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## An Inverter Parallel Control Strategy Research on Variable Virtual Impedance

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# An Inverter Parallel Control Strategy Research on Variable Virtual Impedance

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**Abstract.** In order to solve the imbalance distribution of reactive power in the power system caused by different line impedance in parallel multi-inverter system, This paper analyses the deficiency of traditional droop control and the causes of reactive current circulation. Double closed loop control based on inverter voltage and current, it studies the influence of different system parameters on the equivalent impedance of the inverter, according to the study it introduce virtual impedance, the real-time reactive power is distributed to a given reactive power through the inverter's control system, and then the inverter control system estimates the virtual impedance by deviating the reactive power from the given reactive power. Simulation results show that the method of adjust reactive power on line have certain effectiveness and feasibility.

## 1. Introduction

For the power sharing of the inverter, the traditional droop control method, that is, the active-frequency droop curve and the reactive-voltage droop curve are used to realize the self-synchronization of frequency and voltage[1]. However, most of the current equivalent output impedance of the inverter exhibits resistance, which is difficult to control, and the equivalent output impedance of the conventional droop characteristic is low, which is easy to generate circulation between the inverters, which affects the stability of the grid[2].

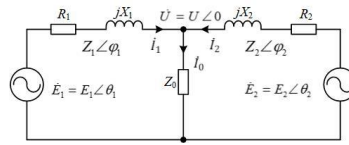
The paper analyses the insufficiency of traditional droop control that cannot divide the reactive power, introduces virtual impedance to adjust the output impedance to be inductive, applies communication technology to coordinate reactive power allocation, adjust the virtual impedance to compensate the inverter outlet voltage to make the reactive power equalization, simulation results verify the correctness of the method.

## 2. Principle and Design

### 2.1. Analysis of traditional droop control method

Figure 1 is a simplified single-phase schematic diagram of two three-phase symmetric inverter parallel systems. In the schematic diagram,  $E_1$ ,  $E_2$  are the output voltage of each inverter,  $\theta_1$ ,  $\theta_2$  are the phase of output voltage of each inverter,  $U$  is the voltage of parallel point,  $Z_1 \angle \varphi_1 = R_1 + jX_1$ ,  $Z_2 \angle \varphi_2 = R_2 + jX_2$  are the equivalent representation of the sum of the output impedance of each inverter and the line impedance.





**Figure 1.** The simplified equivalent mode of two three-phase inverter's parallel  
Can be observed in Figure 1, the output current  $I_i$  of the inverter is:

$$\dot{I}_i = \frac{\dot{E}_i - \dot{U}}{R_i + jX_i} \quad (i=1,2) \quad (1)$$

The complex power of the inverter output is  $S_i = \dot{U} \dot{I}_i^*$ , the reactive power of the active  $P_i$  and the inverter output are respectively:

$$P_i = \frac{E_i U}{Z_i} \cos(\varphi_i - \theta_i) - \frac{U^2}{Z_i} \cos \varphi_i, \quad Q_i = \frac{E_i U}{Z_i} \sin(\varphi_i - \theta_i) - \frac{U^2}{Z_i} \sin \varphi_i \quad (i=1,2) \quad (2)$$

Generally, the load impedance is much larger than the line impedance, so it can be considered  $\theta_i \approx 0$ , Approximate processing is  $\sin \theta_i \approx \theta_i$ ,  $\cos \theta_i \approx 1$ . Line impedance resistance in low voltage lines[3], but the inverter output filter is mostly LC or LCL, which makes the output impedance approximately inductive[4], this paper designs a reasonable virtual impedance parameter to make it close to the inductive, so in this situation we can get  $\varphi_i \approx 90^\circ$ , we can get from simplification of Eq. (2):

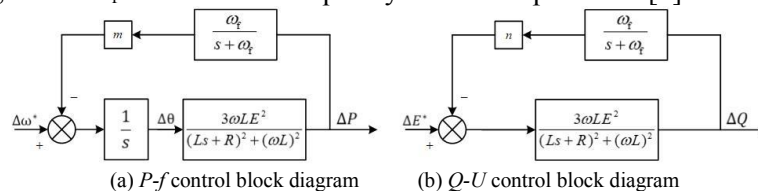
$$P_i = \frac{E_i U}{X_i} \theta_i, \quad Q_i = \frac{U}{X_i} (E_i - U) \quad (i=1,2) \quad (3)$$

Available from Eq. (4), The active power is mainly related to the phase angle difference of the output voltage of the inverter, reactive power is mainly related to the output voltage amplitude of the inverter. Relationship between phase angle difference and angular frequency is  $\omega = d\theta/dt$ . We can control the active power by adjusting the output voltage angular frequency  $\omega$  to control the phase angle difference, and control reactive power by adjusting the output voltage amplitude, so that we can use a simple one-time function to achieve droop control as Eq. (4):

$$\omega_i = \omega^* - mP, \quad U_i = U^* - nQ_i \quad (i=1,2) \quad (4)$$

Where  $\omega^*$ ,  $U^*$  are the reference given to the inverter output frequency and output voltage respectively,  $m$ ,  $n$  are the active frequency droop coefficient and the reactive-voltage droop coefficient.

In actual equipment, add a low pass filter to the feedback loop to filter out high frequency disturbances, the control block diagram of the  $P$ - $f$  and  $Q$ - $U$  drooping small signals can be obtained as shown in Figure 2, where  $\omega_f$  is the cut-off frequency of the low pass filter[4].



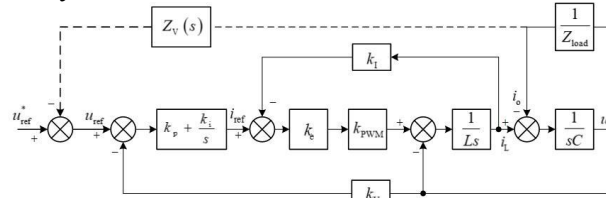
**Figure 2.** System structure of droop control

As can be seen from Figure 2, in the active control loop, a  $1/s$  integral link is introduced, and no static error tracking can be achieved for a given frequency. For the reactive power droop control, there is no integral link, the inverter cannot accurately track the given reference, resulting in uneven distribution of reactive power of each inverter, which is easy to generate reactive current circulation.

## 2.2. Inverter Parallel Control Strategy and Its Output Impedance Design

Due to the different line lengths of different inverters, there are many uncertainties in the line impedance. We need to design a reasonable output impedance to make the impedance characteristics of the inverter to the load consistent, so that the parallel system can operate stably and reliably[5].

The control structure of the inverter is shown in Figure 3. The control strategy is based on the commonly used voltage and current double closed loop control, the outer loop is the voltage control loop, the PI control is used to improve the system output waveform to make it have higher output precision; the inner loop is the output current control loop, which adopts P control for improve the dynamic performance of the system.



**Figure 3.** Inverter voltage and current double closed loop control structure

As shown in Figure 3,  $k_p$  and  $k_i$  are the proportional and integral coefficients of the voltage outer loop PI controller, respectively, and  $k_e$  is the proportional coefficient of the voltage inner loop P controller,  $k_{PWM}$  is the inverter equivalent gain,  $k_U$  and  $k_I$  are the capacitor voltage feedback coefficient and the inductor current feedback coefficient,  $Z_{load}$  is the equivalent impedance of the line circuit impedance and load impedance,  $Z_V(s)$  is the sign of the virtual impedance, and  $u_{ref}^*$  is the voltage reference value after introducing the inductive virtual impedance,  $u$  is the inverter output voltage,  $i_o$  is the output current.

Before introducing the concept of virtual impedance, the equivalent output impedance  $Z_{out}(s)$  of the inverter can be approximated as:

$$Z_{out}(s) \approx \frac{Ls^2}{s + k_U k_e k_{PWM} (k_p s + k_i)} \quad (5)$$

The approximation condition is that the filter capacitor  $C$  has little effect on the equivalent output impedance. After introducing the virtual impedance, the equivalent output impedance  $Z_{out}^*(s)$  of the inverter is:

$$Z_{out}^*(s) = \frac{(k_p s + k_i) k_e k_{PWM}}{(1 + k_U k_e k_{PWM} k_p) s + k_U k_i k_e k_{PWM}} Z_V(s) + Z_{out}(s) \quad (6)$$

If  $Z_V(s) = k_U Ls$ ,  $Z_{out}^*(s) = Ls$  can be obtained. Under the industrial frequency condition, the output impedance of the inverter is approximated as  $Ls$ . If the line impedance is ignored, the output impedance value is determined only by the output inductance value[6]. An inductive virtual impedance  $Z_V(s) = s\omega_c / (s + \omega_c) \cdot L_V$  is introduced, where  $\omega_c$  is the filter cut-off frequency.

By using the above-mentioned strategy of introducing virtual inductive reactance, the appropriate parameters can be selected, so that the inductive reactance is much larger than the line impedance, and the approximate condition is satisfied. However, a large inductive reactance increases the size of the device and affects the filtering effect. Investigating the influence of different parameter selections on the equivalent output impedance helps us to choose the appropriate virtual impedance.

The logarithmic frequency response of a double closed-loop control system under different parameters is studied by Matlab software, Inverter control parameters are shown in Table 1:

**Table 1.** Parameters of double closed loop control

Parameter	$L/\text{mH}$	$C/\mu\text{F}$	$K_e$	$K_p$
1	20	500	0.173	27
2	20	500	0.173	36
3	20	500	0.15	36
Parameter	$K_i$	$\omega_c/\text{rad/s}$	$L_V/\text{mH}$	
1	1.6	100	20	
2	1.6	120	25	
3	2	240	30	

At 50Hz frequency, the output impedance of the inverter corresponding to each parameter is inductive, and the output of the inverter also has inductance addition, so the equivalent output

impedance of the inverter is also inductive. Even if the impedance of the low-voltage line is resistive, the impedance characteristics of the line resistance are negligible relative to the equivalent output impedance, so the traditional droop control method is still applicable.

### 2.3. Online regulation of reactive power

The virtual impedance is used to make the output impedance of the inverter inductive. The traditional droop control method can be used to adjust the reactive power distribution imbalance. Reference [6] proposed a control strategy to improve the droop characteristic curve, and improve the stability of the system under the constraints of the inherent droop coefficient of the system. Reference [7], an adaptive virtual impedance control strategy is proposed to improve the parallel efficiency and reduce the reactive power. The above control methods all coordinate the contradiction between reactive power distribution and output voltage drop, but the control algorithm involves high-power operation, which requires higher computational power of the inverter controller and is more complicated to implement. This paper proposes real-time reactive power distribution through the communication network, avoiding the problem of completely relying on the inverter's own droop characteristic curve to adjust the reactive power, and achieving the goal of accurately distributing reactive power.

It can be known from Eq. 4 that the error of reactive power distribution is related to the voltage amplitude of the inverter. The expression is:

$$\Delta Q = n_2 Q_2 - n_1 Q_1 = E_2 - E_1 \quad (7)$$

The voltage drop of impedance  $Z_i \angle \varphi_i$  can be expressed by the power on the impedance:

$$E_i - U = \frac{X_i Q_i + R_i P_i}{E^*} \quad (i=1,2) \quad (8)$$

Combined with Eq. 5, the reactive power distribution difference is:

$$\Delta Q = n_2 Q_2 - n_1 Q_1 = \frac{\left( \frac{X_2}{n_2} - \frac{X_1}{n_1} \right) (n_1 Q_1 + n_2 Q_2) + \left( \frac{R_2}{m_2} - \frac{R_1}{m_1} \right) (m_1 P_1 + m_2 P_2)}{\frac{X_1}{n_1} + \frac{X_2}{n_2} + 2E^*} \quad (9)$$

The conditions for equalizing the reactive power are:

$$\frac{X_1}{n_1} = \frac{X_2}{n_2}, \frac{R_1}{m_1} = \frac{R_2}{m_2} \quad (10)$$

Since it is difficult to accurately measure the inverter output impedance and the line impedance in actual operation, it is also impossible to satisfy the condition of Eq. 8 only by setting the corresponding virtual impedance. But we can use the droop control curve of reactive power and output voltage, coordinate the reactive power distribution through communication technology, and introduce voltage compensation signal to achieve the equalization of reactive power.

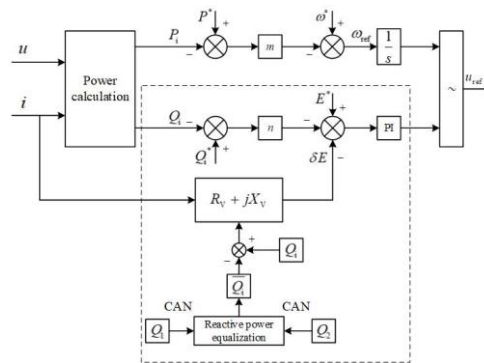
In order to distribute the reactive power of the terminal voltage  $U_1 = U_2$  evenly, the average reactive power of the current parallel inverter can be calculated after reactive power acquisition, and the reactive power allocated by each inverter can be obtained by equation 4:

$$\bar{Q}_1 = \frac{n_2}{n_1 + n_2} (Q_1 + Q_2), \bar{Q}_2 = \frac{n_1}{n_1 + n_2} (Q_1 + Q_2) \quad (11)$$

The introduced voltage compensation signal is:

$$\delta E_1 = n_1 \cdot \frac{n_2 Q_2 - n_1 Q_1}{n_1 + n_2}, \delta E_2 = n_2 \cdot \frac{n_1 Q_1 - n_2 Q_2}{n_1 + n_2} \quad (12)$$

The resulting control chart is shown in Figure 4:



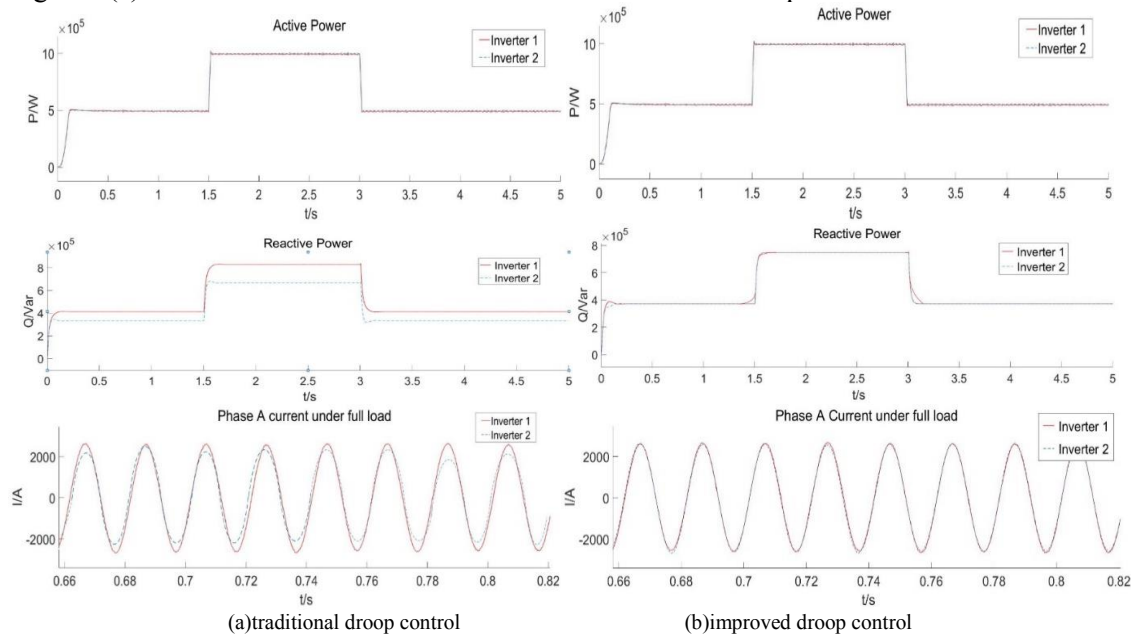
**Figure 4.** Implementation of variable virtual impedance

### 3. Simulation

In order to verify the correctness of the above method, two inverter parallel models were built in Matlab/Simulink environment for simulation analysis. The simulation parameters are as follows:

Inverter rated power 1MW, rated output voltage  $E=390\text{V}$ , DC bus voltage  $U_{dc}=710\text{V}$ , Filter Inductor  $L_f=56\mu\text{H}$ , Filter capacitor  $C_f=1200\mu\text{F}$ , Output inductance  $L_o=20\mu\text{H}$ , line impedance of Inverter 1  $Z_{line1}=5 \times 10^{-4} + j6 \times 10^{-5} \Omega$ , line impedance of Inverter 2  $Z_{line2}=2.5 \times 10^{-4} + j3 \times 10^{-5} \Omega$ , Active power-phase droop coefficient  $m=4 \times 10^{-7} \text{ rad/s} \cdot \text{W}$ , Reactive power-amplitude droop coefficient  $n=2 \times 10^{-6} \text{ V/Var}$ , virtual impedance integral coefficient  $K_i=4 \times 10^{-7}$ .

Figure 5(a) shows the simulation waveform of the traditional droop control method.



**Figure 5.** Simulink results

The angle can be obtained by frequency integration. Due to the error adjustment of the integrator, the active power-frequency droop can achieve accurate equalization of the active power. Due to the difference in line impedance, the output voltage amplitude is different, so the reactive power-voltage sag cannot achieve accurate equalization of reactive power. The larger the output current, the worse the reactive power unevenness is. It can be seen from Figure 5(a) that there is a large circulating current between the parallel inverters at the full load steady state.

Figure 5(b) is a simulation of the improved droop control method simulation waveform. It can be seen from the figure that after real-time adjustment of CAN communication, the active power remains equally divided, and the reactive power deviation can be evenly distributed after the load disturbance.

At the same time, the introduction of the virtual impedance greatly reduces the circulation between the parallel inverters.

#### 4. Conclusion

This paper first introduces the principle of droop control, analyses the conditions of traditional droop control power sharing in detail, and introduces virtual impedance. By designing the control parameters, the inverter output impedance satisfies the conditions of droop decoupling control. On this basis, it is analysed that only the introduction of virtual impedance can not meet the distribution of reactive power, and the virtual impedance needs to be changed according to the change of the load condition. The CAN communication is introduced to adjust the required reactive power distribution in real time. By comparing the given reactive power distribution with the current reactive power, the virtual impedance value is adjusted, and finally the reactive power distribution of the parallel system is realized.

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