A Study on the Implementation of Multi-functional Series Active Power Filter
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국문 요약

정밀 전기·전자 기기 및 컴퓨터 시스템의 사용이 급증함에 따라 전력품질이라는 요소가 전력의 공급자나 수용자에게 중요한 문제로 부각되어지고 있다. 전력 품질의 저해 요인으로는 반도체 스위칭 소자의 사용으로 인한 고조파 전류 유기, 용량성 또는 유도성 부하에 의한 역류 저하, 불평형 부하의 사용, 전력 계통상의 사고 발생 및 복잡이나 고전압 서지에 의한 이상 전압 발생 등을 대표적으로 들 수 있다.

본 논문에서는 적렬형 능동전력필터를 이용하여 이러한 전력 계통상의 품질 저해 요인들을 적절히 보상하고 전체적인 전력 품질을 개선할 수 있는 세어 알고리즘을 제안하였다. 기존 연구 결과 두 가지를 응용한 개선된 적렬형 능동전력필터 제어 방법을 이용하여 고조파 전류 보상과 역류 보상을 하였으며, 또한 새로운 전압 보상 방법을 제안하여 부하측 전압을 평형한 정격 전압 조건이 되도록 하였다. 고조파 전류와 역류 보상을 위한 두 가지의 제어 방법은 기존의 방법에 비하여 좀 더 간단하게 구현 가능한 장점이 있으며, 전압 보상 알고리즘은 계획 제어를 이용하여 보다 안정적인 보상이 가능하다.

제안하는 제어 방법들의 타당성을 증명하기 위해 실험실 규모의 적렬형 능동전력필터 시스템을 구성하였고, 각각의 실험을 통하여 그 효용성을 보였다. 실험은 각각의 제어 방법들을 단계적으로 적용하였으며, 최종적으로는 고조파 전류 보상, 역류 보상 그리고 전압 보상의 기능을 수행하는 다기능 보상기로서의 적렬형 능동전력필터를 구현하였다.
ABSTRACT

Power quality has been become a very important factor in power systems to electric power suppliers and consumers with proliferation of various electric/electronic equipments and computer systems. The major causes of a poor power quality are harmonic currents, poor power factor, voltage sags, voltage unbalances, and etc.

In this paper, novel control methods of series active power filter are proposed wholly to improve power quality. Two control methods of series active power filter, which are applications of former studies and can be easily implemented, are used to compensate the harmonic currents and to improve power factor in the electric source. A new voltage compensation method which is able to implement more stable voltage compensation characteristics owing to the use of a feed-back control is proposed. The harmonical combinations of two compensation methods of harmonic currents and voltage compensation method can constitute control methods for a multi-functional series active power filter.

To verify the validities of the proposed control methods, experiments are carried out for prototypes of 3-phase 3-wire power system and series active power filter system. As a result the excellency of the proposed control methods are clarified.
CHAPTER 1  INTRODUCTION

Power quality has been become a very important factor in the power delivery systems with proliferation of various sensitive loads such as high-precision electric/electronic equipments and computer systems. However, there are various factors to make power quality poor. The utilities more frequently encounter harmonic related problems, such as higher transformer and line losses, reactive power, and resonance problems required derating of distribution equipments, harmonic interactions between customers or between the utility and load reduced system stability and reduced safe operating margins. Source voltage unbalances or voltage sags are causes of higher losses in the power lines and electric machines, damages of electric machines, requirement of derating of distribution equipment. Poor power factor is as well cause of electric power loss[1-15].

Harmonic currents are generated in the electric power systems by nonlinear electric loads using semiconductor switching devices. The passive power filters composed of inductors and capacitors are used to mitigate harmonic currents, but the passive power filter has a lot of drawbacks. The passive power filter eliminates only one of harmonic currents which is tuned to it, so many passive power filters which have various tuned frequencies are required to mitigate various harmonic currents. Additional costs and volumes are also required to use many passive power filters. Since its compensation characteristics are dependent upon source impedance which is not accurately known and varies with the system configurations, it is difficult to expect a good performance in all cases[1]. Nowadays, active power filters are proposed to overcome those drawbacks and to perform a better harmonic currents compensation. There are several types of active
power filters. In general, those are classified into a parallel active power filter[2-4] and a series active power filter[5-6] by a principle of harmonic currents compensation. The parallel active power filter injects compensation currents to the power delivery systems, and the series active power filter blocks flow of harmonic currents from the load to the ac source by compensation voltages. A combined system of a series active power filter and a parallel passive filter is another one to be studied actively[7-11].

Voltage unbalances and voltage sags have recently become a concern due to their effects on the loads and the sources. Voltage compensation of constant loads is normally achieved by means of passive power filters that balance the load impedances. For variable loads, the conventional solution has been the use of static impedance compensation by means of shunt-connected thyristor-controlled reactors. In both cases, the load currents are balanced by adding reactive elements in parallel to the load. The same procedure is used in voltage compensation. The disadvantages of this method are the harmonic generation due to the low switching frequency, an increase in costs and volumes due to using large reactive elements, and a slow response time. Those disadvantages make the research of compensators using a voltage fed PWM(pulse width modulation) inverter which has high switching frequency and fast response time activate[12-13].

Power factor improvement is also an important matter to resolve power quality problems. Because electric loads have inductive or capacitive characteristics, the source current and the source voltage have differences in a phase and it causes a poor power factor of electric source. A compensation method to improve power factor in recent trends of researches is injection of reactive currents by parallel compensators which has the same construction as the parallel active power filter[8].
CHAPTER 1 INTRODUCTION

Besides those single-purposed compensators, complex compensators using active power filters which can compensate harmonic currents as well as unbalanced voltages or power factor by additional control algorithms have been also studied very actively[8-9][14].

This research proposes novel control methods of series active power filter to implement multi-functional compensation, namely harmonic currents compensation, power factor improvement and voltage compensation. The series active power filter can compensate both harmonic current sources, and it can compensate harmonic voltage sources by construction of the combined system with parallel passive filters. It can be constructed cost-effectively and it can implement additional functions by supplement another control algorithms. To compensate harmonic currents and improve power factor, the series active power filter uses two kinds of proposed control methods which can be easily implemented[10-11]. To compensate unbalanced source voltages and voltage sags, a new control method which is able to implement more stable voltage compensation characteristics by means of using a feed-back control is proposed. The harmonical combinations of two kinds of harmonic currents compensation methods and voltage compensation method constitute control methods of multi-functional series active power filter. To verify the validities of the proposed control methods, a laboratory prototype of series active power filter system is constructed and experiments are carried out.
CHAPTER 2 SERIES ACTIVE POWER FILTER

The active power filters have been considered to be a current source connected in parallel with the loads. These approaches are based on the principle of injecting harmonic currents into the ac power systems, of the same amplitude and reverse phase to that of the load harmonic currents. Such parallel active power filters have been studied by many contributors, and have been put into practical use. In the past, harmonic sources were mainly phase-controlled thyristor rectifiers and cycloconverters, which can be regarded as current-source loads, so the parallel active power filter could have been considered the most valuable compensator of harmonic currents. But, since more and more diode rectifiers with smoothing dc capacitors are used in electronic equipments, household appliances, and ac drives, harmonics generated by these loads have become a major issue. Naturally, the parallel active power filters for harmonic compensation of these diode rectifiers have been used. However, it has been found in the field that the parallel active power filters not only cannot cancel the harmonics completely but also cause problems, such as enlarging the dc voltage ripples and ac peak current of the rectifier. These problems are happened, because a diode rectifier with smoothing dc capacitors behaves like a harmonic voltage source rather than as a harmonic current source[15].

The series active power filter has better compensation characteristics than a parallel active power filter in the harmonic voltage sources. It also can compensate harmonic currents in the harmonic current source, when a combined filtering system with parallel passive filters is constructed[15].

In this chapter, it will be described that harmonic voltage sources and harmonic current sources, compensation characteristics of series active power filter and
combined system under harmonic current sources and harmonic voltage sources.

2.1 Harmonic currents on inductive loads

In general, a phase controlled thyristor rectifier uses a sufficient dc inductor to minimize a distortion of dc current. Fig. 2–1 shows a typical three-phase thyristor rectifier. If the dc inductor ($L_t$) has an enough inductance, the output current of rectifier can be maintained to a constant value without any distortion and ac side currents are independent of any circuit parameters besides rectifier. So, thyristor rectifier with a sufficient dc inductor can be considered as an ideal harmonic current source like Fig. 2–2. Because the harmonic currents and their characteristics are less dependent upon the ac side, this type of harmonic source behaves like a current source. Therefore they are called a current-source type of harmonic source or a harmonic current source and represented as a current source.
Fig. 2-2 An equivalent circuit of ideal harmonic current source

But if a dc inductor has not large enough inductance, dc output current of rectifier has distortions and it causes a dependence of ac harmonic currents to the circuit parameters of ac sides. So, in this case thyristor rectifier can't be considered as an ideal harmonic current source. Fig. 2-3 shows an equivalent circuit in case of a small dc inductance where impedance $Z_L$ is in proportion to a magnitude of a dc inductance.

Fig. 2-3 An equivalent circuit of typical harmonic current source
CHAPTER 2 SERIES ACTIVE POWER FILTER

Many researches have been showed that thyristor rectifier with a dc inductance behaves like a harmonic current source and in this case parallel active power filter is a suitable method to compensate harmonic currents.

Fig. 2-4 Source voltage, current and FFT analysis of three phase thyristor rectifier

Fig. 2-4 shows simulation results of three-phase thyristor rectifier with a dc inductor. The simulation is performed in a condition of a balanced three phase voltage sources of 100[Vrms], a source inductance \( (L_s) = 0.1[\text{mH}] \), a dc inductance \( (L_d) = 15[\text{mH}] \), and a load resistance \( (R_d) = 30[\Omega] \). The simulation is carried out by PSIM, a kind of simulation tool, and results show a source voltage of phase a, a source current of phase a and a FFT(fast fourier transformation)
analysis of phase a source current. From the waveform of source current and its FFT analysis, it is clear that source current is contaminated by various harmonic currents in which low order harmonics take a major portion. The THD (total harmonic distortion) value of a source current is about 28.61%. It's a very terrible condition.

2.2 Harmonic currents on capacitive loads

![Three phase diode rectifier diagram]

Fig. 2-5 A three phase diode rectifier

Another common harmonic source is that of diode rectifiers with a smoothing dc capacitor as shown in Fig. 2-5. When the voltage source gets to around positive or negative peak point, a current flows from the ac side to the dc side through diode rectifier. When the source voltage is smaller than the dc side voltage, a current can't flow into the dc side through diode rectifier, in this case the capacitor on dc side supports load current. By this principle a diode rectifier performs a rectifying action and it causes a harmonic currents in the ac side. Although the current is highly distorted, its harmonic amplitude is greatly affected by the impedance of the ac side, whereas the rectifier voltage is characteristic and less dependant upon the
ac impedance. Therefore, a diode rectifier behaves like a voltage source rather than a current source[15].

\[ Z_s \quad Z_L \]

\[ v_s \quad v_{Lh} \]

**Fig. 2-6 An equivalent circuit of typical harmonic voltage source**

Fig. 2-6 shows an equivalent circuit of diode rectifier with a sufficient smoothing dc capacitor. The diode rectifier can be considered an ideal voltage source. But, when a smoothing dc capacitor has not sufficient capacitance, the ideal voltage source has to be replaced by ideal harmonic voltage source \( v_{Lh} \) and series connected impedance \( Z_L \). Many researches have been showed that diode rectifier with dc capacitor behaves like a harmonic voltage source and in this case series active power filter is a suitable method to compensate harmonic currents.

Fig. 2-7 shows simulation results of three-phase diode rectifier with a dc capacitor. The simulation is performed in a condition of balanced three-phase voltage sources of 100[Vrms], a source inductance \( L_s = 0.6[\text{mH}] \), a dc capacitance \( C_l = 2400[\mu \text{F}] \), and a load resistance \( R_i = 30[\Omega] \). This simulation is also carried out by PSIM, and results show a source voltage of phase a, a source current of phase a, and a FFT analysis of phase a source current. From the
CHAPTER 2 SERIES ACTIVE POWER FILTER

waveform of source current and its FFT analysis, it is clear that the source current is contaminated by various harmonic currents in which low order harmonics take a major portion like a previous one. The THD value of a source current is about 65.28%. It's still more terrible.

(a) A source voltage of phase a

(b) A source current of phase a

(c) A FFT analysis of source current of phase a

Fig. 2-7 Source voltage, current and FFT analysis of three phase diode rectifier

2.3 Compensation characteristics of the series active power filter on inductive loads
Fig. 2–8 An equivalent circuit of series active power filter system under inductive load

Fig. 2–8 shows an equivalent circuit of series active power filter system which compensate inductive loads, harmonic current source such as a thyristor rectifier with a dc inductor. In Fig. 2–8, $v_S$ represents a source voltage, $Z_S$ represents a source impedance, $i_{sf}$ and $i_{sh}$ represent a fundamental and a harmonic component of a source current $i_S$ respectively, and $v_{Lf}$ and $v_{Lh}$ represent a fundamental and a harmonic component of a load voltage $v_L$ respectively.

When the series active power filter operates, it can be considered as a voltage source supplying compensation voltage, $v_C$. Therefore, the harmonic voltages of the load side are compensated by a series active power filter which supplies a compensation voltages of the same magnitude and reverse phase with load harmonic voltages, then a source current can be maintained to be a pure sine wave.

If an output voltage of the series active power filter can be controlled to be an
CHAPTER 2 SERIES ACTIVE POWER FILTER

Eq. (2-1), then a source current can be represented as Eq. (2-2).

\[ V_C = KG I_S \]  \hspace{1cm} (2-1)

\[ I_S = \frac{Z_L I_{L0}}{Z_S + Z_L + KG} + \frac{V_S}{Z_S + Z_L + KG} \]  \hspace{1cm} (2-2)

In Eq. (2-1), the G represents transfer function of series active power filter and it is 1 for the harmonic currents and 0 for the fundamental current. The K represents series active power filter gain. If gain K satisfies a following Eq. (2-3), then the output voltage of series active power filter and the source current can be expressed by Eq. (2-4) and Eq. (2-5) respectively.

\[ K \gg |Z_L|_h \quad \text{and} \quad K \gg |Z_S + Z_L|_h \]  \hspace{1cm} (2-3)

\[ V_C \approx Z_L I_{Lh} + V_{sh} \]  \hspace{1cm} (2-4)

\[ I_{sh} \approx 0 \]  \hspace{1cm} (2-5)

That is, if gain K of a series active power filter is much larger than the sum of load impedance and source impedance about harmonic currents, the source current can be a pure sine wave. But, general thyristor rectifier has a very large load impedance( Z_L), so it is difficult to satisfy Eq. (2-3). Because the magnitude of a load impedance approximates an infinite value, the gain K must be increased infinitely to satisfy Eq. (2-3). That means an output voltage of series active power filter is also to be an infinite value. From this consideration, it can be theoretically
told that the series active power filter is not a suitable method to compensate harmonic currents of harmonic current sources such as inductive loads.

But, if parallel passive filters are installed at a load side, the situation is turned over. That is, if the parallel passive filters are installed at a load side, the load impedance \( Z_L \) is turned to a proper value. So the Eq. (2-3) can be satisfied easily and by set a proper gain \( K \) the series active power filter can compensate harmonic currents of harmonic current sources.

Namely, the combined system of a series active power filter and parallel passive filters is able to have an excellent compensation characteristics in harmonic current sources such as inductive loads.

2.4 Compensation characteristics of the series active power filter on capacitive loads

![Diagram](image)

Fig. 2-9 An equivalent circuit of series active power filter system under capacitive load

Fig. 2-9 shows an equivalent circuit of a series active power filter system which
compensate capacitive load, that is harmonic voltage source such as a diode rectifier with a dc smoothing capacitor. If a dc capacitor has a sufficient value, the load impedance ($Z_L$) is nearly zero and the diode rectifier can be replaced to an ideal harmonic voltage source in an equivalent circuit. But, in a real system the dc smoothing capacitor has not an enough value to replace the diode rectifier into an ideal harmonic voltage source, so the equivalent circuit in Fig. 2-9 represents a real diode rectifier system properly.

No matter what the dc capacitor has any capacitance value, the series active power filter can be controlled to supply a compensation voltage $v_C$ that is a same magnitude and a reverse phase, that is $v_C = -v_{Lk}$. Then the harmonic currents in source side ($i_{sh}$) that is originated from harmonic voltages in the load side can be eliminated without any relation to the load impedance, $Z_L$. From this consideration, it can be theoretically told that the series active power filter is a suitable method to compensate harmonic currents of harmonic voltage sources such as capacitive loads.

If an output voltage of the series active power filter can be controlled to be an Eq. (2-6), then a source current can be represented as Eq. (2-7).

$$V_C = KG I_S$$  \hspace{1cm} (2-6)

$$I_S = \frac{V_S - V_L}{Z_S + Z_L + KG}$$  \hspace{1cm} (2-7)

If a gain $K$ satisfies a following Eq. (2-8), then the source current and the output voltage of series active power filter can be expressed by Eq. (2-9) and Eq.
(2-10) respectively.

\[ K \gg 1 \; \text{pu} \gg |Z_S + Z_L| \quad (2-8) \]

\[ I_{Sh} \approx 0 \quad (2-9) \]

\[ V_C = V_{Sh} - V_{Lh} \quad (2-10) \]

As in the previous one, if gain $K$ of a series active power filter is much larger than the sum of a load impedance and a source impedance about harmonic currents, the source current can be a pure sine wave. Unlike the thyristor rectifier with a dc inductor, the diode rectifier with a dc smoothing capacitor has a small value of load impedance ($Z_L$), so the series active power filter can satisfy Eq. (2-8) easily[15].

In the other point of view, if a parallel active power filter is applied to a harmonic voltage source, then the injection currents from a parallel active filter can flow to a load side, and distortions of the source voltage $v_{Sh}$ originated from harmonic currents ($i_{Sh}$) in source side and source impedance ($Z_S$) also causes a large harmonic currents to flow into the load. These effects will largely increase the load harmonic currents and the required volt-ampere (VA) rating of the parallel active filter.

From the above, it is clear that the series active power filter is a more suitable method to compensate a harmonic voltage sources such as capacitive loads.
CHAPTER 3 CONTROL METHODS TO COMPENSATE HARMONIC CURRENTS AND POWER FACTOR

CHAPTER 3 CONTROL METHODS TO COMPENSATE HARMONIC CURRENTS AND POWER FACTOR

In this chapter, two kinds of control methods[10-11] which are products of previous researchers, to compensate harmonic currents and to improve power factor in source will be described in detail. One is uses a new definition of reactive power and a performance function[10], and the other is uses a coordinate transformation of 3-phase to 2-phase[11]. By the two kinds of methods, the compensation voltages can be taken more easily compared to the previous p-q theory[2].

3.1 Control method I

Although the instantaneous reactive power used in many previous researches means a power generated by loads that is to be compensated[2], the newly defined instantaneous reactive power in this method means a power generated from a series active power filter. It is possible because an amount of power delivered from a certain line of the power system into the series active filter is instantly fed to the other lines of the power system, so series active power filter does not generate the instantaneous active power. Therefore, the new instantaneous reactive power $q_k$ is defined with the power of each line of the series active power filter[3][10].

$$q_k = v_{ck} \cdot i_{sk} \quad (3-1)$$

In Eq. (3-1), $k$ represents each phase of 3-phase (a, b, c phase), $v_{ck}$ represents
CHAPTER 3 CONTROL METHODS TO COMPENSATE HARMONIC CURRENTS AND POWER FACTOR

A compensation voltage of each phase in the series active power filter, and $i_{Sk}$ represents a source current of each phase. Because the series active power filter does not generate instantaneous active power, the following constraint is imposed on the Eq. (3-1).

$$\sum_{k=a,b,c} q_k = v_{Ca}i_{Sa} + v_{Cb}i_{Sb} + v_{Cc}i_{Sc} = 0$$  \hspace{1cm} (3-2)

In a 3-phase 3-wire power delivery system, there isn’t zero sequence components of voltage and current in the balanced condition owing to an absence of a neutral line. So, the compensation voltages generated by the series active power filter in each phase can satisfy a following constraint.

$$v_{Ca} + v_{Cb} + v_{Cc} = 0$$  \hspace{1cm} (3-3)

From the above relations, the compensation voltages of a series active power filter can be calculated to the values which minimizes the performance function, $L$, defined in Eq. (3-4) with the constraints of Eq. (3-2) and Eq. (3-3).

$$L = (v_{La} - v_{Ca})^2 + (v_{Lb} - v_{Cb})^2 + (v_{Le} - v_{Cc})^2$$ \hspace{1cm} (3-4)

In Eq. (3-4), $v_{La}$, $v_{Lb}$, $v_{Le}$ represents a load voltage of each phase respectively. Each term of Eq. (3-4) is a square value of a difference between a load voltage and a compensation voltage. If the difference which is a load voltage when it is seen from a source side is to be a pure sine wave, the performance function has its minimum value. That is, as the load voltage seen from a source side gets near
CHAPTER 3 CONTROL METHODS TO COMPENSATE HARMONIC CURRENTS AND POWER FACTOR

to a pure sine wave by a compensation voltage, a value of the performance function approaches the minimum point. So, compensation voltages of series active power filter can be calculated by the following numerical expressions.

\[
\frac{dL}{dv_{Ca}} = 0, \quad \frac{dL}{dv_{Cb}} = 0, \quad \frac{dL}{dv_{Cc}} = 0
\] (3-5)

From Eq. (3-5), the final values of the compensation voltages are as follows.

\[
v_{Ca} = \frac{\sqrt{3} (i_{sa} - i_{sc}) \cdot q}{2( i_{sa}^2 + i_{sb}^2 + i_{sc}^2 - i_{sa} i_{sb} - i_{sa} i_{sc} - i_{sc} i_{sc})}
\]

\[
v_{Cb} = \frac{\sqrt{3} (i_{sc} - i_{sa}) \cdot q}{2( i_{sa}^2 + i_{sb}^2 + i_{sc}^2 - i_{sa} i_{sb} - i_{sa} i_{sc} - i_{sc} i_{sc})}
\] (3-6)

\[
v_{Cc} = \frac{\sqrt{3} (i_{sa} - i_{sb}) \cdot q}{2( i_{sa}^2 + i_{sb}^2 + i_{sc}^2 - i_{sa} i_{sb} - i_{sa} i_{sc} - i_{sc} i_{sc})}
\]

where, \( q = \frac{1}{\sqrt{3}} (i_{sb} - i_{sc}) v_{La} + (i_{sc} - i_{sa}) v_{Lb} + (i_{sa} - i_{sb}) v_{Lc} \)

In Eq. (3-6), the \( q \) is agreed with an instantaneous reactive power defined in \( p-q \) theory[2]. The \( q \) includes dc component( \( \bar{q} \) ) and ac component( \( \tilde{q} \) ), so if only harmonic currents are a compensation target, one makes \( \tilde{q} \) to be included in Eq. (3-6) by a simple filtering and if harmonic currents and power factor are a compensation target, one makes \( q \), include \( \bar{q} \) and \( \tilde{q} \), to be included in Eq. (3-6).

In this method unlike previously established method, the definition of instantaneous active and reactive power is based on an active power filter. Also, the compensation voltages extracted directly through performance function, there is
CHAPTER 3 CONTROL METHODS TO COMPENSATE HARMONIC CURRENTS AND POWER FACTOR

no need to find a proper gain. It means a more comfortable control.

3.2 Control method II

For a 3-phase power system, instantaneous voltages and currents are expressed as instantaneous space vectors like Eq. (3-7) and Eq. (3-8).

\[ \mathbf{v} = [v_a \ v_b \ v_c]^t \]  \hspace{1cm} (3-7)

\[ \mathbf{i} = [i_a \ i_b \ i_c]^t \]  \hspace{1cm} (3-8)

Above instantaneous space vectors can be expressed in \( \alpha - \beta - 0 \) coordinates by 3-phase to 2-phase transformation[4][11].

\[
\begin{bmatrix}
  v_0 \\
  v_a \\
  v_{\beta}
\end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix}
  \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\
  1 & -\frac{1}{2} & -\frac{1}{2} \\
  0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix}
\begin{bmatrix}
  v_a \\
  v_b \\
  v_c
\end{bmatrix}
\]  \hspace{1cm} (3-9)

\[
\begin{bmatrix}
  i_0 \\
  i_a \\
  i_{\beta}
\end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix}
  \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\
  1 & -\frac{1}{2} & -\frac{1}{2} \\
  0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix}
\begin{bmatrix}
  i_a \\
  i_b \\
  i_c
\end{bmatrix}
\]  \hspace{1cm} (3-10)

The instantaneous active and reactive power can be expressed in \( \alpha - \beta - 0 \) coordinates using Eq. (3-9) and Eq. (3-10).
\[ p = \mathbf{v}^t_{(\alpha, \beta, 0)} \cdot \mathbf{i}_{(\alpha, \beta, 0)} = v_\alpha i_\alpha + v_\beta i_\beta + v_0 i_0 \] (3-11)

\[ \mathbf{q} = \mathbf{v}_{(\alpha, \beta, 0)} \times \mathbf{i}_{(\alpha, \beta, 0)} = \begin{bmatrix} q_\alpha \\ q_\beta \\ q_0 \end{bmatrix} = \begin{bmatrix} v_\beta & v_0 \\ i_\beta & i_0 \\ v_0 & v_\alpha \\ i_0 & i_\alpha \\ v_\alpha & v_\beta \\ i_\alpha & i_\beta \end{bmatrix} \] (3-12)

In case of a 3-phase 3-wire balanced power delivery system, there aren't any zero sequence components of voltage (\(v_0\)) and current (\(i_0\)). Therefore, Eq. (3-12) can be rewritten as a following Eq. (3-13).

\[ \mathbf{q} = \mathbf{v}_{(\alpha, \beta, 0)} \times \mathbf{i}_{(\alpha, \beta, 0)} = \begin{bmatrix} q_\alpha \\ q_\beta \\ q_0 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ v_\alpha & v_\beta \\ i_\alpha & i_\beta \end{bmatrix} \] (3-13)

The Eq. (3-12) and Eq. (3-13) are same with the instantaneous reactive power defined in p-q theory. From (3-11)\(\sim\) (3-13), the instantaneous voltage vectors which generate active and reactive power can be expressed as equation (3-14) and (3-15).

\[ \mathbf{v}_{p(\alpha, \beta, 0)} = \text{Proj}_p \mathbf{v} = \frac{\mathbf{v} \cdot \mathbf{p}}{||\mathbf{p}||^2} \mathbf{p} = \frac{\mathbf{i}_{(\alpha, \beta, 0)} \cdot \mathbf{p}}{\mathbf{i}_{(\alpha, \beta, 0)} \cdot \mathbf{i}_{(\alpha, \beta, 0)}} \mathbf{i}_{(\alpha, \beta, 0)} \] (3-14)

\[ \mathbf{v}_{q(\alpha, \beta, 0)} = \frac{\mathbf{q}_{(\alpha, \beta, 0)} \times \mathbf{i}_{(\alpha, \beta, 0)}}{\mathbf{i}_{(\alpha, \beta, 0)} \cdot \mathbf{i}_{(\alpha, \beta, 0)}} \] (3-15)
CHAPTER 3 CONTROL METHODS TO COMPENSATE HARMONIC CURRENTS AND POWER FACTOR

Therefore, the compensation voltages of the series active power filter can be expressed as Eq. (3-16).

\[
v^*_{c(a, \beta, 0)} = \frac{\hat{p}}{i(a, \beta, 0)} \cdot i(a, \beta, 0) + \frac{q(a, \beta, 0) \times i(a, \beta, 0)}{i(a, \beta, 0) \cdot i(a, \beta, 0)}
\]  

(3-16)

Where \( \hat{p} \) indicates an ac component of instantaneous active power and \( q \) indicates an instantaneous reactive power. Like a method I, the \( q \) includes dc component( \( \bar{q} \) ) and ac component( \( \tilde{q} \) ), so if only harmonic currents are a compensation target, one makes \( \tilde{q} \) and \( \hat{p} \) to be included in Eq. (3-16) by a simple filtering and if harmonic currents and power factor are a compensation target, one makes \( \hat{p} \) and \( q \), include \( \bar{q} \) and \( \tilde{q} \), to be included in Eq. (3-16).

The compensation voltages calculated from Eq. (3-16) is on the \( \alpha - \beta - 0 \) coordinates, so when it applies to the 3-phase power system, it has to be transformed to the 3-phase coordinates through 2-phase to 3-phase inverse transformation.

In this method, the compensation voltages are calculated from coordinates transformation. As the compensation voltages are directly taken by the induced equation like a method I, there is no need to find a proper gain. It also means a more comfortable control.
CHAPTER 4 VOLTAGE COMPENSATION METHOD

In this chapter, the method of symmetrical coordinates which is a general analysis method of an unbalanced 3-phase voltages in the power delivery system is described[16]. Also, a proposed control method to compensate 3-phase unbalanced voltages or voltage sags is described. The proposed method uses a transformation of 3-phase line to neutral voltages to the synchronous reference frame, called it d-q transformation[17]. By using a synchronous reference frame, compensation voltages can be achieved easily.

4.1 Method of symmetrical coordinates

By faults in power delivery system or using single-phase loads in 3-phase power system and nonlinear loads, the conditions of unbalanced or sagged source voltages are formed frequently. According to the method of symmetrical coordinates, three unbalanced phasors of 3-phase systems can be resolved into three balanced systems of phasors. Until now many researches for voltage compensation are based on that method.

The balanced sets of components resolved by the method are positive sequence components, negative sequence components and zero sequence components. The positive sequence components consisting of three phasors equal in magnitude, displaced from each other by 120° in phase, and having the same phase sequence as the original phasors. The negative sequence components consisting of three phasors equal in magnitude, displaced from each other by 120° in phase, and having the phase sequence opposite to that of the original phasors. The zero
sequence components consisting of three phasors equal in magnitude and with zero phase displacement from each other. Fig. 4-1 shows a balanced sets of components. The subscript 1 means the positive sequence, the subscript 2 means the negative sequence and the subscript 0 means the zero sequence.

(a) Positive sequence  (b) Negative sequence  (c) Zero sequence

Fig. 4-1 A balanced sets of components

Any unbalanced 3-phase voltages \( \overrightarrow{V_a}, \overrightarrow{V_b}, \overrightarrow{V_c} \) can be analysed by the method into balanced sets of components as Eq. (4-1).

\[
\begin{align*}
\overrightarrow{V_a} &= \overrightarrow{V_{a0}} + \overrightarrow{V_{a1}} + \overrightarrow{V_{a2}} \\
\overrightarrow{V_b} &= \overrightarrow{V_{b0}} + \overrightarrow{V_{b1}} + \overrightarrow{V_{b2}} \\
\overrightarrow{V_c} &= \overrightarrow{V_{c0}} + \overrightarrow{V_{c1}} + \overrightarrow{V_{c2}}
\end{align*}
\]  

(4-1)

If the zero, positive and negative sequence components of phase a voltage are defined as Eq. (4-2) and the operators defined as Eq. (4-3) are used, then the unbalanced 3-phase voltage can be expressed as Eq. (4-4).

\[
\begin{align*}
\overrightarrow{V_{a0}} &= \overrightarrow{V_0}, \quad \overrightarrow{V_{a1}} = \overrightarrow{V_1}, \quad \overrightarrow{V_{a2}} = \overrightarrow{V_2}
\end{align*}
\]  

(4-2)
CHAPTER 4 VOLTAGE COMPENSATION METHOD

\[ a = e^{i \frac{2\pi}{3}} = -\frac{1}{2} + j\frac{\sqrt{3}}{2}, \quad a^2 = e^{i \frac{4\pi}{3}} = -\frac{1}{2} - j\frac{\sqrt{3}}{2} \] (4-3)

\[
\begin{align*}
\vec{V}_a &= \vec{V}_0 + \vec{V}_1 + \vec{V}_2 \\
\vec{V}_b &= \vec{V}_0 + a^2 \vec{V}_1 + a \vec{V}_2 \\
\vec{V}_c &= \vec{V}_0 + a \vec{V}_1 + a^2 \vec{V}_2
\end{align*}
\] (4-4)

From (4-4) and a nature of 'a' operator, that is \(1 + a + a^2 = 0\), \(a^3 = 1\), the zero, positive and negative sequence components can be taken as (4-5).

\[
\begin{align*}
\vec{V}_0 &= \frac{1}{3} \left( \vec{V}_a + \vec{V}_b + \vec{V}_c \right) \\
\vec{V}_1 &= \frac{1}{3} \left( \vec{V}_a + a \vec{V}_b + a^2 \vec{V}_c \right) \\
\vec{V}_2 &= \frac{1}{3} \left( \vec{V}_a + a^2 \vec{V}_b + a \vec{V}_c \right)
\end{align*}
\] (4-5)

If a 3-phase power system is balanced one, there exists only the positive sequence components. But if the system is unbalanced by an external causes, there exists the positive sequence components as well as the negative sequence components and the zero sequence components. In that unbalanced conditions, if the negative and zero sequence components are compensated by any compensator, the 3-phase systems will be balanced. Also, by means of adjusting the magnitude of positive sequence components the regulation of balanced 3-phase power systems can be performed. To make a balanced and regulated 3-phase power systems, the three components of balanced sets must be known and in this method of
the symmetrical coordinates uses an equation Eq. (4-5) to find out that.

### 4.2 Synchronous reference frame

![Diagram](image)

(a) General 3phase coordination  (b) Stationary reference frame  (c) Synchronous reference frame

**Fig. 4-2 A transformation of coordination**

Fig. 4-2 shows three kinds of coordinate systems. Fig. 4-2 (a) is a general-purposed 3-phase coordinate system, called it abc frame. A 3-phase voltages on the abc frame can be transformed into 2-phase voltages on the stationary reference frame like Fig. 4-2 (b), call it $\alpha \beta$ frame. If another frame is rotated with a synchronous speed $\omega$ like Fig. 4-2 (c), then on that rotating frame, the voltage with angular velocity of $\omega$ seems to be a dc value, angular velocity of 0, this reference frame called dq frame.

If a synchronous reference frame with the same angular velocity and the same rotating direction of a positive sequence components is applied to the unbalanced 3-phase voltages, then the positive sequence components looks like a dc value, the negative sequence components looks like an ac value with an angular velocity of $2\omega$, and the zero sequence components looks like an ac value with an angular velocity of $\omega$. This is a basic principle of proposed voltage compensation method and it is a same theory of the
relative velocity in physics which is described in Fig. 4-3.

![Diagram showing object velocities](image)

Fig. 4-3 A basic principle of proposed voltage compensation method

### 4.3 Proposed voltage compensation method

1. The method using a synchronous reference frame synchronized with positive sequence components

\[
\begin{pmatrix}
V_{an} \\
V_{bn} \\
V_{cn}
\end{pmatrix} = V_1 \begin{pmatrix}
\sin(\omega t + \alpha_1) \\
\sin(\omega t + \alpha_1 - \frac{2}{3} \pi) \\
\sin(\omega t + \alpha_1 + \frac{2}{3} \pi)
\end{pmatrix} + V_2 \begin{pmatrix}
\sin(\omega t + \alpha_2) \\
\sin(\omega t + \alpha_2 + \frac{2}{3} \pi) \\
\sin(\omega t + \alpha_2 - \frac{2}{3} \pi)
\end{pmatrix} \\
+ V_0 \begin{pmatrix}
\sin(\omega t + \alpha_0) \\
\sin(\omega t + \alpha_0) \\
\sin(\omega t + \alpha_0)
\end{pmatrix} + \sum V_h \quad (4-6)
\]

The unbalanced 3-phase voltages are expressed as Eq. (4-6) where a subscript 1 represents positive sequence, a subscript 2 represents negative sequence and a subscript 0 represents zero sequence like a previous
CHAPTER 4 VOLTAGE COMPENSATION METHOD

description. To express it on a synchronous reference frame synchronized with positive sequence components, a transformation matrix, called a Park’s transformation, is used. The Park’s transformation as Eq. (4-7) transform values in abc frame into values in dq frame that is synchronized with positive sequence components.

\[
[ P ] = \frac{2}{3} \begin{pmatrix}
\cos \omega t & \cos (\omega t - \frac{2}{3} \pi) & \cos (\omega t + \frac{2}{3} \pi) \\
\sin \omega t & \sin (\omega t - \frac{2}{3} \pi) & \sin (\omega t + \frac{2}{3} \pi) \\
\frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{pmatrix}
\] (4-7)

Through the Park’s transformation of the unbalanced 3–phase voltages such as Eq. (4-6), the voltages on dq frame are expressed by an Eq. of (4-8).

\[
[ P ] \begin{pmatrix}
V_{an} \\
V_{bm} \\
V_{cn}
\end{pmatrix} = V_1 [ P ] \begin{pmatrix}
\sin(\omega t + a_1) \\
\sin(\omega t - \frac{2}{3} \pi + a_1) \\
\sin(\omega t + \frac{2}{3} \pi + a_1)
\end{pmatrix} + V_2 [ P ] \begin{pmatrix}
\sin(\omega t + a_2) \\
\sin(\omega t + \frac{2}{3} \pi + a_2) \\
\sin(\omega t - \frac{2}{3} \pi + a_2)
\end{pmatrix}
\]

\[+ V_0 [ P ] \begin{pmatrix}
\sin(\omega t + a_0) \\
\sin(\omega t + a_0) \\
\sin(\omega t + a_0)
\end{pmatrix} + \sum ([ P ] V_h)
\]

\[
\begin{pmatrix}
V_d \\
V_q \\
V_0
\end{pmatrix} = \begin{pmatrix}
V_1 \sin a_1 \\
V_1 \cos a_1 \\
0
\end{pmatrix} + \begin{pmatrix}
V_2 \sin(2\omega t + a_2) \\
- V_2 \cos(2\omega t + a_2) \\
0
\end{pmatrix} + \begin{pmatrix}
0 \\
0 \\
V_0 \sin(\omega t + a_0)
\end{pmatrix} + \sum (V_h)
\] (4-8)

From the above Eq. (4-8), it is clear that on the synchronous reference
CHAPTER 4 VOLTAGE COMPENSATION METHOD

Frame synchronized with positive sequence components, the positive sequence has a dc value, the negative sequence has an ac value with angular velocity of $2\omega$, and the zero sequence has an ac value of angular velocity of $\omega$. If the ac components except dc values by using a filter are compensated, then there are none of negative and zero sequence components in the 3-phase power systems. The control of a dc component in $q$-axis which is a representation of the active power can regulate the magnitude of load voltages.

In Fig. 4-4, the simulation result of $dq$ transformation using Eq. (4-7) is showed. The condition of unbalanced voltages is a voltage sag of phase $c$ by 20%. The normal magnitude of voltages is 100 [Vrms]. The simulation is performed by PSIM, a simulation tool.

Fig. 4-4 A 3-phase unbalanced voltage and its $dq$ transformation
(2) The method using a synchronous reference frame
synchronized with negative sequence components

In this method contrast to previous one, the synchronous reference frame
is synchronized with negative sequence components. A somewhat varied
form of previous Park’s transformation as Eq. (4-9) can perform this
coordinate transformation, that is values on abc frame into values on dq
frame synchronized with negative sequence components.

\[
\begin{bmatrix} T \end{bmatrix} = \frac{2}{3} \begin{bmatrix}
\cos \omega t & \cos (\omega t + \frac{2}{3} \pi) & \cos (\omega t - \frac{2}{3} \pi) \\
\sin \omega t & \sin (\omega t + \frac{2}{3} \pi) & \sin (\omega t - \frac{2}{3} \pi) \\
\frac{1}{2} & \frac{1}{2} & \frac{1}{2}
\end{bmatrix}
\]  \hspace{1cm} (4-9)

Using Eq. (4-9) and through the same processes as previous one, the
3-phase unbalanced voltages can be expressed as Eq. (4-10).

\[
\begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix} = \begin{bmatrix} V_1 \sin(2\omega t + a_1) \\ V_1 \cos(2\omega t + a_1) \\ 0 \end{bmatrix} + \begin{bmatrix} V_2 \sin a_2 \\ -V_2 \cos a_2 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ V_0 \sin(\omega t + a_0) \end{bmatrix} + \sum (V_h)
\]  \hspace{1cm} (4-10)

From the above Eq. (4-10), it is clear that on the synchronous reference
frame synchronized with negative sequence components, the positive
sequence has an ac value with angular velocity 2\omega, the negative sequence
has a dc value, and the zero sequence has an ac value of angular velocity.
of \( \omega \). If the dc component except ac values by using a filter is compensated, then there are none of negative sequence components in the 3-phase power systems.

In Fig. 4-5, the simulation result of dq transformation using Eq. (4-10) is showed. The condition of unbalanced voltages is also a voltage sag of phase \( c \) by 20\%. The normal magnitude of voltages is 100 [Vrms]. The simulation is performed by PSIM, a simulation tool.

Fig. 4-5 A 3-phase unbalanced voltage and its dq transformation
CHAPTER 5 THE CONSTITUTIONS OF EXPERIMENTAL SYSTEMS

In this chapter, the experimental systems constructed for verifying the proposed compensation methods are described. Here are two kinds of compensation systems. One is constructed by a series active power filter to compensate harmonic voltage sources, and the other is constructed by a series active power filter and parallel passive filters to compensate harmonic current sources.

5.1 Series active power filter system to compensate harmonic voltage sources

Fig. 5-1 The series active power filter system for harmonic voltage sources

Fig. 5-1 shows a constructed compensation system for harmonic voltage
sources such as capacitive loads. The system uses only a series active power filter. The series active power filter is based on a 3-phase voltage-fed PWM (pulse width modulation) inverter and small LC filters are installed in an inverter output to mitigate switching ripples of IGBT. The inverter is connected to the 3-phase power system through 3 single phase transformers. The load is 3-phase diode rectifier with a smoothing dc capacitor. The control board is based on a DSP (digital signal processor), TMS320C31, and sampling time is 143 [μsec].

Table 5-1 The system circuit parameters of series active filter system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source voltage ($V_S$)</td>
<td>100 [Vrms], 60 [Hz]</td>
</tr>
<tr>
<td>Source inductance ($L_S$)</td>
<td>0.65 [mH]</td>
</tr>
<tr>
<td>Inverter DC Link capacitance</td>
<td>2350 [μF]</td>
</tr>
<tr>
<td>LC filter inductance ($L_f$)</td>
<td>3.92 [mH]</td>
</tr>
<tr>
<td>LC filter capacitance ($C_f$)</td>
<td>1 [μF]</td>
</tr>
<tr>
<td>Transformer turn ratio</td>
<td>1 : 2</td>
</tr>
</tbody>
</table>

Table 5-2 The capacitive load parameters

<table>
<thead>
<tr>
<th>Capacitive load</th>
<th>Capacitance</th>
<th>Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2400 [μF]</td>
<td>15 [Ω]</td>
</tr>
</tbody>
</table>
Fig. 5-2 A hardware configuration of the compensation system

Fig. 5-2 shows a signal flow on a total experimental system. The inverter uses three IGBTs of 600V/75A class of Toshiba, the sensing circuits uses voltage transducers LV25-P of LEM and current transducers LA100-P of LEM, A/D converting of input signal is performed by DSP102 of Burr Brown. And PWM generation is realized by coprocessor ADMC201 and gate driver/protection circuit is realized by EXB841 of Fuji.

5.2 Combined system of a series active power filter and parallel passive filters to compensate harmonic current sources

Fig. 5-3 shows a constructed compensation system for harmonic current sources such as inductive loads. The system uses a combined system of a series active power filter and parallel passive filters. Unlike the previous series power filter, in this system a single-phase diode rectifier is installed at inverter dc capacitor to charge it. When the series power filter
compensates voltages or power factor, it needs a sufficient active power. A single-phase diode rectifier supplies sufficient power to inverter. To make conditions of 3-phase unbalanced voltages, 3 single-phase voltage regulators of an auto-transformer type are installed at each phase. A load is a 3-phase diode rectifier with a large dc inductance that is a harmonic current sources.

Fig. 5-3 The combined system of a series active power filter and parallel passive filters for harmonic current sources

The system circuit parameters are showed following Table 5-3. The circuit parameters of parallel passive filters are shown Table 5-4. The parallel passive filters consists of 5th and 7th filter that sinks 5th(300Hz) harmonic current and 7th(420Hz) harmonic current, respectively.
CHAPTER 5 THE CONSTITUTIONS OF EXPERIMENTAL SYSTEMS

Table 5-3 The system circuit parameters of the combined system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source voltage ($V_s$)</td>
<td>100 [Vrms], 60 [Hz]</td>
</tr>
<tr>
<td>Source inductance ($Z_s$)</td>
<td>0.1 [mH]</td>
</tr>
<tr>
<td>Transformer turn ratio</td>
<td>1:1</td>
</tr>
<tr>
<td>Load inductance ($L_{load}$)</td>
<td>15 [mH]</td>
</tr>
<tr>
<td>Load resistance ($R_{load}$)</td>
<td>15 [Ω] / 30 [Ω]</td>
</tr>
<tr>
<td>Inverter DC link capacitance ($C_{inv}$)</td>
<td>2350 [µF]</td>
</tr>
<tr>
<td>LC filter inductance ($L_f$)</td>
<td>3.92 [mH]</td>
</tr>
<tr>
<td>LC filter capacitance ($C_f$)</td>
<td>1 [µF]</td>
</tr>
</tbody>
</table>

Table 5-4 The circuit parameters of parallel passive filter

<table>
<thead>
<tr>
<th>Filter Type</th>
<th>Inductance ($L_{5th}$)</th>
<th>Capacitance ($C_{5th}$)</th>
<th>Inductance ($L_{7th}$)</th>
<th>Capacitance ($C_{7th}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5th passive filter</td>
<td>2 [mH]</td>
<td>140 [µF]</td>
<td>2 [mH]</td>
<td>70 [µF]</td>
</tr>
<tr>
<td>7th passive filter</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In case the system performs a power factor improvement, the load resistance sets 15 [Ω]. The other cases use a load resistance of 30 [Ω].
In this chapter, the experimental results are shown. The previously explained control methods are applied to a series active power filter by stages, respectively. Here are 5 kinds of experiments to be performed. Each one applies combinations of a voltage compensation method and two kinds of harmonics and reactive power compensation methods. The results of harmonic currents compensation for capacitive loads and inductive loads, harmonic currents and power factor compensation for inductive loads, harmonic currents and voltage compensation for inductive loads, and harmonic currents, power factor, and unbalanced voltage compensation for inductive loads are presented.

Here are 3 kinds of indexes to be used for estimating currents and voltages qualities. At first, to estimate contained harmonic components in source currents, the THD (total harmonic distortion) factor is used. Its definition is as Eq. (6-1).

\[ THD = \frac{1}{I_1} \left( \sqrt{\sum_{n=2}^{\infty} I_n^2} \right) \times 100 \quad [\%] \quad (6-1) \]

Where \( I_1 \) represents rms (root mean square) value of a fundamental component and \( I_n \) represents rms value of harmonic components.

Secondly, to estimate degrees of voltage unbalance and magnitude of voltage, the UF (unbalance factor) and the MF (magnitude factor) are used. Its definitions are as Eq. (6-2) and Eq. (6-3).

\[ UF = \frac{V_2}{V_1} \times 100 \quad [\%] \quad (6-2) \]
CHAPTER 6 EXPERIMENTAL RESULTS

\[ MF = \frac{V_1}{V_{ref}} \times 100 \quad [\%] \quad (6-3) \]

Where the \( V_1 \) represents a positive voltage component, the \( V_2 \) represents a negative voltage component, and the \( V_{ref} \) represents a magnitude of rated voltage.

6.1 Harmonic currents compensation of capacitive loads

(a) A current of phase a before compensation
[10A/div, 4ms/div]

(b) A FFT analysis of phase a current before compensation
[2A/div, 100Hz/div]

Fig. 6-1 The phase a source current and FFT analysis before compensation
CHAPTER 6 EXPERIMENTAL RESULTS

Fig. 6-1 shows a source current and its FFT (fast fourier transform) analysis of phase a. From the waveform, it is clear that the source current includes a lot of harmonics, so it is distorted very terribly. Its THD value is about 25.5 [%].

(1) By using method I

(a) A current of phase a after compensation
[10A/div, 4ms/div]

(b) A FFT analysis of phase a current after compensation
[1A/div, 100Hz/div]

Fig. 6-2 The phase a source current and FFT analysis after compensation by method I
CHAPTER 6 EXPERIMENTAL RESULTS

Fig. 6-2 shows a compensation result by the series active power filter operated by method I. After harmonic currents compensation, the THD value is about 4.59[%]. From this result, it is clear that the control method I has an excellent harmonic currents compensation characteristics.

(2) By using method II

(a) A current of phase a after compensation
[10A/div, 4ms/div]

(b) A FFT analysis of phase a current after compensation
[1A/div, 100Hz/div]

Fig. 6-3 The phase a source current and FFT analysis after compensation by method II
CHAPTER 6 EXPERIMENTAL RESULTS

Fig. 6-3 shows a compensation result by the series active power filter operated by method II. After harmonic currents compensation, the THD value is about 4.35[%]. From this result, it is clear that the control method II has also an excellent harmonic currents compensation characteristics.

6.2 Harmonic currents compensation of inductive loads

(a) A current of phase a before compensation
[10A/div, 4ms/div]

(b) A FFT analysis of phase a current before compensation
[1A/div, 100Hz/div]

Fig. 6-4 The phase a source current and FFT analysis before compensation
CHAPTER 6 EXPERIMENTAL RESULTS

Fig. 6-4 shows a source current and its FFT (fast fourier transform) analysis of phase a. The highly distorted source current has a THD value of 31.63[%] approximately.

(1) By using only parallel passive filters

(a) A current of phase a after compensation by parallel passive filters

[10A/div, 4ms/div]

(b) A FFT analysis of phase a current after compensation by parallel passive filters

[2A/div, 100Hz/div]

Fig. 6-5 The phase a source current and FFT analysis after compensation by parallel passive filters

Fig. 6-5 shows a source current and its FFT (fast fourier transform)
analysis of phase a after compensation by parallel passive filters. Though a lot of harmonic currents are reduced by parallel passive filters, it still needs harmonic currents compensation. Its THD value is about 9.08[%].

(2) By using a combined system of parallel passive filters and series active power filter applying method I

(a) A current of phase a after compensation by combined system [10A/div, 4ms/div]

(b) A FFT analysis of phase a current after compensation by combined system [2A/div, 100Hz/div]

Fig. 6-6 The phase a source current and FFT analysis after compensation by combined system applying method I
CHAPTER 6 EXPERIMENTAL RESULTS

Fig. 6-6 shows a source current and its FFT (fast fourier transform) analysis of phase a after compensation by the combined system of parallel passive filters and a series active power filter applying method I. After harmonic currents compensation, the THD value is about 2.49[%). From this result, it is clear that the control method I has an excellent harmonic currents compensation characteristics on inductive loads likely on capacitive loads.

(3) By using a combined system of parallel passive filters and series active power filter applying method II

Fig. 6-7 shows a source current and its FFT (fast fourier transform) analysis of phase a after compensation by the combined system applying method II. After harmonic currents compensation, the THD value is about 2.30[%). From this result, it is clear that the control method II has an excellent harmonic currents compensation characteristics as before.

(a) A current of phase a after compensation by combined system
[10A/div, 4ms/div]
6.3 Harmonic currents and power factor compensation of inductive loads

The reactive powers induced in method I and method II include dc component and ac components. To compensate harmonic currents as before, ac components of reactive power are compensated. But, in this experiments the harmonic currents and power factor are compensated by compensating whole reactive power including dc and ac components.

Fig. 6–8 shows a source current and its FFT analysis before harmonic currents compensated. Fig. 6–9 shows a source current and a source voltage. From this waveform, one knows the source current and voltage are contaminated very seriously, and the source current are lagged behind the source voltage slightly. The THD of source current is about 25.9[\%] and the power factor is about 0.939.
(a) A current of phase a before compensation
[20A/div, 4ms/div]

(b) A FFT analysis of phase a current before compensation
[2A/div, 100Hz/div]

Fig. 6-8 The phase a source current and FFT analysis before compensation
(1) After compensation of only harmonic currents by using parallel passive filters

Fig. 6-10 shows a source current and its FFT analysis after harmonic currents compensated by only parallel passive filters. Fig. 6-11 shows a source current and voltage.
(b) A FFT analysis of phase a current after compensation by parallel passive filters

[2A/div, 100Hz/div]

Fig. 6-10 The phase a source current and FFT analysis after compensation by only parallel passive filters

Fig. 6-11 The phase a source current and voltage after compensation by only parallel passive filters

[50V/div, 20A/div, 4ms/div]

The harmonics of source current are reduced very much by parallel passive filters, but as the THD is about 7.19[%] it needs more compensation. By the parallel passive filters the capacitive currents are generated, so the source current comes to lead the source voltage and it makes poor power factor. Its power factor in this case is about 0.846.
(2) After compensation of harmonic currents and power factor by using a combined system applying method I

Fig. 6-12 shows a source current and its FFT analysis after harmonic currents and power factor are compensated by combined system applying method I. Fig. 6-13 shows a source current and voltage.

(a) A current of phase a after compensation by combined system [20A/div, 4ms/div]

(b) A FFT analysis of phase a current after compensation by combined system [2A/div, 100Hz/div]

Fig. 6-12 The phase a source current and FFT analysis after compensation by combined system applying method I
The harmonics of source current are eliminated nearly. Its THD is about 2.53[%]. The power factor in source side is also improved. The power factor is about 0.991. From this results, one can see that the combined system of a series active power filter and parallel passive filters is able to compensate harmonic currents and power factor very excellently by compensating whole reactive power.

(3) After compensation of harmonic currents and power factor by using a combined system applying method II

Fig. 6-14 shows a source current and its FFT analysis after harmonic currents and power factor are compensated by combined system applying method II. Fig. 6-15 shows a source current and voltage. Likely a previous method I, this method II also shows a very excellent compensation characteristics about harmonic currents and a power factor.
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(a) A current of phase a after compensation by combined system
[20A/div, 4ms/div]

(b) A FFT analysis of phase a current after compensation by combined system
[2A/div, 100Hz/div]

Fig. 6-14 The phase a source current and FFT analysis after compensation by combined system applying method II

The harmonics of source current are also eliminated nearly in this method. Its THD is about 2.83[%]. The power factor in source side is also improved. The power factor is about 0.9889. From this results, one can see that the method II also compensate harmonic currents and a power factor excellently as the previous method I.
6.4 Harmonic currents and voltage compensation of inductive loads

The reactive powers induced in method I and method II include dc component and ac component. In this experiments by compensating only ac component, the harmonic currents are eliminated. By proposed voltage compensation method synchronized with the positive sequence components, the 1-phase or 2-phase saged voltages are compensated. The harmonical combinations of two kinds of harmonic currents compensation methods and a voltage compensation method are well operated, so the combined system makes the source currents into a nearly pure sine wave and the load voltages into balanced and regulated voltage conditions. The source current’s waveform of before and after compensation by only parallel passive filters are the same that showed in section 6.2, so in this section that is omitted.
(1) By using a combined system applying method I and voltage compensation method synchronized with positive sequence.

(a) The unbalanced 3-phase source voltages \(v_T\) — single phase voltage sag

[50V/div, 4ms/div]

(b) The 3-phase load voltages after compensation

Fig. 6-16 The 3-phase unbalanced source voltages and compensated load voltages

[50V/div, 4ms/div]

Fig. 6-16 shows the 3-phase source voltages with a single phase sagged and the compensated 3-phase load voltages and Fig. 6-17 shows the
3-phase source currents and phase a current's FFT analysis after compensation. The UF is about 7.14[%] and the MF is about 93.33[%] in the source voltages. After compensation, the UF is about 1.18[%] and the MF is about 101.67[%] in the load voltages and the phase a current has a THD of 2.84[%] approximately. This results shows that the harmonic currents and voltage compensations are pretty well operated.

(a) The 3-phase source current after compensation
[10A/div, 4ms/div]

(b) The FFT analysis of phase a source current after compensation
[2A/div, 100Hz/div]

Fig. 6-17 The 3-phase source current and phase a current FFT analysis after compensation
Fig. 6-18 shows the 3-phase source voltages with two phases sagged and the compensated 3-phase load voltages and Fig. 6-19 shows the 3-phase source currents and phase a current’s FFT analysis after compensation. The UF is about 5.56[\%] and the MF is about 89.99[\%] in the source voltages. After compensation, the UF is about 1.81[\%] and the MF is about 100.71[\%] in the load voltages and the phase a current has a
THD of 3.18[\%] approximately. This results also shows that the harmonic currents and voltage compensations are pretty well operated.

(a) The 3-phase source current after compensation

[10A/div, 4ms/div]

(b) The FFT analysis of phase a source current after compensation

[2A/div, 100Hz/div]

Fig. 6-19 The 3-phase source current and phase a current FFT analysis after compensation

(2) By using a combined system applying method II and voltage compensation method synchronized with positive sequence
(a) The unbalanced 3-phase source voltages ($v_T$) - single phase voltage sag

\[50\text{V/div}, 4\text{ms/div}]\]

(b) The 3-phase load voltages after compensation

Fig. 6-20 The 3-phase unbalanced source voltages and compensated load voltages

\[50\text{V/div}, 4\text{ms/div}]\]

Fig. 6-20 shows the 3-phase source voltages with a single phase sagged and the compensated 3-phase load voltages and Fig. 6-21 shows the 3-phase source currents and phase a current’s FFT analysis after compensation. The UF is about 7.14[\%] and the MF is about 93.33[\%] in the source voltages. After compensation in this method, the UF is about 1.17[\%] and the MF is about 100.37[\%] in the load voltages and the phase
a current has a THD of 3.05[\%] approximately. This results shows that the harmonic currents and voltage compensations have an excellent compensation characteristics as previous method I.

(a) The 3-phase source current after compensation
[10A/div, 4ms/div]

(b) The FFT analysis of phase a source current after compensation
[2A/div, 100Hz/div]

Fig. 6-21 The 3-phase source current and phase a current FFT analysis after compensation

Fig. 6-22 shows the 3-phase source voltages with two phases sagged and the compensated 3-phase load voltages and Fig. 6-23 shows the
3-phase source currents and phase a current’s FFT analysis after compensation. The UF is about 5.56[\%] and the MF is about 89.99[\%] in the source voltages. After compensation in this case, the UF is about 1.49[\%] and the MF is about 100.04[\%] in the load voltages and the phase a current has a THD of 2.98[\%] approximately. This results also shows that the harmonic currents and voltage compensations are well operated.

(a) The unbalanced 3-phase source voltages ($v_T$)-two phase voltages sag [50V/div, 4ms/div]

(b) The 3-phase load voltages after compensation

Fig. 6-22 The 3-phase unbalanced source voltages and compensated load voltages [50V/div, 4ms/div]
6.5 Harmonic currents, power factor and unbalanced voltage compensation of inductive loads

In this experiments the combined system compensates harmonic currents, power factor and unbalanced source voltages except voltage regulation. At first, the negative sequence components are extracted by using a dq frame
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synchronized with negative sequence components and then calculate instantaneous reactive power by the method I or the method II. Because the compensation voltages of power factor and voltage compensation have the same frequency, the voltages and power factor compensation aren’t well matched each other. So before calculation, the negative sequence components which is extracted above are excluded in the load voltages which will be used to calculate instantaneous reactive power. By this methods the combined system can have the abilities to compensate harmonic currents, power factor and unbalanced source voltages simultaneously. But in this method, the compensation characteristics are worse than the previous methods that have only two kinds of compensation functions. The source current’s waveforms of before and after compensation by only parallel passive filters are the same that showed in section 6.3, so in this section that is omitted. Fig. 6-24 shows a block diagram of series active power filter’s control algorithm described above.

Fig. 6-24 The block diagram of multi-functional series active power filter control algorithm

(1) By using a combined system applying method I and voltage compensation method synchronized with negative sequence
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(a) The 3-phase source currents after compensation

[20A/div, 4ms/div]

(b) The FFT analysis of phase a source current after compensation

[2A/div, 100Hz/div]

Fig. 6-25 The 3-phase source currents and phase a current FFT analysis after compensation

Fig. 6.25 shows 3-phase source currents and the FFT analysis of phase a current. As the THD is about 2.14[%, the compensation characteristic is still excellent. Fig. 6-26 shows the source current and voltage of phase a. As the power factor is about 0.982, the compensation result is inferior to the previous methods as section 6.3. Fig. 6-27 shows single phase sagged source voltages and compensated load voltages. Though the UF of source
voltages is about 7.14%, the UF of compensated load voltages is about 1.52%. But unlike the previous methods as section 6.4, in this method load voltages aren’t regulated.

Fig. 6-26 The source current and voltage of phase a after compensation
[50V/div, 20A/div, 4ms/div]

(a) The unbalanced 3-phase source voltages ($v_T$) - single phase voltage sag
[50V/div, 4ms/div]
(b) The 3-phase load voltages after compensation

Fig. 6-27 The 3-phase unbalanced source voltages and compensated load voltages
[50V/div, 4ms/div]

(2) By using a combined system applying method II and voltage compensation method synchronized with negative sequence

(a) The 3-phase source currents after compensation
[20A/div, 4ms/div]
(b) The FFT analysis of phase a source current after compensation

[2A/div, 100Hz/div]

Fig. 6-28 The 3-phase source currents and phase a current FFT analysis after compensation

Fig. 6-29 The source current and voltage of phase a after compensation

[50V/div, 20A/div, 4ms/div]

Fig. 6.28 shows 3-phase source currents and the FFT analysis of phase a current. As the THD is about 1.75[%], the compensation characteristic is still excellent. Fig. 6-29 shows the source current and voltage of phase a. As the power factor is about 0.981, the compensation result is inferior to the previous methods as section 6.3. Fig. 6-30 shows single phase sagged
source voltages and compensated load voltages. Though the UF of source voltages is about 7.14\%, the UF of compensated load voltages is about 2.06\%. Also, load voltages aren’t regulated in this method.

(a) The unbalanced 3-phase source voltages($v_r$)—single phase voltage sag

[50V/div, 4ms/div]

(b) The 3-phase load voltages after compensation

Fig. 6-30 The 3-phase unbalanced source voltages and compensated load voltages

[50V/div, 4ms/div]
CHAPTER 7 CONCLUSIONS

This thesis deals with an implementation of the multi-functional series active power filter. To compensate harmonic currents and to correct power factor, the two kinds of control methods are applied and to compensate source voltages, a novel control method is proposed. By the harmonical combinations of those methods, five kinds of experiments are performed with the series active power filter system or the combined system of a series active power filter and parallel passive filters to verify the excellency of proposed methods. In each experiments, the complex compensation functions are operated satisfactorily.

The harmonic currents are seriously reduced by compensation, in case of capacitive loads the THD is about 5[%] and in case of inductive loads the THD is about 3[%]. The power factor also improved very well. By compensation, the power factor is recovered at unity approximately. Voltage compensation method also shows a superior performances. The UF is nearly 1[%] and the MF is nearly 100[%] by compensation.

From the experimental results, it is clear that the proposed control methods have an excellent compensation characteristics and the series active power filter system can play an important role for the improvement of power quality in the future. This research is expected to be a basis of the future research about various compensators of power quality.
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지난 2년의 석사과정 동안 이 시간을 꿈꾸어 왔습니다. 조용한 연구실에 앉아서 논문의 맨 마지막 페이지를 채워줄 감사의 글을 쓰는 시간을 말입니다. 많이 힘들었던 시간들도 이젠 꿈처럼 느껴집니다. 감사 305호실이라 칭하곤 했던 전력전자 연구실이 이젠 제게 세상에서 제일 편안하고 안락한 공간으로 느껴지는데 어느덧 이 글을 마지막으로 떠나야 한다고 생각하니 아쉬운 맘을 압니다.

제게 연구하는 사람의 자세를 일관워준 존경하는 김영석 지도 교수님께 깊은 감사를 드립니다. 부족한 논문을 성실히 지도해 주신 이릭출 교수님과 이복희 교수님께도 감사 드립니다. 또한 제게 전기공학의 길을 열어주신 인하대학교 전기공학과 모든 교수님들께 존경과 감사의 마음을 드리고 싶습니다.

부족한 아들을 위해 평생을 헌신하신 아버지 어머니, 별로 도움도 안 되는 엉아 때문에 맘 고생이 심한 두 동생 제화와 제옥이 우리 가족 모두 건강하고 행복하기를 바랍니다. 이재는 할아버지 할머니가 되신 큰아버지, 큰어머니 그리고 작은아버지 작은어머니, 언제나 사람이 넘치고 따뜻한 사촌 형제분들과 형수님 매형들, 조카들 모두에게 행복한 날만 계속되기를 바랍니다. 제겐 너무 과분한 사랑을 주시는 의삼촌과 의사촌 종현이와 태현이도 항상 건강하고 행복하시기를 기원합니다.

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