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A Compensator for Lateral Current Reduction Applied to Autonomously Controlled UPSs Connected in Parallel

Eduardo Kazuhide Sato[†] and Atsuo Kawamura[*]

[†*] Department of Electrical and Computer Engineering., Yokohama National University, Yokohama, Japan

ABSTRACT

This paper presents a compensator for reduction of the reactive lateral current in multiple autonomously controlled uninterruptible power supplies (UPS) connected in parallel. This compensator acts directly on the control equation for voltage amplitude and it provides an improved current distribution especially in the case of parallel connection of UPSs with different output power ratings. Observations show that the original control equation for output voltage amplitude is efficient for voltage regulation but it causes great variation of voltage levels. A compensator with the same structure is added to counterbalance the variation caused by the original control equation. Simulations show promising results with the employment of the proposed compensator. Our simulations are confirmed by experimental results using three UPSs with different output ratings and voltage limiters (1%) connected in parallel under various conditions.

Keywords: uninterruptible power supply (UPS), independent control, lateral current, parallel connection

1. Introduction

Some designs of an independent control for multiple UPSs connected in parallel have been proposed in recent years. Most of them depend on the measurement of both output voltage and current[1-2]. An autonomous control with only measurement of the output current was first proposed in[3]. From the calculation of the active and reactive current, this control approach gives, respectively, the output voltage phase angle and amplitude by means of a very simple scheme based on proportional and integral controllers. Experimental results have demonstrated synchronous, stable and promising performance[3-7]. Nevertheless, under certain conditions, a reactive lateral current can flow between UPSs causing unbalanced current distribution [4-5]. Increasing the proportional gain of the control equation in response to the amplitude of the output voltage gives a good current distribution[6] but it becomes inefficient with the use of voltage limiters. In order to take advantage of the results obtained in[6], the present paper proposes a compensator which reduces the effect of the high proportional gain, the main cause of the large variation in the voltage levels. With the proposed compensator, the control scheme continues to be very simple and autonomous. Experimental results show excellent performance of the proposed independent control under various conditions.

2. Control Scheme

Fig. 1 shows the control scheme for a UPS (unit or module) connected to an AC system, which is assumed to

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[†] Corresponding Author: eduardo@kawalab.dnj.ynu.ac.jp,
Tel: +81-45-339-4162, Fax: +81-45-338-1157, Yokohama Nat'l Univ.
[*] Yokohama National University

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be composed of other units as well as electrical loads.

At an instant t, the output current i is measured and captured by a DSP board loaded with the control software. From current i, the active and reactive components, I_p and I_q, respectively are given by

$$I_p = \frac{2}{T}\int_{t-T}^{t} i(t)\cos(\omega t + hs)dt \tag{1}$$

$$I_q = \frac{2}{T}\int_{t-T}^{t} i(t)\sin(\omega t + hs)dt \tag{2}$$

where T is the inverse of the frequency, ω is the angular frequency, and hs is one of the controllable variables.

Using (1) and (2), there are some ripples during transients. Thus, a low pass filter for each current component is employed and it results in

$$\hat{I}_p = a\int_{0}^{t}(I_p - \hat{I}_p)dt \tag{3}$$

$$\hat{I}_q = a\int_{0}^{t}(I_q - \hat{I}_q)dt \tag{4}$$

where $\hat{I}_p$ and $\hat{I}_q$ are the filtered current components of I_p and I_q, respectively; and a is a constant, the cutoff frequency of the lowpass filter in [rad/s].

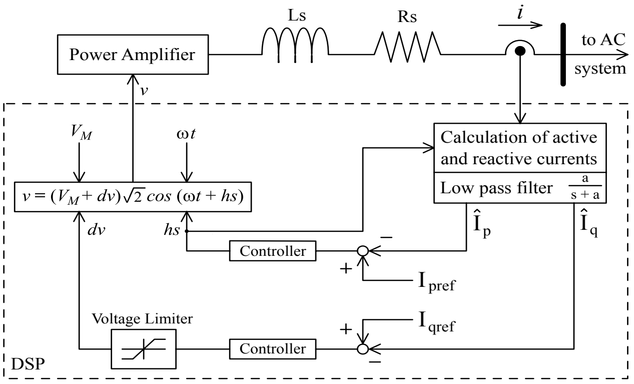

Fig. 1　Control scheme of the proposed independent control for one UPS

Given $\hat{I}_p$ and $\hat{I}_q$, the controllers determine the output voltage phase angle hs and amplitude variation dv as follows

$$hs = kp_1(I_{pref} - \hat{I}_p) + kp_2\int_{0}^{t}(I_{pref} - \hat{I}_p)dt \tag{5}$$

$$dv = kq_1(I_{qref} - \hat{I}_q) \tag{6}$$

(5) is merely a proportional-integral (PI) control scheme while (6) comprises a sole proportional element. Their representation as a block diagram is shown in Fig. 2.

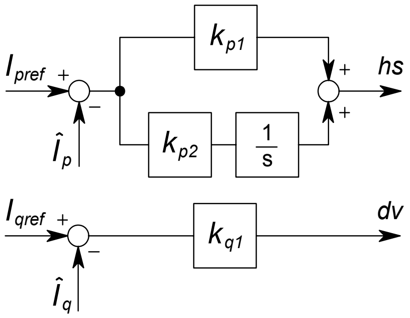

Fig. 2　Block diagram of the controllers of the proposed independent control.

Finally, the output voltage of the UPS is the amplified signal of the output voltage reference v, which is

$$v = (V_M + dv)\sqrt{2}\cos(\omega t + hs) \tag{7}$$

where V_M is the rms value of the voltage amplitude. Here, controllable variable hs in (7) is one step forward to the value of hs in (1) and (2).

3. Impedance Drop Compensator

3.1 Reactive Lateral Current

Using (6) as the control equation for the amplitude of the output voltage, a lateral current (or circulating current) can flow between the modules. As a result, this circulating current produces an unbalanced current distribution [4-6].

By employing a high proportional gain (kq_1) in equation (6), current distribution can be substantially increased because this action reduces the offset error of the proportional scheme [6]. However, a high kq_1 results in high variation of the amplitude of the output voltage. Under this condition, when voltage limiters are employed to maintain a minimal quality of the output voltage amplitude, the controlled voltage of the UPS easily reaches the limit and dv is unable to compensate for any voltage error. Consequently, in case of disturbances, although the system remains stable, a lateral current can flow between the UPSs. Such current can subject some units to overcurrent. Fig. 3 is the simulation result

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showing the active and reactive current waveforms when a high gain kq_1 is employed with voltage limiters (±1%) in the case where there is a change in amplitude of the output voltage. With this disturbance (after t=30[s]), it clearly shows an unbalanced reactive current distribution. Thus, operating the system with high gain kq_1 and voltage limiters may result in the flow of reactive circulating current between UPSs.

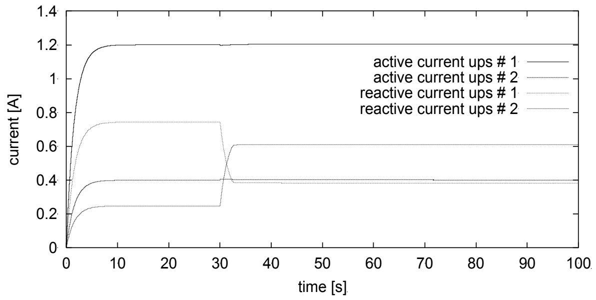

Fig. 3 Simulation result showing the active and reactive current waveforms for two UPSs connected in parallel with different output power ratings and employment of voltage limiters (±1%) in the case where there is a change in amplitude of the voltage at t = 30[s]. The proportional gain of the control equation for dv is much higher than its equivalent gain for hs (kq1 » kp1)

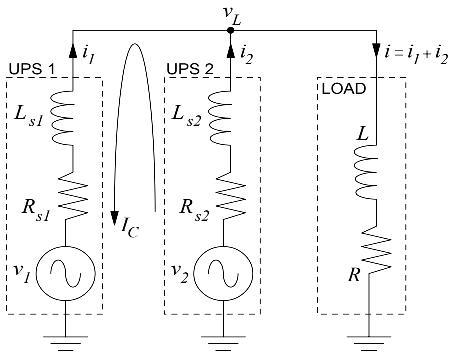

Fig. 4 An elementary parallel-connected UPS system with a resistive-inductive load

3.2 Voltage Difference and Lateral Current

It is easier to observe the reactive lateral current when the amplitudes of the output voltage of the UPSs are different. Thus, we verify this condition in order to further understand the action of (6) as the control equation for the amplitude of the output voltage. Using the simulation results of the circuit shown in Fig. 4, we plot some phasor diagrams for various situations. In this part of the paper, we consider two units with different output power ratings (the ratio is 3:1). The simulation results and phasor diagrams show that (6) efficiently suppresses the voltage difference, but also causes great variation in the amplitude of the output voltage making it unsuitable for a real work environment. Combining the efficiency of equation (6) with a compensator, we have a control equation for the amplitude of the output voltage with good performance even with employment of voltage limiters (±1%).

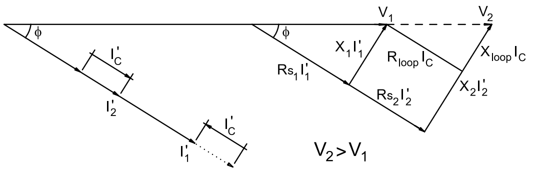

Fig. 5 Phasor diagram for a system with two UPSs with different output power ratings (the ratio is 3:1) when V2 >V1

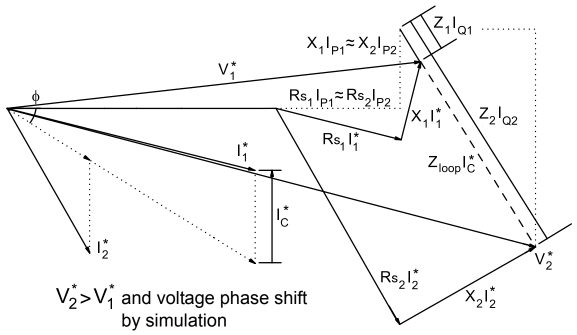

Fig. 6 Phasor diagram for a system with two UPSs with different output power ratings (the ratio is 3:1) when V2 >V1 and using (5) as control of active current distribution

1) $V_2 > V_1$: Fig. 5 d depicts a phasor diagram in the case where there is a voltage difference of $V_2 > V_1$. From this figure, we observe that

- there is a flow of lateral current represented by I_C, which reduces the current I_1 and increases I_2;
- the currents of the UPSs are no longer proportional due to the flow of circulating current;
- the voltage drops across the internal impedances of the UPSs are different and the voltage difference Δv_{21} (V_2 - V_1) is given by

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$$\Delta \boldsymbol{v}_{21} = \boldsymbol{V}_2 - \boldsymbol{V}_1 = \boldsymbol{Z}_{loop} \boldsymbol{I}_C \tag{8}$$

where $Z_{loop} = Z_1 + Z_2$ and $\boldsymbol{Z} = \sqrt{\boldsymbol{Rs}^2 + \omega^2 \boldsymbol{Ls}^2}$

Rs and Ls are the internal resistance and impedance, respectively, of the UPS.

Here, neither (5) nor (6) are used in the simulations.

2) $V_2 > V_1$ with control of active current distribution: Under the same conditions but adding (5) to control the distribution of active current, we have the situation depicted in Fig. 6, where

- there is a good balance of active current;
- the flow of lateral current I_C becomes exclusively reactive;
- the current distribution is still affected by the flow of reactive circulating current.

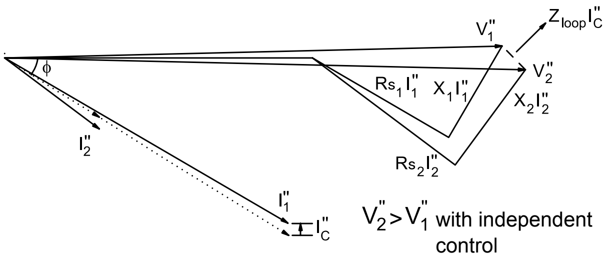

Fig. 7 Phasor diagram for a system with two UPSs with different output power ratings (the ratio is 3:1) when V2 > V1 and using (5) and (6) as controls of active and reactive current distribution

As the lateral current I_C is only reactive, when $V_2 > V_1$, we have

$$\widehat{\boldsymbol{I}}_{q1} = \boldsymbol{I}_{qL1} - \boldsymbol{I}_C \tag{9}$$

$$\widehat{\boldsymbol{I}}_{q2} = \boldsymbol{I}_{qL2} + \boldsymbol{I}_C \tag{10}$$

where I_{qL} is the component of I_q which is supplying the load and it is proportional with the components of other units according to the rating, so that $I_{qL1} : I_{qL2} = S_1 : S_2$.

3) $V_2 > V_1$ using (5) and (6) as control equations: Using (5) and (6) as control equations, we observe that (6) is able to minimize the lateral current as seen in Fig. 7.

However, considering this situation ($V_2 > V_1$), (10) in (6) for UPS # 2 gives

$$\boldsymbol{dv}_2 = \boldsymbol{kq}_{12} \boldsymbol{I}_{qref2} - \boldsymbol{kq}_{12} (\widehat{\boldsymbol{I}}_{qL2} + \boldsymbol{I}_C). \tag{11}$$

For a minimal offset error, kq_{12} has to be high. Consequently, for heavy load conditions, it implies a high variation of dv and this variable becomes too negative even without the flow of lateral current. With the employment of voltage limiters, dv easily reaches the limit and becomes unable to compensate for any voltage difference.

This paper presents a compensator, which reduces the effect of high variations of dv due to the term where gain kq_1 exists.

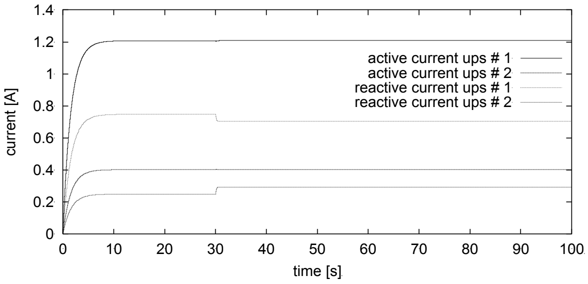

Fig. 8 Simulation results showing the active and reactive current waveforms for two UPSs connected in parallel with different output power ratings and employment of voltage limiters (±1%) and impedance drop compensator in the case where there is a change in amplitude of the voltage at t = 30 [s]

3.3 Mathematical Expression of the Compensator

In order to minimize the effect of a high kq_1 and, at the same time, to be effective in the reduction of the voltage difference, a new term with opposite signal is added in (6) and it becomes

$$\boldsymbol{dv} = \boldsymbol{kq}_1 (\boldsymbol{I}_{qref} - \widehat{\boldsymbol{I}}_q) + \boldsymbol{kc} \widehat{\boldsymbol{I}}_q \tag{12}$$

where kc is the compensator gain, which is as high as gain kq_1 and is also adjusted according to the rating ($kc_1 : kc_2 = S_1 : S_2$). Dimensional analysis suggests that both gain kq_1 and kc have the same unit, Ω, i.e. the new term in (12) counterbalances the voltage drop caused by $\boldsymbol{kq}_1 \widehat{\boldsymbol{I}}_q$. Thus, it is called here as the impedance drop compensator.

By selecting gain kc to be slightly lower than kq_1, simulation results as seen in Fig. 8 show promising performance with the employment of the proposed compensator.

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4. Experimental Results

In order to verify the efficiency of the proposed compensator in terms of reduction of the reactive lateral current, some experiments are carried out for three units connected in parallel with different output power ratings.

4.1 System Description

Fig. 9 shows the scheme of the experimental setup with three modules connected in parallel. Each UPS is represented by a power amplifier connected in series with a RL impedance. If the internal impedances of each UPS are different, we have a system with distinct output power ratings. Thus, for N UPSs connected in parallel, we have

$$Z_1S_1 = Z_2S_2 = \cdots = Z_NS_N \tag{13}$$

Using the parameters of Table 1, the ratio of the experimental setup is 6:3:2. A digital signal processor (DSP) – TMS320C32-50MHz – loaded with the control software, processes the information as shown in Fig. 1. Due to power limitation of the amplifiers, the rms voltage V_M is taken to be 80[V]. The nominal frequency is taken to be 50 [Hz]. Other parameters of the circuit and control are shown in Table 1. A voltage limiter (1%) is applied at the output of the controller for variable dv so that $-0.8[V] \le dv \le 0.8[V]$.

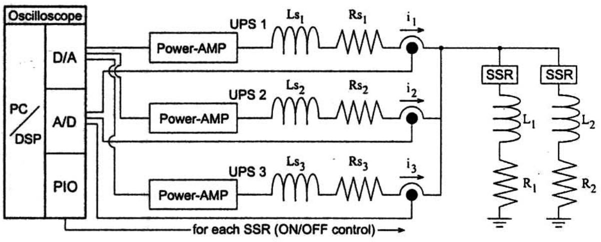

Fig. 9 Scheme of the experimental setup for three parallel-connected UPSs

In this paper, three conditions are verified in the experiments:

- change in amplitude of the voltage in both UPS #2 (+0.2[V]) and UPS #3 (-0.4[V]) at t = 30[s];
- voltage phase shift in both UPS #2 (+2.5[°]) and UPS #3 (-5.0[°]) at t = 30[s];
- change of load according to the sequence shown in Table 2.

Table 1 Parameters used in the experiments

	UPS # 1		UPS # 2		UPS # 3
Rs_1	0.5 Ω	Rs_2	1.0 Ω	Rs_3	1.5 Ω
Ls_1	1 mH	Ls_2	2 mH	Ls_3	3 mH
I_{pref1}	0.28 A	I_{pref2}	0.14 A	I_{pref3}	0.09 A
I_{qref1}	0.15 A	I_{qref2}	0.08 A	I_{qref3}	0.05 A
a	0.63	a	0.63	a	0.63
kp_{11}	0.5	kp_{12}	1.0	kp_{13}	1.5
kp_{21}	0.05	kp_{22}	0.10	kp_{23}	0.15
kq_1	5.0	kq_2	10.0	kq_3	15.0
kc_1	2.95	kc_2	5.90	kc_3	8.85

Table 2 Load resistance and inductance.

Period [s]	R_1 [Ω]	L_1 [mH]	R_2 [Ω]	L_2 [mH]	Status
0 ~ 40	100	200	100	200	100%
40 ~ 70	100	200	-	-	50%
70 ~ 100	-	-	-	-	0%

4.2 Results

1) Change in Amplitude of the Output Voltage: Figs. 10, 11 and 12 show the experimental results when a change in

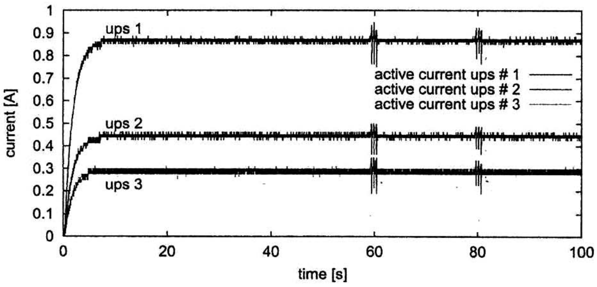

Fig. 10 Active current waveforms for three UPSs connected in parallel with different output power ratings in the case where there is a change in amplitude of the output voltage at t = 30[s]

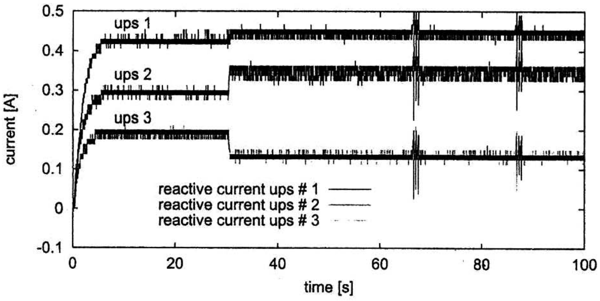

Fig. 11 Reactive current waveforms for three UPSs connected in parallel with different output power ratings in the case where there is a change in amplitude of the output voltage at t = 30[s]

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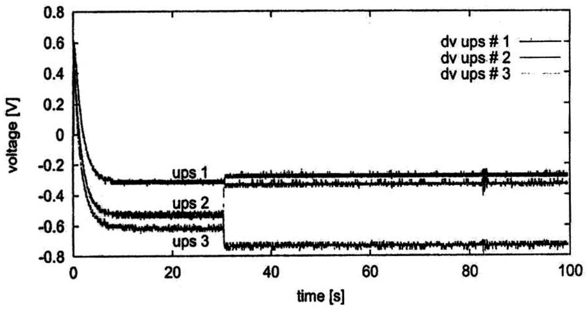

Fig. 12 Control variable *dv* in the case where there is a change in amplitude of the output voltage at t = 30[s]

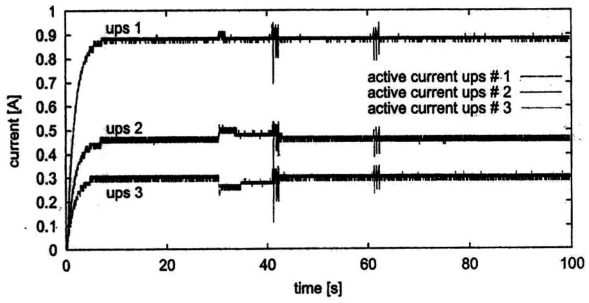

Fig. 13 Active current waveforms for three UPSs connected in parallel with different output power ratings in the case where there is a voltage phase shift at t = 30[s]

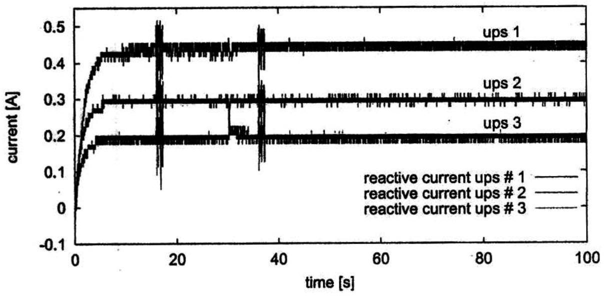

Fig. 14 Reactive current waveforms for three UPSs connected in parallel with different output power ratings in the case where there is a voltage phase shift at t = 30[s]

amplitude of the output voltage occurs simultaneously in two units. Active current waveforms are displayed in Fig. 10 while reactive current waveforms are shown in Fig. 11. The behavior of control variable *dv* is plotted in Fig. 12. Although this condition is especially difficult for reactive current distribution, Fig. 11 shows a satisfactory current balance with the employment of the proposed compensator.

2) Voltage Phase Shift: Figs. 13, 14 and 15 show the experimental results when a voltage phase shift occurs simultaneously in two units. Active current waveforms are displayed in Fig. 13 and reactive current waveforms are

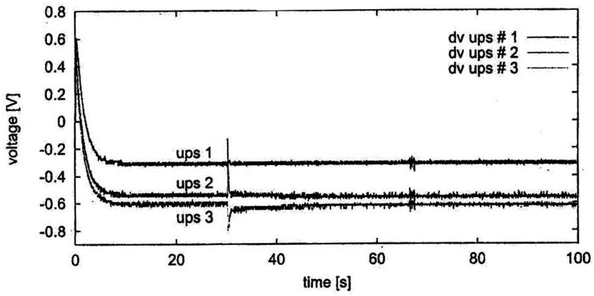

Fig. 15 Controllable variable *dv* in the case where there is a voltage phase shift at t = 30[s]

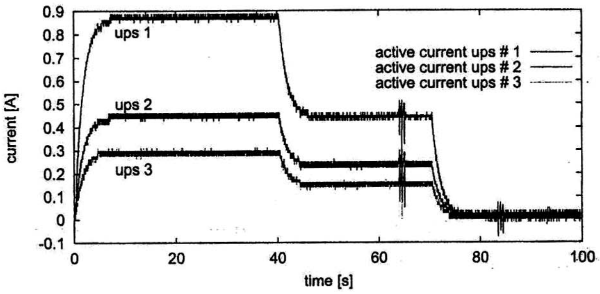

Fig. 16 Active current waveforms for three UPSs connected in parallel with different output power ratings in the case where there is a change in load

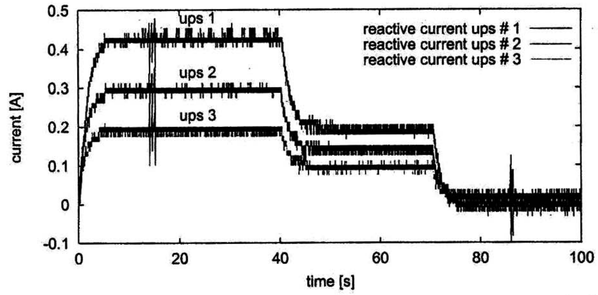

Fig. 17 Reactive current waveforms for three UPSs connected in parallel with different output power ratings in the case where there is a change in load

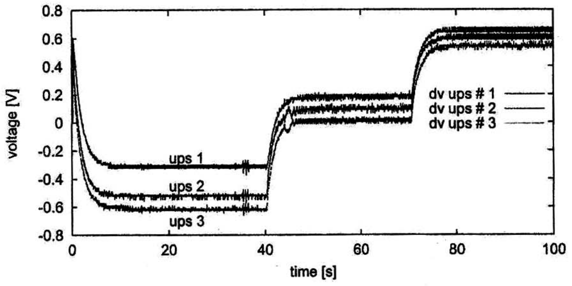

Fig. 18 Control variable *dv* in case of change of in load

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shown in Fig. 14. Variable *dv* is plotted in Fig. 15. Under these conditions, the controllers perform very well in terms of current distribution for both active and reactive components.

3) Change in Load: Figs. 16, 17 and 18 refer to the situation where the load changes from a full load to zero. Active and reactive current waveforms are displayed in Fig. 16 and Fig. 17, respectively. Variable *dv* is plotted in Fig. 18. Again, the system performs well as *dv* varies within voltage limiters under any load condition.

5. Conclusions

The present paper proposes a compensator for reduction of the reactive lateral current in multiple UPSs connected in parallel. This compensator is applied to the control equation for amplitude of the output voltage, part of an independent control scheme, which guarantees autonomous operation for each UPS without signal exchange between units. The control is achieved with only the measurement of the output current by means of a very simple control scheme, which includes the impedance drop compensator. Experimental results show excellent performance under various conditions.

Further analysis and verification under rectifier load conditions will be addressed at a future opportunity.

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Eduardo Kazuhide Sato was born in Paranavaí, Brazil. He received the B.S. and the M.S. degree, both in electrical engineering, from Federal University of Paraná, Curitiba, Brazil, in 2000, and from Yokohama National University, Yokohama, Japan, in 2003, respectively. He is currently working toward Ph.D. degree in electrical engineering at Yokohama National University, Yokohama, Japan. His research interests include power converters, digital control, power systems and control theory. He is a student member of IEE of Japan, IEICE and IEEE.

Atsuo Kawamura was born in Yamaguchi Prefecture, Japan, in December 1953. He received the B.S.E.E., M.S.E.E., and Ph.D. degrees in electrical engineering from the University of Tokyo, Tokyo, Japan, in 1976, 1978, and 1981, respectively. In 1981 he joined the Department of Electrical and Computer Engineering at the University of Missouri-Columbia as a Postdoctoral Fellow, and was an Assistant Professor there from 1983 through 1986. He joined the Department of Electrical and Computer Engineering, Yokohama National University, Yokohama, Japan in 1986 as an associate professor, and in 1996 he became a professor. His interests are in power electronics, digital control, electric vehicles, robotics, train traction control and so on. He received the IEEE IAS Transactions Prize Paper Award in 1988, the Prize Paper Award of IEE of Japan in 1996, and IEEE IES Transactions Best Paper Awards in 2001 and 2002. He was the conference chairperson of the IEEE/IAS and IEEJ/IAS joint Power Conversion Conference (PCC-Yokohama) in 1993. He served as the Technical Program Chairman of IEEE Power Electronics Specialist Conference in 1998 (PESC'98) and also the Workshop on Advanced Motion Control in 2000(AMC2000). Dr. Kawamura is a member of the IEE of Japan, IEEE, Robotics Society of Japan and so on.

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