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A New Control Method for a Single-Phase Hybrid Active Power Filter based on a Rotating Reference Frame

Jin-Sun Kim[†] and Young-Seok Kim[*]

[†*]Dept. of Electrical and Electronics Eng., Inha University, Inchon, Korea

ABSTRACT

To get instantaneous reference data in a single power system with vector space phasors, the instantaneous load current is adopted as a phase and another new signal, which is delayed through filtering by the phase-delay property of a low-pass filter, is used as the secondary phase. Because the two-phases have a different phase, the instantaneous value of the harmonic current can be obtained without a time-delay in calculation. The reference voltage is created by multiplying the coefficient k by the compensation current using the rotating reference frame synchronized with the source-frequency. To verify the validity of the proposed control method, experiments are carried out on a prototype of the single-phase hybrid active power filter system.

Keywords: Harmonic current, Imaginary phase, Single-phase hybrid active power filter, Instantaneous compensation, Rotating reference frames

1. Introduction

Appliances that use a diode or thyristor rectifier in the source stage behave as a nonlinear load and the usage of these become major reasons for power quality degradation. To resolve these problems, traditionally, active power filters (APF) have been used because of their low installation cost and high performance efficiency. However, they have several drawbacks such as; large size, resonance and fixed compensation characteristics[1]. Active power filters (APF) have been developed to

mitigate the problems of passive power filters. Compared with conventional APFs the hybrid active power filter has many advantages: the required rating of the series active power filter is considerably smaller than that of conventional series active power filters and the initial running cost of the combined system is as cheap as a typical shunt APF [2][3].

When three-phase shunt active power filters are installed at the utility-plant point of common coupling (PCC), the current harmonics and reactive power circulate between source and load at all times and the currents among the loads interfere with each other. If each single–phase active power filter is employed to compensate for the harmonics of each group of the single-phase loads, the possibility of interference among

the loads will be reduced because of the isolation characteristic. The resulting input current will not be distorted even if one active power filter fails [4].

In this paper, a single-phase hybrid solution for a harmonic detection method is presented. The harmonic components of the load current can be derived by using the positive and negative sequence components of the current phasors in the rotating reference frames.

Finally, the reference of compensation voltage for a single-phase series active power filter can be calculated by multiplying k by the harmonic components [5].

2. Harmonic Current Detecting Principle of the Single Phase

2.1 Single-phase to two-phase transformation

The actual current $i_{L,\text{Re}}(\omega t)$ and the signal of the current $i_{L,LPF}(\omega t)$ delayed by filtering with θ are expressed as follows [6]:

$$i_{L,Re}(\omega t) = I_{Re\,1}\,\sin(\omega t - \varphi) +$$
$$\sum_{n=2}^{\infty} I_{Re\,2n\text{-}1}\sin[(2n-1)\omega t - \varphi_{2n-1}] \quad (1)$$

$$i_{L,LPF}(\omega t) = I_{LPF1}\,\sin(\omega t - \theta - \varphi) +$$
$$\sum_{n=2}^{\infty} I_{LPF2n-1}\sin[(2n-1)(\omega t - \theta) - \varphi_{2n-1}] \quad (2)$$

Suppose $i_{L,\text{Re}}(\omega t)$ is a component of the α axis and $i_{L,LPF}(\omega t)$ is a component of the β axis in two-phase co-ordinates as follows:

$$i_\alpha = i_{L,Re}(\omega t), \qquad i_\beta = i_{L,LPF}(\omega t) \quad (3)$$

From (3), we obtain the orthogonal co-ordinate where:

$\vec{i}_{pos}$ is an instantaneous positive sequence component of the current vector with an angular velocity of ω and $\vec{i}_{neg}$ is an instantaneous negative sequence component of the current vector with an angular velocity of $-\omega$.

2.2 $\alpha - \beta$ to $d_{pos} - q_{pos}$ Reference frame

The aim of this section is obtained by separating the current phasor into ac and dc components in the synchronously rotating frames, called the $d_{pos} - q_{pos}$ and $d_{neg} - q_{neg}$ reference frames. They rotate at speeds of ω and $-\omega$, respectively as can be seen in Fig.1 and Fig. 2.

Because the harmonic components, except the fundamental component of the current space phasor, will become alternative components in the d-q reference frame, they will be cut off by a low-pass filter [7].

Then, the following equations will be applicable only for the fundamental component ($i_{\alpha1}$, $i_{\beta1}$) of i_α and i_β involving the dc current in (3) after the co-ordinate transformation. If the difference between the actual phase and fictitious phase does not correct 90°, the components of the other axis may contain the harmonic component due to interference caused by the other components of the axis. These problems can be resolved by eliminating the interference of the axis by using positive and negative sequence components in the d-q reference frame.
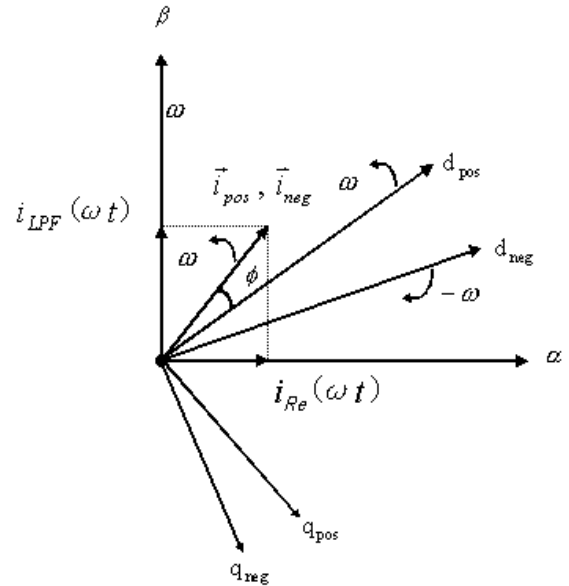

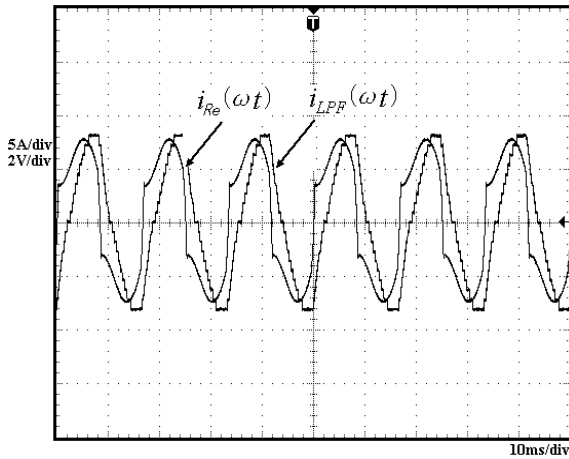Fig. 1. The relationship between the $\alpha - \beta$ and d-q reference frames.

Fig. 2.   Signals of the load current and the fictitious current.

Transforming the $\alpha - \beta$ reference frame into the $d_{pos} - q_{pos}$ reference frame which rotates at speed, (3) can be represented by the following matrix form:

$$\begin{bmatrix} i_{d\,pos} \\ i_{q\,pos} \end{bmatrix} = \begin{bmatrix} \sin \omega t & -\cos \omega t \\ -\cos \omega t & -\sin \omega t \end{bmatrix} \begin{bmatrix} i_{\alpha 1} \\ i_{\beta 1} \end{bmatrix}$$
$$= \begin{bmatrix} \sin \omega t \cdot i_{\alpha 1} - \cos \omega t \cdot i_{\beta 1} \\ -\cos \omega t \cdot i_{\alpha 1} - \sin \omega t \cdot i_{\beta 1} \end{bmatrix} \quad (4)$$

The $i_{d\,pos}$ and $i_{q\,pos}$ can be respectively split into two parts (dc values and ac values), respectively, as:

$$\bar{i}_{d\,pos} = \frac{1}{2}\left[I_{Re1} \cos \phi + I_{LPF1} \sin(\phi + \theta) \right] \quad (5)$$

$$\widetilde{i}_{d\,pos} = -\frac{1}{2}\left[I_{Re1} \cos \phi - I_{LPF1} \sin(\phi + \theta) \right] \cos 2\omega t$$
$$-\frac{1}{2}\left[I_{Re1} \sin \phi + I_{LPF1} \cos(\phi + \theta) \right] \sin 2\omega t \quad (6)$$

$$\bar{i}_{q\,pos} = \frac{1}{2}\left[I_{Re1} \sin \varphi + I_{LPF1} \cos(\varphi + \theta) \right] \quad (7)$$

$$\widetilde{i}_{d\,pos} = -\frac{1}{2}\left[I_{Re1} \cos \varphi - I_{LPF1} \sin(\varphi + \theta) \right] \cos 2\omega t$$
$$+\frac{1}{2}\left[I_{Re1} \sin \varphi + I_{LPF1} \cos(\varphi + \theta) \right] \cos 2\omega t \quad (8)$$

2.3 $\alpha - \beta$ to $d_{neg} - q_{neg}$ **Reference frame**

Transforming the $\alpha - \beta$ reference frame into the $d_{neg} - q_{neg}$ reference frame which rotates at a speed of $-\omega$, (3) can be represented by the following matrix form:

$$\begin{bmatrix} i_{d\,neg} \\ i_{q\,neg} \end{bmatrix} = \begin{bmatrix} \sin(-\omega t) & -\cos(-\omega t) \\ -\sin(-\omega t) & -\sin(-\omega t) \end{bmatrix} \begin{bmatrix} i_{\alpha 1} \\ i_{\beta 1} \end{bmatrix}$$
$$= \begin{bmatrix} -\sin \omega t \cdot i_{\alpha 1} - \cos \omega t \cdot i_{\beta 1} \\ -\cos \omega t \cdot i_{\alpha 1} + \sin \omega t \cdot i_{\beta 1} \end{bmatrix} \quad (9)$$

The $i_{d\,neg}$ and $i_{q\,neg}$ can be divided into two parts (dc values and ac values) respectively as:

$$\bar{i}_{d\,neg} = -\frac{1}{2}\left[I_{Re1} \cos \varphi + I_{LPF1} \sin(\phi + \theta) \right] \quad (10)$$

$$\widetilde{i}_{d\,negs} = -\frac{1}{2}\left[I_{Re1} \cos \varphi - I_{LPF1} \sin(\phi + \theta) \right] \cos 2\omega t$$
$$+\frac{1}{2}\left[I_{Re1} \sin \varphi + I_{LPF1} \cos(\phi + \theta) \right] \sin 2\omega t \quad (11)$$

$$\bar{i}_{q\,neg} = \frac{1}{2}\left[I_{Re1} \sin \varphi + I_{LPF1} \cos(\varphi + \theta) \right] \quad (12)$$

$$\widetilde{i}_{q\,negs} = -\frac{1}{2}\left[I_{Re1} \cos \varphi - I_{LPF1} \sin(\phi + \theta) \right] \cos 2\omega t$$
$$+\frac{1}{2}\left[I_{Re1} \sin \varphi - I_{LPF1} \cos(\phi + \theta) \right] \sin 2\omega t \quad (13)$$

2.4 The decision of reference

To obtain the fundamental component of the load current, two synchronously rotating reference frames and the processes for obtaining the dc component of the d-axis and the q-axis in the d-q reference frame were required.

Using (5) and (10), the dc component of the d-axis can be expressed as:

$$\bar{i}_d = \bar{i}_{d\,pos} - \bar{i}_{d\,neg} = I_{Re1} \cos \phi \quad (14)$$

Using (7) and (12), the dc component of the q-axis can be made as:

$$\bar{i}_q = \bar{i}_{q\,pos} + \bar{i}_{q\,neg} = I_{Re1} \sin \phi \quad (15)$$

However, the real load current $i_{L,Re}$ is valid in the actual compensation and the fundamental component of

the load current is a component of the α-axis which corresponds to the dc component of the current phasor in the d-q reference frame.

Therefore, the reverse-transformation of the co-coordinates is needed and is expressed by following matrix forms:

$$\begin{bmatrix} i_{\alpha f} \\ i_{\beta f} \end{bmatrix} = \begin{bmatrix} \sin \omega t & -\cos \omega t \\ -\cos \omega t & -\sin \omega t \end{bmatrix}^{-1} \begin{bmatrix} \bar{i}_d \\ \bar{i}_q \end{bmatrix} \quad (16)$$

where,

$$i_{\alpha f} = \sin \omega t \cdot \bar{i}_d - \cos \omega t \cdot \bar{i}_q = I_{\mathrm{Re1}} \sin(\omega t - \phi)$$

The reference for the current can be obtained by subtracting the fundamental component from the load currents as follows:

$$i_{ref} = i_{L,\mathrm{Re}} - i_{\alpha f} \quad (17)$$

$$v_{ref} = k \cdot i_{ref} \quad (18)$$

Finally, the reference for the voltage in (18) is obtained by multiplying the coefficient k by the value of the current in (17). A block diagram of the entire control algorithm is represented in Fig. 3.

3. The System Configuration

Fig. 4 shows the circuits of the series active power filter system and the M67 DSP board for control that were used
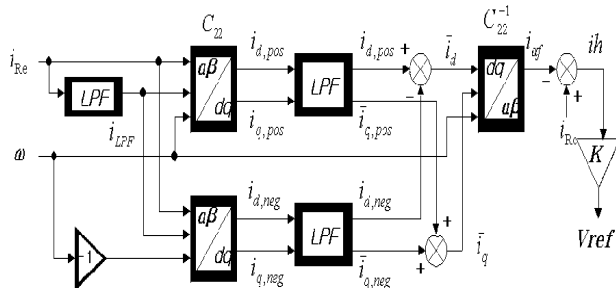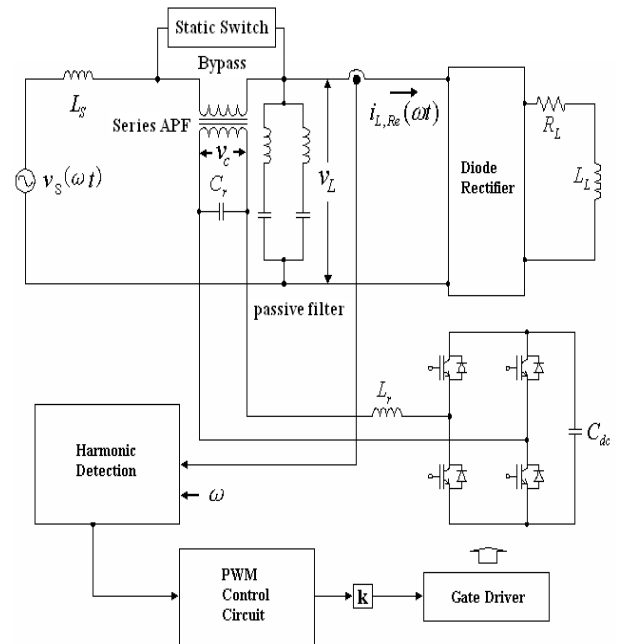
Fig. 3. Detecting algorithms of harmonics.

Fig. 4. Configuration for single-phase hybrid active power filter.

in the experiments. As shown in the control circuits, the M67 DSP board communicates with the PC via a PCI slot and an emulator.

Table 1. The System parameters of the single-phase APF.

Type Parameters	
Supply voltage, Frequency	110[V], 60[Hz]
Source inductor (L_S)	0.1[mH]
Transformer turn ratio	1 : 2
Load inductor (L_L)	35[mH]
Load resistance (R_L)	15[Ω]
Inverter dc-link capacitor (C_{dc})	4700[μF]
LC-filter inductor (L_r)	4[mH]
LC-filter capacitor (C_r)	0.5[μF]

The source currents, the load voltage and the inverter dc-link voltage are transformed into an inner value of ±10 V by the sensing circuits which consist of PTs and CTs. The transformed load current, source voltages and inverter dc-link voltage are converted into 16-bit digital values, and then this value is fed into the DSP.

These input values are used to calculate the voltage compensation reference. Then, this calculated voltage compensation reference is transformed into an analog reference signal through the digital-to-analog converter.

The PWM signal is then generated by the comparison of the analog reference signal and the triangular wave. The generated PWM signal drives the three-phase voltage source inverter.

The inverter switching frequency is chosen to be 20kHz and the system parameters for the APF and shunt passive filters are given in table 1 and 2 respectively.

Table 2.   The System parameters of the parallel passive filters.

3rd passive filter	Inductor	[5.2mH]
	Capacitor	150[μF]
5th passive filter	Inductor	2[mH]
	Capacitor	70[μF]

4. Experimental Results

Fig. 5 shows the experimental waveforms without compensation. Fig. 5*a* shows the load current and the source voltage waveforms with a power factor that was 0.941 lagging. Also the source voltage and current were distorted by the harmonic current source.

Fig. 5*b* and 5*c* show the source current and voltage spectra. The THDs are 22.9% and 5.2% respectively.

The positive sequence components of the current space phasor and its amplitude $\left\|\vec{i}_{pos}\right\|$ in $d_{pos} - q_{pos}$ reference frame are shown in Fig. 5*d*. The signal of the amplitude $\left\|\vec{i}_{pos}\right\|$ in the $d_{pos} - q_{pos}$ reference frame are shown in Fig. 5*d*. The signal of the amplitude $\left\|\vec{i}_{pos}\right\|$ can be

(a) Source voltage and load current waveforms

(b) Load current i_L spectra

(c) Source voltage spectra

(d) Positive sequence components of the current space phasor and their amplitudes

(e) Negative components of current space phasors and their dc sequence components filtering by the low-pass filter
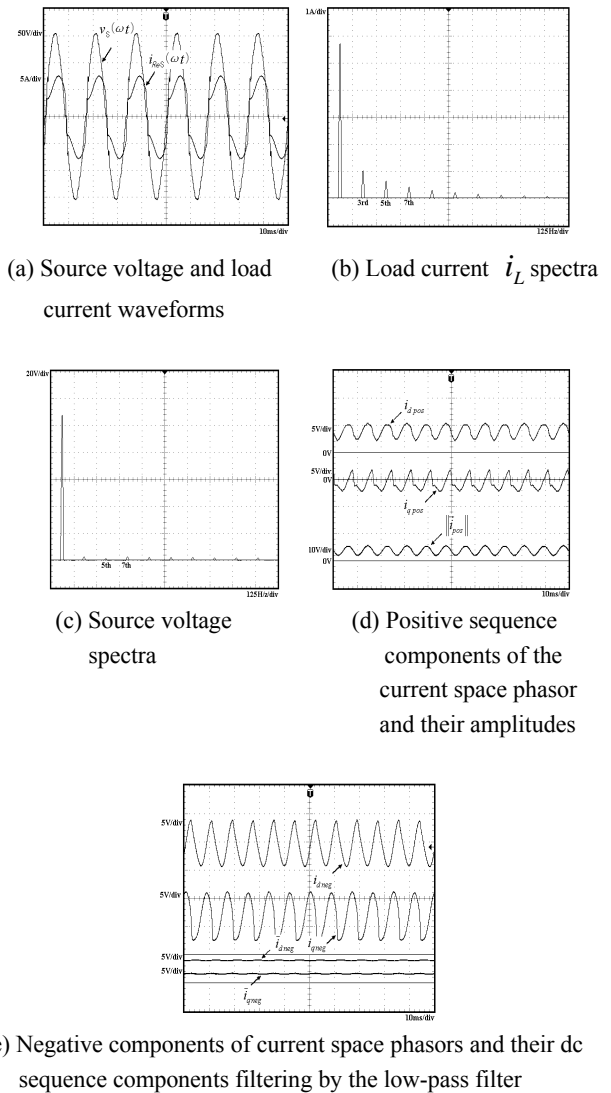
Fig. 5.   Wave-forms before compensation.

separated into dc and ac components. Also, the negative components of the current space phasors and their dc sequence components, both filtered by the low-pass filter in the $d_{neg} - q_{neg}$ reference frame, are shown in Fig 5*e*.

Fig. 6 shows the experimental waveforms when compensated with shunt passive filters. Figure 6*a* shows the source current and source voltage waveforms with a power factor of about 0.463 leading. Fig. 6*b* and Fig. 6*c* illustrate the source current and source voltage spectra, respectively. The source current and source voltage THD were 4.4% and 2.61%, respectively. The amplitude of the source current is increased, and the power factor is improved
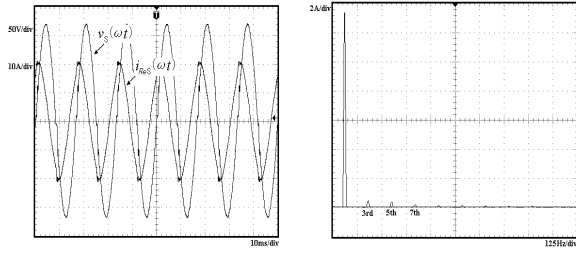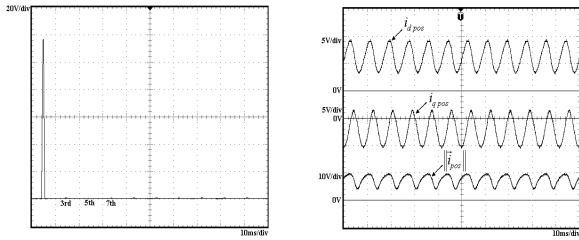
(a) Source voltage and
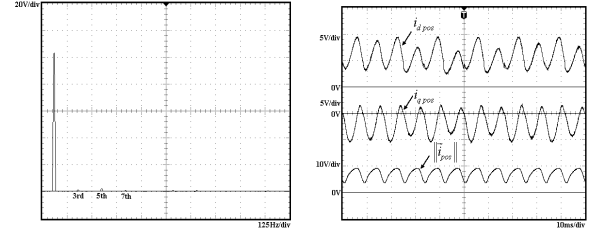load current waveforms
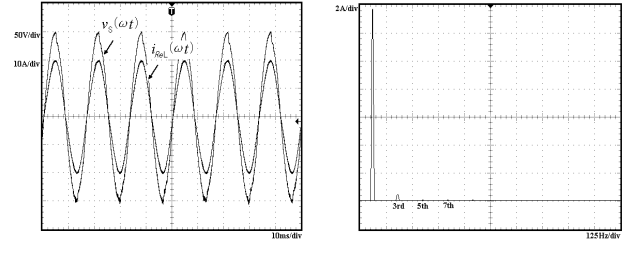
(b) Load current i_L spectra

(c) Source voltage
spectra

(d) Positive sequence
components of the
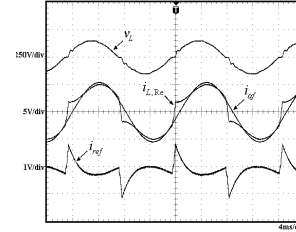current space phasor
and their amplitudes

Fig. 6. Experimental waveforms when compensated with the
shunt filters.

because of the effectiveness of the parallel passive filter.

Fig. 6*b* and Fig. 6*c* show that the 3rd and 5th harmonics
of the source current are almost cancelled by the shunt
passive filters. The positive sequence components of the
current space phasors and their amplitudes $\left\|\vec{i}_{pos}\right\|$ in the
$d_{pos} - q_{pos}$ reference frame are shown in Fig. 5*d*. As the
waveform of the current is improved by the parallel
passive filter, the shapes of positive sequence components
in the $d_{pos} - q_{pos}$ reference frame become more similar
to a sinusoidal signal.

Fig. 7 shows the experimental waveforms compensated
with a shunt passive filters and a series active power filter.

Fig. 7*a* shows the source current and source voltage
waveforms with a power factor of about 0.998. Figures 6*b*
and Fig. 6*c* show the source current and source voltage
spectra, respectively. The source current THD is 3.8% and
the source voltage THD is 2.2%. These experimental

(a) Source voltage and load
current waveforms

(b) Load current i_L spectra

(c) Source voltage
Spectra

(d) Positive sequence
components of the
current space phasor
and their amplitudes

(e) Load voltage, load current, fundamental component and
reference waveforms

Fig. 7. Experimental wave-forms compensated by the shunt
filters and active power filter.

results show that the series active power filter
complemented the defects of the parallel passive filter and
cooperated in harmonic compensation. In Fig. 7*d,*
the shapes of the positive sequence components in the
$d_{pos} - q_{pos}$ reference frame are almost sinusoidal.

Fig. 7*e* shows the process of the reference i_{ref} by
subtraction of the fundamental component from the load
currents.

Fig. 8 shows the loci of the current space phasor in the
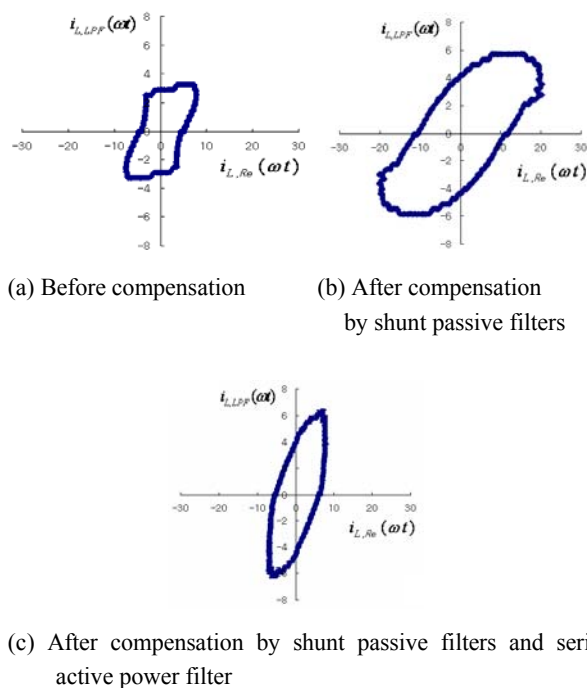α-β reference frame. By comparing these three waveforms

(a) Before compensation (b) After compensation by shunt passive filters

(c) After compensation by shunt passive filters and series active power filter

Fig. 8.   Loci of current vector in α-β co-ordinates.

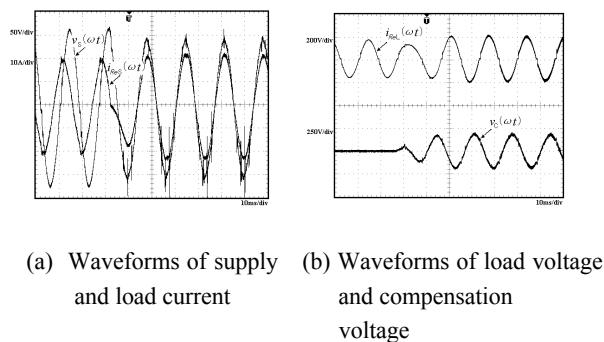(a) Waveforms of supply and load current (b) Waveforms of load voltage and compensation voltage

Fig. 9.   Waveforms during transient states.

it can be seen that the better the harmonics are compensated for, the smoother the waveforms become and the closer they come to the shape of an ellipse. Because the harmonic components of the source current are almost zero, the shape of the waveform of Fig. 8c becomes an ellipse when these harmonic components are compensated for by a combined system of parallel passive filters and a series active power filter. Figure 9 displays the transient waveforms compensated by a series active power filter. Before the series APF supplies the reactive power for compensating harmonics, a load is fed through the bypass as shown in Fig. 4. When the static switch is open, the

phenomenon of the transient state is observed and the harmonics are instantaneously compensated. These results mean that even though the load varies strongly with time, instantaneous compensation is possible.

5. Conclusions

A control scheme for a single-phase hybrid active power filter based on the rotating reference frame method to compensate harmonics was proposed in this paper. To perform the high-speed calculation for real-time control, a M67 DSP board was used. The experimental results showed that the instantaneous calculation of the reference is possible without the delay of phase T/4 even when the load current in the transient states changes rapidly. The THD of source current was improved by 3.8% and the required rating of the series active power filter can be considerably smaller than that of a conventional active power filter because the APF only compensate for the other components and not the 3rd and 5th harmonics. The THD of the source current meets the regulations of IEEE std. 519. These experimental results verified the effectiveness of the control algorithm.

Acknowledgment

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Jin-Sun Kim received his B.S. and M.S. degrees in electrical engineering from the University of the Inha, Incheon, Korea, in 1986 and 1988, respectively, and a Ph.D. in electrical engineering from Inha University, Incheon, Korea, in 2005. He was with the Department of Electrical-Instrumental and project-engineering, LG Petrochemical CO. Ltd. and LG Engineering CO. Ltd where he was a electrical and project engineer 1988~1998. His current research interests include power electronics, electrical machines, power supplies, and electrical circuits.

Young-Seok Kim received his B.S degree in Electrical Engineering from Inha University, Korea in 1977, and his M.S. and Ph.D. in Electrical Engineering from Nagoya University, Japan in 1984 and 1987, respectively. In 1989, he joined Inha University in Korea where he is currently a professor in the School of Electrical Engineering. His current research interests include sensorless motor drives, active power filters and power converting for renewable energy.