Abstract: The parallel operation of several low-capacity inverters is better than a singular high-capacity inverter owing to the advantages of better extensibility and reliability. A simplified control method for parallel-connected inverters is proposed, which can balance the current distribution among the parallel-connected inverters with no interconnected communication lines. To verify the performance of the proposed control method, a prototype consisting of two inverters has been developed. The experimental results verify that the performance of the proposed control method is as desired.

1 Introduction

Inverters is used to convert DC energy to AC energy, and they are widely used in UPS (uninterruptible power supplies), power converter interfaces for renewable energy generation, energy storage systems and backup power supply systems. Among these applications, the application in UPS is still the most important. To provide high-capacity and high-quality AC electric power, UPS can be implemented by using a high-capacity inverter or several low-capacity inverters. The use of a singular high-capacity inverter has the following disadvantages [1]:

- The power rating of inverter is limited by the power rating of the power electronic devices.
- From the viewpoint of a manufacturer, a singular inverter causes wasted time and money for developing different products for different power ratings. This also makes the production and management more complex.
- The extensibility is poor.
- The reliability is poor.

For the above reasons, the inverter that gives the performance of parallel operation is an important trend nowadays. The major problem for parallel-connected operation of several low-capacity inverters is the unbalanced current distribution among them, which may result in overcurrent of an individual inverter. Furthermore, parallel-connected inverters may act as a circulating current among them. This increases the power loss in the inverters and reduces the power efficiency of the entire parallel-connected system.

In this paper, a simplified control method for the parallel-connected inverters is proposed. This method can equalise the output currents of these inverters and reduce the circulating current among them effectively with no interconnected communication line. To verify the performance of the proposed control method, a prototype consisting of two inverters has been developed and tested.

2 Review of control methods for parallel-connected inverters

The conventional control methods for parallel-connected inverters can be classified into two types. One is the active current distribution type [1–7], and the other is the droop type [8–12].

2.1 Active current distribution control

The type of parallel-connected inverters that uses active current distribution control adapts the current-mode control. The voltage-source inverter, combined with a filter inductor and controlled by current-mode control, can generate a controllable current. Therefore, the voltage-source inverter can act as a current source although the power source of the voltage-source inverter is a DC voltage. Hence, the simplified equivalent circuit of a parallel-connected inverter using active current distribution control is shown as Fig. 1. The object of the active current distribution control is to generate a reference current for each parallel-connected inverter, and it can be subdivided into three methods: the master slave control method [1–4], the concentrated distribution control method [5, 6] and the ring control method [7]. The master slave control method specifies an inverter as the master, and the others are all specified as the slaves. The specified master inverter supplies a reference current to the slave inverters. The concentrated distribution control method uses a concentrated control
circuit to determine a reference current for all parallel-connected inverters. Thus, the individual control circuit of each inverter, using current-mode control, controls its output current to trace the same reference current. Therefore, the output currents of parallel-connected inverters are regulated to be equal. In the above two methods, the output currents of all parallel-connected inverters must be collected, and the number of parallel-connected inverters must be pre-known. If one of the parallel-connected inverters fails, the parallel-connected system will fail. In the ring control method, the output current of an inverter is the reference current of the next inverter, and the output current of the last inverter is the reference current of the first inverter. Hence, the control circuits of parallel-connected inverters are constructed as a ring, and the output currents of the parallel-connected inverters are controlled to be the same.

### 2.2 Droop control method

The droop control method [8–12] for the parallel-connected inverters can avoid the communication of reference current. The inverters with the droop control method generally adapt the voltage-mode control, and the control object is the inverter’s output voltage. A link inductor is inserted between the inverter and the load bus. The phase and amplitude of the inverter’s output voltage are the control parameters in voltage-mode control. The droop control method is defined such that the amplitude and frequency of the reference voltage signal will droop as the load current increases. Figure 2 shows the equivalent circuit for the parallel-connected inverters, where $X_L$ is the link reactance. The operation theory of the droop control method for parallel-connected inverters is similar to the parallel operation of synchronous generators. Because a link inductor must be inserted in the output of each inverter for the conventional droop method, it will result in additional hardware and installation cost. In addition, the control circuit contains two control loops to regulate the real power and the reactive power, respectively. Hence, its control circuit is complicated.

In general, parallel-connected inverters using the active current distribution control method have the performance of well balancing current distribution and high quality of output voltage because the parallel-connected inverters can be regarded as the current sources. However, the reference current in the active current distribution control method must be communicated among the parallel-connected inverters. The communication of this information can be interfered, and the reliability of parallel-connected inverters will be degraded. In addition, the communication of the reference current among the parallel-connected inverters is difficult in some applications. The droop control method can avoid the requirement of communicating information among the parallel-connected inverters. However, the droop control method has the disadvantages of poor voltage regulation, high voltage distortion and loss of synchronisation between the utility voltage and the inverter’s output voltage as it is used in UPS applications.

### 3 Basic operation theory of proposed method

The proposed control method for parallel-connected inverters has a similar advantage as the droop control method in that each inverter acts as a voltage source to avoid the communication of the reference current. The equivalent circuit of two parallel-connected inverters using the proposed control method can be simplified as shown in Fig. 3a, where $X_1$ and $X_2$ are the filter reactances of the inverters, not the link reactance that was shown in Fig. 2, and the load is simplified as a current source. If the output voltages of parallel-connected inverters are not the same, it will result in a circulating current between the parallel-connected inverters, which can be derived as

$$I_{cir} = (V_{o1} - V_{o2})/(X_1 + X_2)$$

where $V_{o1}$ and $V_{o2}$ are the output voltages of inverter 1 and inverter 2. As seen in (1), if the amplitudes or phases of $V_{o1}$ and $V_{o2}$ are not equal, a circulating current between inverter 1 and inverter 2 will occur. This circulating current is proportional to the voltage difference of the parallel-connected inverters, and it may result in overcurrent damage to the inverters. In practice, it is very hard to guarantee that the amplitude and phase of $V_{o1}$ and $V_{o2}$ are the same without any communication between the parallel-connected inverters, and then the circulating current cannot be avoided. Hence, the circulating current is still a serious problem for parallel-connected inverters controlled by voltage-mode control.

As seen in (1), the value of impedance $X_1 + X_2$ can limit the amplitude of the circulating current and avoid the overcurrent damage. However, a large filter inductor will result in a significant voltage drop of the output voltage, large size, heavy weight, poor energy efficiency and high voltage distortion. The proposed control method for the parallel-connected inverters is based on the concept of increasing the equivalent output impedance of the inverter. Nevertheless, the equivalent output impedance is virtual.

![Fig. 2 Equivalent circuit of parallel-connected inverters using droop-type control](image1)

![Fig. 3 Equivalent circuit of two parallel-connected inverters using proposed control method](image2)
This paper has proposed a control method for parallel-connected inverters. This method can effectively equal the current distribution of the output current and reduce the circulating currents among parallel-connected inverters. A prototype consisting of two inverters has been developed to verify the performance of the proposed control method. The experimental results show that the proposed control method has the expected performance.

7 References