An Improved Multiple-loop Controller for Parallel Operation of Single-phase Inverters with No Control Interconnections

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***Abstract*- In this paper, we present a multiple-loop control scheme which is able to improve the transient response and power sharing accuracy of parallel-connected single-phase inverters with no control interconnections, and we also analysis the active and reactive circulating current of the parallel system model. A multiple-loop controller is developed, by adding four compensation loops to the traditional droop method. The output voltage and load current compensation loops are added in the scheme to improve the performance and robust of a single inverter. The instantaneous reference adjustment loop and variable output impedance adjustment loop are added to enhance dynamic performance of parallel inverters, as well as reduce the circulating current at the parallel inverter's startup and running. The proposed controller provides both steady-state objectives and a good transient performance. Two 1kVA DSP-based single-phase UPS inverters are designed and implemented. Simulation and experimental results are all reported, confirming the validity of the proposed control technique.**

I. INTRODUCTION

With the fast development of power electronics, parallel operation of inverter is increasingly developed to obtain N+1 redundant power system and creat a modular power distribution system[1,2]. The reliability as well as the power capability of the supply system can be increased by replacing a single inverter unit with more and smaller inverter units in parallel. Many methods of operating inverters in parallel can be found in the paper[3,4,5]. These techniques need some forms of control interconnection among the parallel inverters. These interconnecting wires not only restrict the location of the inverter units, but can also act as a source of noise and failure. Therefore, the system is not truly distributed or redundant.

The control schemes for parallel operation of inverters without control interconnection were presented in paper [6,7,8,9]. They are mainly based on droop method steams from the power system theory[10]. This droop method only use locally power measurements. To achieve good active and reactive power sharing, the controller makes tight adjustments over the frequency and amplitude of the output voltage of parallel inverters. However, the conventional droop method has a slow and oscillating transient response, since it requires low-pass filters to calculate the average value of the active and reactive power. And the line impedance is allways unknown, which can result in an unbalance reactive power flow. Then, the stability and the dynamics of the whole system are bounded by the maximum allowed adjustment of the output voltage amplitude and frequency.

In this paper, we proposed a multiple-loop control scheme which is able to improve the transient response and power sharing accuracy of parallel-connected inverters with no control interconnections. A multiple-loop controller was developed, by adding four compensation loops to the conventional droop method. This novel controller include two additional parts. The output voltage and load current compensation loops are added in the scheme to improve the performance and robust of a single inverter. The instantaneous reference adjustment loop and variable output impedance adjustment loop are added to enhance dynamic performance of the parallel inverters, as well as to reduce the circulating current at the parallel inverters' startup and running. The proposed controller provides both steady-state objectives and good transient performance. Two 1kVA DSP-based single-phase UPS inverters are designed and implemented. Simulation and experimental results are all reported, confirming the validity of the proposed control technique.

II. THE SYSTEM OF PARALLEL INVERTERS

A . Analysis of the circulating current characteristic

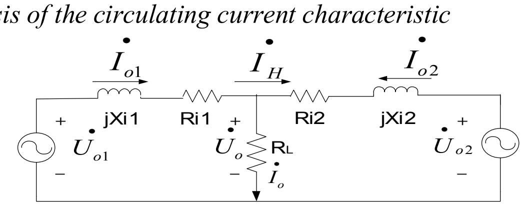

Fig.1 Parallel inverters system

Fig.1 shows the system of parallel inverters. And $\dot{U}_{o1}$ and $\dot{U}_{o2}$ is two inverters' open circuit voltage separately, $\dot{U}_o$ is the AC bus voltage, $Z = R_i + jX_i$ is the equivalent output impendence with two inverter modules. And the line impendence here is ignored. The angle of equivalent output impendence is α . Assuming that $R_{i1} = R_{i2} = R_i$, $X_{i1} = X_{i2} = X_i$. The circulating current $\dot{I}_H$, real and reactive

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power circulation P_H , Q_H of two inverters can be derived from Fig.1 as follows.

Where $\dot{U}_{o1} = U_{o1}\angle\delta_1$, $\dot{U}_{o2} = U_{o2}\angle\delta_2$,

a). When $\delta_1 = \delta_2$, $U_{o1} \neq U_{o2}$,

$$\dot{I}_H = \frac{\dot{U}_{o1} - \dot{U}_{o2}}{2(R_i + jX_i)} = \frac{\Delta U_o}{2\sqrt{R_i^2 + X_i^2}}\angle -\alpha \tag{1}$$

$$P_H = \frac{\Delta U_o * U_o}{2\sqrt{R_i^2 + X_i^2}}\cos\alpha \tag{2}$$

$$Q_H = \frac{\Delta U_o * U_o}{2\sqrt{R_i^2 + X_i^2}}\sin\alpha \tag{3}$$

b). When $U_{o1} = U_{o2}$, $\delta_1 \neq \delta_2$, $\Delta\delta = \delta_1 - \delta_2$,

$$\dot{I}_H = \frac{\dot{U}_{o1} - \dot{U}_{o2}}{2(R_i + jX_i)} \approx \frac{\Delta\delta U_{o1}}{2\sqrt{R_i^2 + X_i^2}}\angle(\pi/2 - \alpha + \Delta\delta/2) \tag{4}$$

$$P_H = \frac{U_{o1}U_o\Delta\delta}{2\sqrt{R_i^2 + X_i^2}}\sin\alpha \tag{5}$$

$$Q_H = -\frac{U_{o1}U_o\Delta\delta}{2\sqrt{R_i^2 + X_i^2}}\cos\alpha \tag{6}$$

From the equations above, we can see that the magnitude of circulating current caused by amplitude and phase difference of two inverters' output voltage. It is proportional to the voltage difference and reciprocal of output impedance's modulus, the ratio of reactive and real power caused by circulating current equals to $\tan\alpha$.

B . The Conventional droop control method

As mentioned previously, every resource needs an electric power interface to transfer energy to the common bus. We can model every unit as an inverter connected to the common bus through decoupling impedance, as shown in Fig.1. Because of the closed-loop control techniques, the output impedance of inverter is always highly inductive. $Z\angle\theta \approx X\angle 90^\circ$. And we can easily know the active and reactive powers drawn to the bus can be expressed as:

$$P_{o1} = \frac{U_{o1}U_0}{X}\sin\delta_1 \tag{7}$$

$$Q_{o1} = \frac{U_o(U_{o1}\cos\delta_1 - U_o)}{X} \tag{8}$$

Where X is the output reactance of one inverter, δ_1 is the phase angle between the output voltage of the inverter and the voltage of the common AC bus. And the value of δ_1 is always very little. And the equations above can be derived as follows:

$$\Delta P_{o1} = \frac{U_{o1}U_o}{X1} * \Delta\delta_1 \tag{9}$$

$$\Delta Q_{o1} = \frac{U_o}{X1} * \Delta U_{o1} \tag{10}$$

Depending on the equations above, the conventional droop methods we can get, which introduces the following droops in the amplitude V and the frequency ω of the inverter output voltage.

$$\omega = \omega_0 - m * P \tag{11}$$

$$V = V_0 - n * Q \tag{12}$$

To implement the droop method expressed by (11) and (12), the conventional droop method have a slow and oscillating transient response, since it requires low-pass filters to calculate the average value of the active and reactive power. So the conventional droop method has the limited transient response. And the performance of the systems is deeply impacted by the droop coefficients, the output impedance and the power calculation dynamics.

III. PROPOSED MULTIPLE-LOOP CONTROL TECHNIQUE

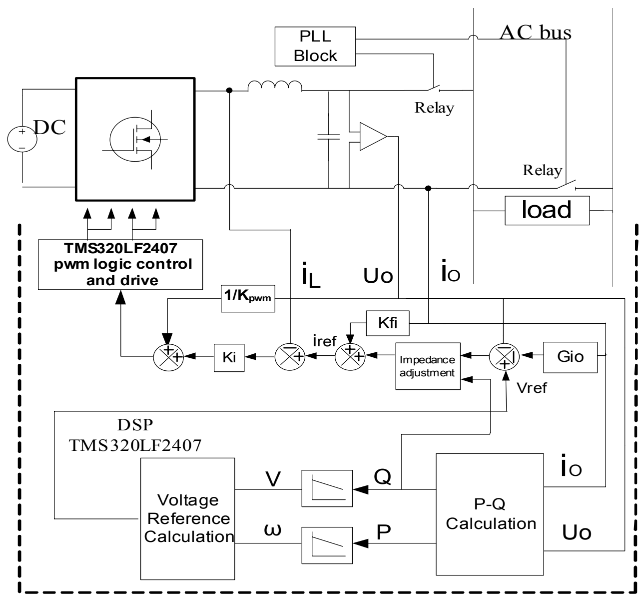
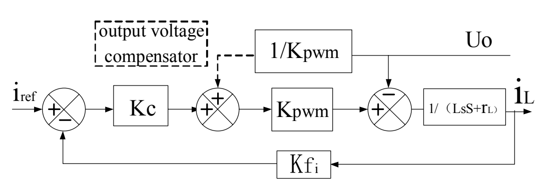


Fig.2 Proposed Multiple-loop control scheme

A block diagram for the multiple-loop controller for parallel inverters with no interconnections is shown in Fig.2. This novel controller includes two additional parts: the output voltage and load current compensation loops; the instantaneous reference adjustment loop and variable impedance adjustment loop. It improves the conventional droop method, and provides a proper output impedence based on the output current value. It can also make good active and reactive power sharing accuracy and reduce the circulating current with good transient response.

A. Output voltage and load current compensation loops



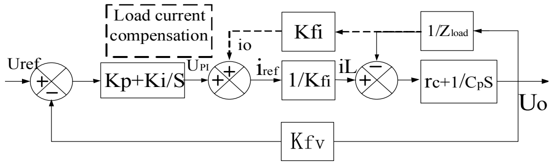


Fig.3 Block diagram of the output voltage and load current compensation loops

Fig.3 shows the multiple-loop control scheme implemented in the experimental prototype [11]. Three signals are sensed as feedback: inductance current (iL), load current (io) and output voltage (Uo). The inductance current is used to buildup the inner current loop, the output voltage is sensed for the outer voltage loop. Where Kpwm is the gain of the PWM inverter. If the output voltage feedback compensation gain is set to 1/Kpwm, the disturbance of the unknown load can be eliminated. The current controller gain Ki is set to high proportional gain, the resulting current loop can be quite simplified to a constant gain 1/Kfi. We also add the load current feedback to the controller, so the defects caused by the load current variation can be remedied perfectly.

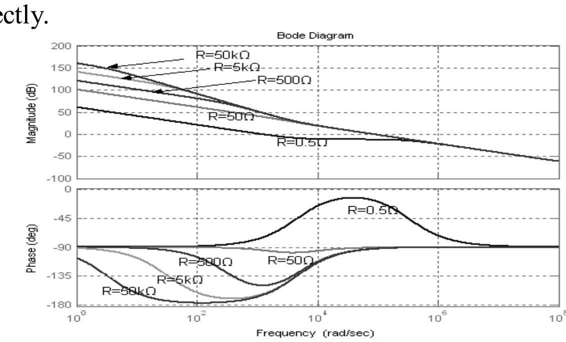


Fig.4 the frequency response of the system without compensations when load variation

As shown in Fig.4 clearly, without the compensation loops, the variation of load makes the system become instable, and the disturbance of load can also impact on the controller. So the controller system with output voltage and load current compensation loops can remedy the defects caused by the variation and disturbance of loads.

B. The instantaneous reference adjustment loop and variable impedance adjustment loop

The DSP-based controller also includes a PLL block in order to synchronize the inverter with the common bus. So when an inverter is suddenly connected to the common ac bus, a large startup circulating current appears due to the phase lock loop(PLL) module error. And the output peak current is expressed as:

$$I_p \approx \frac{U_o}{\omega L} \times \Delta \phi \ .$$

In conventional droop method, the adjustment of the output voltage frequency and amplitude only occur after each line cycle. So the startup circulating current will be very large. To reduce the initial current peak, a refernce adjustment loop is proposed. And if we use the new voltage reference, when the peak current occurs, the voltage reference can remedy it immediately. The ω_i must be greater than the voltage frequency due to no influencing on the voltage feedback.

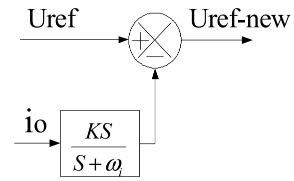


Fig.5 New diagram of the instantaneous reference adjustment

This loop can reduce the startup circulating current obviously, and improve power sharing accuracy. Fig.6 show the step response of the close-loop system when ωi changes. The conventional control scheme with no additional loop is compared with them in Fig.6. According to the harmonic current frequency , we can choose proper ωi to reach the best performance of the parallel inverters controller in Fig.6.

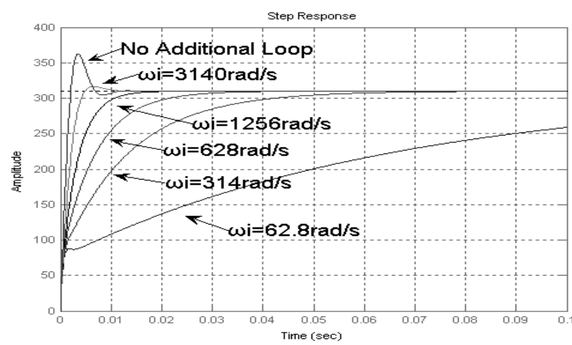


Fig.6 Step response of the close-loop system when ωi changes

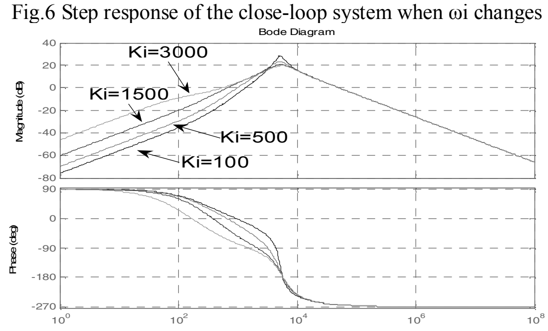


Fig.7 Output-impedance sensitivity with the integral coefficient (Ki) variation

Fig.7 shows the frequency-domain behavior of the output impedance through a Bode diagram. As it can be seen, the impedance is near inductive in the frequency range of interest that encloses the line frequency. And the impedance becomes less as the integral coefficient (Ki) of the voltage error PI controller shown in Fig.3 increases.

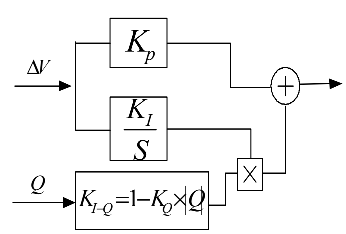
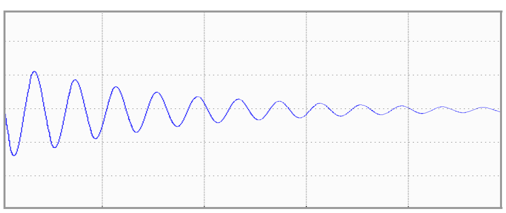


Fig.8 The variable impedance adjustment loop

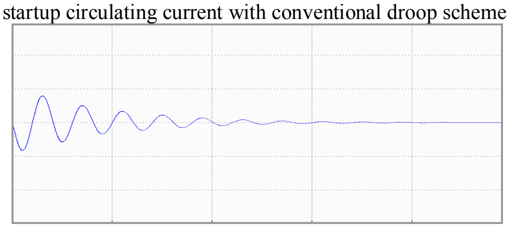
The variable impedance adjustment loop is constructed as shown in Fig.8. The integral coefficient (Ki) is depending on the reactive power sharing shown in Fig.8. In normal running state, the reactive power is near a small value, so the Ki is nearly a constant. When the reactive power is unbalance extremely, its effect on the integral coefficient (Ki) will make the output impedance changes. The changes can improve the power sharing accuracy and reduce the circulating current with good transient response.

IV. SIMULATION AND EXPERIMENTAL RESULTS

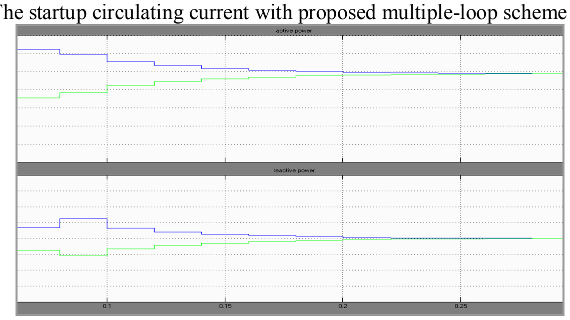
Two 1 kVA single-phase UPS inverter units were built and tested in order to show the validity of the proposed approach. Each inverter consisted of a single-phase insulated gate bipolar transistor (IGBT) full-bridge with a switching frequency of 20 kHz and an output filter, with the following parameters: 2mH, 6.6uF. The controllers of these inverters were based on the proposed multiple-loop control scheme. The controller was implemented using a TMS320LF2407A, 16-bit fixed-point 40 MHz digital signal processor (DSP) from Texas Instruments. The control parameters were chosen to ensure stability, proper transient response, and good phase matching. The DSP controller also includes a phase lock loop (PLL) block in order to synchronize the inverter with the common AC bus. When this occurs, the soft-start operation begins and the static bypass switch is turned on, then the control program is initiated. A model of multiple-loop control parallel inverters system is also built up using MATLAB/SIMULINK.



(a)The startup circulating current with conventional droop scheme



(b)The startup circulating current with proposed multiple-loop scheme



(c)The active and reactive power of the parallel inverters

Fig.9 (a), (b), (c) Simulation results of the parallel inverters system with initial phase error

Fig.9 (a) and (b) show that the startup circulating currents of the parallel inverters using the conventional droop method and the proposed control scheme respectively. The initial current peak due to the initial phase error between parallel inverters is much smaller through the improved multiple-loop controll scheme. In a sharp contrast with the conventional droop method, the controller presented show an excellent dynamic respose and good power sharing accuracy.

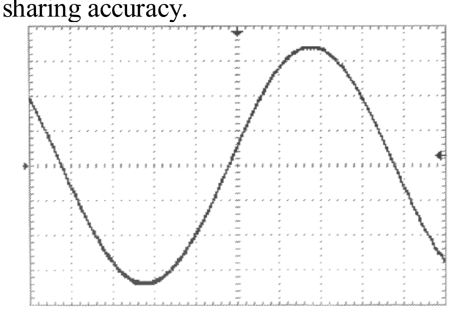


Fig.10 Experimental results of output voltage in parallel system (Y: 100v/div X: 2.5ms/div)

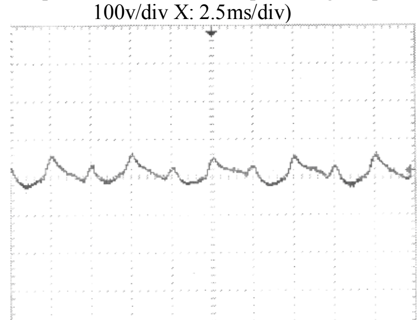


Fig.11 Experimental results of circulating current in parallel system (Y: 1A/div X: 10ms/div)

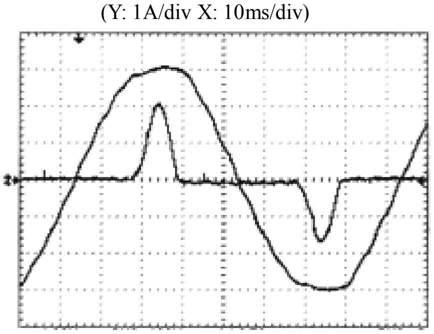


Fig.12 Experimental results of output voltage and load current under rectifier load (Y1: 100V/div Y2: 5A/div X: 2.5ms/div)

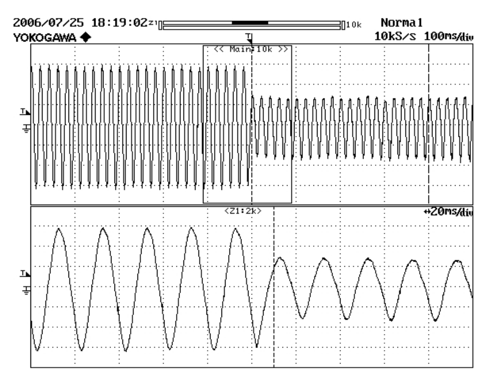


Fig.13 The output current of Inverter#1 when Inverter#2 connects to the AC bus (X-axis: top 100 ms/div, bottom: 20 ms/div; Y-axis: 4A/div)

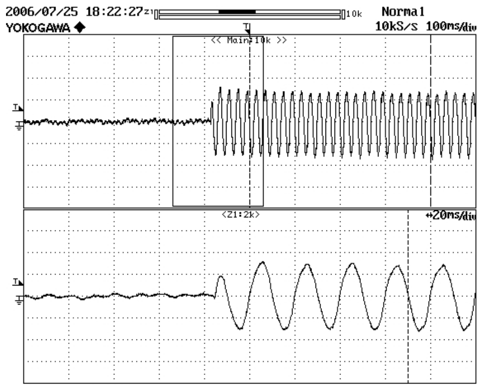


Fig.14 The output current of Inverter#2 when Inverter#2 connects to the AC bus (X-axis: top 100 ms/div, bottom: 20 ms/div; Y-axis: 4A/div)

These results confirm that the proposed controller achieves an excellent dynamic response than that of the classical droop method approach. The waveform of parallel inverter's output votage is perfect with very low THD content under linear load as well as rectifier load. A faster transient response, better dynamic performance, and less circulating current are achieved with the proposed control solution. The experimental results reported here show the effectiveness of the proposed multiple-loop control technique.

V. CONCLUSIONS

In this paper, a novel wireless power sharing controller for parallel operation of UPS inverters has been proposed. Based on the droop method, the mutiple-loop controller is developed, by adding four compensation loops to the conventional droop method. Both the time and frequency domain behavior of the controller have been examined. Simulation and experimental results have been included to show that the dynamic response and power sharing accuracy are significantly improved. The proposed controller provides both steady-state objectives and a good transient performance.

REFERENCES

[1]. C. Byungcho. "Comparative Study on Paralleling Schemes of Converter Modules for Distributed Power Applications," IEEE Transactions on Industrial Electronics, 1998, Vol.45, No.2, pp.195-199

[2]. S. H. Duan, Y. Meng, J. Xiong, et al, "Parallel operation control technique of voltage source inverters in UPS," IEEE PEDS'99, pp.884-887

[3]. S. Tamai and M. Kinoshita, "Parallel operation of digital controlled UPS system," in Proc.1991 Int. Conf. Industrial Electronics, Control, and Instrumentation, pp.326-331.

[4]. H. Oshima, Y. Miyazawa, and A. Hirata, "Parallel redundant UPS with instantaneous PWM control," in Proc. INTELEC'91, Nov. 1991, pp.436-442.

[5]. Ogasawara, S.; Takagaki, J.; Akagi, H, et al, "A novel control scheme of a parallel current-controlled PWM inverter," Industry Applications, IEEE Transactions on，1992，Vol 28, Issue 5, Sept.-Oct. Pp:1023 – 1030

[6]. Wallace, K.; Mantov, G.; "Wireless load sharing of single phase telecom inverters," The 21st International Telecommunications Energy Conference, 1999. INTELEC '99. 6-9 Page(s):7

[7]. J. M. Guerrero, L.Garcia de Vicuna, J. Matas, M. Castilla, and J. Miret, "A wireless controller to enhance dynamic performance of parallel inverters in distributed generation systems," IEEE Trans. Power Electron., vol.19, no. 5, pp.1205-1213, Sept.2004.

[8]. Yu Meng; Shanxu Duan; Yong Kang; Jian Chen;Research on voltage source inverters with wireless parallel operation,"Power Electronics and Motion Control Conference, 2000. Proceedings. PIEMC 2000. The Third International Volume 2, 15-18 Aug. 2000 Page(s):808 - 812 vol.2

[9]. Tuladhar, H.Jin, T. Unger, and K. Mauch, "Control of parallel inverters in distributed ac power systems with consideration of line impedance," IEEE Trans. Ind. Applicat., vol.36, no.1, pp.131-138, Jan./Feb.2000.

[10]. R. Bergen, Power Systems Analysis. Englewood Cliffs. NJ: Prentice-Hall, 1986.

[11]. Shih-Liang Jung, Hsiang-Sung Huang, Meng-Yuch Chang, Ying-Yu Tzou, "DSP-based multiple-loop control strategy for single-phase inverters used in AC power sources", page 706-712, vol. 1, PESC 97