Standby Power Supply with Active Power Filter Ability Using Digital Controller

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Abstracts - **This paper presents a standby power supply/active power filter(SPS/APF) system. This system provides combined functions of high efficiency power backup and harmful harmonics elimination. Based on the bilateral converter using current forced switching scheme, the line current can be sinusoidally regulated with unity power factor in APF mode and the voltage waveform distortion can be kept small in SPS mode by instantaneous voltage control. Introduction of the harmonic problems generated by the nonlinear loads, the calculation method of the instantaneous reactive current components achieving current distortion compensation and power factor correction, and the full digital control hardware and software schemes using a TMS320C25 digital signal processor are discussed in detail. Finally, the theoretical analysis is verified both by simulated and experimental results in a 3[kW] laboratory prototype system.**

I. INTRODUCTION

Utility power quality has become an important issue recently for critical loads such as computers and delicate electronic instruments. The uninterruptible power supply(UPS) system can supply a high quality power to keep the power source of these equipments from disturbances of noise and power outage. In conventional UPS system, a phase controlled rectifier is used to create DC bus to which batteries are connected, and an inverter connected to this DC bus supplies the load directly, thus avoiding interruption in the load voltage. Nevertheless the advantages of simplicity and reliability, this UPS system has a higher cost and a lower efficiency compared to the standby power supply(SPS) system, since this system is based on the topology of two power conversion stages. Moreover, since most of these critical loads have the capability of "riding through" a momentary power outage for durations up to several ms, a SPS system can provide adequate protection. Therefore, the SPS market is growing much faster than the UPS market for personal computer loads.[1,2]

A versatile SPS topology, using the bilateral PWM converter has been studied.[3,4] This system normally operates as an active power filter(APF). The load is supplied directly from the power lines, and the PWM converter acts as APF to compensate the harmonics and reactive power generated from the nonlinear load, thus obtaining a sinusoidal line current and unity power factor. The converter also operates as a PWM rectifier to the battery. When the AC line source fails, the power flow is automatically transferred, with the load being supplied from the battery-fed inverter. The system has the following advantages: a near unity power factor, reduced line current harmonics, and higher efficiency. The main objective of this system is to compensate the load current harmonics, rather than to eliminate the distortion of the load voltage, which is due to the distorted utility supply voltage.

This paper presents a digital control techniques of PWM converter for SPS system with active power filter ability. The compensation principle of instantaneous reactive power in APF and the novel digital calculation method of the reactive current from the nonlinear load current is proposed, and the full digital control hardware and software schemes using a TMS320C25 digital signal processor are discussed in detail. Finally, the theoretical analysis is verified both by simulated and experimental results in a 3[kW] laboratory prototype system.

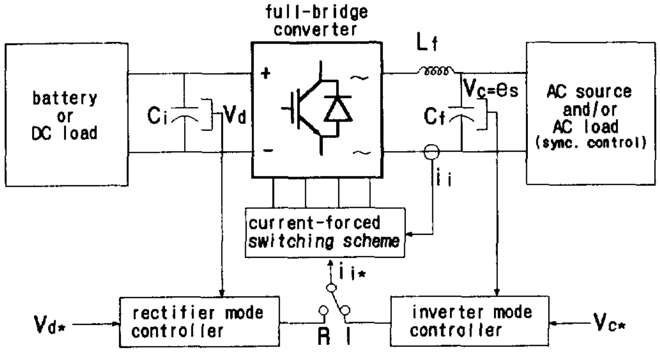


Fig. 1. Schematic diagram of bilateral converter system.

II. SYSTEM CONFIGURATIONS

A. Bilateral converter without active power filtering

The schematic diagram of the bilateral converter system is shown in Fig. 1. The rectifier mode controller and the inverter mode controller are automatically selected by the R/I mode select switch. In the rectifier mode operation, the line current can be controlled sinusoidally with the unity power factor using the instantaneous current control techniques, and the DC voltage is regulated with low ripple. In addition, the sinusoidal AC output voltage with low harmonic distortion and good regulation characteristics in the inverter mode can be obtained using the instantaneous voltage control techniques. The voltage and current waveforms in rectifier mode and in inverter mode are shown in Fig. 2 and Fig. 3, respectively. The line current is sinusoidal and in phase with the line voltage in rectifier mode and the inverter output voltage is controlled sinusoidally in inverter mode not only in the RL load but also rectifier load.

B. Standby power supply with active power filtering

Even though it works as APF, the power circuit is not changed. When the line source is normal, this SPS system is under the **bypass mode**. Therefore, the AC line source feeds the load directly, and the bilateral converter supplies the instantaneous reactive power to compensate the current harmonics and reactive power and a small active power to regulate the DC battery voltage. Fig. 4 shows the basic configuration of the active filtering action in bypass mode. The reference current is calculated from the reactive current calculator, and the converter output current is forced to track this reference current. Therefore, the line source current is sinusoidally regulated with unity power factor even under the nonlinear load.

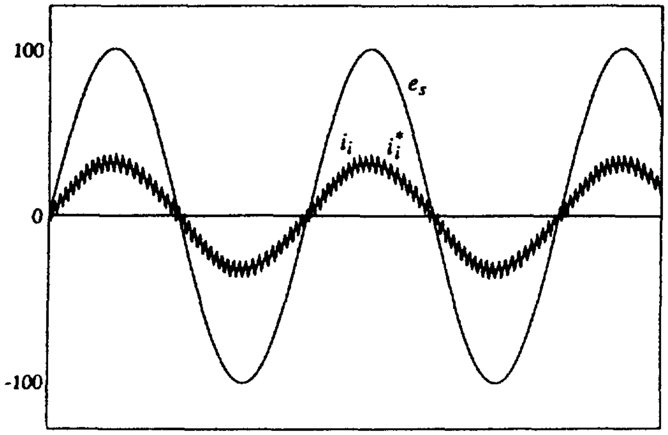


Fig. 2. Voltage and current waveforms in rectifier mode.

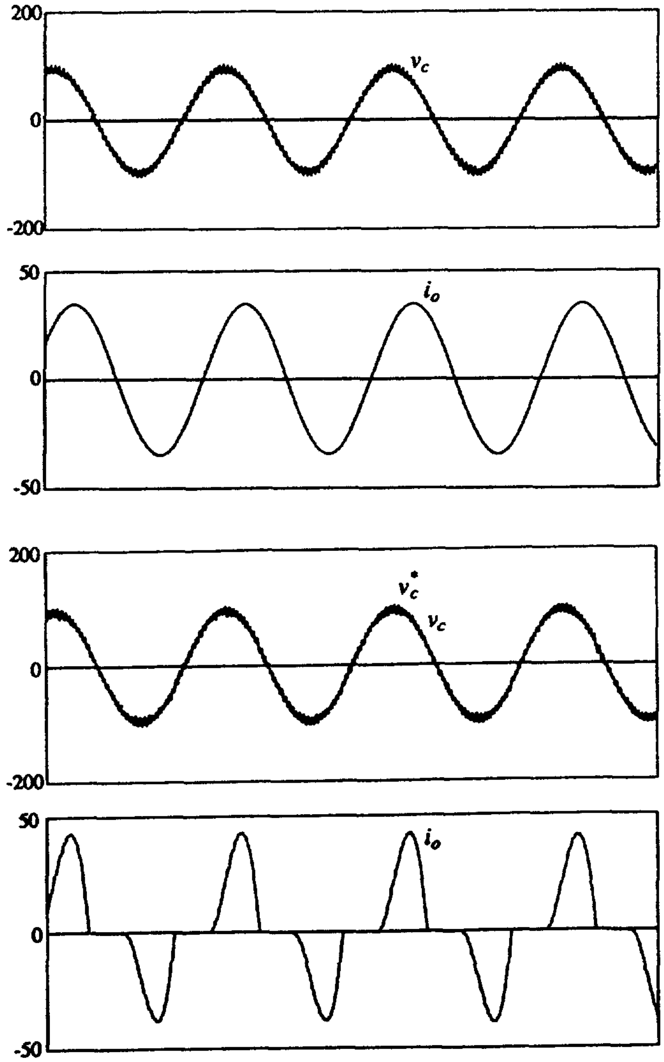


Fig. 3. Voltage and current waveforms in inverter mode.
(a) RL load. (b) Rectifier load.

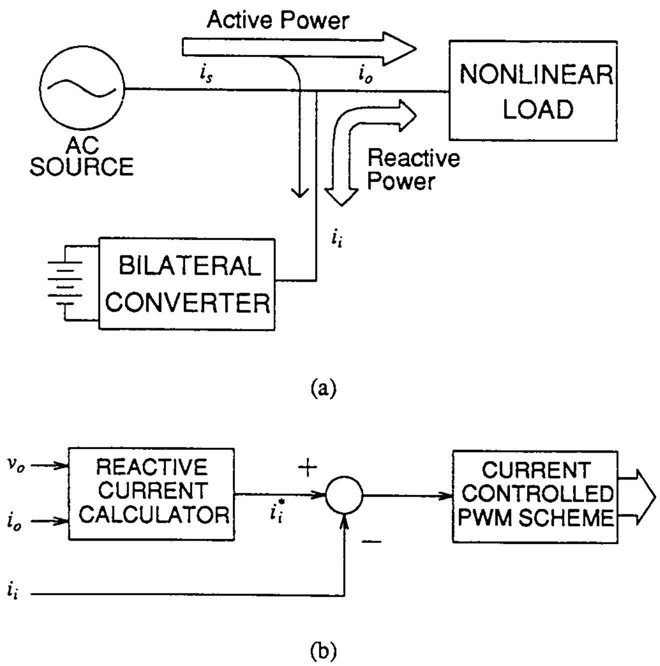


Fig. 4. Basic configuration of active filtering action.
(a) Power flow. (b) Control block diagram.

When the system detects an abnormal condition of AC line source such as a deviation of voltage and/or frequency, the bilateral converter converts to the **stand-alone mode.** Then, the load is supplied from the battery-fed inverter. But the system has high THD for nonlinear loads, for example, the rectifier load drawing the rectangular-shaped current causes the voltage dips and notches in the AC output. To overcome this problem, many kinds of instantaneous voltage control techniques have been studied. Especially, the theoretical approach and some simulation and experimental results about the digital control techniques of the instantaneous voltage control were already reported in [5]. Therefore, the scope of this paper is limited to the digital control techniques of instantaneous reactive power compensation for SPS system in bypass mode.

III. COMPENSATION PRINCIPLE OF ACTIVE POWER FILTER

A. Definition of instantaneous reactive current

If the ideal source voltage is

$$v = V_m \sin \omega t \tag{1}$$

then, the source current in nonlinear load

$$i = \sum_{n=1}^{\infty} I_{mn} \sin(n\omega t + \varphi_n) \tag{2}$$

can be decomposed into components i_a, i_r, where

$$i_a = I_{m1} \cos \varphi_1 \sin \omega t \tag{3}$$

$$i_r = I_{m1} \sin \varphi_1 \cos \omega t + \sum_{n=2}^{\infty} I_{mn} \sin(n\omega t + \varphi_n). \tag{4}$$

Using from (1) to (4), the instantaneous power p may be represented as

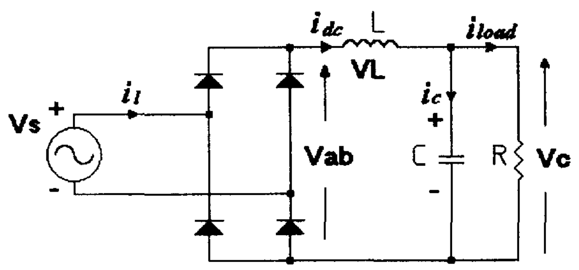
$$\begin{aligned} p &= v \cdot i \\ &= v \cdot (i_a + i_r) \\ &= p_i + q_i \end{aligned} \tag{5}$$

where

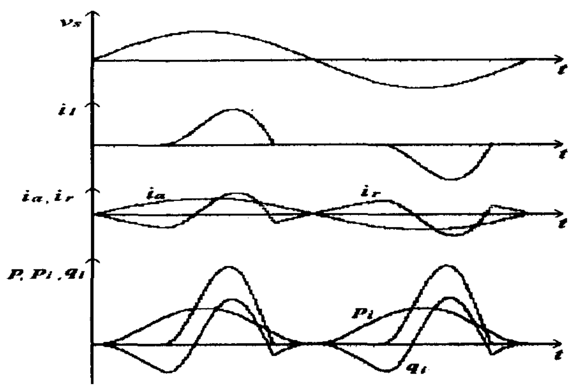
$$\begin{aligned} p_i &= v \cdot i_a \\ &= \frac{1}{2} V_m I_{m1} \cos \varphi_1 (1 - \cos 2\omega t) \end{aligned} \tag{6}$$

$$\begin{aligned} q_i &= v \cdot i_r \\ &= \frac{1}{2} V_m I_{m1} \sin \varphi_1 \sin 2\omega t \\ &\quad + V_m \sin \omega t \cdot \sum_{n=2}^{\infty} I_{mn} \sin(n\omega t + \varphi_n). \end{aligned} \tag{7}$$

The first term of (5), p_i may be interpreted as the active part of p. This term represents the unidirectional power, whose mean value equals the average power, P. The second term of (5), q_i may be interpreted as the reactive part of p_i. This term represents the bidirectional power, whose mean value equals zero every half period. The physical meaning of p_i and q_i is instantaneous power because of the product of the instantaneous voltage and the instantaneous current. Here, the authors named p_i and q_i "instantaneous active power" and "instantaneous reactive power", respectively. And the current components, i_a and i_r are named "instantaneous active current" and



(a)



(b)

Fig. 5. (a) Diode bridge rectifier. (b) Waveforms of instantaneous currents and powers.

"instantaneous reactive current", which is the source of the instantaneous active power and the instantaneous reactive power, respectively.[6]

B. Harmonics and Reactive Power Compensation

Most of the switchmode power supplies present a nonlinear impedance characteristics to the utility line source, generating large harmonic currents and reactive power with well known adverse effects.[7] Therefore, the reactive current is instantaneously calculated, and the output current of the PWM converter should be controlled to follow this waveform for active compensation.

The input current of the bilateral converter is forced to track the reference current waveform. To compensate the current harmonics and reactive power in AC line source side, the instantaneous reactive current generated from the reactive current calculator is used as the reference current waveform. Then, the instantaneous reactive current, i_r is supplied from the bilateral converter and the line source provides only the instantaneous active current, i_a which is sinusoidal and same phase with the source voltage.

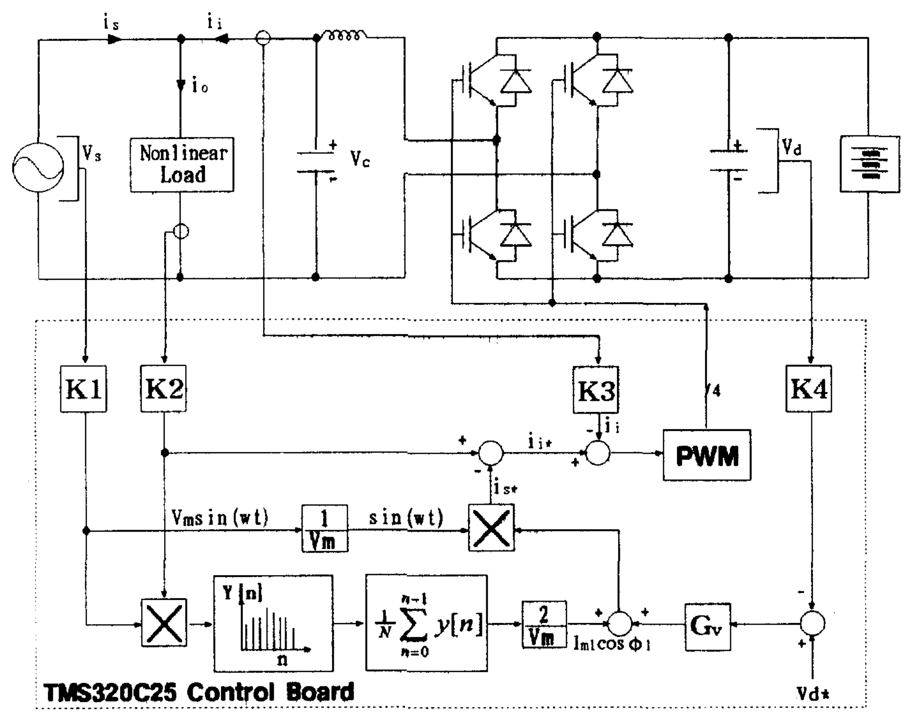


Fig. 6. Power circuit configuration of proposed SPS system and control block diagram for active power filtering.

$$i_s = i_o - i_r = i_a \quad (7)$$

As an example, Fig.5 shows the diode bridge rectifier and the waveforms of instantaneous currents and powers defined previously. It is clear that the instantaneous reactive current is the source of the instantaneous reactive power and the source current can be sinusoidal and in phase with the source voltage by compensation of the instantaneous reactive current.

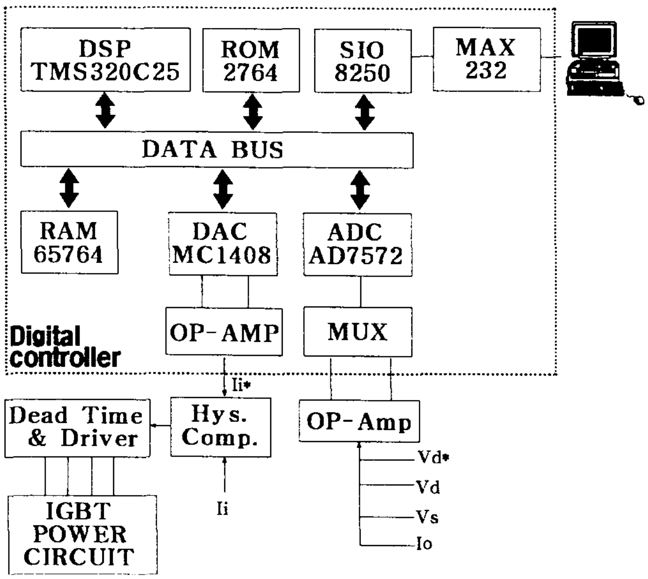


Fig. 7. Hardware block diagram of digital controller.

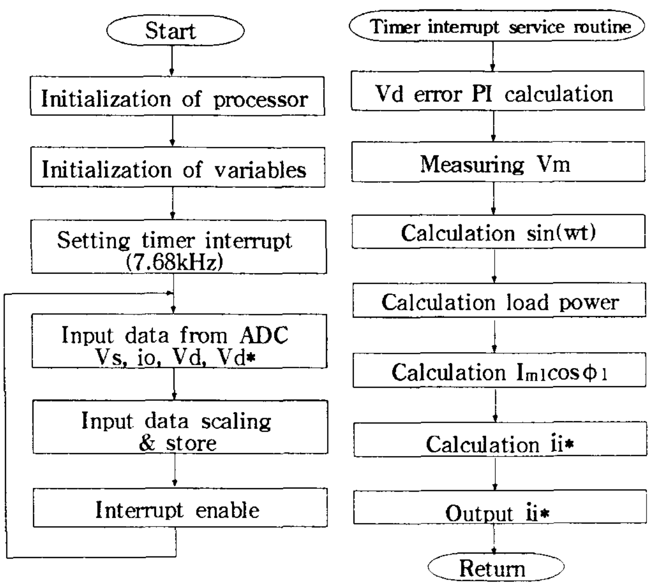


Fig. 8. Flow-chart of the control software.

IV. DIGITAL CALCULATION METHOD OF INSTANTANEOUS REACTIVE CURRENT

The inverter control technology of SPS system when it is working as a stand-alone mode is based on how to get the quick voltage control response to produce the sinusoidal AC output voltage especially for the nonlinear loads such as diode bridge. And as the controllers of inverters, the real-time digital control techniques using microprocessors or digital signal processors(DSP) are becoming more popular. This digital control technique of the inverter output voltage was already presented.[5] The intend of this paper is mainly to introduce a digital control algorithm of the instantaneous reactive current calculation technique working as APF in bypass mode.

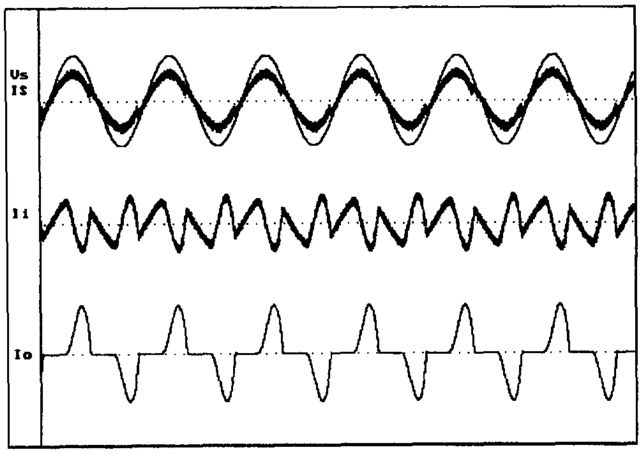
Fig.6 shows the power circuit configuration of the proposed SPS system and the control block diagram for active power filtering. In this proposed digital calculation scheme, the instantaneous active current component of the load current is calculated firstly from the instantaneous active power. The window of the integral interval for the calculation of the instantaneous active power is shifted one sampling interval every sampling, thus the transient errors can be eliminated in one period at least. After then, the instantaneous reactive current component is calculated by subtracting the instantaneous active current component from the load current.

Before generating the reference current which is correspond to the instantaneous reactive current, the DC voltage control error is considered to regulate the DC battery voltage. So the voltage error is added to the instantaneous active current.

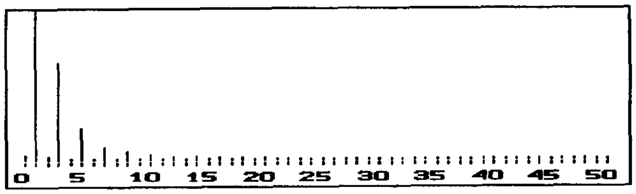
Fig.7 shows the hardware block diagram of digital controller and Fig.8 shows the flow-chart of the control software. To achieve real time operation, a TMS320C25 digital signal processor(DSP) has been chosen as the controller.

V. SIMULATION AND EXPERIMENTAL RESULTS

Fig.9 shows the simulated line source current and voltage, the compensation current, and the load current under the steady state condition of the full bridge load. Evidently, the line source current is exactly in phase with the line voltage and nearly sinusoidal after compensation. Thus, the input power factor approaches unity. Fig. 10 shows the simulated transient response at load current change, respectively. The line current is stabilized in one period. This shows that the reactive current calculator



(a)



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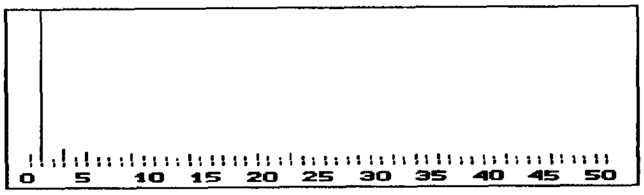

(c)

Fig. 9. Simulation results under the steady-state condition.
(a) Waveforms.
(a) Harmonic spectrum before compensation.
(b) Harmonic spectrum after compensation.

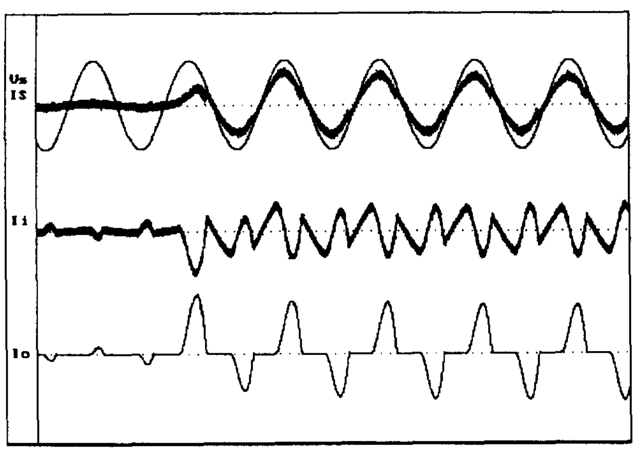

Fig. 10. Simulation results under the transient condition.

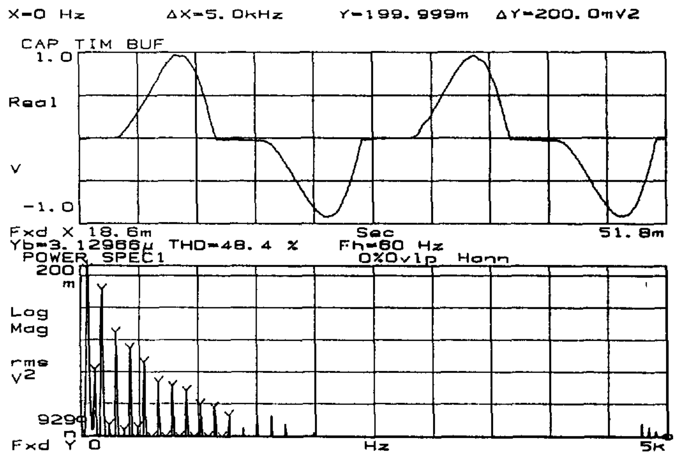

Fig. 11. Experimental line current waveform and harmonic spectrum before compensation.

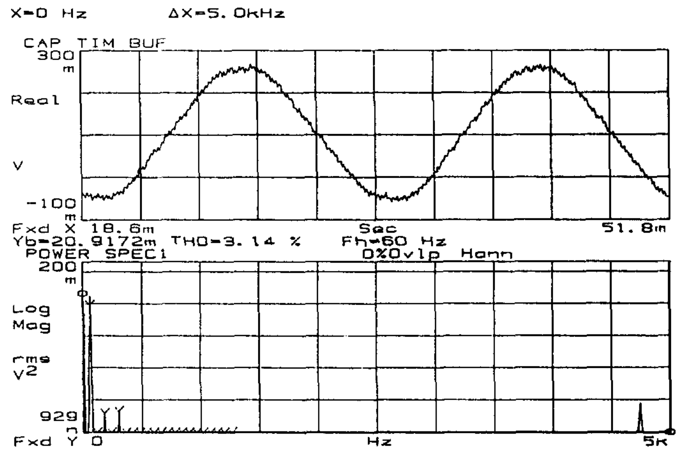

Fig. 11. Experimental line current waveform and harmonic spectrum after compensation.

eliminates the transient error in one period.

For verification, a laboratory prototype SPS of about 3[kW] is setup. The experimental results are shown in Fig.11 and Fig.12. They shows that the experimental results confirm with the simulation results. From the simulation and experimental results, the harmonics and reactive power is well compensated, so the total harmonic distortion factor(THD_i) is improved from 48.4[%] to 3.14[%] and the power factor is controlled almost unity.

VI. CONCLUSION

This paper has described a SPS system which has an active power filtering ability. Bilateral bridge converter is used for a practical power circuit and DSP control is used to configure the control circuit.

The instantaneous active/reactive current based on the definition of the instantaneous active/reactive power is defined to compensate the line current harmonics and reactive power. It is verified through the simulations and experiments that the proposed compensation algorithm is effective not only under the steady-state condition but also under the transient condition. By shifting the integral interval every sampling, the transient effects under the varing load condition can be eliminated perfectly after one period. This proposed system is expandable to the three-phase system, and it is suitable for the applications of low or medium power SPS systems, where the cost of the AC/DC converter system is not negligible.

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