

Grid-following & Grid-forming Control of the Voltage Source Converter

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Introduction:

As the core component, the grid-connected voltage source converter plays a crucial role in the stable operation of the renewable energy generation system. At present, the control strategy of the grid-connected converter typically includes grid-following (GFL) control and grid-forming (GFM) control. The traditional control strategy of converter is GFL control, which measures the phase of the point of common coupling (PCC) with the help of the phase-locked loop (PLL), and controls the output power by adjusting the output current. However, under the condition of weak grid, the converter controlled by the GFL control is prone to the problem of oscillation instability.

Compared with GFL control, the GFM control strategy has better stability margin under weak grid conditions. The common GFM control strategy mainly includes droop control and virtual synchronous generator (VSG) control, which take the active power as the control target.

In this tutorial, we will try to understand the basics of PLL and droop control for the grid-connected voltage source converter. Real-time digital simulations using OPAL-RT (with RT-LAB environment) are used to validate the control schemes. At the end of this tutorial, you should be able to:

- Understand the basics of grid-following & grid-forming control of the voltage source converter
- Develop the simulation model for grid-following & grid-forming control

In order to follow the tutorial, you should

- Be able to do basic real time simulations in OPAL-RT
- Have the basic knowledge of Clark transform and Park transform

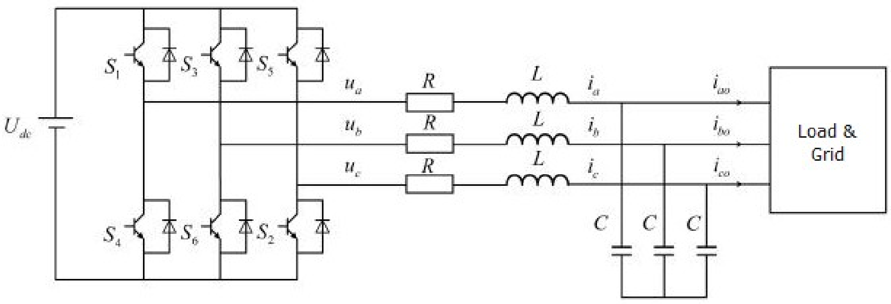
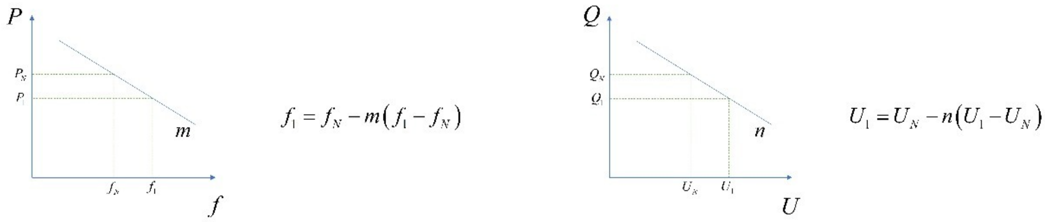


Fig. 1: The grid-connected voltage source converter

Overview of Test System:

- **Droop control**

The grid-forming control actively provide the reference of voltage magnitude and phase angle. Take the droop control strategy as instance, the grid-forming control can be applied in the grid-connected voltage source converter (750 V) configuration as shown in Fig. 1.



(a) (b)

Fig. 2 (a) Frequency characteristic and (b) voltage characteristic

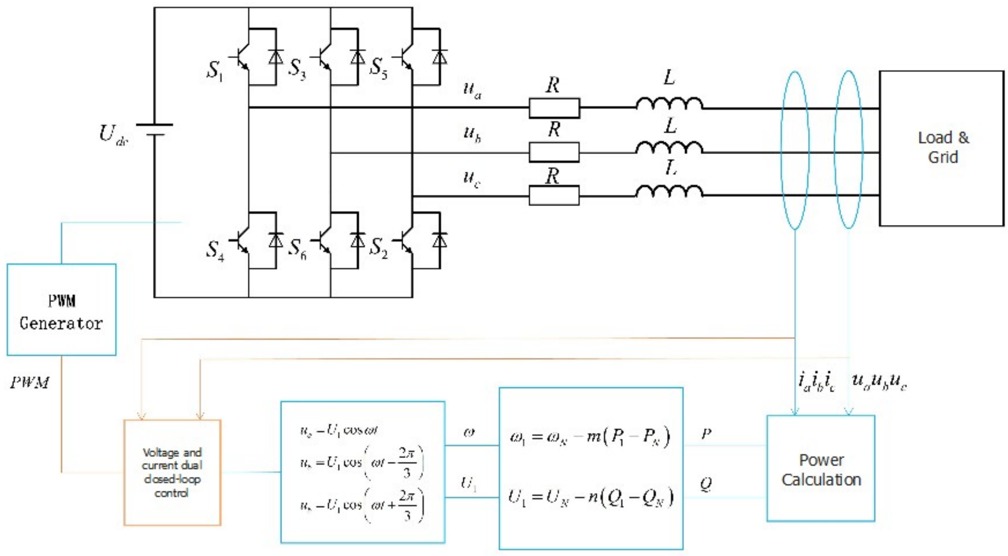


Fig. 3 Grid-forming control

Based on the operating characteristics of the generator as shown in Fig. 2, we know that the frequency varies with the output active power; the voltage varies with the output reactive power. Therefore, the output frequency f and voltage of the inverter U can be regulated based on the measured active power and reactive power, and the inverter is able to emulate the operation state of synchronous generator.

By calculating f and U, we can obtain the reference signal of voltage. In order to achieve the given output value of the inverter, the voltage and current dual closed-loop control is adopted.

With regard to the power calculation, we adopt the instantaneous power of three-phase symmetrical circuits under equal amplitude transformation conditions.

$$P = \frac{3}{2}\left(u_d i_d + u_q i_q\right)$$

$$Q = \frac{3}{2}\left(u_q i_d - u_d i_q\right)$$

- **Phase lock loop**

In the grid-following control, the voltage phase angle should be tracked through the PLL, which is not obtained from the active power. This is the most significant difference between the grid-following control and the grid-forming control.

The basic control block of PLL can be illustrated as follows:

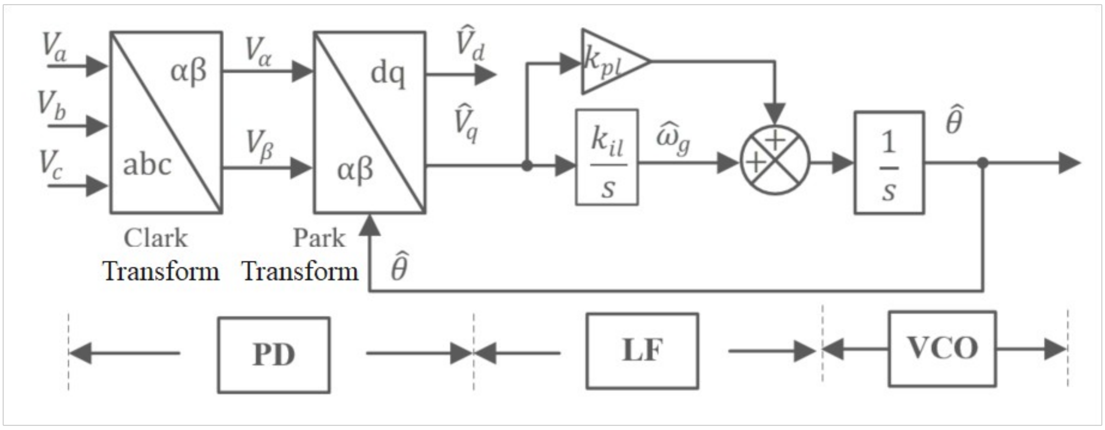


Fig. 4 The basic control block of PLL

Based on the output voltage phase angle, we can convert the abc components of grid voltage into the d-q components. The successful tracking can be described by the 0 q-component, hence the PLL can be easily achieved by using a simple PI control strategy.

Inverter modelling for voltage and current dual closed-loop control:

- **Inner current loop**

By adjusting the output voltage of inverter, the current flowing through the RL branch can be controlled. Take the phase A as instance, the equations for the RL branch voltage and current (taking the neutral point of the power grid as the reference ground) can be written as follows:

$$u_a = Ri_a + L\frac{di_a}{dt} + e_a$$

To model a three-phase grid connected inverter, the equations of voltage and current in matrix form can be written as follows:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = R\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}$$

According to the principle of coordinate transformation, the matrix equation can be written in the d-q rotating coordinate as follows:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = R\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 & -\omega L \\ \omega L & 0 \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + L\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} e_d \\ e_q \end{bmatrix}$$

$$u_d = Ri_d - \omega L i_q + L\frac{di_d}{dt} + e_d$$

$$u_q = Ri_q + \omega L i_d + L\frac{di_q}{dt} + e_q$$

Convert the equations from the time domain to the Laplace domain

$$\begin{cases} u_d = Ri_d - \omega L i_q + sLi_d + e_d \\ u_q = Ri_q + \omega L i_d + sLi_q + e_q \end{cases}$$

Then we can obtain the relationship between the input and the output

$$\begin{cases} i_d = \dfrac{1}{R+sL}\left(u_d - e_d + \omega L i_q\right) \\ i_q = \dfrac{1}{R+sL}\left(u_q - e_q - \omega L i_d\right) \end{cases} \tag{1}$$

The system structure diagram can be drawn as follows:

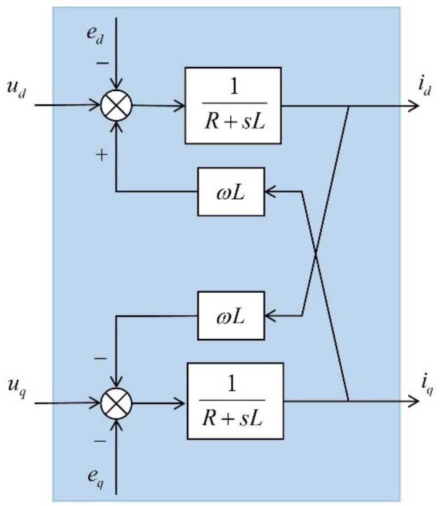


Fig. 5 Mathematical model of the RL system

It is evident that the d-axis current and the q-axis current are coupled with each other. Therefore, the model needs to be modified as

$$\begin{cases} u_d = u_{id} - \omega L i_q + e_d \\ u_q = u_{iq} + \omega L i_d + e_q \end{cases} \tag{2}$$

Combing Eqs. (1) and (2), we can obtain

$$\begin{cases} i_d = \dfrac{1}{R+sL} u_{id} \\ i_q = \dfrac{1}{R+sL} u_{iq} \end{cases}$$

Hence the coupling terms and the grid voltage can be cancelled out. u_{id} and u_{iq} can control i_d and i_q. The system structure diagram can be drawn as follows:

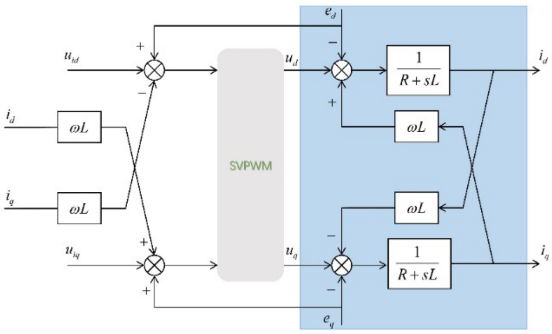
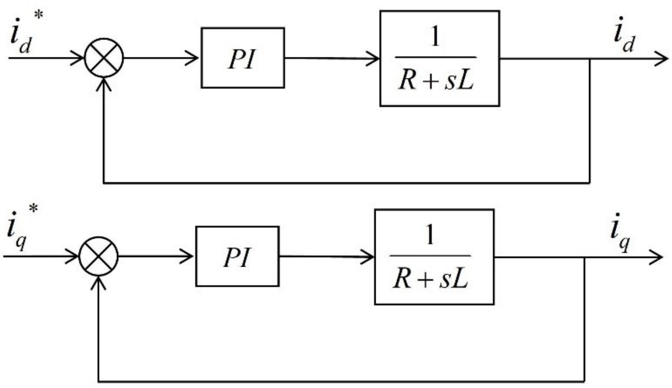


Fig. 6 RL System decoupling control

Add current feedback and PI control, we obtain

$$\begin{cases} u_{id} = \left(k_{pi} + \dfrac{k_{ii}}{s}\right)\left(i_d^* - i_d\right) \\ u_{iq} = \left(k_{pi} + \dfrac{k_{ii}}{s}\right)\left(i_q^* - i_q\right) \end{cases}$$



According to the transfer function given above, the inverter outputs include terms which can cancel out the coupling terms, terms which can cancel out the grid voltage, and a quantity that can control i_d and i_q independently.

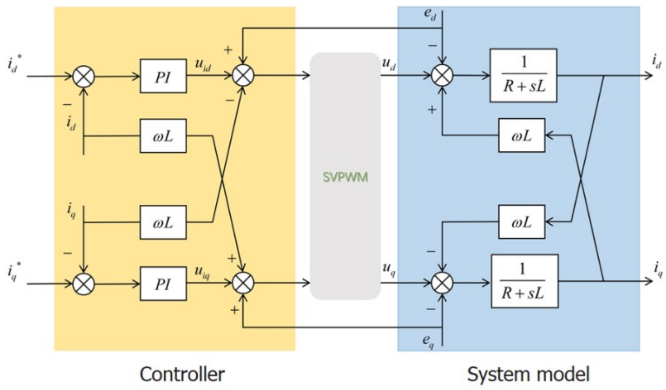


Fig. 7 Inner current loop

- **Outer voltage loop**

With regard to the filter circuit, we need to model it can analyse its control principle of outer voltage loop. Take phase A as instance, the equation of filter circuit can be written as

$$i_a = C\frac{du_{ao}}{dt} + i_{ao}$$

To model a three-phase grid connected inverter, the equations of voltage and current in matrix form can be written as follows:

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = C\frac{d}{dt}\begin{bmatrix} u_{ao} \\ u_{bo} \\ u_{co} \end{bmatrix} + \begin{bmatrix} i_{ao} \\ i_{bo} \\ i_{co} \end{bmatrix}$$

According to the principle of coordinate transformation, the matrix equation can be written in the d-q rotating coordinate as follows:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} 0 & -\omega C \\ \omega C & 0 \end{bmatrix}\begin{bmatrix} u_{od} \\ u_{oq} \end{bmatrix} + C\frac{d}{dt}\begin{bmatrix} u_{od} \\ u_{oq} \end{bmatrix} + \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix}$$

$$i_d = -\omega C u_{oq} + C\frac{du_{od}}{dt} + i_{od}$$

$$i_q = \omega C u_{od} + C\frac{du_{oq}}{dt} + i_{oq}$$

Convert the equations from the time domain to the Laplace domain

$$\begin{cases} i_d = -\omega C u_{oq} + sCu_{od} + i_{od} \\ i_q = \omega C u_{od} + sCu_{oq} + i_{oq} \end{cases}$$
$$\downarrow$$
$$\begin{cases} u_{od} = \frac{1}{sC}\left(i_d - i_{od} + \omega C u_{oq}\right) \\ u_{oq} = \frac{1}{sC}\left(i_q - i_{oq} - \omega C u_{od}\right) \end{cases}$$

It is noteworthy that the currents are inputs which determine the variation of capacitive voltage and the voltages are outputs.

The system structure diagram can be drawn as follows:

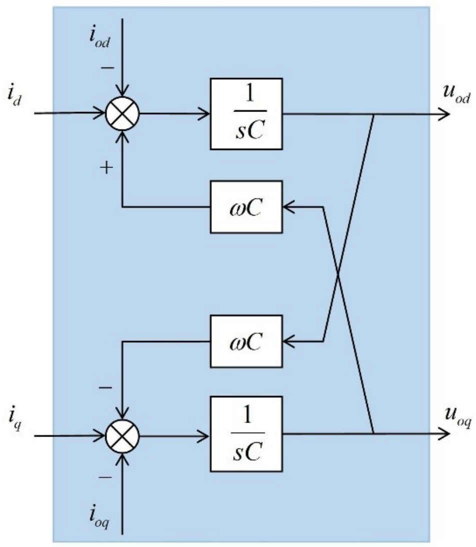


Fig. 8 Mathematical model of the C branch

In order to cancel out the coupling terms, the system structure diagram can be modified as follows:

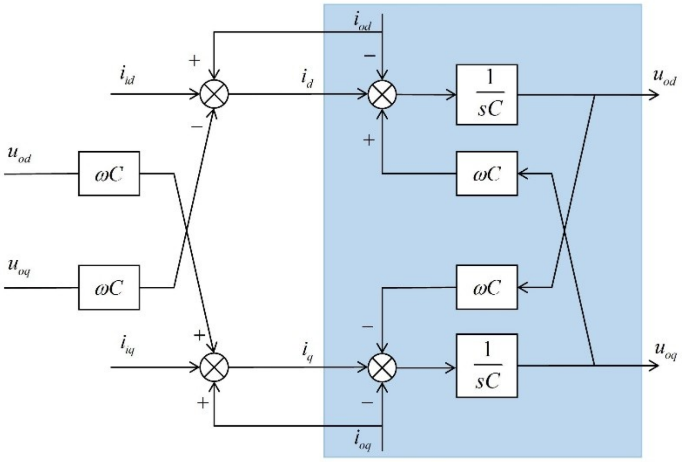


Fig. 9 C branch decoupling control

- **Dual closed-loop control**

Combing the RL system and C branch, we obtain the integral system structure model as follows:

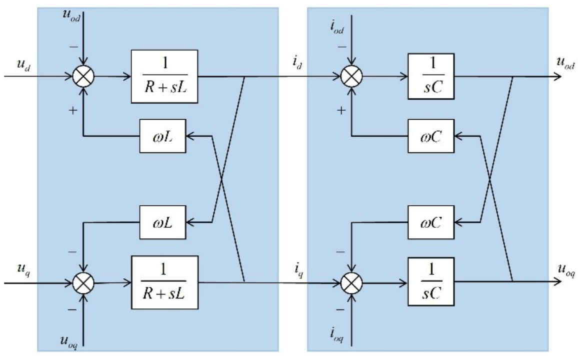


Fig. 10 Mathematical model of the RL system and the C branch

Add the current and voltage dual closed-loop control, we obtain

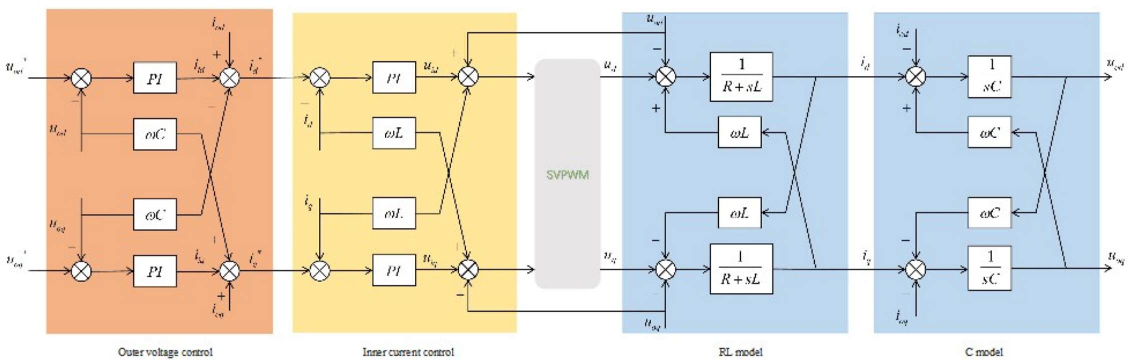


Fig. 11 Dual closed loop contro

Discussion about the control loop selection

- **Grid-forming control**

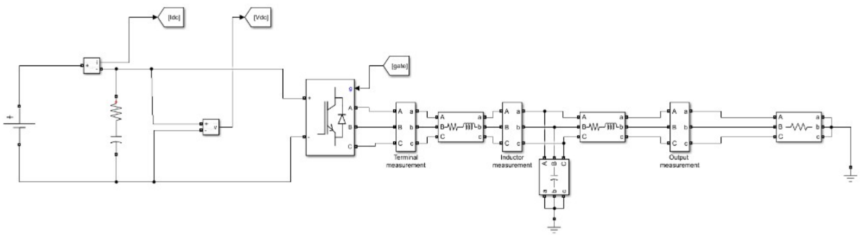
In the grid-forming control, we use active power to obtain the phase angle, and we use reactive power to obtain the reference value of grid voltage. Therefore, the control loop of grid-forming control has to include the voltage control, and the dual closed loop control in Fig. 11 should be selected.

- **Grid-following control**

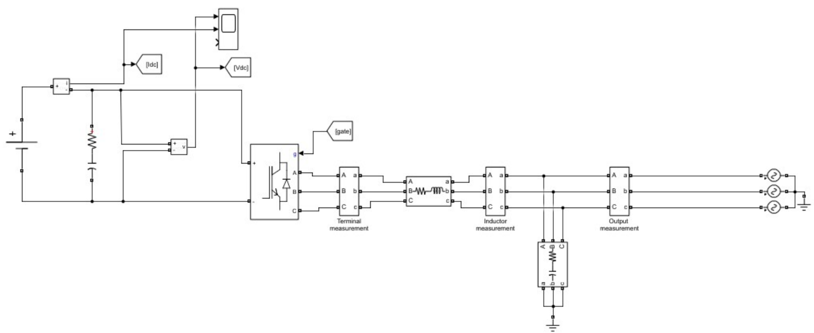
With regard to the grid-following control, we use PLL to obtain the phase angle, while there is no limit for selecting the voltage magnitude reference or the current magnitude reference. Therefore, both the inner current loop in Fig. 7 and the dual closed loop control in Fig. 11 can be selected for the grid-following control. In this tutorial, we choose the inner current loop control.

RT-LAB simulation results

A simulation model of grid-connected voltage source converter (10kW) is established in OPAL-RT as shown in Fig. 12. Fig. 13 shows the power calculation and the coordinate transformation from abc to d-q. With regard to control strategies, the dual closed loop control for grid-forming control is illustrated in Fig. 14 and the inner current loop control is illustrated in Fig. 15. Fig. 16 demonstrates the most significant difference between the grid-forming control and the grid-following control.

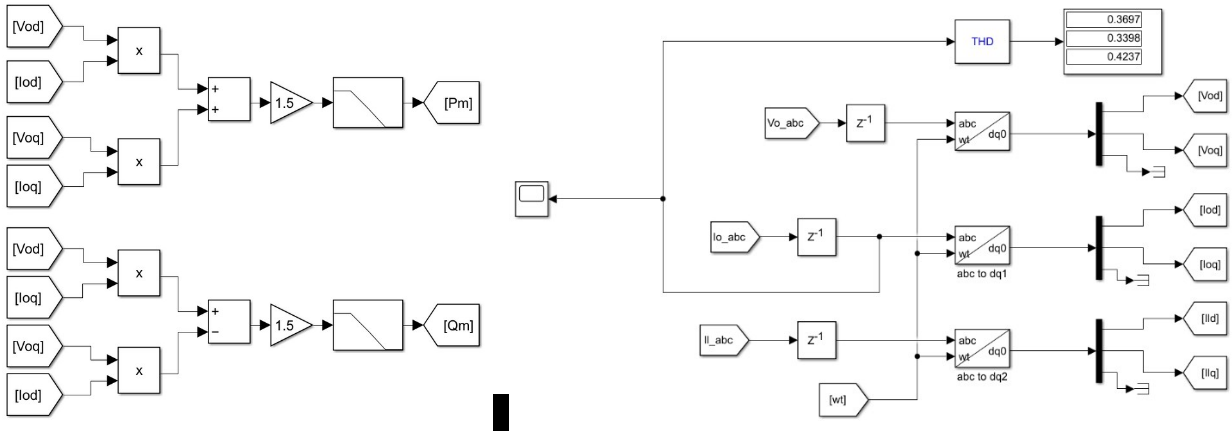


(a)



(b)

Fig. 12 Simulation model of grid-connected voltage source converter for (a) grid-forming control, (b) grid-following control



(a) (b)

Fig. 13 (a) Power calculation and (b) coordinate transformation

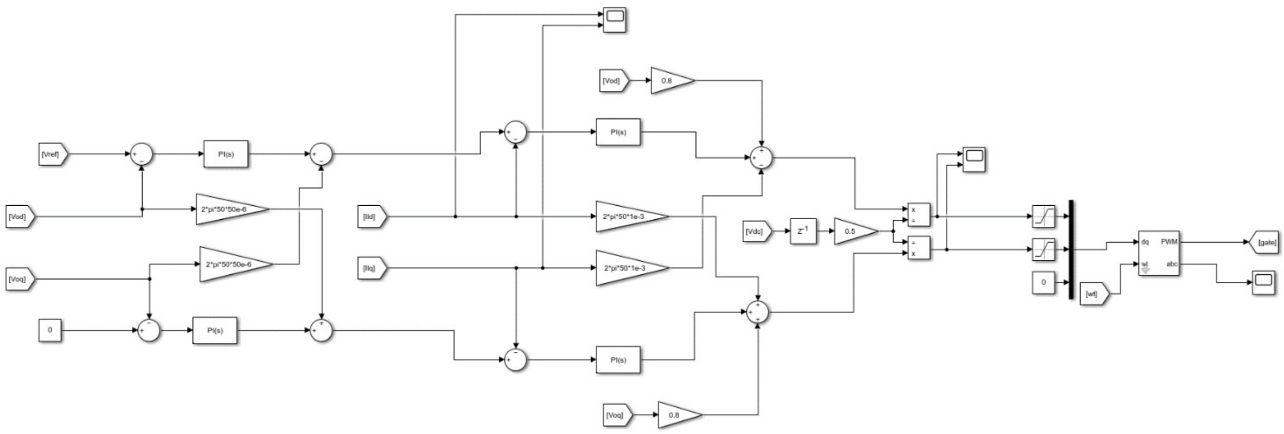


Fig. 14 Dual closed loop control for grid-forming control

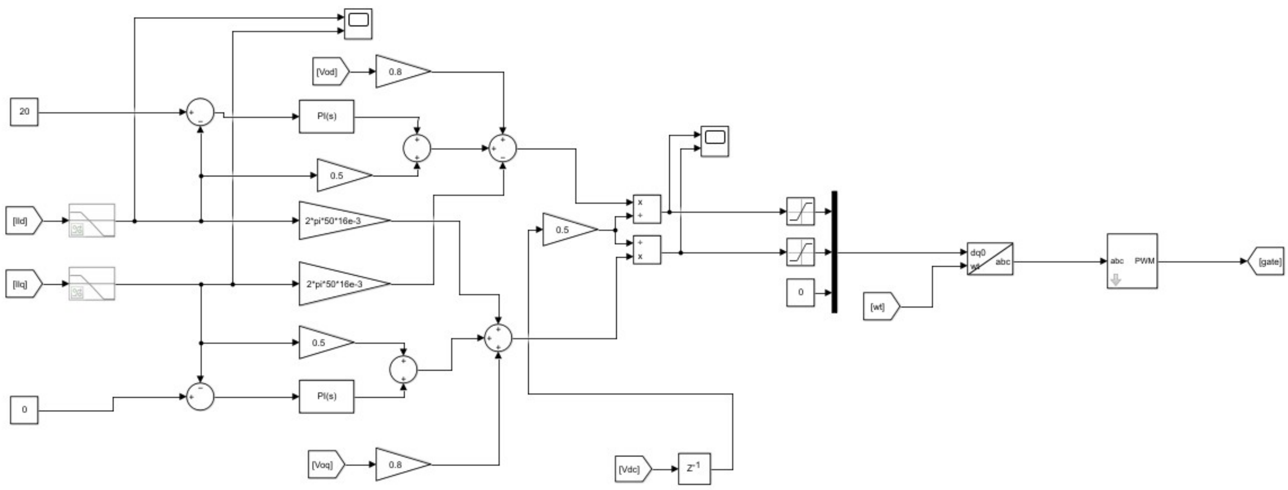
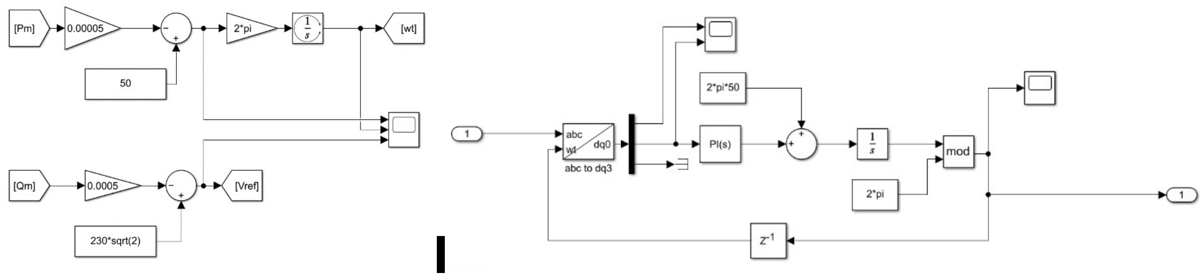


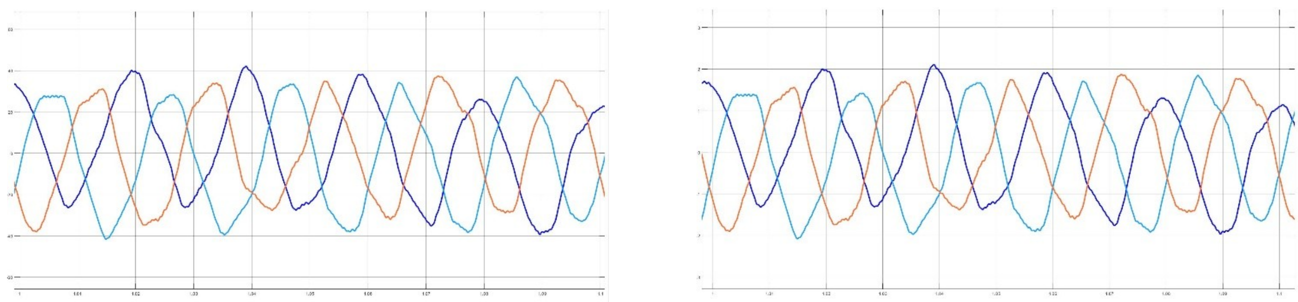
Fig. 15 Inner current loop control for grid-following control



(a) (b)

Fig. 16 (a) Droop control in grid-forming control, (b) PLL in grid-following control

In the grid-forming control, the inverter output voltage and current are shown in Fig. 17, and the output active power (blue line) and reactive power (red line) are shown in Fig. 18.



(a) (b)

Fig. 17 (a) Inverter output voltage (b) inverter output current

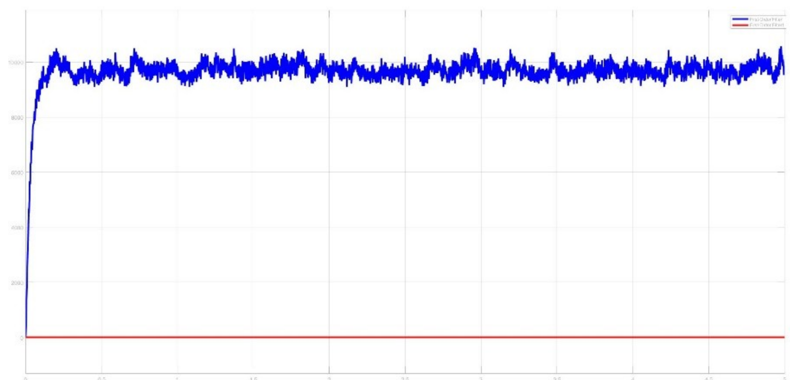
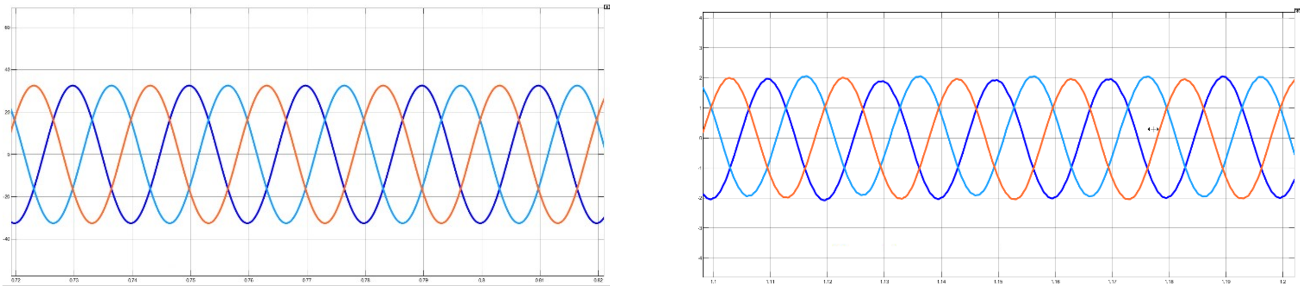


Fig. 18 Output active power and reactive power

In the grid-following control, the inverter output voltage and current are shown in Fig. 19, and the output active power (blue line) and reactive power (red line) are shown in Fig. 20.



(a) (b)

Fig. 19 (a) Inverter output voltage (b) inverter output current

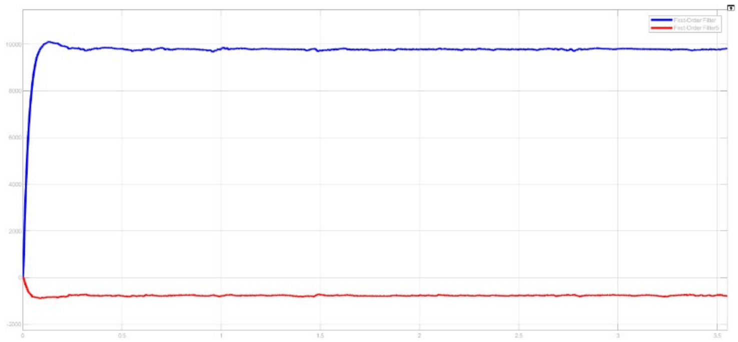


Fig. 20 Output active power and reactive power