Autonomously Decentralized Control of Multiple UPS's for Higher Reliability

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1. Introduction

The UPS (abbreviation of Uninterruptible Power Supply) is a power source which works as a back-up power supply in case of the power failure for the very critical loads such as hospital operation room electronics and airport flight control electronics equipment. When the multiple UPS's are redundantly connected for improvement of the total reliability, the master-slave control is widely employed, in which one UPS plays as a master, and issues the commands to the other UPS's in terms of amplitude, frequency, and phase of the output voltage so that the output of the UPS's becomes as desired by the master UPS[1]. As a result, the load sharing is achieved, and the reliability becomes higher even if one or two UPS's are in malfunction. To achieve this control algorithm, several sensor information on current, voltage and/or power flow should be centralized to the master UPS. The metal wiring or fiber wiring for these signals are also required. If a new control algorithm is realized without these sensors and wiring, the reliability of the system becomes much higher, and the cost of the total hardware decreases.

In this paper an autonomously decentralized control of multiple UPS's is proposed, in which no master UPS exists and no wiring for the signal exchange is required, but the total system becomes stable and the load sharing is achieved almost as desired. The basic idea, simulation and the experiment for verification are presented. The section 2 describes the modeling of the investigated system and the decentralized control law. In the section 3, the simulation and experimental results are shown with different conditions. The section 4 concludes this paper.

2. Modeling of the System and Control Law for Two UPS's

2.1 Assumption and control law

Fig. 1 depicts the proposed system modeling for this paper. Only two UPS's are assumed to exit in the system, and they are independently controlled each other. Each UPS's can only control the output voltage in terms of phase, which can be continuously increased or decreased depending on the proposed control law. In this paper, the frequency and the phase can be changed, but the amplitude remains constant for simplicity.

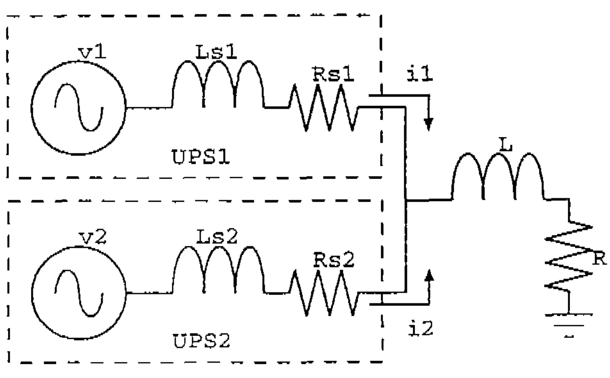


Fig.1 UPS Model in this paper

The output voltage can be expressed as (1) and (2),

$$V_1 = V_m \cos(\omega t + h_{s1}) \cdots\cdots(1)$$

,where Vm is the voltage amplitude, and the hs1 and hs2 are controllable variables.

The target of two UPS system is that

$$V_2 = V_m \cos(\omega t + h_{s2}) \cdots\cdots(2)$$

the total system must be stable under any condition such as (1) one UPS has a slightly different frequency, or the sudden phase shift occurs, (2) the load changes, (3) one UPS stops, (4) the load should be share by two UPS's as

$$h_{s1} = k_{p11}(I_{pref} - I_{p1}) + k_{p21}\int_0^t (I_{pref} - I_{p1})dt + k_{q11}(I_{qref} - I_{q1}) + k_{q21}\int_0^t (I_{qref} - I_{q1})dt \cdots\cdots(3)$$

$$h_{s2} = k_{p12}(I_{pref} - I_{p2}) + k_{p22}\int_0^t (I_{pref} - I_{p2})dt + k_{q12}(I_{qref} - I_{q2}) + k_{q22}\int_0^t (I_{qref} - I_{q2})dt \cdots\cdots(4)$$

desired.

To achieve this specification, a very simple but general control law is proposed as follows,

,where kp and kq are gains. And Ip and Iq

$$I_{p1}/2 = \frac{1}{T}\int_t^{t+T} i_1(t)\cos(\omega_1 t + h_{s1})dt \cdots\cdots(5)$$

$$I_{q1}/2 = \frac{1}{T}\int_t^{t+T} i_1(t)\sin(\omega_1 t + h_{s1})dt \cdots\cdots(6)$$

correspond to the active and reactive power component current of each UPS, as calculated in the next equations.

$$I_{pout} = \int_0^t a(I_{pin} - I_{pout})dt \cdots\cdots(7)$$

The Ip and Iq have ripples in the transient, thus the signals are filtered by the low pass filter (a/(s+a)), as follows.

$$I_{qout} = \int_0^t a(I_{qin} - I_{qout})dt \cdots\cdots(8)$$

,where a is the filter constant.

2.2 Determination of kp

The determination of kp is very important. The value is determined by the try and error approach, based on the following idea.

The simplified model of the generator can be expressed as (9),

$$J\frac{d\omega}{dt} = T_t - T_e \cdots\cdots(9)$$

, where Te and Tt are the electrical and turbine torque, and Te is proportional to the internal phase angle θ . J is the Inertia.

If the turbine torque Tt is constant, and the electrical torque Te changes, then the frequency in (9) changes proportional to the inverse of the inertia J, and the phase angle will also change. On the other hand, equations (3) and (4) indicate the phase hs is proportional to the integration of the error between the active power components current reference Ipref and the actual current Ip. Comparing this relation to (9), the gain kp should be proportional to the 1/J, then the gain seems to be determined by the generator model. This means that the inertia J is proportional to the kVA rating of the generator, thus gain kp is anti-proportional to the kVA rating of the UPS.

This explanation is not based on the precise mathematical model, thus the further study will be reported in the next available opportunity.

3. Simulations and Experiments

3.1 Conditions for Simulations

The two UPS's are in the steady state, and the following two conditions for the UPS rating and other three cases for load characteristics are tested.

A: UPS rating

(A-1) two UPS have the same rating of 1 kVA

(A-2) one UPS is 1 kVA, and the other is 0.1 kVA

B: load conditions

(B-1) the phase of two UPS's has abruptly changed one degree.

(B-2) the load changes from the half rating to a full load.

(B-3) the load changes from the half rating to no load.

3.2 Simulations

(1) Case of two 1 kVA rating UPS's

The transient waveform when the 1 ° phase shift occurs at the UPS#2 is shown in Fig. 2. The voltage waveforms look no change, but the current waveforms have some transient, but they soon become stable. When the load is increased twice, the ip1 and iq1 also become double, and when the load changes to zero, the current becomes zero, as shown in Fig.3-a and b.

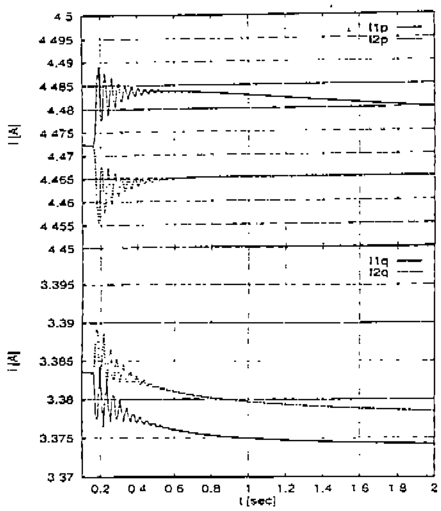


Fig.3-a Transient Waveforms when the laod is doubled for two 1kVA UPS's

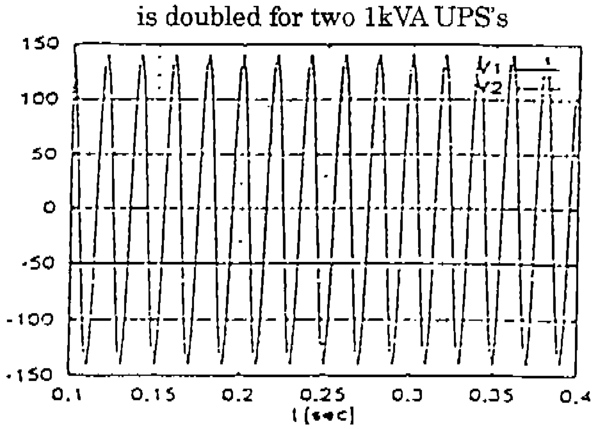
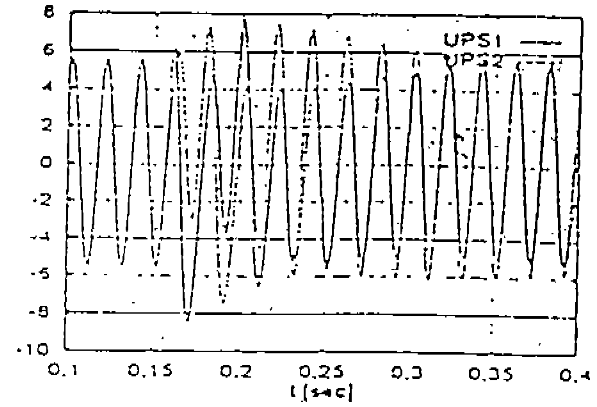
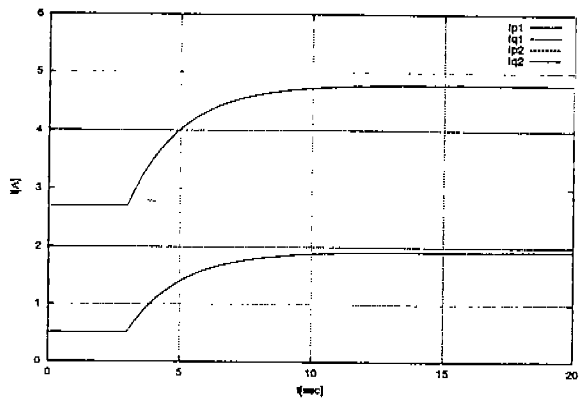


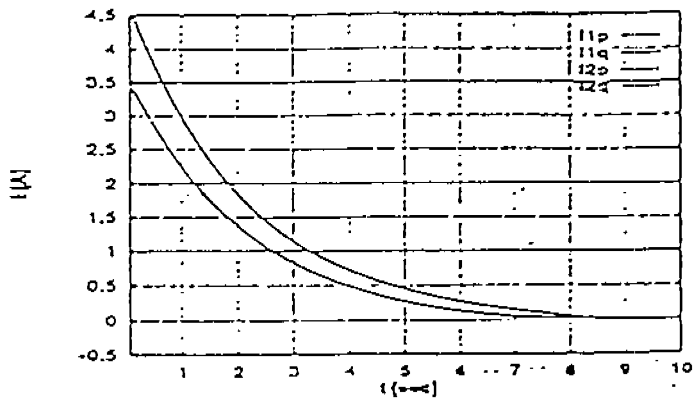
Fig.3-b Transient Waveforms when the load Is changed to zero for two 1kVA UPS's



(a) Change of Ip and Iq



(b) Voltage Waveforms



(c) Current Waveforms

Fig.2 Transient Waveforms in case of 1 degree abrupt phase shift between two 1kVA UPS's

(2) case of 1 kVA and 0.1 kVA UPS's

The parameters are shown in Table 1,2 and 3. Fig.4 is the case when the 1 ° phase shift occurs at the UPS#2. The current of UPS#2 fluctuates at the transient, but it soon becomes stable. When the load changes double or zero, the autonomous load sharing is observed in Fig. 5-a and b. From Fig.5-a, it is observed that the load sharing is about 1:10 in spite of the original intention of 1:10 load sharing. Note that no information is exchanged between two UPS's.

Table1 Circuit parameter

Vm(V)	100.0
R1(Ω)	0.01
Ls1(mH)	0.1
R2(Ω)	0.1
Ls2(mH)	1.0
L(mH)	25.0
R(Ω)	16.6

Table2 Gains

	UPS#1	UPS#2
Kp1	0.06	0.6
Kp2	0.014	0.14
Kq1	-0.06	-0.6
Kq2	-0.014	-0.14

Table3 References

	UPS#1	UPS#2
Ipref(A)	4.9	0.49
Iqref(A)	0.91	0.091

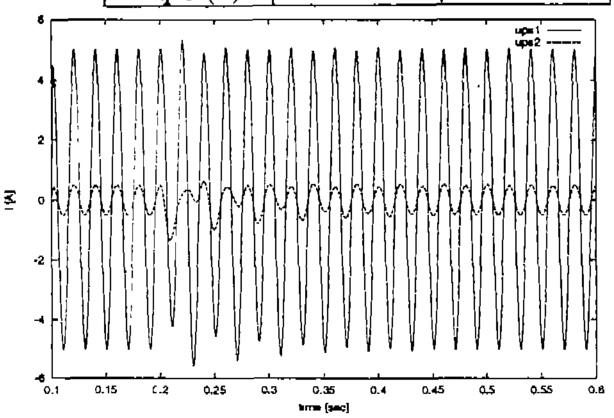


Fig.4 Transient waveforms in case of 1 degree abrupt phase shift between 1 and 0.1 kVA UPS's

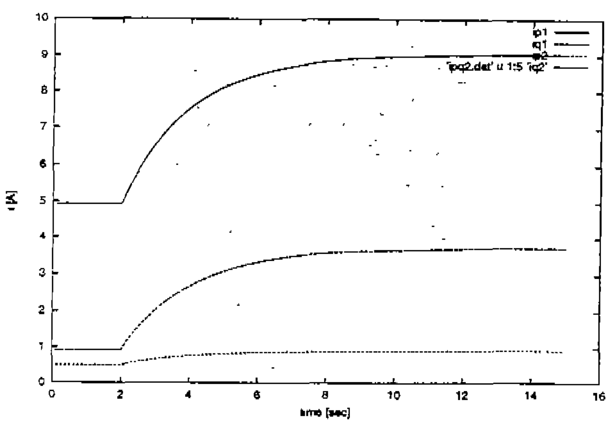


Fig.5-a Transient Waveform when the load is doubled for 1 and 0.1 kVA UPS's

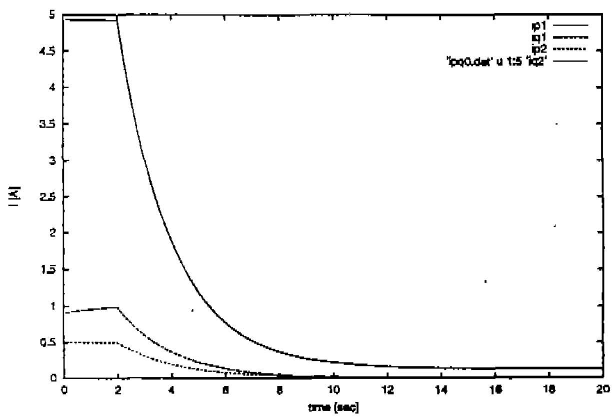


Fig.5-b Transient waveforms when the laod is changed to zero for 1 and 0.1 kVA UPS's

3.3 Experiments – a case of 1:10 ratio rating of two UPS's

The Fig.6 is the current waveform when the 0.1 ° phase shift occur. Almost nothing happens. The parameters and gains are almost the same as in Fig. 1,2 and 3.

The Fig.7-a and b are the current transient waveforms when the two UPS, which have 1:10 ratio ratings. The load sharing ration is about 1:10 after the load is increased. The circuit parameters are a little different in Fig. 7, as shown in Table 4. The internal parameters are selected to be large, so that that the lateral current across USP's is suppressed. This problem should be solved in the practical applications.

Table4 Circuit parameters for Fig.7

R1(Ω)	1.0
Ls1(mH)	1.0
R2(Ω)	10.0
Ls2(mH)	10.0
L(mH)	16.6
R(Ω)	15.0

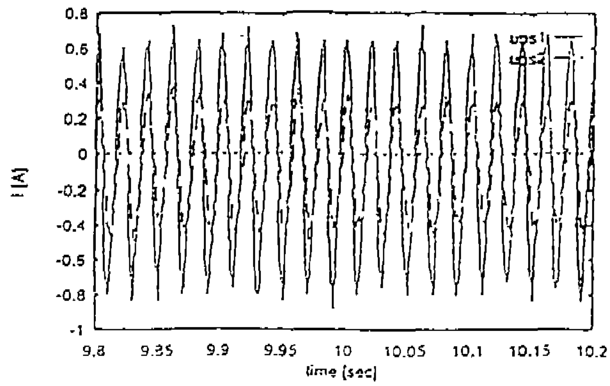


Fig. 6 Current waveforms when the phase of the UPS2 abruptly changes 0.1 degree (experiments)

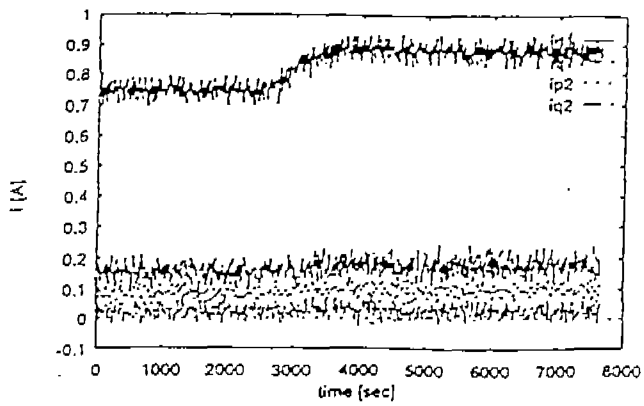


Fig. 7-a Transient waveform when the load is increased (experiments)

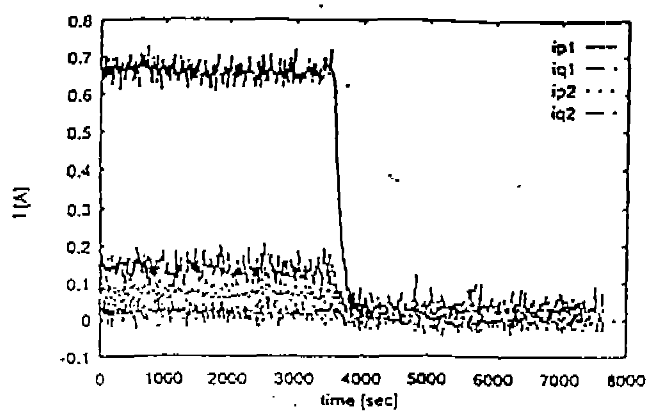


Fig. 7-b Transient waveform when the load is changed to zero

4.Conclusions

In this paper an autonomously decentralized control of multiple UPS's is proposed, in which the signal exchange between UPS's is not required, but the total system becomes stable and the load sharing is achieved as almost desired. The basic idea, simulation and the experiment for verification were presented. Only two UPS model was employed in this paper. The case of more UPS's connection will be under investigation. The further study will be presented at the next opportunity including the optimal selection of gains. Authors express their thanks to Mr. Kageyama for his help in preparing this manuscript.

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