SANYO DENKI TECHNICAL REPORT No.10 November-2000
General Theses

# UPS Parallel Operation Analysis Considering Line Resistance Influence

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## 1. Introduction

The parallel run of uninterruptible power supply units (UPSs) has been analyzed before. But, in many of these analyses, the inverter is replaced with a mere voltage source and line resistance is handled as a very small value (1) .

This project developed a model of the parallel run of the inverter including its control system, analyzed it while allowing for line resistance, and considered its effects on cross currents. Based on these analyses, the paper proposes a method of parallel running making aggressive use of the effects of line resistance and reports the actions observed.

## 2. Analysis of parallel running

### 2.1 Concept based on a traditional model and the differences between it and actual practice

When a parallel run is analyzed, a model as illustrated in Fig. 1 is generally used.

When this model is used under the conditions where $r_s = 0$ and no load is imposed, the voltage sources are connected together with a reactor 2L. At that time, the cross current $I_{cross}$ is given by the following equation:

$$I_{cross} = \frac{1}{j\omega 2L}\left(V_{inv2} - V_{inv1}\right)$$

From this equation, one can see that the cross current flowing through the model in Fig. 1 is inversely proportional to L and is delayed in phase by 90°; from the potential between the voltage sources. Therefore, when an amplitude difference is given as shown in the vector diagram in Fig. 2 (a), the cross current for the reactive portion alone is generated. On the other hand, when a phase difference is given as shown in Fig. 2(b), the cross current – most of which is the active portion – is generated.

To see what happens in an actual UPS, the authors added a control circuit to the model shown in Fig. 1 and performed a simulation. The model used in the simulation is illustrated in Fig. 3, and a block diagram of the control circuit portion is shown in Fig. 4. The simulation results obtained when $r_s = 0$ in this model are shown in Fig. 5.

Fig. 5 shows the results of a simulation performed at no load with an amplitude difference of only 2% given to the output voltage instruction to each device. From this diagram, one can see that, when a controlled inverter is connected in parallel, the cross current flowing through it includes not only the reactive power portion but the active power portion as well. From this, one can estimate that inverter control affects the way the cross current flows, as compared to the model shown in Fig. 1.

### 2.2 Analysis of the model including the control circuit

The above studies conclude that the discussion of the parallel control of a UPS requires an analysis including the control system.

A simultaneous equation made in complex numbers on the basis of Figs. 3 and 4 can be as follows:

$$\begin{bmatrix} 0 \\ V_{ref1} \\ V_{ref2} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} \frac{1}{R_{Load}} + j(\omega C - \frac{1}{\omega L_{Load}}) & 0 & 0 & -1 & -1 \\ \frac{K}{1+K} G(j\omega) & \frac{1}{1+K} & 0 & 0 & 0 \\ \frac{K}{1+K} G(j\omega) & 0 & \frac{1}{1+K} & 0 & 0 \\ 1 & -1 & 0 & rs + j\omega L & 0 \\ 1 & 0 & -1 & 0 & rs + j\omega L \end{bmatrix} \begin{bmatrix} V_{out} \\ V_{inv1} \\ V_{inv2} \\ I_{inv1} \\ I_{inv2} \end{bmatrix}$$

Solving this equation determines the voltage and current in a parallel run. To that end, $V_{ref1}$ and $V_{ref2}$ can be defined as

$$\begin{cases} V_{ref1} = V_1 e^{-j\theta_1} \\ V_{ref2} = V_2 e^{-j\theta_2} \end{cases}$$

and $V_1$, $V_2$, q $_1$ and q $_2$ can be defined arbitrarily to solve this equation. The voltage and current of each part can thus be determined. In this project, the authors wish to analyze the behavior of the cross current when there are changes in amplitude and phase between respective UPS outputs. Therefore, what must be done is to solve the equation while varying the amplitude ratio ( $V_2 / V_2$ ) and the phase difference ( q $_1$ − q $_2$ ). Determining the power on the basis of the voltage and current obtained by solving this equation r++es in the active and reactive powers with regard to the amplitude ratio and phase difference using the constants shown in Table 1 are shown in Figs. 6 (a) and (b).

Table 1. Constants of each part used in analysis

| Code | Constant | Unit |
|---|---|---|
| $r_s$ | 0 | [ W ] |
| $L$ | 1.3 | [mH] |
| $C$ | 20 | [ m F] |
| $K$ | 4 | |
| $T_1$ | 36.3 | [ m sec.] |
| $T_2$ | 123 | [ m sec.] |
| $R_{Load}$ | No load | |
| $L_{Load}$ | | |

In these graphs, the slope represents the effect of the amplitude ratio, while the distance between lines represents the effect of the phase difference. One can therefore see that the active and reactive powers are subjected more strongly to the effect of the amplitude as the slope increases. In addition, it is subjected more strongly to the effect of the phase difference as the distance between lines increases.

From the graph in Fig. 6(a), one finds that the change in amplitude has given the active power curve a slope that is not possible in the model shown in Fig. 1. This suggests that, in a controlled UPS, the active power is also affected by changes in amplitude.

### 2.3 Effects of control gain on parallel running

Next, let us consider how the control gain affects the cross current. Figs. 7 (a) and (b) are graphs showing the power shares of the cross current when a parallel run is performed with the control gain varied when the amplitude ratio as an instruction value is 2% and the phase difference is 1°.

From this figure, one can see that, as one increases the gain, both the active and the reactive portions of the cross current increase.

From the above results, one can see that the cross current in a parallel run is largely affected by the control gain. This indicates that passing the current through the control circuit gives the inverter output voltage an amplitude and phase difference greater than those present in the voltage instruction value.

The only element that is changing the phase on the control circuit shown in Fig. 4 is the phase compensation element G(s). This element is inserted to stabilize the system. The deviation in phase generated here is amplified by the control gain, thus causing major changes in the phase in the inverter output. When this changes the gain, the cross current presumably gets affected.

### 2.4 Effects of line resistance $r_s$ on a parallel run

Next, let us consider the resistance portion $r_s$, which the authors have ignored in the above analysis. The authors have so far let $r_s = 0$ to clarify that the cross current generates an active portion under a change in amplitude as well due to the control. However, an actual device always contains some kind of resistance. Therefore, let us first consider what the $r_s$ of the actual device is. Fig. 8 shows a graph of output voltage when a resistance load is applied to a real unit having almost the same circuit configuration as the model shown in Fig. 3.

From this graph, one can see that the UPS can be loaded to reduce the output voltage by about 8V. In actual practice, it is not that all causes are related to the $r_s$. Strictly speaking, it includes the nonlinear resistance due to the PWM and other elements. Here, however, one assumes that all is due to the $r_s$. If one calculates the above equation without giving amplitude or phase difference and using each parameter including loads and in such a manner that the voltage drop becomes 8V, the result of the device used in this test ( $r_s$ ) is about 2.3.

Based on the above findings, the authors examined how the active and the reactive portions of the cross current will change due to changes in the $r_s$. The relationship between the amplitude ratio and phase difference in a parallel run of the active and the reactive powers when $r_s$ is changed to 2.5 and to 5 in the model shown in Fig. 2, are shown in Figs. 9 and 10.

From Figs. 9 and 10, one can see that, as $r_s$ increases to a magnitude of some degree, the active portion of the change accounts for the larger percentage due to the change in amplitude, and the reactive portion of the change accounts for the larger percentage due to the change in phase in the cross current in a parallel run. One can also see that increasing $r_s$ further desensitizes both the active and reactive portions to changes in amplitude and phase.

From the above discussion, one can see that, when considering the parallel run of the inverter, the traditional model of controlling the reactive and active powers by amplitude and phase difference due to the presence of inverter control itself and the effect of line impedance $r_s$ does not necessarily hold.

## 3. Parallel control process

## 3.1 Proposing the parallel control process

As discussed so far, as $r_s$ increases, the less vulnerable the system is to the amplitude or phase in a parallel run. In that case, it becomes easier to control active power by amplitude. One can therefore divide the load by controlling the amplitude. Thus, the authors are considering a method of control that positively advances this way of thinking. However, in practice, this will lead to a loss, so that the resistance equivalent to $r_s$ cannot be placed in the main circuit. In this paper, therefore, the authors propose a control process as illustrated in Fig. 11. This circuit is so designed that its reactor current is fed back to the control circuit shown in Fig. 4.

Then, a block diagram based on the above diagram and made of a single unit as prepared by introducing the control system of the UPS is shown in Fig. 12.

Here, the authors are considering how the proposed control circuit shown in Fig. 11 affects the control system of the UPS. In the block diagram in Fig. 12, let $I_{Load} = 0$ and determine the transmission function of the output with regard to the voltage instruction value, and one can obtain the following equation:

$$\frac{V_{out}}{V_{ref}} = \frac{K+1}{Lcs^2 + (r_s + K_L)Cs + KG(s) + 1}$$

Looking at this equation, one finds that the line resistance $r_s$ and the reactor current feedback gain $K_L$ are included in the same term. This means that $r_s$ and $K_L$ have equal roles, and increasing $K_L$ produces results similar to those obtained when $r_s$ is increased without a loss on the main circuit. If the effect of G(s) is not considered, this term will become a pure term of attenuation.

A revised buildup of a simultaneous equation from the block diagram shown in Fig. 12 to confirm the above is as follows:

$$\begin{bmatrix} 0 \\ V_{ref1} \\ V_{ref2} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} \frac{1}{R_{Load}} + j(\omega C - \frac{1}{\omega L_{Load}}) & 0 & 0 & -1 & -1 \\ \frac{K}{1+K} G(j\omega) & \frac{1}{1+K} & 0 & \frac{K_L}{1+K} & 0 \\ \frac{K}{1+K} G(j\omega) & 0 & \frac{1}{1+K} & 0 & \frac{K_L}{1+K} \\ 1 & -1 & 0 & rs + j\omega L & 0 \\ 1 & 0 & -1 & 0 & rs + j\omega L \end{bmatrix} \begin{bmatrix} V_{out} \\ V_{inv1} \\ V_{inv2} \\ I_{inv1} \\ I_{inv2} \end{bmatrix}$$

Graphs showing the active and reactive portions of the cross current when $r_s = 0$ and $K_L = 2.5$ using this equation are shown in Fig. 13.

From the fact that Fig. 13 and Fig. 9 are similar graphs, one can see that $K_L$ is an alternative to $r_s$.

## 3.2 Experiment results

Output voltage and current waveforms of the inverter in a parallel run when $K_L = 2.5$ using this control are shown in Figs. 14 and 15.

Fig. 14 shows a waveform obtained when two units worth of rectifier load are applied when two units are run in parallel. This waveform allows one to check a good operation with hardly any cross current. With a harmonic cross current, the term sL exercises a particularly great influence. The load share presumably approaches equality more than the linear load. Fig. 15, on the other hand, shows a case when a second unit is introduced when one unit worth of load is applied to the rectifier load. This waveform shows how the load is applied with hardly any fluctuation. This is presumably due to $K_L$ functioning as a damper for transient fluctuations. These experiments demonstrate that a parallel run using the proposed control circuit functions well.

## 4. Conclusion

This paper has analyzed a parallel run of the UPS and checked the effects of the control gain and line resistance $r_s$ with regard to the cross current in a parallel run. The paper also presented a control process using the phenomenon where increasing $r_s$ makes both the active and reactive portions less vulnerable to the effects of the amplitude and phase difference, and demonstrated that it functions.

Among the future challenges are the transient response and a quantitative analysis of that response.

**Reference**

(1) Yanagi and Kondo, " Considering the Active and Reactive Power Control by Adjusting the Voltage Phase and Amplitude of a Parallel UPS, " A Collection of Lecture Papers from the National Congress of the Industrial Application Department, The Institute of Electrical Engineers of Japan, 1996, No. 67

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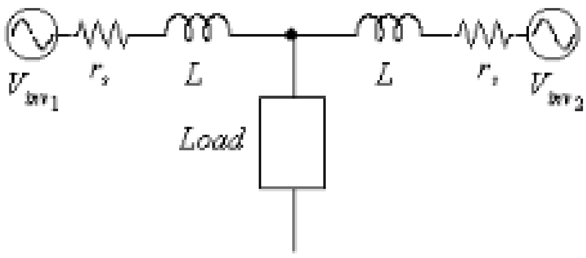
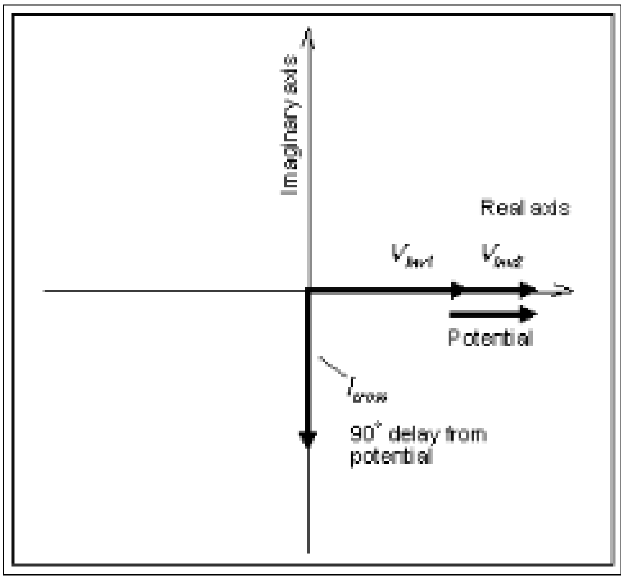
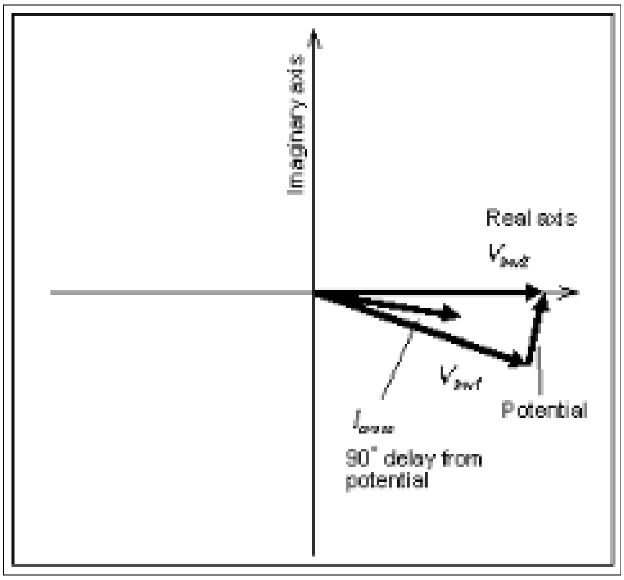



Fig. 1 Parallel connected model of UPS




(a) Amplitude difference only




(b) Phase difference only

Fig. 2 Vector diagram in a parallel connected model

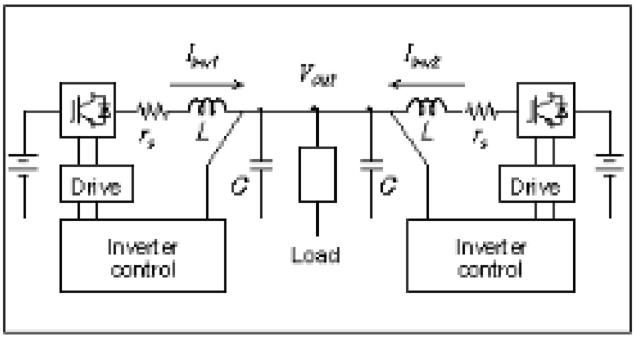



Fig. 3 Parallel connected model of UPS used in the simulation

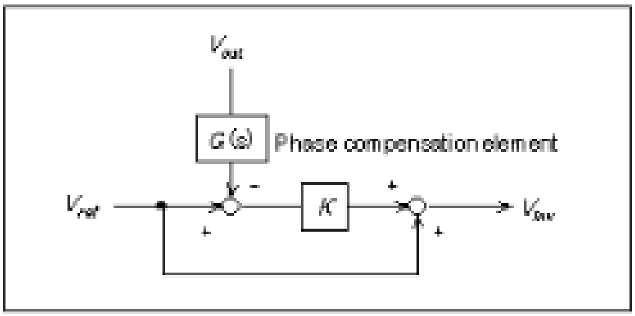



Fig. 4 Block diagram of inverter control

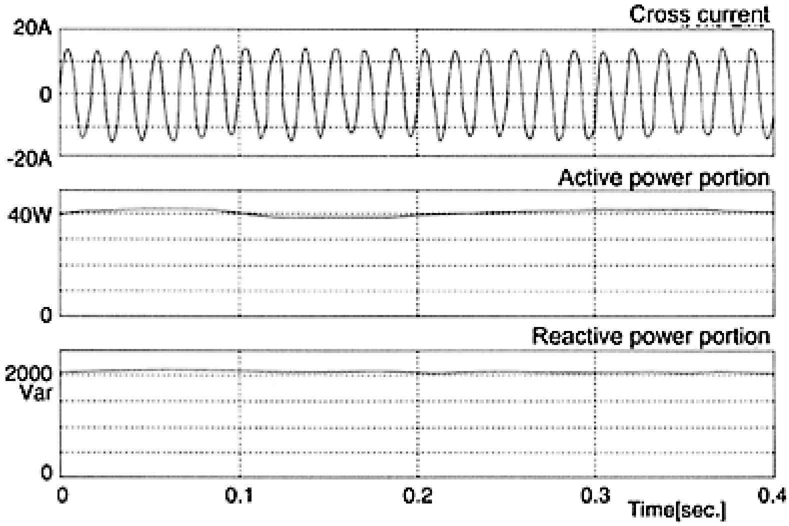
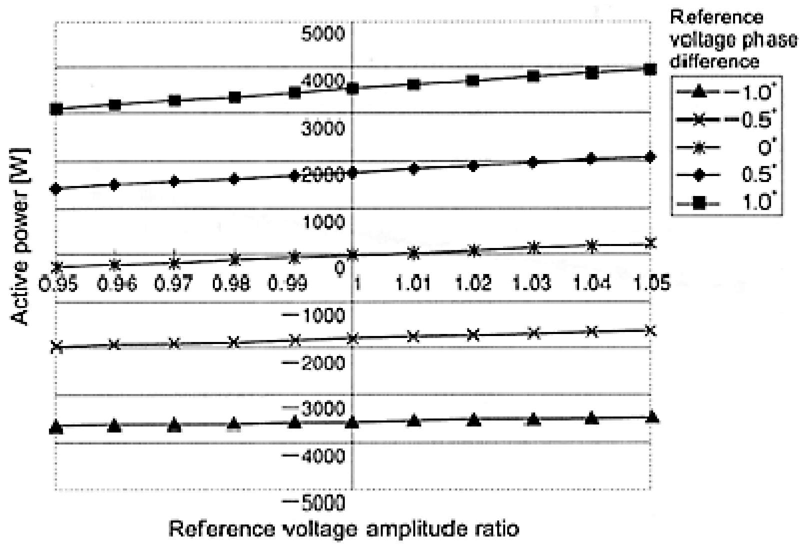
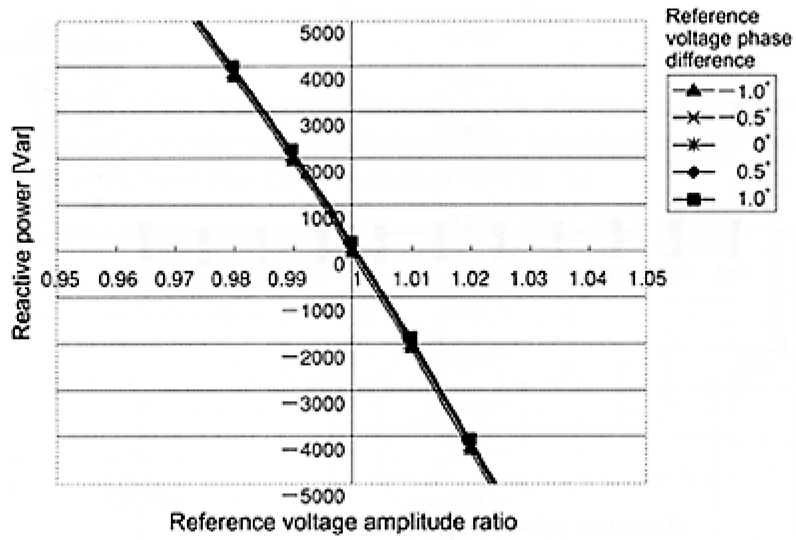



Fig. 5 Simulation results obtained in a parallel run

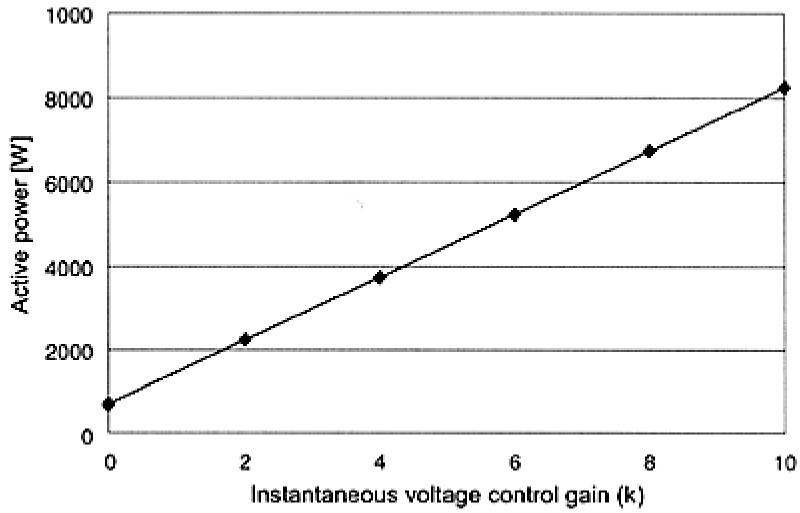


(a) Active power

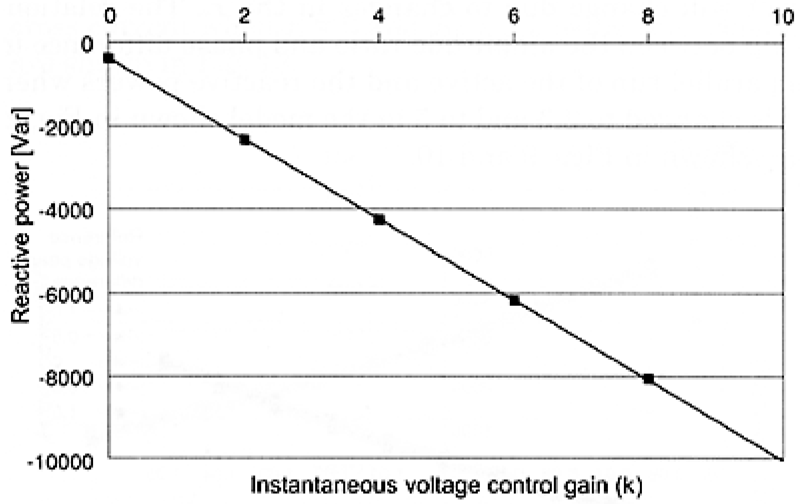


(b) Reactive power

Fig. 6 Active and reactive powers of the cross current
with regard to voltage ratio and amplitude difference




(a) Active power




(b) Reactive power

Fig. 7 Active and reactive powers
of the cross current with regard to the gain

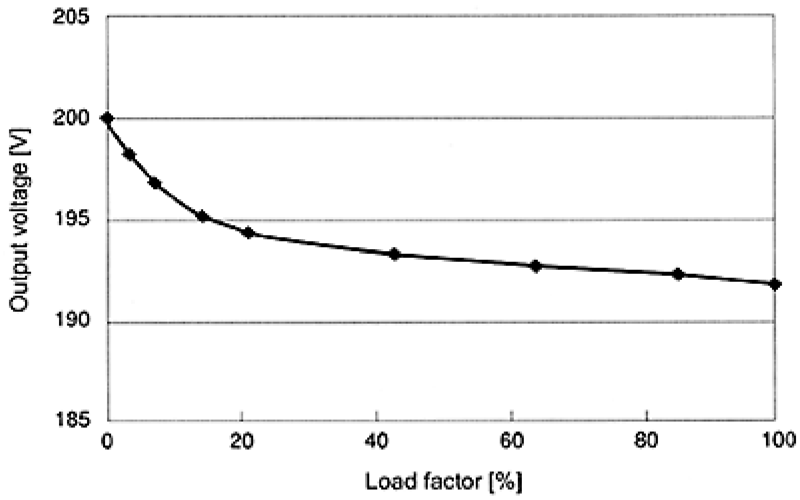
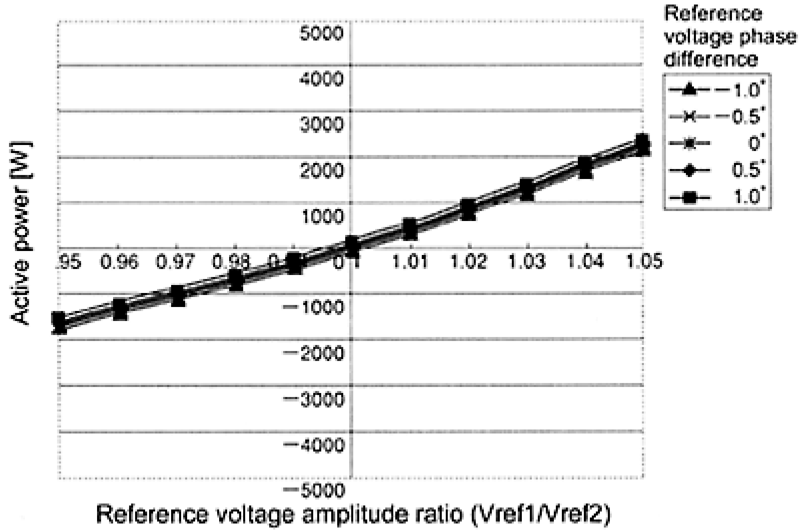
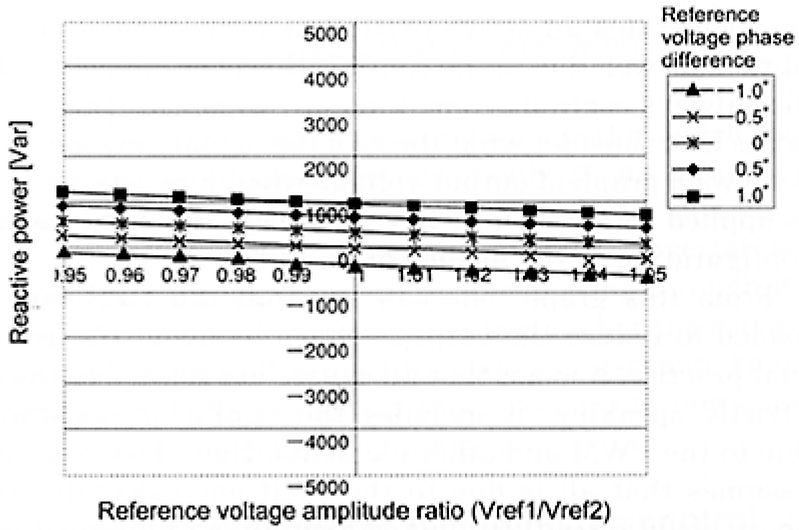



Fig. 8 Output voltage with regard to load factor

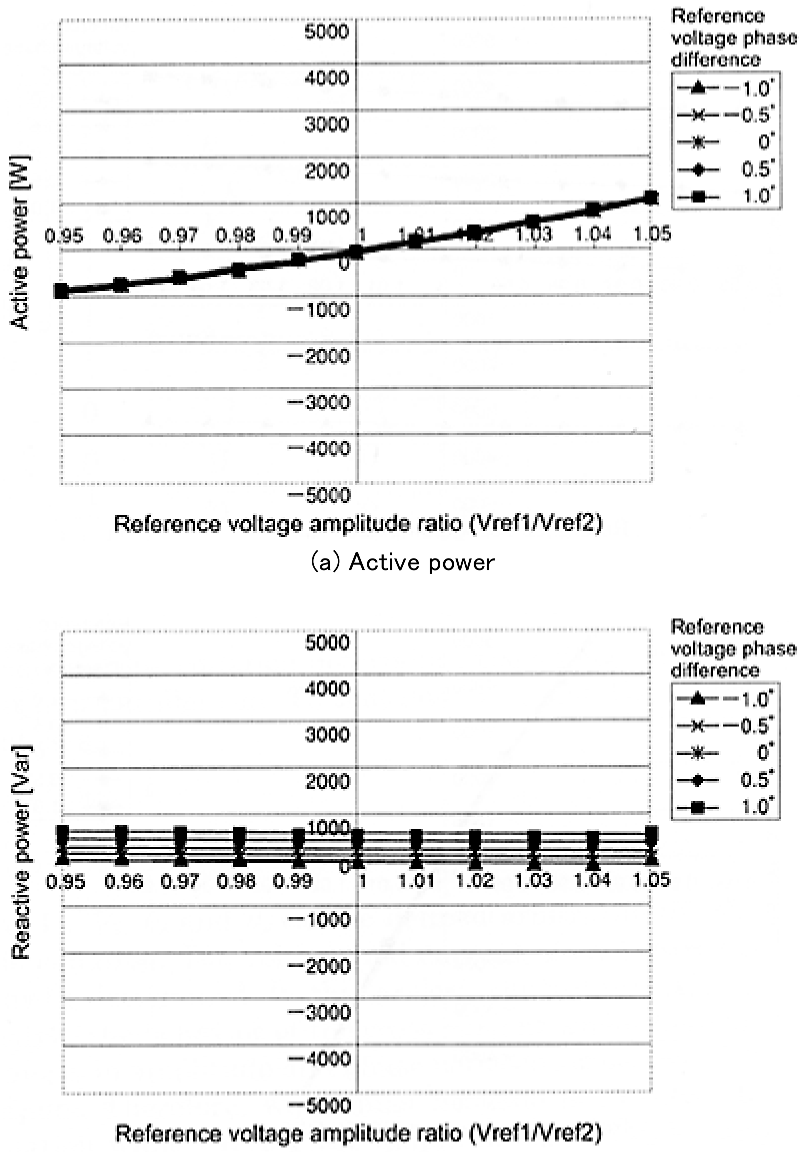



(a) Active power




(b) Reactive power

Fig. 9 Active and reactive powers of the cross current (rs = 2.5)




(a) Active power



(b) Reactive power

Fig. 10 Active and reactive powers of the cross current (rs = 5.0)

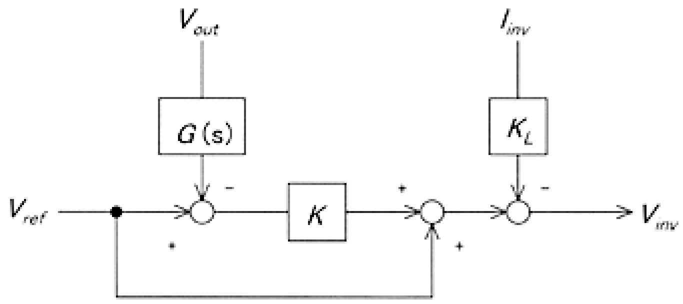



Fig. 11 Proposed control circuit

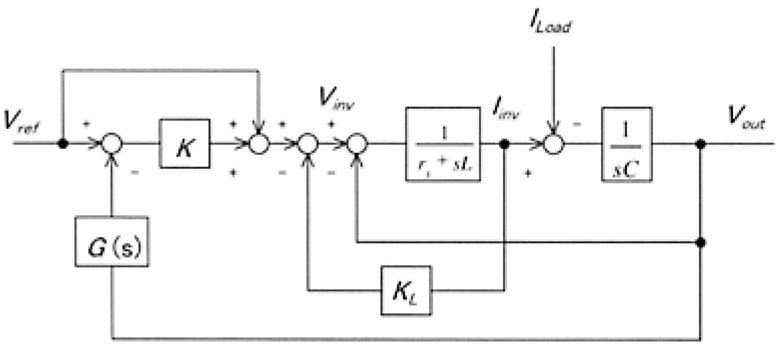
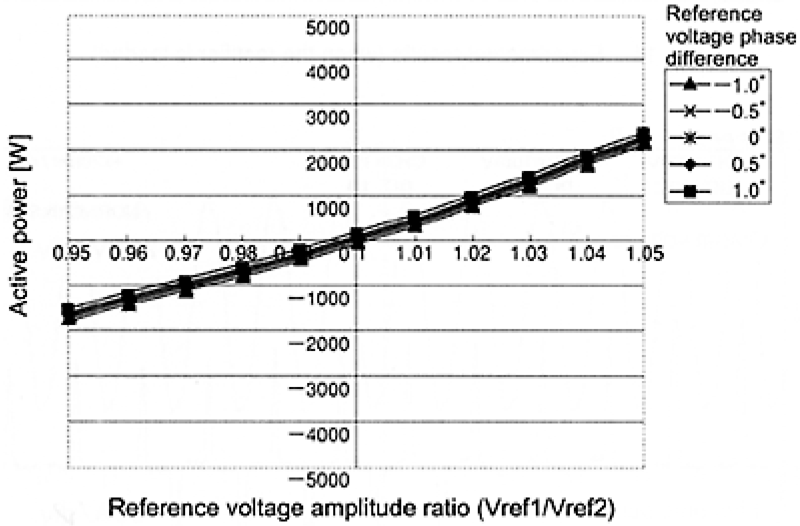
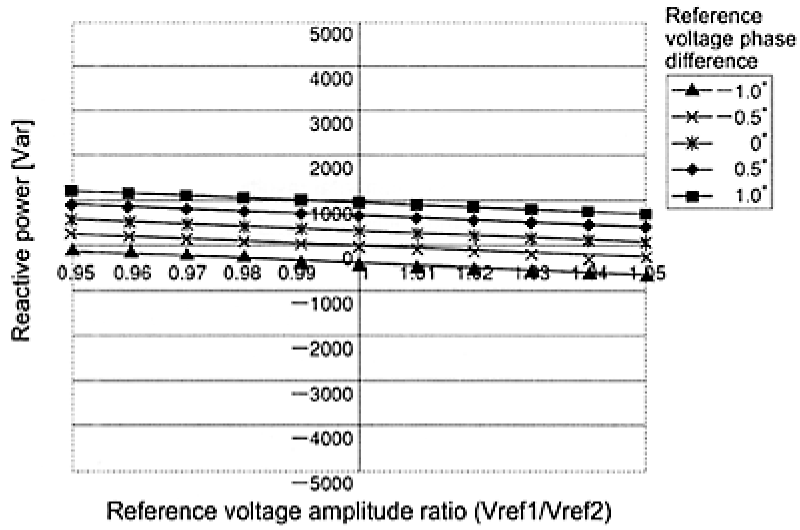



Fig. 12 Block diagram of parallel run control of UPS



(a) Active power



(b) Reactive power

Fig. 13 Active and reactive powers of the cross current ( $r_s = 0$, $K_L = 2.5$)

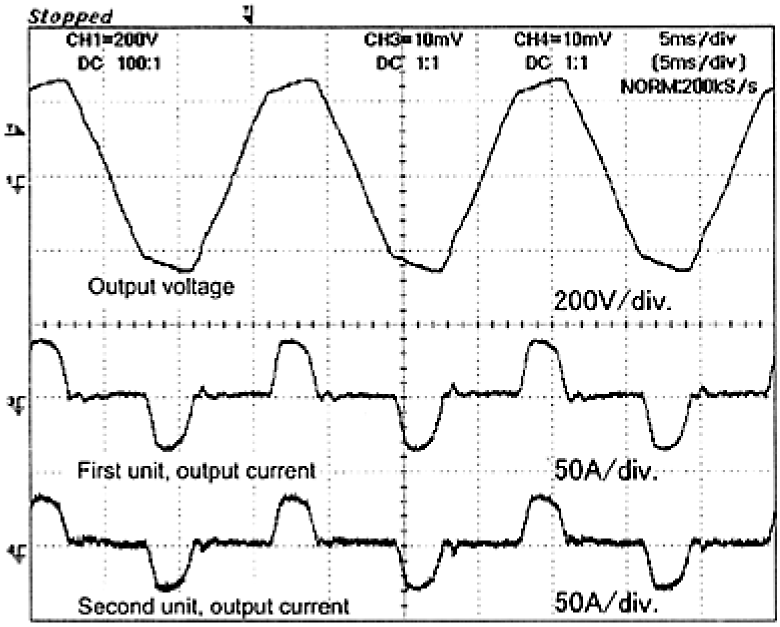



Fig. 14 Experimental results (when the rectifier is loaded)

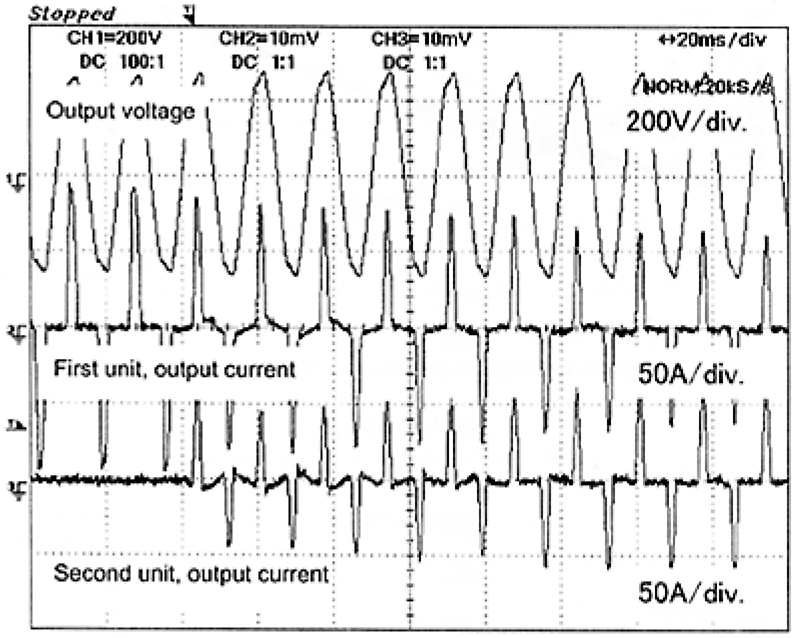



Fig. 15 Experimental results
(when the rectifier is loaded, with a second unit introduced)