

A Novel Control Method of 400-Hz Paralleled Single-Phase Inverter with Nonlinear Load

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Abstract. This paper deals with the harmonic current sharing for the parallel operation of 400 Hz inverters. As is known, the sharing of harmonic current is not guaranteed by the conventional droop method. For high power 400 Hz inverters, the modulation frequency ratio is fairly low, which cause difficulties to maintain low total harmonic distortion content in the output voltage. A new technique which allowed paralleled inverters to share linear and nonlinear load is presented. With this new approach, the harmonic circulating current between the inverters could be identified. The new method also introduces droop method and repetitive control into the control system to eliminate the cross currents. The results from the simulation in Matlab and the experiment in the 1.5 kW platform show the validity and effectiveness of the proposed solution.

Keywords: medium frequency, UPS, parallel operation, droop method, repetitive control

1. Introduction

The 400Hz medium frequency UPS systems have become increasingly important in the fields of critical loads such as hospital equipment, communication system, and computer system. The reliability as well as the power capability of the UPS systems can be increased by replacing a single voltage-source inverter with multiple smaller voltage-source inverters in parallel as a defect inverter unit can be removed off line without affecting the operation of other inverters [1].

As a power supply source, the voltage output is not allowed to change dramatically when the load changes. That means the equivalent output impedance of the inverters is tiny. As a result, the inevitable little difference between inverters can cause huge cross currents. A lot of methods are raised to eliminate the cross currents. Some methods allowed inverters to exchange information by communication wire to decide the value of voltage [2-4], and the others keep inverters completely wireless interconnected [5].

However, technical challenges for these methods are the current sharing in all loading conditions, especially with the nonlinear load. Although many methods of operating inverters in parallel can be found in the literatures, there is yet not a satisfactory method to achieve an accurate sharing in both fundamental-frequency and harmonic load currents [6]. This paper presents a new control scheme based on a repetitive controller combined with the droop method to gain the goals mentioned above.

In this paper, a repetitive control approach is used to deal with the distortion in the voltage output induced by nonlinear loads. An improved droop control method basing on a well-known concept in power systems can eliminate the cross currents among inverters without any wire interconnection.

2. System Analysis

2.1 Circuit analysis for paralleled inverters

The equivalent circuit of two sets of inverters connected to the common bus is shown in Fig. 1.

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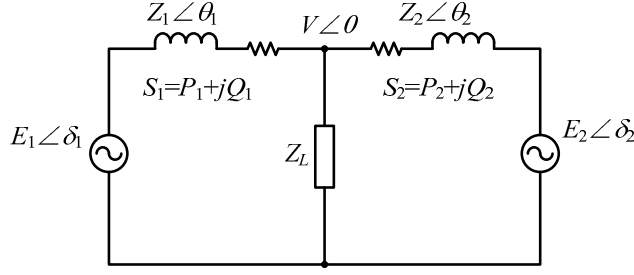


Figure 1. Equivalent circuit of two sets of inverters

Taking only one inverter into account, the power flow in this circuit can be expressed below.

$$S = P + jQ \quad (1)$$

In (1), P , Q is active and reactive power which are described as,

$$P = \frac{EV}{Z} \cos(\theta - \delta) - \frac{V^2}{Z} \cos \theta \quad (2)$$

$$Q = \frac{EV}{Z} \sin(\theta - \delta) - \frac{V^2}{Z} \sin \theta \quad (3)$$

where δ is the phase angle between the output voltage of the inverter and the voltage of the common bus, Z is the output impedance of the inverter ($Z = R + jX$) and θ is the impedance angle, E and V are the amplitude of the output voltage of the inverter and the common bus' voltage respectively.

If $X \gg R$, then R may be ignored and $\theta \approx 90^\circ$. Also if the power angle δ is very small, then $\sin \delta \approx \delta$ and $\cos \delta \approx 1$. (2) and (3) then become as,

$$\delta = \frac{XP}{EV} \quad (4)$$

$$E - V = \frac{XQ}{V} \quad (5)$$

From the equations above, we can conclude that the power angle depends predominantly on P , and the voltage deference depends predominantly on Q . In other words, the angle δ can be controlled by active power P , while the inverter output voltage $E - V$ is controlled by reactive power Q .

All mentioned above is the premise for droop theory. By using this droop characteristic, we can reach the goal of accurate load sharing among the inverter units.

Especially, the analysis above only refers to a single inverter. In fact, $E_1 \angle \delta_1$ and $E_2 \angle \delta_2$, $Z_1 \angle \theta_1$, and $Z_2 \angle \theta_2$ are both different between two inverters controlled independently. In the process of analysis and simulation, we can assume that $E_1 \angle \delta_1$ is equal to $E_2 \angle \delta_2$, and then attribute the actual error into the error between $Z_1 \angle \theta_1$ and $Z_2 \angle \theta_2$. It means the total difference of the inverters is caused by the equivalent output impedance. The paper's design and simulation are based on this assumption.

2.2 Analysis on the harmonic currents

There are plenty of harmonic currents in the nonlinear load, and the voltage distortion caused by them is compensated by inverters paralleled.

The analysis on the harmonic currents can be done in two aspects: fundamental and harmonic currents.

1) Analysis on Fundamental-Frequency Current:

A simplified equivalent circuit as Fig. 1 shows that the nonlinear load can be replaced by a linear load only considering the fundamental-frequency aspect. So the conclusion we draw from Part A can be applied here.

2) Analysis on Harmonic Currents

A simplified equivalent circuit as Fig. 2 shows that the nonlinear load can be regarded as a current source because the inverter's output voltage is nearly constant. Taking the single k^{th} harmonic component of 400Hz and the equivalent output impedance Z_{1k}, Z_{2k} into consideration, the impedance is nearly inductive because the

inductance of the wire is far bigger than the resistance. As a result, the reactive power will be the majority in the harmonic current's power and it meets the premise for droop theory mentioned above.

In the aspects of compensation for harmonic distortion, E_{1k} E_{2k} produced by inverters are used to eliminate the distortion in the C point which is caused by harmonic current I_k and the harmonic voltage in B is requested to be nearly zero as shown in Fig. 2. According to the theory in Part A, the sharing of the harmonic currents in the two inverters can be achieved by tuning the amplitude of the compensation voltage E_{1k} and E_{2k} . Solution Method Introduction.

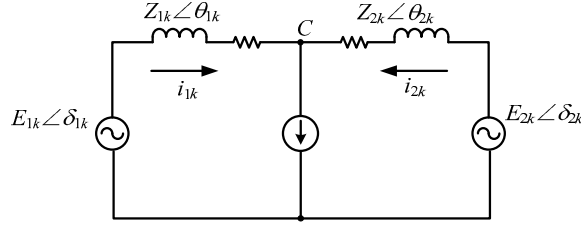


Figure 2. Equivalent circuit of kth harmonic frequency

2.3 Complex control scheme

Fig. 3 shows the complex control scheme composed of a repetitive controller and a multiple-feedback loop controller. The repetitive controller can minimize voltage distortion resulted from periodic disturbances, whereas the multiple feedback loop controller is used to change the control structure and to improve the transient response. Therefore, it is possible to take advantage of both two controllers to form a two-layer controller more effective than either one of the two separately [7].

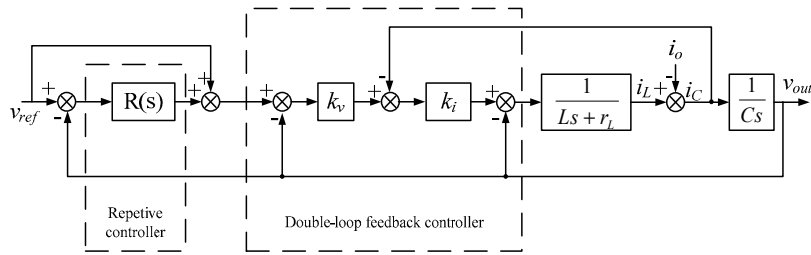


Figure 3. Block diagram of the proposed complex controller

In this paper's design, the repetitive controller is in the charge of the major compensation of harmonic distortion while the multiple feedback loop controller deals with the compensation of the fundamental-frequency voltage drop.

The designs of the two controllers will be presented in the following subsections. Fig.3 shows the double loop feedback control scheme which is based on the capacitor current feedback. The capacitor current is sensed for the regulation of the inner current loop to provide a fast transient response. Moreover, the outer voltage loop regulates the output voltage to make sure that the output voltage is within the acceptable range [8].

Fig. 4 shows repetitive controller which is based on the internal model principle [9, 10]. In this block diagram, $r(k)$ is the sinusoidal reference, $e(k)$ is the output voltage error, $d(k)$ is the disturbance input, and $u(k)$ is the output voltage. We can see that the repetitive controller calculates its correction component using $e(k)$, then the correction component is added to $r(k)$ to achieve output voltage waveform correction.

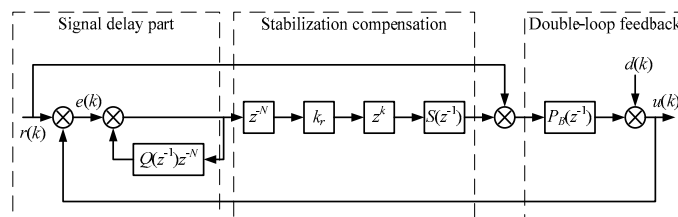


Figure 4. Block diagram of the repetitive controller

The part of Signal Delay is the core of the repetitive controller. It postpones the error correction by one fundamental cycle to produce an internal model.

The part of Stabilization Compensation is used to improve the structure of the system so as to eliminate the possible harmonic peak and also to use z^k to make the phase delay cancellation possible. In this proposed repetitive controller, the majority of the distortion can be compensated and the output can be much closer to requested sinusoidal waveform.

2.4 Decomposing of currents

It is an important part in this paper to decompose the currents into active, reactive and harmonic components as Fig.5 shows [9]. Firstly, three phase currents are constructed from single phase current I_0 through the delay of 120° and 240° respectively and then are changed into α - β coordinate by the 3-2 transform. Secondly, a phase-locked loop (PLL) is used to get the sine and cosine value of output voltage U_0 . Then, the i_α , i_β can be changed into DC component I_p (active current), I_q (reactive current) through p-q transform and Low Pass Filter. In the end, I_h (harmonic currents) can be derived by removing fundamental component for I_0 .

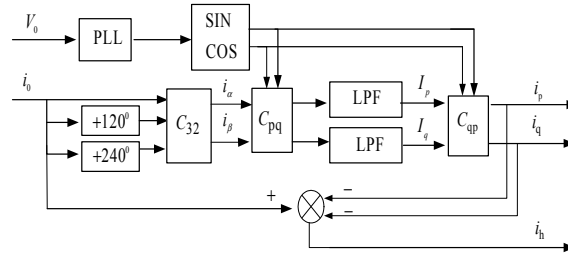


Figure 5. Block diagram of the currents' decomposing

2.5 Droop theory

The droop theory is well applied in large-scale power systems, and it is also introduced into the control system of UPS to eliminate the cross current in the parallel of the inverters.

1) Realization of Droop Theory

Traditionally, the droop theory is realized by detecting the active power and reactive power. However, in this paper, the direct goal is to control the sharing of the currents. Furthermore, the current decomposing takes more advantage over the power decomposing because it can avoid the disturbance of output voltage U_0 [9]. As a result, the real power, reactive power, and the distortion power are replaced by the decomposed currents I_p , I_q , I_h . and the formulas for droop calculating are listed as follows.

$$\varphi = \varphi^* - mI_p \quad (6)$$

$$E = E^* - nI_q \quad (7)$$

$$K = K^* - dI_h \quad (8)$$

and E^* are the output voltage's angular phase and amplitude at no load, K^* is the attenuation factor for the repetitive controller, and m , n , and d are the droop coefficients for the frequency, amplitude and the attenuation factor, respectively.

2) the Way to Determine the Coefficient

In the traditional paralleled system, there is usually an electric reactor between the inverter and the load. It benefits to the current sharing and the system stabilization. However, it degrades the quality of the output voltage, especially causing the drop of the amplitude of the output voltage and it also increases the inverter's bulk and cost.

In nature, the droop theory used here is just to simulate the electric reactor using DSP algorithm. Furthermore, there is also a method to recover the loss of the voltage's quality [6].

Both the equivalent output impedance of inverter on rated condition and the range of the error in amplitude and phase of output voltage are measurable. So they can be attributed into an equivalent value Z , $Z \approx jX$. According to (4) and (5), we can get,

$$P = VI_p \approx \frac{EV}{X} \delta \quad (9)$$

$$Q = VI_q \approx \frac{V}{X}(E - V) \quad (10)$$

The droop coefficient m and n can be determined according to (6), (7), (9) and (10), then we know some relationships such as $m \approx \frac{E}{X}N$, $n \approx \frac{1}{X}N$.

The two equations above help us to get the proper droop coefficient which can gain perfect current-sharing performance in the idealized condition. In our engineering procedure, the value of m and n should not be too large because it might make the quality of the output voltage degraded.

To find the range of d , the part $Q(z^{-1})$ is quite important in the repetitive controller which decides the precision of the distortion compensation.

The K is changed within the range of 0.95~1 according to the I_d and d in (8). The value of Q is renewed online by replacing Q with the product of Q and K according to

$$Q^* = K * Q \quad (11)$$

In this way, we can control the amplitude of compensation voltage E_{1k} and E_{2k} to achieve the goal of harmonic currents' sharing as shown in Fig. 6.

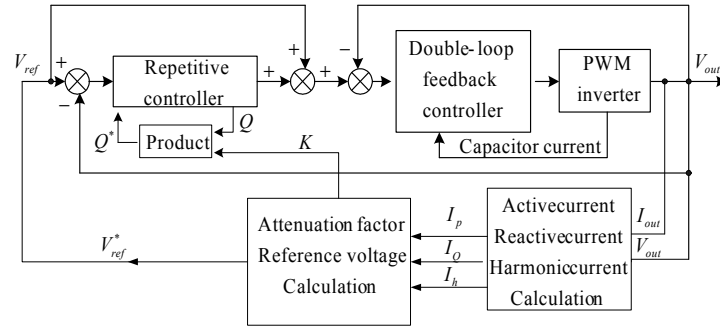


Figure 6. Block diagram of the proposed controller

3. Simulation of Control Scheme

The parameters of the simulation are listed as follows:

DC bus voltage: 260V

Output voltage: 115V, 400Hz

Sampling frequency: 16 KHz

Filter Inductor: 500μH

Filter Capacitor: 50μF

It has been mentioned that the error in amplitude and phase of output voltage can be attributed into an equivalent value Z . So the two equivalent values are assumed that:

$$Z_1: 0.001+j0.02790 \Omega$$

$$Z_2: 0.0005+j0.01395 \Omega$$

Simulation1:

To verify the validity of the control scheme with linear load, the simulation is proceeded on condition that the equations (. . . - $m I_p$ and $E = E^* - n I_q$) take into effect.

$$\text{Load impedance: } 1 + j2.5133 \sim$$

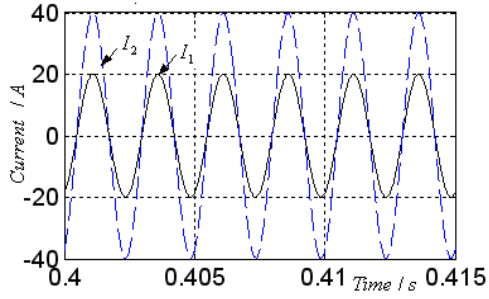


Figure 7. currents sharing without proposed control

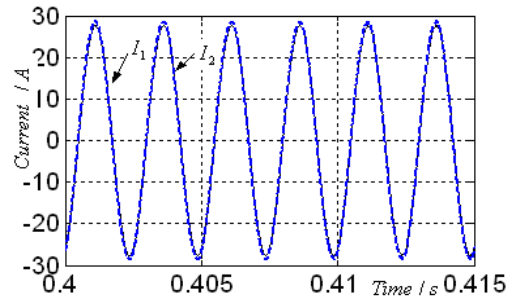


Figure 8. currents sharing with proposed control

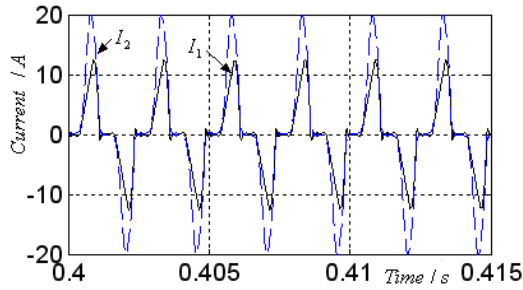


Figure 9. currents sharing without proposed control

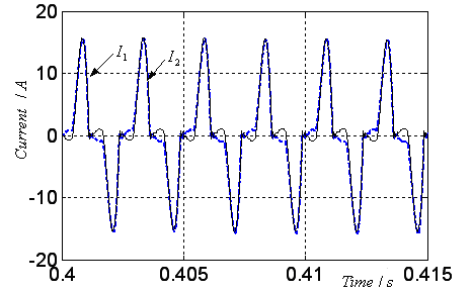


Figure 10. currents sharing with proposed control

I_1 and I_2 mean the output currents of inverter 1 and inverter 2. Fig. 7 shows us the distribution of the load current between inverters without control: the absolute error of the impedance is quite small but the cross current increases quite largely. Fig. 8 shows us the effect of the sharing control: the output currents of the two inverters are nearly same. In TABLE I, the RMS of cross current is changed from 7.048A to 0.324A.

Simulation 2:

To verify the validity of the control scheme with nonlinear load, the simulation is proceeded on condition that the equation ($K=K^* -d I_h$) takes into effect, too.

Load is a bridge rectifier with a capacitor filter. The input voltage: 115V, the current: 13.69A, THD: 57.20%.

Fig. 9 and Fig. 10 show us the different sharing performance of harmonic currents when we add harmonic sharing algorithm into the controller. The data in TABLE II proves that the improved droop method takes into good effect to eliminate the fundamental and the harmonic cross currents.

Table 1 Current s Sharing with Linear Load

RMS (A)	Without control		With control	
	Inverter1	Inverter2	Inverter1	Inverter2
Output current	14.15	28.24	19.52	20.17
Circulating current	7.048		0.324	

Table 2Current s Sharing with Linear Load

RMS (A)	Without control		With control	
	Inverter1	Inverter2	Inverter1	Inverter2
Fundamental output	5.108	8.598	6.685	6.891
Harmonic output	3.127	4.89	3.789	4.11
Fundamental cross current	1.761		0.175	
Harmonic cross current	1.183		0.452	

4. Experimental Results

Two 1.5-kW single-phase inverters are built to verify the validity of the proposed method. One Texas Instruments TMS320F2812 digital signal processor (DSP) controls each inverter which is consisted of a single-phase IGBT full-bridge with a switching frequency of 16 kHz and an LC output filter.

A nonlinear load is constructed by a bridge rectifier, a LC filter and a resistive load. TABLE III shows its parameters.

Table 3 Parameters for the Inverters and the Load

Parameters	Symbol	Nominal Value
Output Voltage (rms)	V_{out}	115V
Filter Inductor of load	L	748 μ H
Filter Capacitor of load	C	673 μ F
Resistive load	R	9.68 Ω

Fig. 11 shows the voltage and current steady-state waveforms of one of the inverters when connected to the nonlinear load alone. Fig. 12 shows the voltage and current waveforms of the same inverter when paralleled to another inverter. The current becomes half of previous value as they share the same load. Under nonlinear load there is little distortion in the output of the voltage waveform.

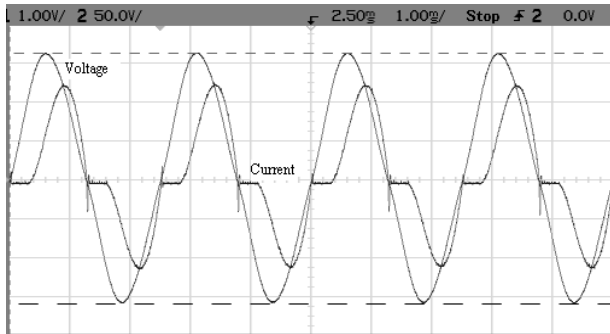


Figure 11. current and voltage output without paralleling (X-axis: 1ms/div, Y-axis: 10A /div, 50V /div)

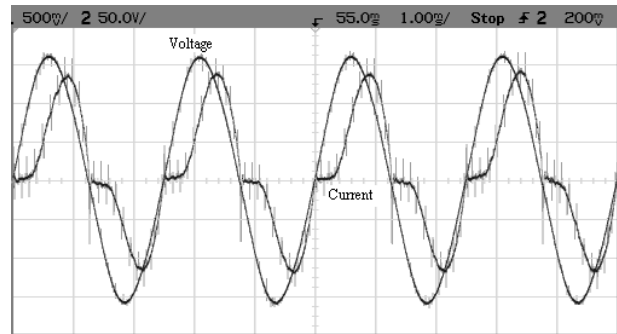


Figure 12. current and voltage output with paralleling (X-axis: 1ms/div, Y-axis: 5A /div, 50V /div)

Fig. 13 shows the distribution of the load current between the two inverters. According to Fig. 13, we can draw the conclusion that the proposed controller achieves a low cross current between two inverters in steady-state.

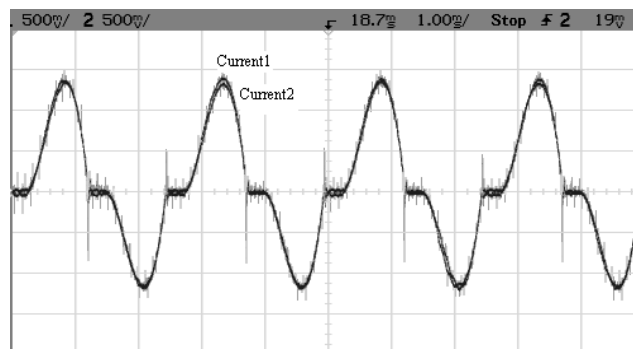


Figure 13. currents sharing with proposed control.(X-axis: 1ms/div, Y-axis: 5A/div, 5A/div)

5. Conclusion

In this paper, a novel droop control for parallel-connected inverters with nonlinear load was present. The repetitive controller was applied into the system to control harmonic currents sharing as well as the compensation of the output voltage. The simulation and the experiment results confirmed the validity of this proposed algorithm.

6. References

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