# A Novel Controller for Parallel Operation of Inverters Based on Decomposing of Output Current

Meng Xie[1,2] Yaohua Li[2] Kun Cai[2] Ping Wang[2] Xiaosong Sheng[2]
1.Graduate School of Chinese Academy of Science
2.Institute of Electrical Engineering Chinese Academy of Science
P.O.X. 2703, 100080, Beijing China
Email: simon@mail.iee.ac.cn

***Abstract***—In this paper, a novel control scheme for parallel-connected inverters without communication wires is presented. This paper analyses the cross current between parallel-connected inverters, and divides the current into two parts: AC cross current and DC cross current. In the previous literature, almost all the control schemes try to eliminate the AC cross current. DC cross current, however, is neglected. In this paper a new technique without control interconnections based on decomposing of output current is proposed, it uses fundamental voltage and frequency droop method to allow inverters to share the load current and uses a novel DC-offset voltage droop method to eliminate the DC cross current. From the analytical models and experiment results, the proposed controller for parallel operation of inverters is verified.

***Keywords-inverter; parallel operation; cross current; droop method***

## I. INTRODUCTION

In recent years, uninterrupted power supply systems have become increasingly important, especially for critical loads such as computer systems, instrumentation plants, communication systems, and hospital equipment. With the increasing demand of such power supply with high capability and reliability, parallel operation of inverters is often presented as a good solution. Generally, the parallel operation of lower-power inverter modules offers a number of advantages over a single, high-power, centralized power supply. The most important advantage of parallel operation is that it offers a higher reliability in case one inverter fails the remained (n-1) modules can deliver the full power and the critical load remains unaffected. However, in order to achieve a parallel operation the modules have to be strictly controlled to keep the same amplitude, phase and frequency, otherwise large cross currents can damage one or more of the parallel inverters [1].

Accordingly, the main object of parallel controller is to eliminate the cross current among inverters. Although many methods of operating inverters in parallel have been presented in the literature [2,3], most of them need some forms of control interconnection among the inverters. These interconnecting wires not only restrict the location of the inverter units, but also act as a source of noise and failure. Recently, it has been proposed several control techniques without control wire interconnections. To achieve good load current sharing, the control loop makes tight adjustments over the output voltage frequency and amplitude of the inverter to compensate the unbalances of the active and reactive power unbalances [4-8]. This concept, also called droop method, is derived from the power system theory, in which the frequency of a generator droops when power drawn to the utility line increases.

In the previous literature about droop method, output current of inverter is divided into two parts: active part and reactive part, and then they are adjusted respectively. AC cross current can be effectively avoided by means of these control schemes, but DC cross current which is caused by the different DC-offset of output voltage among inverters is neglected. In this paper a new technique without control interconnections based on decomposing of output current is proposed, it uses fundamental voltage and frequency droop method to allow inverters to share the load current and uses a novel DC-offset voltage droop method to eliminate the DC cross current.

In Section II, configuration of parallel system is modeled and the cross current is analyzed. A novel controller without control interconnections is presented to eliminate both the AC and DC cross current in Section III. Experiment results of two 1.5kW inverters are present in Section IV, followed by a summary of the paper in the conclusion section.

## II. SYSTEM MODELING AND ANALYSIS

The equivalent circuit of two inverters parallel connected is shown in Fig.1, where $V_1$ and $V_2$ are the output voltage of two inverters, $Z_1$ and $Z_2$ are their output impedance, $Z_L$ is the load impedance.

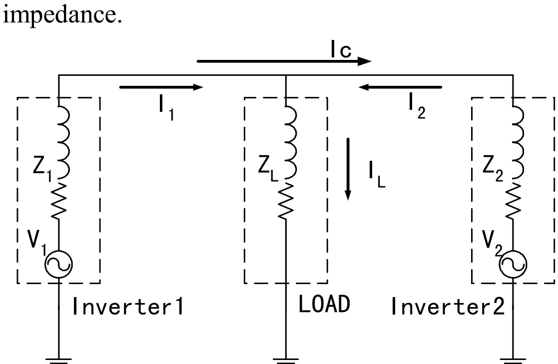


Fig.1: Equivalent circuit of two parallel-connected inverters

In practical system, as shown in Fig.2, not only the amplitude and phase of $V_1$ and $V_2$ are different, but also each output voltage may have a small DC component which is caused by the error of the sensor or the other uncertain factors.

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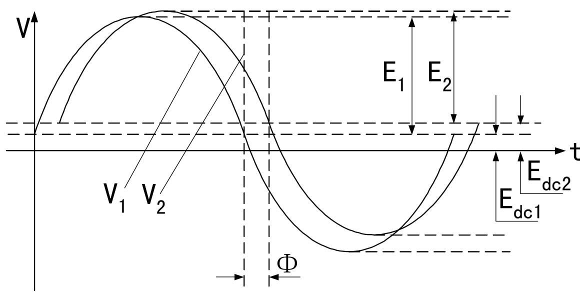


Fig.2: Difference between the output voltage of two inverters

Here, $V_1$ and $V_2$ are represented as follow (1),(2):

$$\begin{aligned}\dot{V}_1 &= \dot{E}_{ac1} + E_{dc1} = E_1 \cdot Cos\varphi_1 + E_{dc1} \\ &= E \cdot Cos\omega t + E_{dc1}\end{aligned} \tag{1}$$

$$\begin{aligned}\dot{V}_2 &= \dot{E}_{ac2} + E_{dc2} = E_2 \cdot Cos\varphi_2 + E_{dc2} \\ &= (E + \Delta E) \cdot Cos(\omega t + \varphi) + E_{dc2}\end{aligned} \tag{2}$$

where $E$ equal to $E_1$, $\Delta E$ and $\varphi$ are the amplitude and phase differences between two output voltage; $E_{dc1}$ and $E_{dc2}$ are the DC-offset of two output voltage.

Then the cross current between two inverters can be obtained from Fig.1:

$$\begin{aligned}\dot{I}_c &= \frac{\dot{V}_1 - \dot{V}_2}{Z_1 + Z_2} \\ &= \frac{\dot{E}_{ac1} - \dot{E}_{ac2}}{Z_1 + Z_2} + \frac{E_{dc1} - E_{dc2}}{r_1 + r_2} \\ &= \dot{I}_{c\_ac} + I_{c\_dc}\end{aligned} \tag{3}$$

where $r_1$ and $r_2$ are the output resistance of two inverters, and $Z_1, Z_2$ is their output impedance:

$$Z_1 = r_1 + j\omega L_1 \tag{4}$$

$$Z_2 = r_2 + j\omega L_2 \tag{5}$$

where $L_1$ and $L_2$ are their output inductances.

As shown in formula (3), cross current $I_c$ can be divided into two parts: AC cross current ($\dot{I}_{c-ac}$) and DC cross current ($I_{c-dc}$):

$$\dot{I}_{c\_ac} = \frac{\dot{E}_{ac1} - \dot{E}_{ac2}}{Z_1 + Z_2} \tag{6}$$

$$I_{c\_dc} = \frac{E_{dc1} - E_{dc2}}{r_1 + r_2} \tag{7}$$

From equation (6) and (7), it is clearly that AC cross current is caused by the difference between AC components of two output voltage and the various DC-offset voltage lead to DC cross current. Further more, AC cross current is in inverse proportional to the value of output impedance, whereas, the denominator of formula (7) is only the value of output resistance. Then, the cross current will be analyzed in two different conditions.

### *A.* $E_{dc1} = E_{dc2} = 0$

Now, assuming that $E_{dc1} = E_{dc2} = 0$ and $r_1 + r_2 << Z_1 + Z_2$, then only the AC cross current is remained and the equation (3) can be simplified as follows:

$$\dot{I}_c = \frac{\dot{E}_{ac1} - \dot{E}_{ac2}}{j\omega(L_1 + L_2)} \tag{8}$$

This formula shows that AC cross current is in inverse proportion to the value of $L_1$+$L_2$ and has 90-degree phase delay by the voltage difference of each inverter [6]. The vector diagram of Fig.3 indicates that the reactive cross current occurs from the amplitude difference of each output voltage (Fig.3a) and the active cross current occurs from phase difference of each output voltage (Fig.3b).

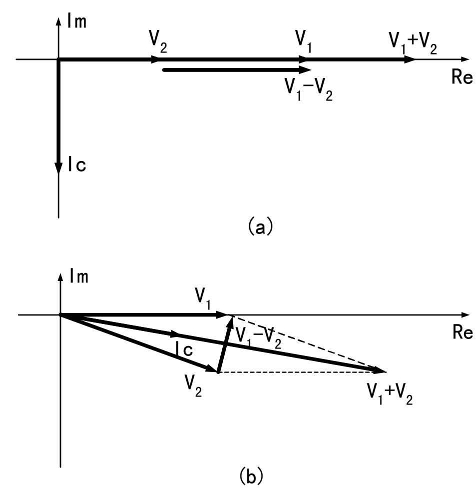


Fig.3. Generation of cross currents by a difference in amplitude (a) or phase (b)

Thus, parallel operation control becomes comparatively easy by adjusting the amplitude and phase of each inverter output voltage to eliminate the reactive and active cross current respectively. Furthermore, since the control is based on information available locally at the inverter terminals, the controller can work without interconnections except for the ac power connection.

### *B.* $E_{dc1} \neq E_{dc2} \neq 0$

In practical applications, the situation that $E_{dc1} \neq E_{dc2} \neq 0$ will result in that $I_{c-dc}$ is contained in cross current. When inverters are not connected together, their DC-offset voltage may be very small and will not influence the normal running of the devices. Nevertheless, for the reason that $r_1 + r_2 << Z_1 + Z_2$, from the equation (7) it can be derived that a very small difference between $E_{dc1}$ and $E_{dc2}$ will lead to a large DC cross current.

Fig.4 shows the output current waveform of two parallel-connected inverters used conventional parallel operation control scheme. In the figure, two inverters are parallel connected at time “$t_o$”. After time “$t_o$”, there is a large $I_{c-dc}$ in the output current and $I_{c-dc1} = -I_{c-dc2}$, though the AC components of two output currents are almost the same. This proves that the conventional method is useless in dealing with the DC cross current. It is to be note that two inverters are set to have notable DC-offset voltage before parallel connected in order to show the DC cross current distinctly.

Since a higher DC-offset voltage leads to a positive DC cross current, if we can find a method to droop the DC-offset voltage of the inverter whose output current contains a positive DC component, the DC cross current can be eliminated easily.

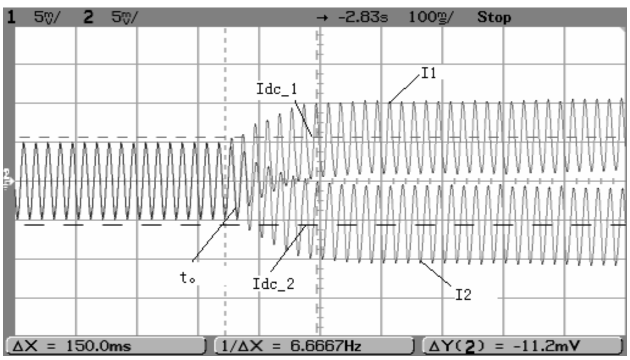


Fig.4. Inverter output current waveform

(X-axis: 100ms/div, Y-axis: 5A/div)

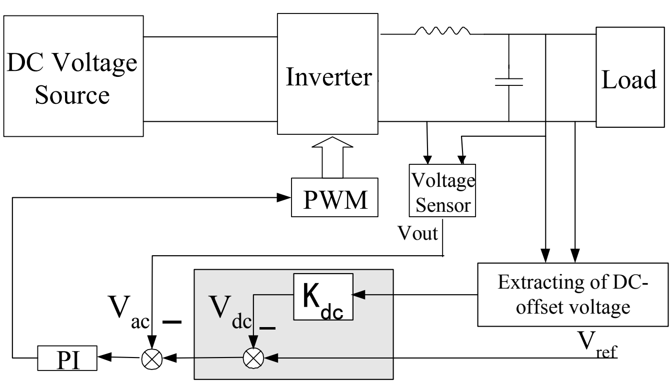


Fig.5 The scheme of eliminating DC voltage bias of a single inverter

In the single inverter controlling, if there is a DC-offset in output voltage, a special circuit is used to extract the DC-offset voltage. Then the offset multiplied with a proportional constant can be subtracted from the reference voltage signal. Accordingly, the offset voltage will be eliminated by the voltage loop as shown in Fig.5. The function of this method is to remedy the DC-offset in output voltage from changing the reference voltage. In common applications of single inverters, the symmetry degree of voltage can always meet the demand of using, even though such measure is not adopted. That is to say, such method is not necessary in single inverter application. From formula (7), however, a very small difference between two DC-offset voltage will lead to a large DC cross current when two inverters is parallel connected. So a technique similar to the method shown in Fig.5 must be introduced to avoid the DC cross current.

## III. PARALLEL INVERTER CONTROLLER DESIGN

A novel control scheme is shown in Fig.7. The system is composed of a voltage source SPWM inverter with a LC output filter, sensor circuit and controller. The output control of inverter and the parallel control are integrated into a single controller. The output control uses two PI controllers to stabilize the output voltage by means of feedback signal of output inductance current and output capacitor voltage. Output current is divided into three part: $I_{dc}$ (DC component of current), $I_q$ (reactive component of current) and $I_p$ (active component of current) in parallel control element. Then, $I_q$ and $I_p$ are used to eliminate the AC cross current and $I_{dc}$ is used to avoid the DC cross current. The controller only use the information of itself and the only connection of the inverter with others is AC Bus, control interconnections, thus, can be avoided.

### *A. Decomposing of Output Current*

In the first place, output current is divided into AC and DC component as shown in Fig.6. Current I passes through a low pass filter LPF1 whose bandwidth is much lower than the fundamental frequency of current, and $I_{dc}$ can be acquired. Then, subtracting $I_{dc}$ from I, we can obtain $I_{ac}$.

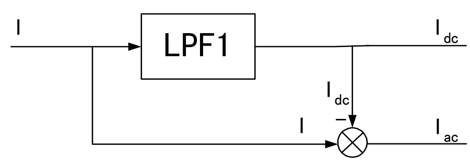


Fig.6: decomposing of output current

Fig.8 shows the algorithm used to calculate $I_p$ (active current) and $I_q$ (reactive current) from $I_{ac}$ and output voltage. Firstly, three phase current is constructed from single phase current $I_{ac}$ through the delay of 120° and 240° respectively. Then, from the 3-2 transform, we can get the current in α - β coordinate.

The matrix C32 in Fig.8 is:

$$C_{32} = \sqrt{2/3} \bullet \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \tag{9}$$

On the other hand, a phase-locked loop (PLL) is used to obtain the sine and cosine value of output voltage. Then, from formula (10), and passing through LPF, $I_p$ and $I_q$ can be acquired.

$$\begin{bmatrix} \tilde{i}_p \\ \tilde{i}_q \end{bmatrix} = C_{pq} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \sin\omega t & -\cos\omega t \\ -\cos\omega t & -\sin\omega t \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \tag{10}$$

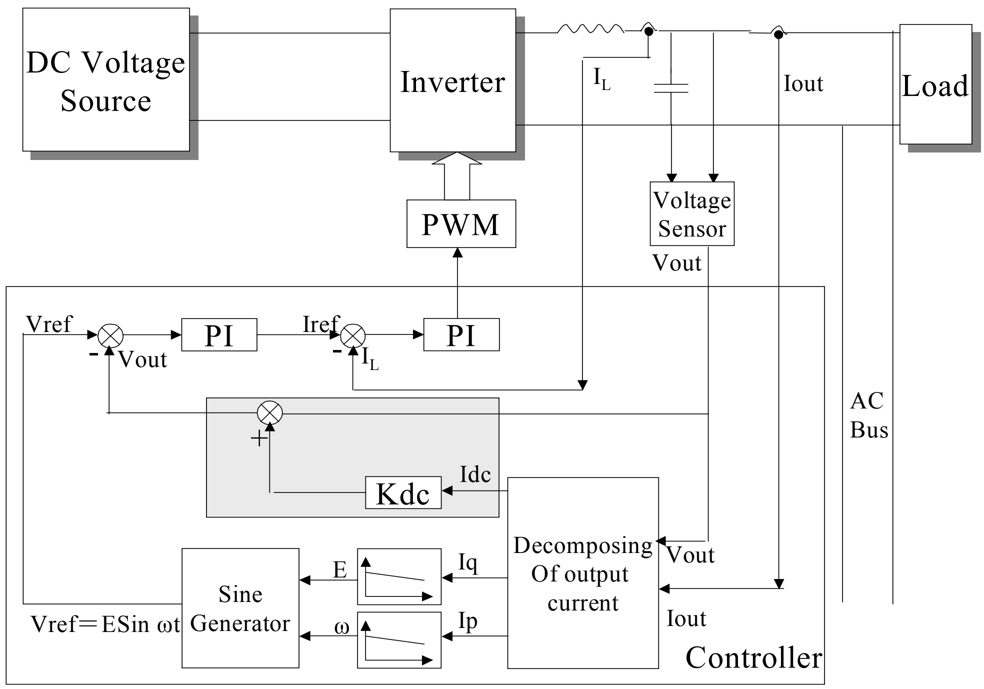


Fig.7 New parallel operation controller

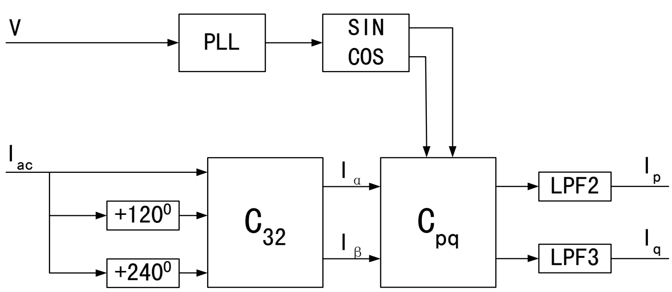


Fig.8: decomposing of Iac

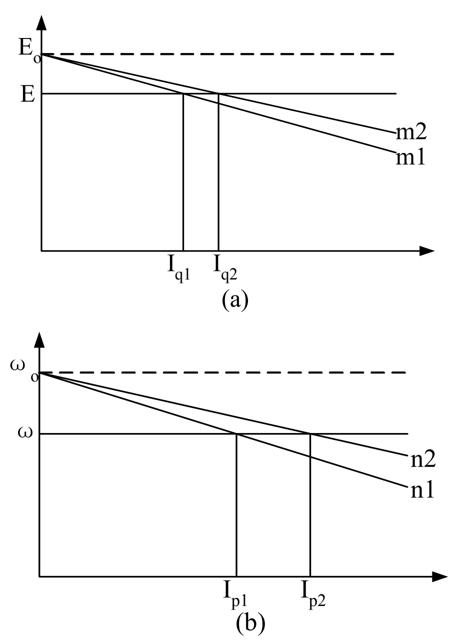


Fig.9: The Iq-E and Ip-ω droop scheme

*B. AC Cross Current Control*

The problem of eliminating the AC cross current can be solved by introducing an artificial droop in the inverter voltage amplitude and frequency. Based on the predetermined droop characteristics [4], the following droops in the amplitude $E$ and the frequency $\omega$ of the inverter output voltage are introduced by means of $I_p$ and $I_q$:

$$E = E_o - m \cdot I_q \tag{11}$$

$$\omega = \omega_o - n \cdot I_p \tag{12}$$

where

$E_o$: voltage amplitude at no load

$\omega_o$: frequency at no load

$m$: droop coefficient for E

$n$: droop coefficient for $\omega$

The droop characteristics for two inverters of different power ratings are shown in Fig.9.

To ensure proper load current sharing according to inverter rating, the droop coefficients are selected as follows:

$$m_1 \cdot S_1 = m_2 \cdot S_2 = \ldots = m_n \cdot S_n \tag{13}$$

$$n_1 \cdot S_1 = n_2 \cdot S_2 = \ldots = n_n \cdot S_n \tag{14}$$

where $S_1$, $S_2$ ... $S_n$ are the apparent power ratings of the inverters. According to Fig.9, if $m_1$=$m_2$ and $n_1$=$n_2$, two inverters can be seen to share the $I_p$ and $I_q$. This droop method, however, can only share the AC current, it is useless to deal with DC cross current. Consequently, an additional method should be applied to eliminate the DC cross current.

### *C. DC Cross Current Control*

In parallel operation system, the output voltage of each inverter is forced to be equal, and it cannot reflect the offset of each inverter voltage. On the other hand, DC cross current is caused by the difference of each DC-offset voltage, and the inverter which has a higher offset voltage will own a positive DC cross current, and vice versa. Consequently, $I_{dc}$ can act as the $V_{dc}$ in Fig.5.

In the new scheme as shown in Fig.7, by adding $I_{dc}$ multiplied with $K_{dc}$ (a proportional constant) to the voltage feedback signal, controller possesses the droop ability of DC-offset voltage relating to the DC cross current, that is, inverter DC-offset voltage will decrease with the positive DC cross current. According to Fig.10, as the example of parallel operation of two inverters, the different DC-offset voltage lead to $I_{dco}$ (initial DC cross current) firstly, then the DC-offset voltage of the inverter who has a positive DC cross current will decrease by means of $V_{dc}$-$I_{dc}$ droop scheme, and the offset of the other will increase because of the negative DC cross current. Ultimately, they will have the same $V_{dc,}$ and DC cross current is eliminated.

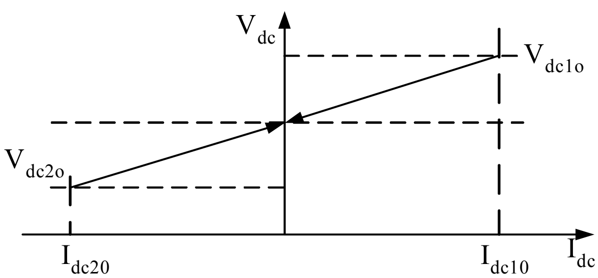


Fig.10 Vdc-Idc droop scheme

It is to be noted that this droop scheme can only make inverters have the same DC-offset voltage so as to avoid the DC cross current, whereas it cannot get rid of the DC-offset voltage.

## IV. EXPERIMENTAL RESULTS

To verify the validity of the proposed approach two 1.5-kW single-phase inverters are built and tested. Each inverter consisted of a single-phase IGBT full-bridge with a switching frequency of 8kHz and an LC output filter. The controller is implemented by means of a Texas Instruments TMS320F240 digital signal processor (DSP). TABLE I shows the parameters for the inverters.

Fig.11 shows the voltage and current steady-state waveforms of one of the parallel connected inverters. According to Fig.12, the dynamic performance of the parallel system is evaluated in case of connecting inverter2 when inverter1 is supplying all the power required by a 1.5kW load. There is almost no DC cross current. Fig.13 shows that the proposed controller achieves a low circulating current between two inverters in steady-state.

TABLE I.

PARAMETERS OF INVERTERS CONNECTED IN PARALLEL

| Parameters | Inverter1 | Inverters |
|---|---|---|
| DC Bus Voltage | 172V | 169V |
| Output Voltage (rms) | 110V | 109V |
| Output Frequency | 400Hz | 400Hz |
| Filter Inductor | 496μH | 498μH |
| Filter Capacitor | 20 μ F | 21 μ F |

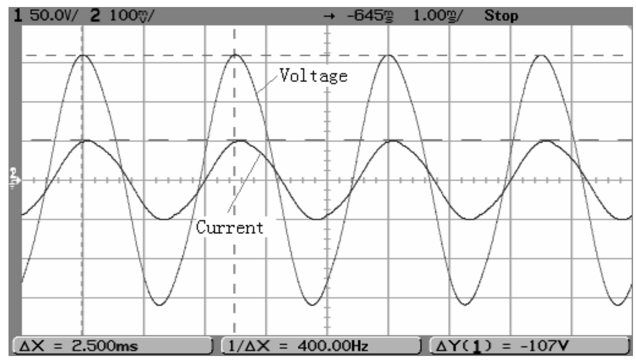


Fig.11: Voltage and current of a inverter in parallel operation

(X-axis: 1ms/div, Y-axis: 50V/div, 10A/div)

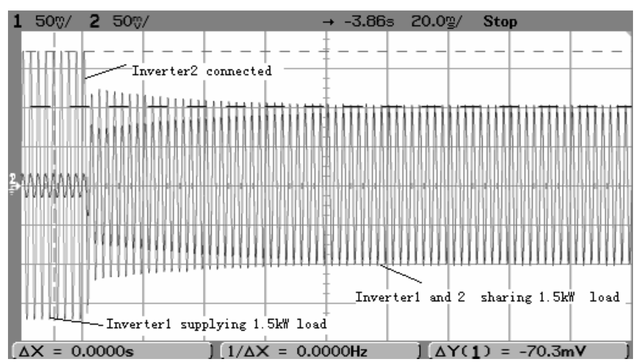


Fig.12: Transient response of current of two inverters

(X-axis: 20ms/div, Y-axis: 5A/div)

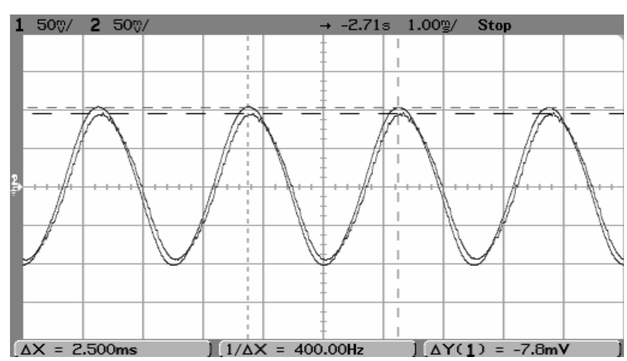


Fig.13: current Steady-state waveform of two inverters

(X-axis: 1ms/div, Y-axis: 5A/div)

## V. CONCLUSIONS

In this paper, a novel control scheme for parallel-connected inverters without communication wires is presented. The controller decomposes the output current into two parts, and then, it uses fundamental voltage and frequency droop method to allow inverters to share the load current and uses a novel DC-offset voltage droop method to eliminate the DC cross current. The experiment results reported here show the effectiveness of the proposed approach.


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