Control of Series Active Power Filters Compensating for Source Voltage Unbalance and Current Harmonics

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Abstract – In this paper, a novel control scheme compensating source voltage unbalance and current harmonics for hybrid active power filters is proposed. The reference voltage for compensation is derived from the differences between the fundamental source and load voltages and their instantaneous values, where the positive sequence component which is simply obtained by using digital all-pass filters is used as the fundamental voltages. The reference voltages for the 5th and 7th harmonic compensation are predicted a sampling period ahead to reduce the delay in inverter voltage control loop. The validity of the proposed scheme has been verified by experimental results.

I. INTRODUCTION

In recent years, there has been considerable interest in the concern of power quality and voltage stability at nonlinear load[1]. In these problems, harmonic contamination can be solved by the help of shunt active power filters regarded as a current source compensating for the harmonic current due to nonlinear load. However, since this type of filter cannot cope with unbalanced source voltages, series active filters which had operated mainly as voltage regulators or harmonic isolators were introduced at the end of 1980’s[2]. Even though the series type active filter is most preferable to protect the consumers from an inadequate supply voltage quality[3, 4], there is a generic complexity in implementation, since additional low/high-pass filters are included in generating the reference voltages[5, 6].

In this paper, a novel control scheme compensating source voltage unbalance and harmonic currents for the combined system of series active and shunt passive power filters is proposed, where the difference between the fundamental component of the source and load voltages and their instantaneous values is used in deriving the reference voltages for compensation. Since the positive sequence component of source voltages which is obtained simply by using digital all-pass filters without phase error and magnitude reduction is used in calculating the fundamental component of the source and load voltages, low/high-pass filters are unnecessary to derive them. In order to reduce the delay in voltage control loop for compensation, the reference of 5th and 7th harmonic components is predicted a sampling period ahead. The validity of the proposed scheme has been verified for 3[kVA] prototype active power filter system.

II. HYBRID SYSTEM OF SERIES ACTIVE AND SHUNT PASSIVE FILTERS

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

A. Positive sequence component and phase angle of unbalanced source voltages

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

\[
\begin{align*}
\begin{bmatrix}
e_{a(+)} \\
e_{b(+)} \\
e_{c(+)} \\
\end{bmatrix} =
\begin{bmatrix}
\frac{1}{3}e_a - \frac{e_b}{2} - \frac{e_c}{2} \\
\frac{1}{3}e_b - \frac{e_c}{2} - \frac{e_a}{2} \\
\frac{1}{3}e_c - \frac{e_a}{2} - \frac{e_b}{2}
\end{bmatrix} - \frac{1}{j2\sqrt{3}} \begin{bmatrix}
e_b - e_c \\
e_c - e_a \\
e_a - e_b
\end{bmatrix}
\end{align*}
\]

(1)

where \(e_a, e_b, e_c\) and \(e_{a(+)}, e_{b(+)}, e_{c(+)}\) are instantaneous phase voltages and positive components, respectively. The \(j\) in (1) means the phase shift of 90°, which is simply implemented by using digital all-pass filters[7] as

\[
Y(s) = \frac{s^2 - bs + c}{s^2 + bs + c}X(s).
\]

Since the all-pass filter generates a desired phase shift only between the input and the output, with the magnitude kept unchanged, it gives better performance than low/band pass filters in deriving the positive sequence voltage component[3].

However, the positive sequence component of \(e_{a(+)}, e_{b(+)}\), and \(e_{c(+)}\) is a balanced voltage set, its reference phase angle can be calculated as (3), by using d-q transformation,

\[
\theta = \tan^{-1} \frac{-e_{d(+)}}{e_{q(+)}}.
\]
where,
\[
\begin{align*}
e_{q(+)} &= (2e_{d(+)} - e_{b(+)} - e_{c(+)})/3 \\
e_{d(+)} &= (e_{c(+)} - e_{b(+)})/\sqrt{3}
\end{align*}
\]

(4)

B. Compensation of source voltage unbalance

By using (3), (4) can be transformed in a synchronous reference frame as

\[
\begin{bmatrix}
e^*_{d(+)} \\
e^*_{q(+)}
\end{bmatrix} =
\begin{bmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
e_{q(+)} \\
e_{d(+)}
\end{bmatrix}
\]

(5)

where, superscript "*" means a quantity in a synchronous reference frame. The required fundamental voltage set of the source can be calculated as

\[
\begin{bmatrix}
e_{a,ba} \\
e_{b,ba} \\
e_{c,ba}
\end{bmatrix} = \frac{1}{E} \begin{bmatrix}
e_{d,ba} \\
e_{q,ba}
\end{bmatrix}
\]

(6)

where \( K_u = \frac{E}{E^*} \), and \( E \) is the desired magnitude of the balanced set.

Since (6) is the desired source voltage, the reference voltage set compensating for the unbalance is calculated as

\[
\begin{bmatrix}
v^*_{va} \\
v^*_{vb} \\
v^*_{vc}
\end{bmatrix} =
\begin{bmatrix}
e_{a,ba} - e_a \\
e_{b,ba} - e_b \\
e_{c,ba} - e_c
\end{bmatrix}
\]

(7)

C. Compensation of harmonic currents

Fig. 2 shows the control block diagram in [8]. In this figure, \( e_s \) and \( v_L \) are the source and load voltages, respectively, and \( v_c \) is the injected voltage for harmonic current compensation.

Because the source impedance including the transformer impedance is represented as \( a_s \), the open-loop transfer function having high-pass filters can be expressed as

\[
G(s) = \frac{K}{sL} \cdot G_{PWM}(s) \cdot G_{HPF}(s) \cdot 2G_{pq}(s)
\]

(8)

where, \( G_{PWM} \), \( 2G_{pq}(s) \) and \( G_{HPF}(s) \) are the transfer function of modulation, pq 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

\[
G(s) = \frac{K}{sL} e^{-\tau s}
\]

(9)

where \( \tau \) is the total time delay in (8).

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

\[
\frac{\pi}{2} \geq \frac{\omega}{L}
\]

(10)

Since using high-pass filters as in (8) increases \( \tau \), the gain \( K \) cannot be set so large to compensate for the harmonics sufficiently. So, if the reference voltage is derived without using the high/low-pass filter, the compensation performance of active power filters will be improved.

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

\[
i_{sh} = \frac{e_{sh} - v_L - v_{Lh}}{Z_s}
\]

(11)

where \( v_{Lh} \) and \( e_{sh} \) are harmonic components of the load and source voltages, respectively, and \( v_c \) is the voltage to be injected from the inverter, and \( Z_s \) is the source-side impedance.

If the reference voltage for harmonic current compensation is chosen as,

\[
v_c^* = -v_{Lh}
\]

(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, (6) is the desired fundamental voltage of the load. Therefore, \( v_{Lk} \) can be calculated as

\[
v_{Lk} = e_{bal} - v_L \tag{13}
\]

where, \( v_L \) is estimated as

\[
v_{L} = e_u - v_{cu} - i_{su} \cdot z_s \tag{14}
\]

By using (14), the load voltage sensor is not required.

In case of inductive load of the diode rectifier, it is desirable that the voltage component for current-source type harmonic compensation should be added to (12) as

\[
\begin{align*}
v^{*}_{ka} &= K_{ab}(i_{sa} - i_{sa}) + v_{Lh/kb} \\
v^{*}_{kb} &= K_{ab}(i_{sb} - i_{sb}) + v_{Lh/kb} \\
&= K_{ab}(i_{sa} - i_{sa}) + v_{Lh/kb}
\end{align*}
\tag{15}
\]

where, the fundamental component of the source current is given by

\[
\begin{bmatrix}
i_{sd} \\
i_{sh} \\
i_{sl}
\end{bmatrix} = 
\begin{bmatrix}
1 & 0 & 0 \\
-1/2 - \sqrt{3}/2 & \cos \theta & \sin \theta \\
-1/2 - \sqrt{3}/2 & -\sin \theta & \cos \theta
\end{bmatrix} \begin{bmatrix}
i_{sd,mean} \\
i_{sh,mean} \\
i_{sl,mean}
\end{bmatrix}
\tag{16}
\]

In (16), \( i_{sd,mean} \) and \( i_{sh,mean} \) are mean values of the source currents in synchronous reference frame.

**D. Control of PWM inverter**

Fig. 4 shows the block diagram of reference generation schemes for harmonic current and source voltage unbalance. From (7) and (15), the references of the inverter output voltage are expressed as

\[
\begin{align*}
v_{ca}^{*} &= v_{ca} + v_{ca}^{*} \\
v_{cb}^{*} &= v_{cb} + v_{cb}^{*} \\
v_{cc}^{*} &= v_{cc} + v_{cc}^{*}
\end{align*}
\tag{17}
\]

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

**III. PREDICTION OF REFERENCE VOLTAGES**

To avoid the calculation delay of microprocessors, prediction of the reference voltage for compensation is needed. It is sufficient to consider only the 5th and 7th harmonic components in (18).

Fig. 5 shows the block diagram for extracting only the 5th and 7th harmonic components from the total reference voltage for harmonic current compensation and for predicting the values one sampling time ahead. Suppose (17) is including the 5th and 7th harmonic components as

\[
\begin{align*}
v_{5a}^{*} &= V_{5a}\cdot e^{j(\theta - \phi)} \\
v_{7a}^{*} &= V_{7a}\cdot e^{j(\theta - \phi)}
\end{align*}
\tag{18}
\]

Transforming (18) in synchronous reference frames of the 5th and 7th harmonics,

\[
\begin{align*}
v_{h}^{5a} &= e^{-j\theta} \cdot V_{5a}^{*} \\
v_{h}^{7a} &= e^{-j\theta} \cdot V_{7a}^{*}
\end{align*}
\tag{19}
\]

In (19), the 5th and 7th components are transformed in dc value. The dc signals are acquired easily by low-pass filter as

\[
\begin{align*}
v_{h}^{5a} &= e^{-j\theta} \cdot V_{5a}^{*} \cdot e^{-j(\theta - \phi)} = V_{5a}^{*} e^{j\theta} \\
v_{h}^{7a} &= e^{-j\theta} \cdot V_{7a}^{*} \cdot e^{-j(\theta - \phi)} = V_{7a}^{*} e^{j\theta}
\end{align*}
\tag{20}
\]

Eq. (20) is inversely transformed in stationary reference frame as
Fig. 5 Block diagram for reference prediction

Table 1. System parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage [V]</td>
<td>100 [V peak]</td>
</tr>
<tr>
<td>5th passive filter L</td>
<td>1.4 [mH], C=200 [µF]</td>
</tr>
<tr>
<td>7th passive filter L</td>
<td>1.4 [mH], C=100 [µF]</td>
</tr>
<tr>
<td>DC link capacitor C</td>
<td>2350 [µF]</td>
</tr>
<tr>
<td>Inverter output filter L</td>
<td>1.4 [mH], C=10 [µF]</td>
</tr>
<tr>
<td>Switching frequency f_s</td>
<td>3.5 [kHz]</td>
</tr>
<tr>
<td>Series transformer T</td>
<td>11 [kVA], 110/110 [V]</td>
</tr>
</tbody>
</table>

The unbalanced source voltages are given as:

\[ e_a = 110 \sin \omega t \]
\[ e_b = 90 \sin (\omega t - 130^\circ) \]
\[ e_c = 90 \sin (\omega t + 130^\circ) \]  \hspace{1cm} (25)

which are adjustable by an programmable power supply.

Fig. 7 shows the unbalanced source voltage, its positive and negative sequence component, and phase angle referred to the positive sequence component, from the top. Even though the source voltage is unbalanced, it is shown that a balanced set of positive sequence components is obtained, from which the phase angle is acquired. Since all-pass filters are used for that, no phase delay and magnitude reduction appear.

Fig. 8 shows the source current in case only passive filters without the active filter is connected to the system. Due to the source voltage unbalance, the source currents are also unbalanced and distorted with amplified negative sequence components by the capacitive dc link of diode rectifier[10].

The waveform of reference calculated from (22) is compared with that of conventional reference in Fig. 9. It should be noted that the fundamental and harmonic components higher than the 7th order are excluded in the modified reference as shown in (b).

Fig. 10 shows the control performance of the proposed method. When \( v_{cq}^* (k+1) \) instead of \( v_{cq}^* (k) \) is used, the response of the voltage is faster.

The output voltages of the inverter are shown in Fig. 11. In (a), the reference voltage in (17) is used and in (b), sum of (23) and (24) is employed. With the proposed method,
Fig. 7 Source voltage and phase angle
(a) source voltage
(b) positive sequence component
(c) negative sequence component
(d) phase angle

Fig. 8 Current waveforms without compensation

Fig. 9 Reference modification and harmonic spectrum
(a) conventional reference
(b) modified reference

Fig. 10 Control performance with predicted reference

Fig. 11 Inverter output voltage
(a) conventional method
(b) proposed method

Fig. 12 Waveforms with compensation
(a) load voltage
(b) load current
(c) source current
the phase delay disappeared.

Fig. 12 shows the source current and load voltage waveforms with compensation. The negative sequence component of the source current is reduced from 0.3[A] to 0.17[A], since the phase error in voltage control loop is removed by the proposed method. The load voltage also is a balanced set and maintains its desired magnitude.

Fig. 13 shows the harmonic spectrum of the load and source currents. The THD of the current is decreased to 3% from 44.3%.

V. CONCLUSIONS

Based on the positive sequence component of the source voltage which is simply obtained by all-pass filters, the phase angle as well as the reference voltage generation to compensate for unbalanced source voltage and harmonic current have been derived simpler than other conventional methods usually using low/high-pass filters. This method is easy to implement and to tune controller gains since the reference voltage and phase angle can be derived by simple arithmetic manipulation without phase-delayed digital filters. The validity of the compensating performance has been verified by the experimental results for a 3[kVA] proto-type active power filter controlled by TMS320C31 DSP chip. The negative sequence component in the source voltage has been reduced to 2.9% from 10% and the total harmonic distortion (THD) of the source current has been much reduced to 3.8% from 44.5%.

VI. REFERENCES


