Compensation of Source Voltage Unbalance and Current Harmonics in Series Active and Shunt Passive Power Filters

G-Myoung Lee
School of Electrical Eng. and Computer Science
Yeungnam University
214-1, Daedong, Kyongsan, 712-749,Korea

Dong-Choon Lee
School of Electrical Eng. and Computer Science
Yeungnam University
214-1, Daedong, Kyongsan, 712-749,Korea

Abstract – In this paper, a novel control scheme compensating source voltage unbalance and harmonic currents for hybrid active power filters is proposed, where no low/high-pass filters are used in compensation voltage composition. The phase angle and compensation voltages for source harmonic current and unbalanced voltage components are derived from the positive sequence component of the unbalanced voltage set, which is simply obtained by using digital all-pass filters. Since a balanced set of the source voltage obtained by scaling the positive sequence components is used as reference values for source current and load voltage, it is possible to eliminate the necessity of low/high-pass filters in the reference generation. Therefore the control algorithm is much simpler and gives more stable performance than the conventional method. In addition, the source harmonic current is eliminated by compensating for the harmonic voltage of the load side added to feedback control of the fundamental component.

1. INTRODUCTION

In recent year, there has been a considerable interest in the development of active power filters because of increasing concern of power quality and voltage stability at nonlinear load[1]. These problems are partly solved by the help of shunt active power filters, which have been widely investigated. The shunt active power filters are considered as a current source compensating for the harmonic current due to nonlinear load like thyristor rectifiers. This type of filter cannot cope with unbalanced source voltages in spite of its compensation ability of reactive power[2].

On the other hand, series active filters, which work as current harmonic isolators rather than harmonic generators in case of shunt-type, can compensate for utility unbalance and current harmonics[3, 4]. With the conventional p-q theory, there is a generic complexity calculating reference voltages and currents to be compensated and reference phase angle[5] since it has no information on unbalanced voltage to be compensated and includes low/high-pass filters in harmonic component detection[6]. Moreover, the control stability will be deteriorated by the delay time of these digital filters[8].

In this paper, a control scheme based on the positive sequence component of the unbalanced source voltage is proposed, where no low/high-pass filters are used in compensation voltage calculation. By using a digital all-pass filter, the positive sequence component can be simply obtained without using low/band pass filters which may cause the phase delay and magnitude reduction. From the positive sequence component, the phase angle of the reference frame and the reference voltage for compensating unbalanced source and current harmonics is derived easily without low/high pass filters. So, with the proposed scheme, derivation of the whole control algorithm becomes much simpler and gives more stable performance than the conventional methods. The validity of proposed scheme is verified with experiments for 3[kVA] proto-type system.

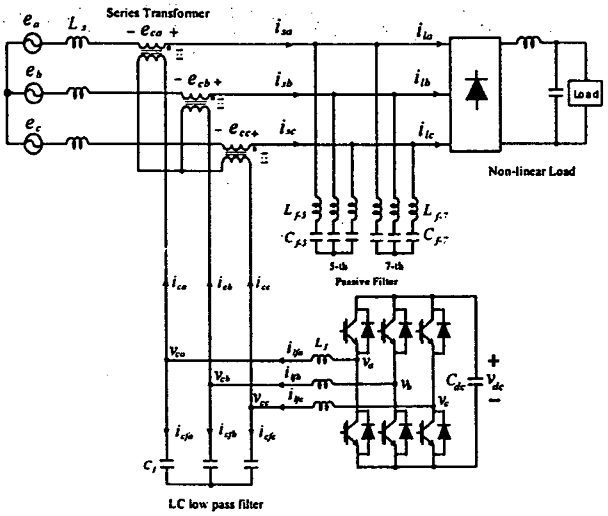

Fig. 1 Hybrid system of series active and shunt passive filter

2. CONTROL OF SERIES ACTIVE POWER FILTER WITH SHUNT PASSIVE FILTERS

A. The configuration of series active power filter with shunt passive power filter

Fig. 1 shows the power circuit of a series active power filter with shunt passive filter. A three-phase inverter is connected in series with the power line via a series transformer in order to inject compensating voltages, which can eliminate the effect of the source voltage unbalance and current harmonics. Turn ratio of the transformer is unity. The LC passive filters are added to compensate for 5th and 7th harmonic currents, which work as harmonic sink and lower the capacity of active power filter. The load is a three-phase diode rectifier that gives nonlinear characteristics.

B. The effect of delay in the reference detect

Fig. 2 shows the control block diagram of 'the first generation control circuit' of [8] where the high pass filter is used in the reference. In this figure, e_s and v_L is source and load voltage, respectively and v_c is the compensating voltage of harmonic currents. If the source impedance is only inductive as ωL, the open-loop transfer function including high-pass filters can be expressed as

$$G(s) = \frac{K}{sL} G_{PWM}(s) \cdot 2G_{pq}(s) \cdot G_{HPF}(s) \qquad (1)$$

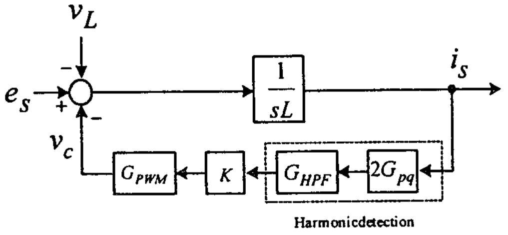

Fig .2 Control block diagram using high pass filter.

where, G_{PWM} , $2G_{pq}(s)$ and $G_{HPF}(s)$ are transfer functions of modulation, p-q transformation circuit, and high-pass filters, respectively.

If these transfer functions are assumed to have the first-order time delay, the open-loop transfer function is given by

$$G(s) = \frac{K}{sL} e^{-s\tau} \tag{2}$$

where, τ is the total of time delay in (1).

From Nyquist's stability criterion, the stable operation of the system must meet the following condition[8];

$$\frac{\pi}{2} \geq \frac{\tau K}{L} \tag{3}$$

It suggests that the time delay of high-pass filter may increase τ and weaken the stability of the system. In turn, a sufficient gain of K for harmonic compensation is not available. Therefore, the algorithm deriving the reference voltage for compensation without the high/low-pass filter will improve the performance of active power filter.

C. Positive sequence component and phase angle detection from unbalanced source voltages.

For unbalanced utility, the phase angle of the reference frame is determined from the positive sequence component of unbalanced source voltages, which is expressed as

$$\begin{bmatrix} e_{a(+)} \\ e_{b(+)} \\ e_{c(+)} \end{bmatrix} = \begin{bmatrix} \frac{1}{3}\left\{e_a - \frac{e_b}{2} - \frac{e_c}{2}\right\} - \frac{1}{j2\sqrt{3}}(e_b - e_c) \\ \frac{1}{3}\left\{e_b - \frac{e_c}{2} - \frac{e_a}{2}\right\} - \frac{1}{j2\sqrt{3}}(e_c - e_a) \\ \frac{1}{3}\left\{e_c - \frac{e_b}{2} - \frac{e_a}{2}\right\} - \frac{1}{j2\sqrt{3}}(e_a - e_b) \end{bmatrix} \tag{4}$$

where, e_a, e_b, e_c and $e_{a(+)}, e_{b(+)}, e_{c(+)}$ are instantaneous phase voltages and their positive components, respectively. The j in (4) means the phase shift of 90°, which is simply implemented by using digital all-pass filters[7] as

$$Y(s) = \frac{s^2 - bs + c}{s^2 + bs + c} X(s) . \tag{5}$$

Since the all-pass filter generates a phase shift only between the input and the output, with the magnitude kept

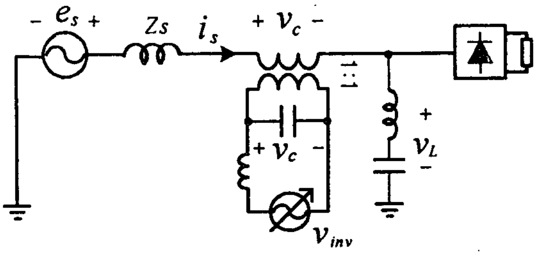

Fig. 3 Per-phase equivalent circuit of series active filter

unchanged, it gives better performance than low/band pass filters being used in positive sequence voltage detection conventionally.

Since the positive sequence component of $e_{a(+)}$, $e_{b(+)}$, and $e_{c(+)}$ in (4) is a balanced set, its reference phase angle can be calculated as (6), by using d-q transformation,

$$\theta = \tan^{-1} \frac{-e_{ds(+)}}{e_{qs(+)}} \tag{6}$$

where,

$$\begin{aligned} e_{qs(+)} &= (2e_{a(+)} - e_{b(+)} - e_{c(+)})/3 \\ e_{ds(+)} &= (e_{c(+)} - e_{b(+)})/\sqrt{3} \end{aligned} \tag{7}$$

D. Compensation of source voltage unbalance

Using (6), (7) is transformed in a synchronous reference frame as

$$\begin{bmatrix} e^e_{q(+)} \\ e^e_{d(+)} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} e_{qs(+)} \\ e_{ds(+)} \end{bmatrix} \tag{8}$$

where, superscript "e" means a quantity in a synchronous reference frame. The original balanced source voltage set can be recovered from the positive sequence component as

$$\begin{bmatrix} e_{a,bal} \\ e_{b,bal} \\ e_{c,bal} \end{bmatrix} = K_u \begin{bmatrix} e_{a(+)} \\ e_{b(+)} \\ e_{c(+)} \end{bmatrix} \tag{9}$$

where, $K_u = E / e^e_{q(+)}$, and E is the desired magnitude of the balanced set.

Since (9) is the desired source voltage, the reference voltages compensating for the source voltage unbalance are obtained as

$$\begin{bmatrix} v^*_{va} \\ v^*_{va} \\ v^*_{va} \end{bmatrix} = \begin{bmatrix} e_{a,bal} - e_a \\ e_{b,bal} - e_b \\ e_{c,bal} - e_c \end{bmatrix} \tag{10}$$

It should be noted that no low/high-pass filters have not used in deriving (10)

E. Compensation of harmonic currents

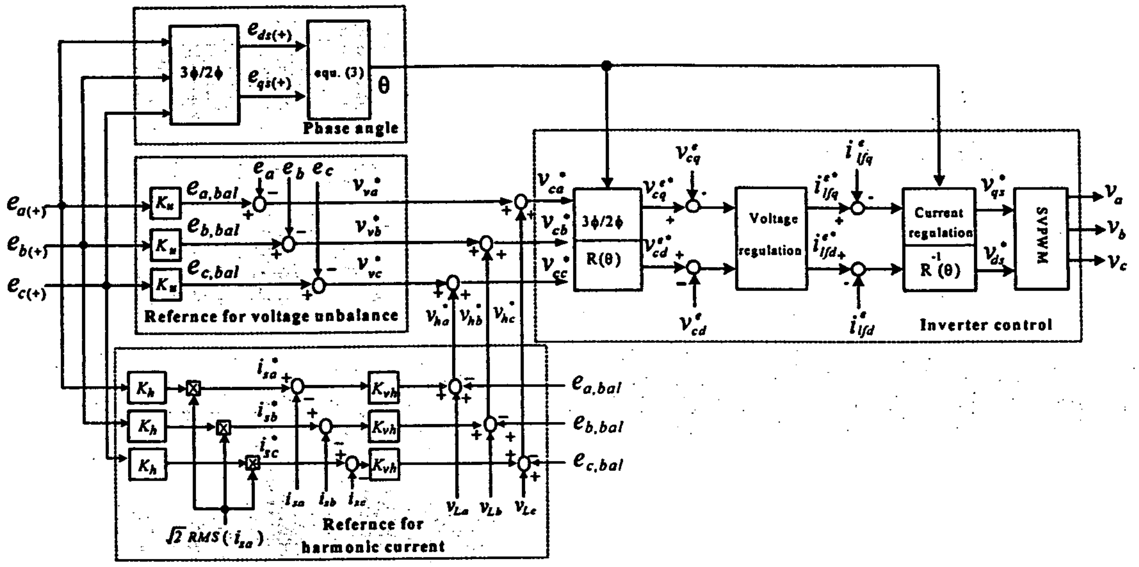

Fig. 4 Block diagram for reference voltage generation and inverter control

Fig. 3 shows a per-phase equivalent circuit of the series active power filter with a shunt passive filter. From the figure, the source harmonic current is expressed as

$$i_{sh}=\frac{e_{sh}-v_c-v_{Lh}}{z_s} \tag{11}$$

where, v_{Lh} and e_{sh} are harmonic components of the load voltage and of the source voltage, respectively, and v_c is a compensating voltage to be injected, and z_s is source-side impedance.

If the reference voltage to compensate for harmonic currents is chosen as,

$$v_c^*=-v_{Lh}, \tag{12}$$

ideally, i_{sh} is suppressed to be zero. It means that the effect of nonlinear load on the source current can be eliminated.

Since z_s is very small and v_c doesn't work for the fundamental component, (9) is the desired fundamental voltage of load. Therefore, v_{Lh} can be calculated as

$$\begin{bmatrix} v_{Lah} \\ v_{Lbh} \\ v_{Lch} \end{bmatrix}=\begin{bmatrix} e_{a,bal}-v_{La} \\ e_{b,bal}-v_{Lb} \\ e_{c,bal}-v_{Lc} \end{bmatrix} \tag{13}$$

where, no high pass filter is used to obtain (13).

To avoid employing the load voltage sensor, the v_L is estimated as

$$\begin{aligned} \hat{v}_{La} &= e_a-v_{ca}-i_{sa}\cdot z_s \\ \hat{v}_{Lb} &= e_b-v_{cb}-i_{sb}\cdot z_s \, . \\ \hat{v}_{Lc} &= e_c-v_{cc}-i_{sc}\cdot z_s \end{aligned} \tag{14}$$

where, z_s is assumed as 0.2% of load impedance.

In case of the inductive dc link, the harmonic current of source must be included in the compensating voltage. In this paper, the compensating reference in synchronous reference frame is obtained from the difference between the source current and its mean value which is derived as

$$\begin{aligned} I_{sq,\text{mean}} &= \frac{1}{n}\sum_{k=1}^{n} i_{sq}^e(k) \\ I_{sd,\text{mean}} &= \frac{1}{n}\sum_{k=1}^{n} i_{sd}^e(k) \end{aligned} \tag{15}$$

where, i_{sq}^e and i_{sq}^e are the source current in synchronous reference frame and n is the iteration number of calculation, respectively. From (15) the desired fundamental component of three-phase source current is derived as

$$\begin{bmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{bmatrix}=\begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}\begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}\begin{bmatrix} I_{sq\text{mean}} & I_{sd\text{mean}} \\ I_{sd\text{mean}} & I_{sq\text{mean}} \end{bmatrix} \tag{16}$$

Combining (12) and (16), the reference voltage compensating for the harmonic component of the source current is given by

$$\begin{aligned} v_{ha}^* &= K_{vh}(i_{sa}^*-i_{sa})+v_{Lah} \\ v_{hb}^* &= K_{vh}(i_{sb}^*-i_{sb})+v_{Lbh} \\ v_{hc}^* &= K_{vh}(i_{sc}^*-i_{sc})+v_{Lch} \end{aligned} \tag{17}$$

where, K_{vh} is a constant.

F. Control of PWM inverter

Fig. 4 shows the block diagram of reference generation and inverter control scheme. It is noted that no low/high-pass filters except all-pass filters are used for generating the compensating voltage references, which causes no phase delay. From (10) and (17), the reference voltage for the inverter output capacitor are expressed as

$$\begin{aligned} v_{ca}^* &= v_{ha}^*+v_{va}^* \\ v_{cb}^* &= v_{hb}^*+v_{vb}^* \, . \\ v_{cc}^* &= v_{hc}^*+v_{vc}^* \end{aligned} \tag{18}$$

In the inverter control block, the output voltage and current of the inverter are controlled in synchronous reference frame.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

The system parameters for experiment are listed in Table 1.

Table 1. System parameters

Input voltage[V]	100[V peak]
5th passive filter	L=1.4[mH], C=200[μF]
7th passive filter	L=1.4[mH], C=100[μF]
DC link capacitor	C=2350[μF]
Inverter output filter	L=1.4[mH], C=10[μF]
Switching frequency	3.5[kHz]
Series transformer	1[kVA], turn ratio=1

The unbalanced set of source voltage that is adjusted by ac programmable power supply is given as

$$\begin{aligned} e_a &= 110\sin\omega t \\ e_b &= 90\sin(\omega t - 130^\circ) \\ e_c &= 90\sin(\omega t + 130^\circ) \end{aligned} \qquad (19)$$

Fig. 5 shows the unbalanced source voltage, its positive and negative sequence components, and the phase angle referred to the positive sequence component from the top. Even though the source voltage includes negative sequence components, a balanced set of positive sequence component and the phase angle for control are obtained. Since it is derived from all-pass filters, no phase delay and magnitude reduction appears.

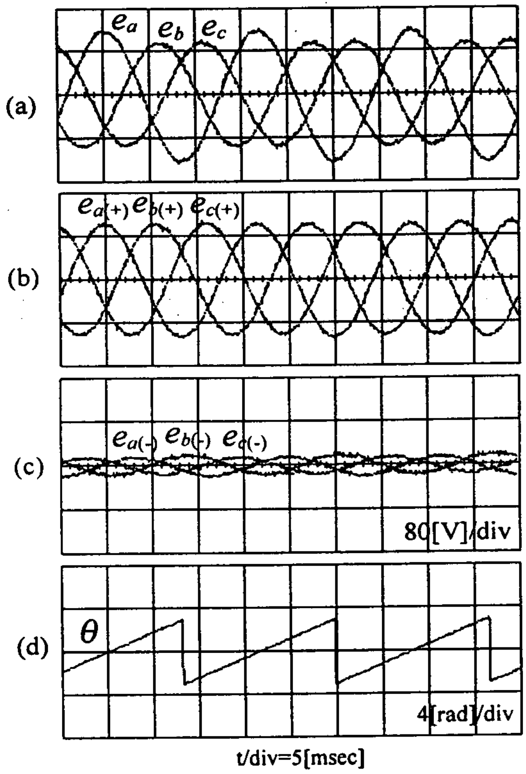

Fig. 5 Source voltage and phase angle
(a) source voltage
(b) positive sequence component
(c) negative sequence component
(d) phase angle

Fig. 6 shows load voltage, load current, and source current waveforms without compensation, from the top. Due to the source voltage unbalance, the source current and the load voltage are also unbalanced. The load current is significantly distorted due to the diode rectifier. In figure (c), it is shown that the shunt passive filters don't eliminate all of the harmonic components of source current.

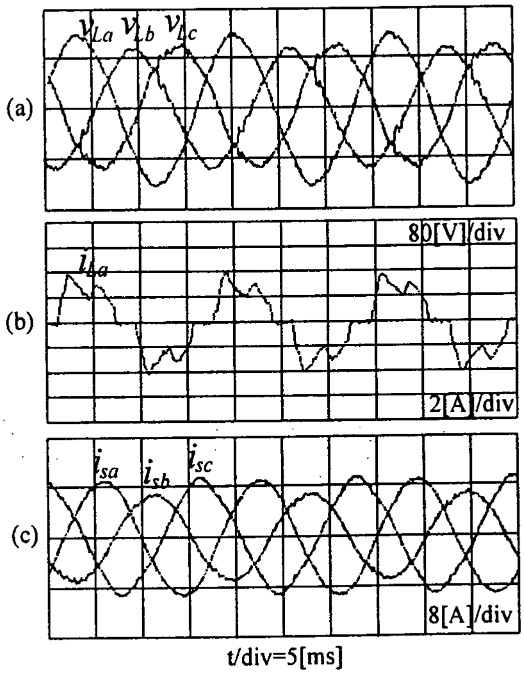

Fig. 6 Waveforms without compensation
(a) load voltage (b) load current (c) source current

Fig. 7 shows the control performance of the compensating voltage controlled in synchronous reference frame, which is well performed.

Fig. 8 shows load voltage, load current and source current waveforms with compensation, from the top. The load voltage and source current become a balanced set and the remained harmonic components of source current are almost suppressed.

Fig. 9 shows the harmonic spectrum of load voltage, load current, and source current waveforms, which correspond to those in Fig. 8. In spite of abundant harmonics of the load current, the source current has no low-order harmonics. The unbalanced source voltage causes the third harmonic component of load current as shown in (b).

4. CONCLUSION

Based on the positive sequence component of the source voltage which is simply obtained by an all pass filter, the phase angle detection as well as the reference voltage generation to compensate for unbalanced voltage and harmonic current have been derived simpler than other

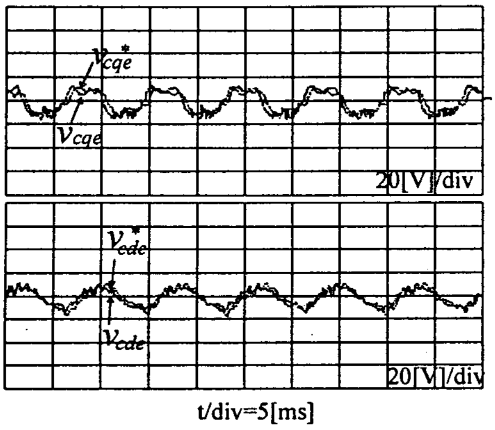

Fig. 7 Control performance of inverter output voltage

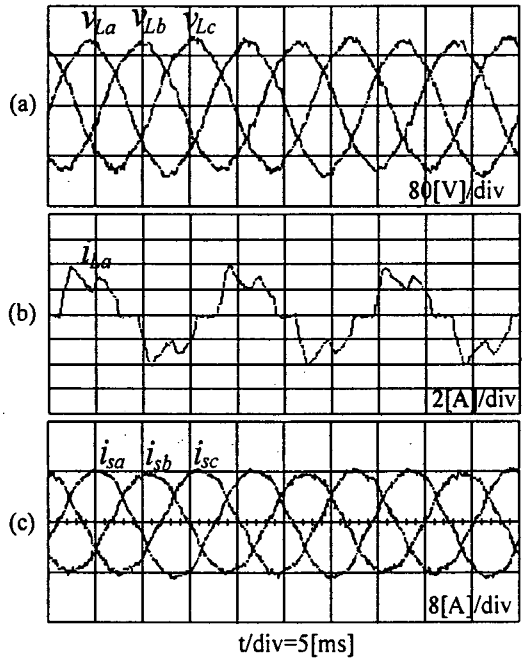

Fig. 8 Various waveforms with compensation
(a) load voltage (b) load current (c) source current

methods using low/high-pass filters. This method is easy to implement and to tune controller gains since the references and phase angle can be derived by simple arithmetic calculation without any time delay. The compensating performance of the proposed method has been presented by the experimental results for 3[kVA] proto-type active power filter controlled by TMS320C31 DSP chip. The negative sequence component included in the source voltage has been reduced to 1.9% from 10% and the total harmonic distortion (THD) of the source current has been reduced to 3.8% from 44.5%.

This work was supported by Korea Research Foundation Grant (KRF-2000-E00158)

V. REFERENCES

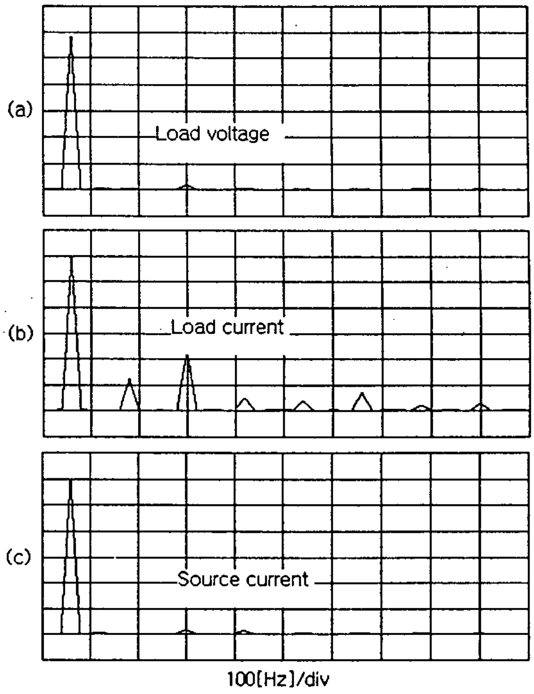

Fig. 9 Harmonic spectrum of the current
(a) load voltage (b) load current (c) source current

[1] A. Campos, G. Joos, P. D. Ziogas, and, J. F. Lindsay, "Analysis and design of a series voltage unbalance compensator based on a three-phase VSI operating with unbalanced switching functions," *IEEE Trans. on P. E.*, vol. 9, no. 3, pp. 269-274, 1994.

[2] J. W. Dixon, J. J. Garcia, and L. A. Moran, "Control system for three-phase active power filter which simultaneously compensates power factor and unbalanced load," *IEEE Trans. on I.E.*, vol. 42, no. 5, pp. 636-641, 1995.

[3] F. Z. Peng, H. Akagi, and A. Nabae, "A new approach to harmonic compensation in power systems – a combined system of shunt passive and series active filters," *IEEE Trans. on I.A.*, vol. 26, no. 6, pp 983-990, 1990

[4] M. El-Habrouk, M. K. Darwish, and P. Mehta, "Active power filters: a review," *IEE Proc.-Electr. Power Appl.*, vol. 147, no. 5, pp. 403-413, 2000.

[5] J. W. Dixon, G. Venegas, and L.A. Moran," A series active power filter based on a sinusoidal current-controlled voltage source inverter," , *IEEE Trans. on I.E.*, vol. 44, no. 5, pp 612-620, 1997

[6] L. Moran, I. Pastorini, J. Dixon, and R. Walace, "Series active power filter compensates current harmonics and voltage unbalance simultaneously," *IEE Proc.-Gener. Transm. Distrib.*, vol 147, no. 1, pp. 31-36, 2000.

[7] S. S. Lee, J. K. Kang, and S. K. Sul, " A new phase detecting method for power conversion systems considering distorted condition in power system," *IEEE IAS Conf. Rec.*, pp. 2167-2172, 1999.

[8] S. Srianthumrong, H. Fujita, and H. Akagi, "Stability Analysis of a Series active Filter Integrated with a Double-Series Diode Rectifier," *IEEE PESC Conf.* 2000.