Parallel Operation of Single Phase Inverter Modules With No Control Interconnections

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Abstract — We have developed a control technique for operating two or more single phase inverter modules in parallel with no auxiliary interconnections. This technique uses frequency, fundamental voltage, and harmonic voltage droop to allow independent inverters to share the load in proportion to their capacities. Simulation results are provided to prove the concept.

I. Introduction

Reliable power is something that we, in North America, often take for granted. This is not the case in many parts of the world; there are many scheduled and unscheduled outages. To provide reliable power under these conditions requires an uninterruptible power supply (UPS) which can be easily expanded to meet the needs of a growing demand. A system such as this should also be fault tolerant and include the capability for redundancy. These goals can be met by paralleling together smaller inverters if a control scheme can be designed to allow them to operate independently yet still share the load.

The conventional approach to paralleling modules requires interconnection between them to achieve balanced load sharing[1,2,3,4]. Often there is a common circuit block which, if it fails, renders the entire system inoperable. One of the methods of ensuring the proper sharing of loads among the parallel connected inverters is to use a master-slave configuration[4]: a voltage controlled PWM inverter is used as the master module and slave modules are current controlled. The master module controls the output voltage and generates the current command for the slave modules. This gives very good load sharing despite the presence of line impedances and is straight forward to design and implement. There are, however, some serious disadvantages: the system is now not truly redundant, the system reliability is reduced since a failure in the master brings the whole system down, and finally the interconnecting lines can be a source of noise or failure.

To achieve true modularity each module must be able to operate independently. We propose a control scheme using real power, reactive VA and distortion VA as control variables to allow independent operation of the modules. Each module has its own control loops and the only interconnection between modules is the paralleling of the ac power lines from each unit. Load sharing is achieved within each module by drooping the output frequency, voltage, and the harmonic voltages as functions of the real power, reactive VA, and distortion VA respectively which that unit is putting out. This will make the system both simple (to the end user) and expandable.

Published work has, so far, discussed this problem only as it applies to three phase systems with linear loads[5,6]. Since UPSs are frequently configured as single phase[7] and may be presented with a large proportion of nonlinear load - which must also be shared - the control issues are somewhat different. The focus of this paper is to present a technique to parallel two or more single phase inverters and share both linear and nonlinear loads. Using a conventional sinewave inverter with inner current and outer voltage loops, we manipulate the voltage command and the gain of the voltage loop. We have performed simulation studies on systems involving two paralleled modules to show the validity of this approach. The method works well for more than two modules and also for paralleled modules of different power ratings.

II. System Structure

Fig. 1 shows a power supply system with parallel connected single phase inverter modules and a load connected on the ac bus. To model the equivalent impedance of the connecting line, an impedance Z_{line} is inserted between the inverter module and the load bus. It is important to note that the line impedance for the UPS system is mostly resistive and so can not be represented by

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a simple inductance[1].

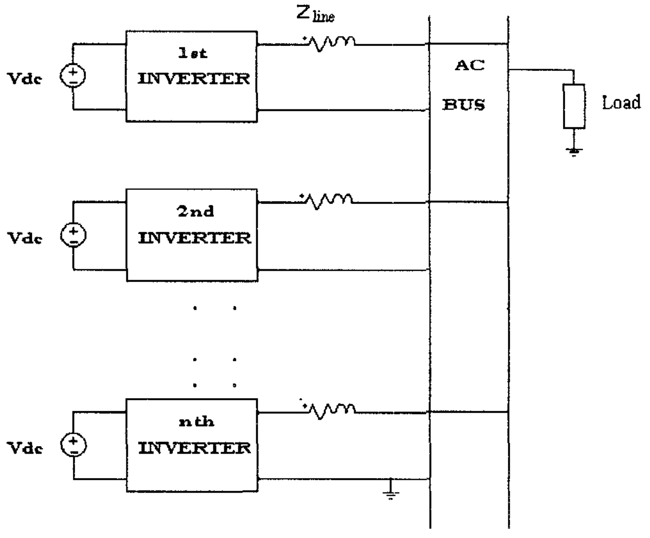
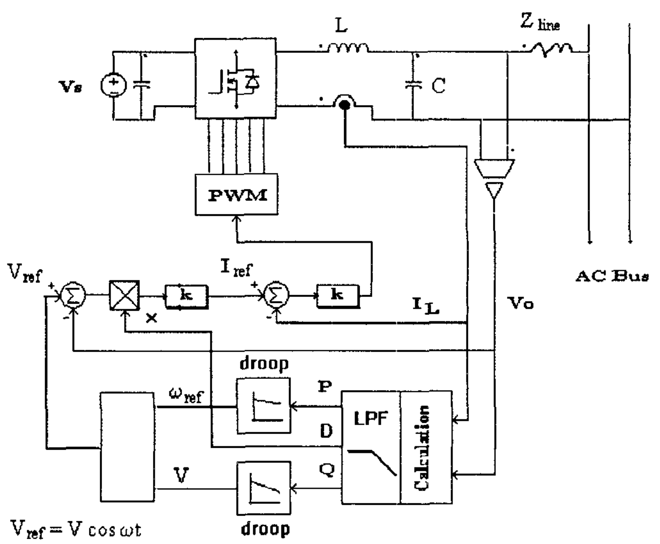


Fig. 1. Single phase ac power supply system with parallel inverter modules.

One inverter module with the proposed control technique is illustrated in Fig. 2.



where

P = real power
Q = reactive VA
D = distortion VA

Fig. 2. One inverter module with the proposed control scheme.

The key block of each module is a pulse-width modulated full-bridge inverter with an inner current loop and outer voltage loop. An LC filter is applied at the inverter output to reduce the high frequency components. The inductor current and the capacitor voltage are sensed as the feedback variables: the inner current loop provides inherent current limiting and simplifies the outer voltage loop design, the voltage loop regulates the output voltage.

When these units are paralleled together they should share the real, reactive and distortion currents in proportion to their power ratings. While this load sharing problem is similar to that faced by the utility system there are a number of differences:

- The utility system is three phase while the UPS system under consideration is one phase. Three phase systems offer the ability to resolve a single rotating vector for control purposes. They also allow a simple transformation to derive dc quantities from the AC variables thus making the control easier. Neither of these approaches is available in a single phase system.
- Most of the deliverable VA from the utility goes into loads that are linear and of fairly good power factor: large consumers pay a penalty for presenting poor power factor to the utility. Conversely the UPS may be called upon to deliver its full VA rating into nonlinear loads.
- The synchronous generators on the utility have a comparatively higher output impedance (on a per unit basis) than the inverters used in the paralleled UPS system.
- The synchronous generators automatically tend to droop their speed as a function of the output power; this is not naturally present in inverters .
- The synchronous generators have a fairly slow dynamic associated with the field current control - impacting the bandwidth of the voltage control. Inverters are capable of having a high bandwidth voltage control loop.
- The utility interconnecting lines are mostly inductive (of known value and thus can be canceled by line capacitors where needed) while the interconnections on this system are more resistive and not so well known.

These differences must be considered before applying the load sharing techniques used in the utility to sharing the load on a localized multi-module UPS grid composed of inverters.

[1] for example 100 ft of 14 gauge 2 wire cable has a resistance of 0.5 Ω and an inductive reactance of 0.01 Ω at 60 Hz.

Our work has shown that most of the control techniques used in the utility system can be adapted for the UPS system with some modifications. Some useful techniques from the power electronics area are also considered. We have tried to develop a control method which takes the best of both worlds.

III. Proposed Control Technique

A. To Share Linear Loads

First let us review some of the terms and theory related to the power flow in an ac system.

Consider two inverters connected to a linear load through pure inductances as shown in Fig. 3. Representing the line impedance with a pure inductance is done to simplify the analysis; note that the nature of the line impedance has a profound effect on the load sharing control.

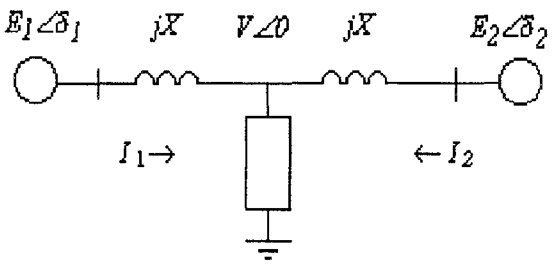


Fig. 3. Two inverters connected to a load.

The complex power at the load due to the inverter 1 is given by

$$S_1 = P_1 + jQ_1 = VI^*_1 \tag{1}$$

where I^*_1 is the conjugate of the inverter 1 current and is given by

$$I^*_1 = \left[\frac{E_1\cos\delta_1 + j\sin\delta_1 - V}{jX}\right]^* \tag{2}$$

$$\therefore S_1 = V\left[\frac{E_1\cos\delta_1 + j\sin\delta_1 - V}{jX}\right]^* \tag{3}$$

This gives us

$$P_1 = \frac{E_1 V}{jX}\sin\delta_1 \tag{4}$$

$$Q_1 = \frac{E_1 V\cos\delta_1 - V^2}{jX} \tag{5}$$

Similarly for the second inverter,

$$P_2 = \frac{E_2 V}{jX}\sin\delta_2 \tag{6}$$

$$Q_2 = \frac{E_2 V\cos\delta_2 - V^2}{jX} \tag{7}$$

For stable operation the real and reactive power flow from the inverters to the load should be properly controlled: there should be no real power circulation between two inverters. Eqs. (4) - (7) show that the real power flow predominantly depends on the power angles δ_1 and δ_2 while the reactive power flow is mostly influenced by the amplitude of the inverter voltages E_1 and E_2. To avoid overloading one inverter we want each inverter to respond to the load change so as to automatically take a share proportional to its power rating.

Since the inverter is a relatively stiff source, with unique values of open circuit frequency and voltage (due to component tolerances), large circulating currents would result if they were simply paralleled without additional control. This problem can be solved by introducing an artificial droop in the inverter frequency and voltage. Based on these predetermined droop characteristics, we have the frequency and the voltage amplitude:

$$\omega = \omega_o - m\cdot P \tag{8}$$

$$V = V_o - n\cdot Q \tag{9}$$

where

ω_o = frequency at no load
V_o = voltage amplitude at no load
m = droop coefficient for ω
n = droop coefficient for V

The droop characteristics for two inverters of different power ratings are shown in Fig.4.

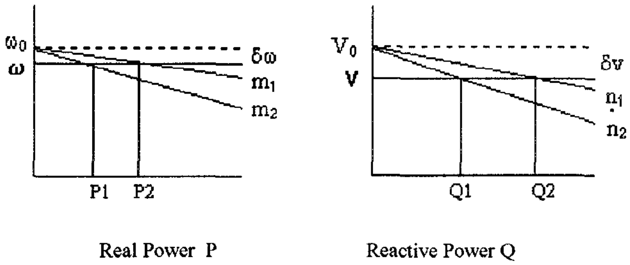


Fig. 4. Frequency and voltage droop.

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

$$m_1 \cdot S_1 = m_2 \cdot S_2 = m_3 \cdot S_3 \;....\; = m_n \cdot S_n \qquad (10)$$

$$n_1 S_1 = n_2 S_2 = n_3 S_3 \;....\; = n_n S_n \qquad (11)$$

where S_1, S_2 ... S_n are the apparent power ratings of the inverters.

Now, in Fig. 4, two inverters can be seen to share the real and reactive loads proportionately. The total load of the system is Q_1+Q_2 reactive and $P_1 + P_2$ real.

Because of the droop characteristics, the frequency and voltage of the system will drop to such a value that all units will be operating in a new lower frequency and voltage eliminating the circulating current. Thus the concept of droop leads each module to respond to the power flow in a controlled way. The tradeoff of this approach is the deviation in frequency and voltage from the nominal values; in theory these deviations can be made arbitrarily small but practical concerns will put a lower bound on how small the droop factors can be. This works well for linear loads but it will not help to share the distortion component caused by nonlinear loads.

B. To Share Nonlinear Loads

The total harmonic distortion for typical nonlinear loads (i.e. rectified capacitor loads such as most dc power supplies) can be as high as 150%. That is, the rms sum of the current harmonics is 1.5x the magnitude of the fundamental current. If the paralleled modules cannot ensure sharing of these harmonics then the system must be severely derated in the presence of nonlinear loads. This provides the motivation for sharing the current distortion components induced by nonlinear loads as well as the fundamental components associated with both linear and nonlinear loads.

In this case, the current will have significant content up to the 9th harmonic of 60Hz. Assuming the inverter voltage is sinusoidal, we derive expressions for the real power, reactive VA and distortion VA:

$$e_1 = \sqrt{2}E_1 \sin \varpi t \qquad (12)$$

$$i_1 = \sqrt{2}\{I_1 \sin(\varpi t - \phi_1) + I_2 \sin(2\varpi t - \phi_2) + \ldots + I_9 \sin(9\varpi t - \phi_9)\} \qquad (13)$$

where

I_n are the rms values of current components
Φ_n are the phase angles between the currents and the output voltage.

rms voltage $= E_1$(sinusoidal)

$$\text{rms current} = I = \sqrt{(I_1^2 + I_2^2 + I_3^2 + \ldots + I_9^2)} \qquad (14)$$

The apparent power is:

$$S = E_1 \times I \qquad (15)$$

$$\therefore S^2 = E_1^2 \times I^2$$

$$S^2 = E_1^2 I_1^2 \cos^2 \Phi_1 + E_1^2 I_1^2 \sin^2 \Phi_1 + E_1^2 \sum_{n=2}^{9} I_n^2 \qquad (16)$$

or

$$S^2 = P^2 + Q^2 + D^2 \qquad (17)$$

where

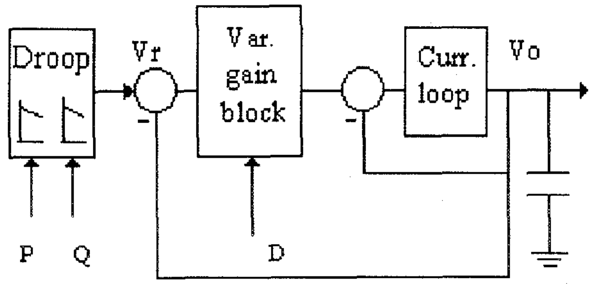
$P = E_1 I_1 \cos \Phi_1$ is the real power.

$Q = E_1 I_1 \sin \Phi_1$ is the reactive VA.

$D^2 = E_1^2 \Sigma I_n^2$ for $n = 2 .. 9$ is the distortion VA squared.

The distortion VA is due to the combination of voltage and current components of unlike frequencies. While there is no power (avg(VxI) = 0) in these harmonic terms, there are VA in them ($V_{rms} x I_{rms} \neq 0$).

Unlike the fundamental reactive VA, the flow of the distortion VA can not be influenced by adjusting the fundamental component of the inverter voltage alone. One method of solving this problem is to adjust the gain of the voltage loop as a function of the distortion VA. Fig. 5 depicts the control mechanism.



where

P = real power
Q = reactive VA
D = distortion VA

Fig. 5. The distortion VA is controls the gain of the voltage loop.

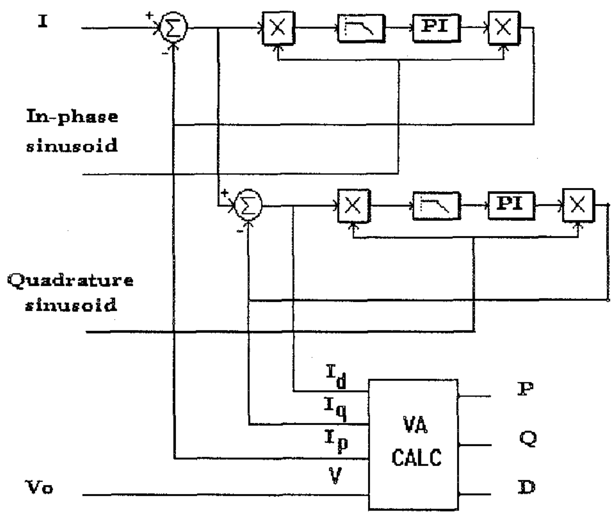


Fig. 6. Calculation of real power, reactive VA and distortion VA

By reducing the gain (and bandwidth) of the voltage loop in the presence of distortion components we effectively build in an output impedance which is basically what droop is. In this way we droop the harmonic voltage components which then encourages the separate modules to share the current harmonics.

The downside of this approach is a reduction in waveform quality. As is true generally of droop methods, the higher the droop the better the sharing. In this case a higher droop means a proportionate reduction in the voltage loop bandwidth and thus a reduction in waveform quality. It is up to the designer to strike an acceptable compromise between waveform quality and the accuracy of load sharing.

IV. Calculation Of Powers

One key block of the control scheme is the power calculation block. The computation algorithm must be such that both linear and nonlinear loads can be handled. This block must be carefully designed as its dynamics will impact overall system performance.

Fig. 6. shows the algorithm used to calculate all three power components. All the information required to calculate the power components is available in the filter inductor current and the inverter output voltage. The algorithm first splits the inductor current into its components and then multiplies them by the output voltage vector to yield the power components.

The inductor current is made up of the following terms [8]:

$$i_L(t) = i_0\,(t) + i_p(t) + i_q(t) + i_d(t) \tag{18}$$

where

i_0	=	dc component
i_p	=	in phase component
i_q	=	the quadrature reactive component.
i_d	=	the distortion component.

We can extract each of these components separately from the inductor current. Extracting the dc component is quite easy. To find the in-phase current component we multiply the current signal by a sinusoid that is in phase with the output voltage signal.

$$i\,(t)\sin\omega t = I_0 \sin\omega t + \tfrac{I_p}{2}[1-\cos 2\omega t] + ... + ac..terms.. \tag{19}$$

Eq. (19) has only one dc term which is proportional to I_p. Thus a low pass filter will be able to recover the in-phase current. The sinusoid in phase with the output voltage multiplied by the dc value, Ip, will give an estimation of the in-phase current. This estimate is then subtracted from the total current. The closed loop control will enable us to extract the in-phase current from the inductor current completely.

A similar method is used to extract the quadrature current from the inductor current. Then by subtracting the dc, in-phase, and the quadrature current from the inductor current, we can obtain the harmonic current (distortion current).

Knowing these current components and the output voltage, the real power, reactive VA, and distortion VA can be calculated.

V. Effect Of Line Impedance

Line impedance will affect the accuracy of load sharing. If the system can be informed of the value of the line impedance then this can be compensated. In the absence of this information, more droop can be used to improve sharing - but only to a point. For a two module case we have derived the following equation to find the droop required to achieve a desired accuracy of load sharing in the face of line impedances Z_1 and Z_2:

$$d = 100 (Z_1 - (1+x)Z_2) / V.\, x \qquad (20)$$

where

d	=	the droop required.
x	=	% of deviation in load sharing.
Z_1 & Z_2	=	line impedances.
V	=	load voltage.

VI. Simulation Results

Simulation results for two parallel connected modules of different power ratings supplying nonlinear loads are shown to illustrate the validity of the proposed approach. Two general purpose simulation packages - PSIM and Pspice - were used for the simulation studies. Fig. 7 shows the configuration of the simulated system. Table 1 shows the parameters for the inverters.

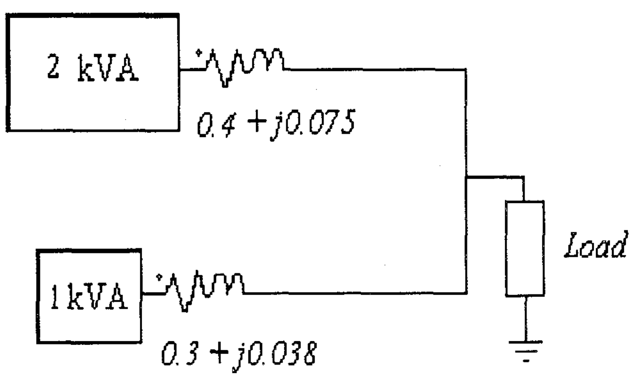


Fig. 7. Two parallel modules supplying a load.

TABLE I

PARAMETERS OF INVERTERS CONNECTED IN PARALLEL.

Parameters	Inverter1	Inverter 2
Filter Inductor	1.2 mH	1.2 mH
Filter Capacitor	15 uF	15 uF
Voltage	120 V	120 V
Frequency	60 Hz	60 Hz
Frequency Droop	0.001 rad/s/W	0.002 rad/s/W
Voltage Droop	0.01V/VAR	0.02 V/VAR
VA RATING	2000	1000
Harmonic Droop	0.0005 pu/VAR	0.001 pu/VAR
Line Impedance	0.4 + j0.075 Ω	0.3 + j0.038 Ω

A. Linear Load

The initial load of 5 Ω and 26 mH is stepped to 2.5 Ω and 13 mH at 0.23 sec. Since inverter module 1 has a frequency droop coefficient that is half of that in inverter module 2, it should provide twice as much real power. This is verified in Fig. 8.

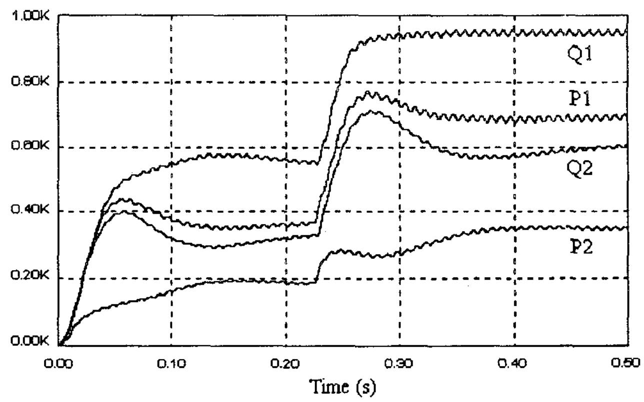


Fig. 8. Output power of two parallel inverter modules.

It is interesting to note that the real power is perfectly shared between the modules while the reactive power sharing is not strictly proportional. The reason for this discrepancy is the line impedance between the inverter modules and the load bus causing the inverter output voltages to differ from the load voltage.

B. Nonlinear Load

We used fullwave and halfwave rectified loads to check the same configuration of inverters for sharing of nonlinear loads. Figs. 9 and 10 show the load and module currents for the fullwave and halfwave simulations respectively. Module 1 is supposed to be supplying twice the current of module 2.

While this is not exactly the case (due to line impedances), the sharing is pretty good. The circulating current is also quite small.

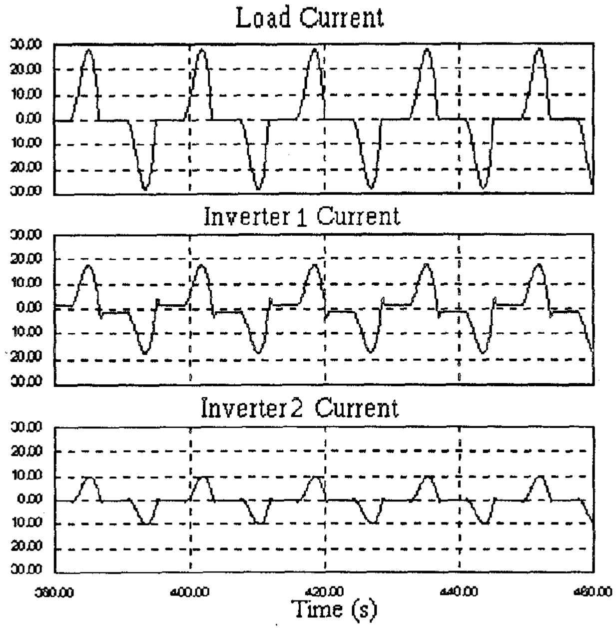


Fig. 9. Load current and currents put by each module.

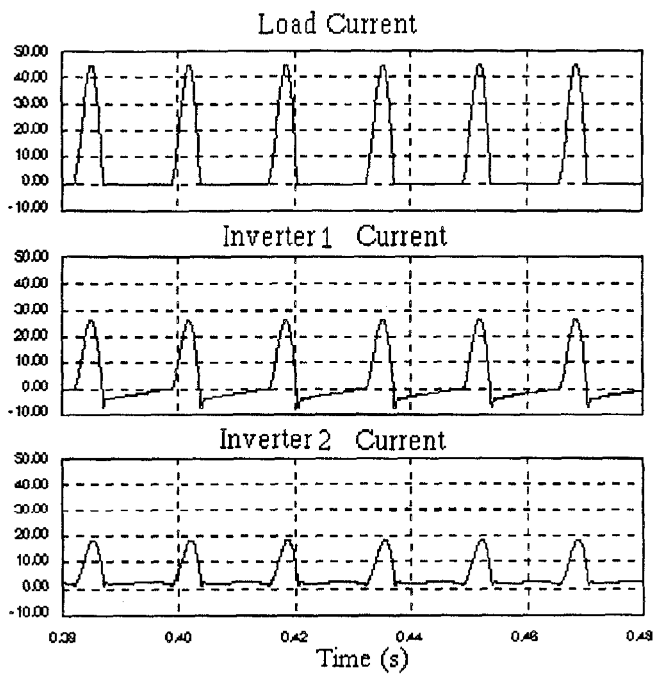


Fig. 10. Load and inverter currents for a halfwave rectifier load with harmonic droop in effect.

VII. Conclusions

We have presented a control technique for operating single phase inverters in parallel with no interconnections except for the ac power connection. By selecting frequency, voltage and the harmonic droop characteristics, proper load sharing can be automatically achieved for both linear and nonlinear loads. Simulation results prove the validity of this technique.

The primary disadvantage of this system is that the output waveform deviates from nominal in amplitude, frequency, and quality as a function of the load on the system.

Acknowledgment

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