New trends in active filters for power conditioning

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New Trends in Active Filters for Power Conditioning

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Abstract—**Attention has been paid to active filters for power conditioning which provide the following multifunctions: reactive power compensation, harmonic compensation, flicker/imbalance compensation, and/or voltage regulation. Active filters in a range of 50 kVA–60 MVA have been practically installed in Japan. In the near future, the term "active filters" will have a much wider meaning than it did in the 1970's. For instance, active filters intended for harmonic solutions are expanding their functions from harmonic compensation of nonlinear loads into harmonic isolation between utilities and consumers, and harmonic damping throughout power distribution systems. This paper presents the present status of active filters based on state-of-the-art power electronics technology, and their future prospects and directions toward the 21st century, including the personal views and expectations of the author.**

Index Terms—**Active filters, harmonics, passive filters, power conditioning, power quality, power systems, PWM inverters**

I. Introduction

With significant development of power electronics technology, the proliferation of nonlinear loads such as static power converters has deteriorated power quality in power transmission/distribution systems. Notably, voltage harmonics resulting from current harmonics produced by the nonlinear loads have become a serious problem in many countries.

Since their basic compensation principles were proposed around 1970, much research has been done on active filters and their practical applications [1]–[6]. In addition, state-of-the-art power electronics technology has enabled engineers to put active filters into practical use. Several hundred shunt active filters consisting of voltage-fed pulsewidth modulated (PWM) inverters using insulated-gate bipolar transistors (IGBT's) or gate-turn-off (GTO) thyristors are operating successfully in Japan. They have been installed by individual high-power consumers on their own premises in the vicinity of one or more harmonic-producing loads. These filters have provided the required harmonic filtering and control performance in comparison to conventional shunt passive filters and static var compensators consisting of capacitor banks and thyristor-controlled reactors.

This paper presents the present status of active filters and new trends in active filters for power conditioning in industrial plants and distribution systems, including the personal views and expectations of the author. This paper is organized as follows. Section II shows measured supply voltage harmonics in a power system in Japan for different voltage levels. Section III provides classification of active filters from their objectives, system configuration, power circuit, and control strategy. Section IV gives two practical application examples of active filters, along with their system configuration and objectives. Sections V and VI describe the future prospects of active filters toward the 21st century with much attention to the "unified power quality conditioner" and shunt active filters, which will be concentratedly or dispersively installed by utilities in the near future, respectively.

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II. Voltage Harmonics in Power Systems

A. Harmonic-Producing Loads

Nonlinear loads drawing nonsinusoidal currents from utilities are classified into identified and unidentified loads. High-power diode/thyristor rectifiers, cycloconverters, and arc furnaces are typically characterized as identified harmonic-producing loads because utilities identify the individual nonlinear loads installed by high-power consumers on power distribution systems in many cases. The utilities determine the point of common coupling with high-power consumers who install their own harmonic-producing loads on power distribution systems, and also can determine the amount of harmonic current injected from an individual consumer.

A "single" low-power diode rectifier produces a negligible amount of harmonic current. However, multiple low-power diode rectifiers can inject a large amount of harmonics into power distribution systems. A low-power diode rectifier used as a utility interface in an electric appliance is typically considered an unidentified harmonic-producing load. Few researchers and engineers in power electronics and the power engineering area have paid attention to unidentified harmonic-producing loads. The guidelines for harmonic mitigation, announced on October 3, 1994, in Japan, are currently applied on a voluntary basis to keep current and voltage harmonic levels in check and promote better practices in both power systems and equipment design. Table I shows an analogy in unidentified and identified sources between harmonic pollution and air pollution.

B. Harmonic Propagation in Power Distribution Systems

Tables II and III show maximum and minimum values of total voltage harmonic distortion (THD) and dominant voltage harmonics in a typical power system in Japan, measured between April 28 and May 9, 1994 [34]. The individual voltage harmonics and THD in high-voltage power system

TABLE I
ANALOGY BETWEEN HARMONIC POLLUTION AND AIR POLLUTION

sources	harmonic pollution	air pollution
unidentified	• TV sets, and personal computers • adjustable speed heat pumps	• gasoline-fueled vehicles • diesel-powered vehicles
identified	• bulk rectifiers • cycloconverters • arc furnaces	• chemical plants • coal and oil steam power stations

TABLE II
VOLTAGE HARMONICS IN A POWER SYSTEM [%]

[%]

voltage (kV)		THD	3rd	5th	7th
500	max.	2.4	0.5	2.3	0.0
	min.	1.0	0.2	0.9	0.0
275 ~ 220	max.	3.2	1.1	2.4	0.5
	min.	1.6	0.7	0.8	0.1
187 ~ 154	max.	2.3	0.4	2.4	0.8
	min.	0.9	0.1	0.8	0.0
77 ~ 66	max.	3.2	1.1	2.4	0.5
	min.	1.9	0.7	0.7	0.1
allowable	–	3.0	2.0	2.5	2.0

TABLE III
VOLTAGE HARMONICS IN A 6.6-kV DISTRIBUTION SYSTEM [%]

[%]

area		THD	3rd	5th	7th
residential	max.	4.9	0.5	4.7	1.4
	min.	2.8	0.2	2.6	0.8
commercial & industrial	max.	3.7	0.6	3.4	1.6
	min.	0.8	0.1	0.3	0.5
allowable	–	5.0	3.0	4.0	3.0

tend to be less than those in the medium-voltage (6.6-kV) distribution system. The primary reason is that expansion and interlinkage of high-voltage power systems has made high-voltage systems more stiff with an increase of short-circuit capacity. For the distribution system, the maximum value of 5th harmonic voltage in the residential area investigated exceeds its allowable level of 4%, and that of THD is marginally lower than its allowable level of 5%.

Oku *et al.* have reported the serious status of harmonic pollution in Japan. The maximum value of 5th harmonic voltage in the downtown area of a 6.6-kV power distribution system exceeds 7% under light load conditions at night. They also have pointed out another significant phenomenon. The 5th harmonic voltage increases on the 6.6-kV bus in the secondary of the primary distribution transformer installed in a substation, whereas it decreases on the 77-kV bus in the primary under light load conditions at night [30]. These observations based on the actual measurement suggest that the 5th harmonic voltage increase at night is due to "harmonic propagation" as a result of series and/or parallel harmonic resonance between line inductors and shunt capacitors for power factor correction installed on the distribution system [43]. This implies that not only harmonic compensation but also harmonic damping is a viable and effective way of solving harmonic pollution in power distribution systems. Hence, utilities have the responsibility for actively damping harmonic propagation throughout power distribution systems. Individual consumers and end-users are responsible for keeping the current harmonics produced by their own equipment within specified limits.

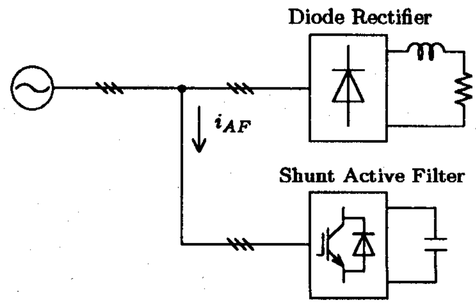


Fig. 1. Shunt active filter used alone.

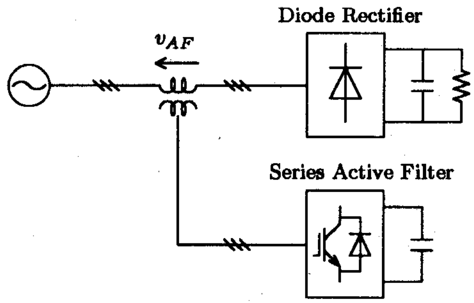


Fig. 2. Series active filter used alone.

III. CLASSIFICATION OF ACTIVE FILTERS

Various types of active filters have been proposed in many technical literatures [18], [27]. Classification of active filters is made from different points of view. Active filters are divided into ac and dc filters. Active dc filters have been designed to compensate for current and/or voltage harmonics on the dc side of thyristor converters for HVDC systems [14], [20], [26] and on the dc link of a PWM rectifier/inverter for traction systems [39]. Emphasis, however, is put on active ac filters in this paper because the term "active filters" refers to active ac filters in most cases.

A. Classification by Objectives: Who Is Responsible for Installing Active Filters?

The objective of "who is responsible for installing active filters" classifies them into the following two groups:

- active filters installed by *individual consumers* on their own premises near one or more identified harmonic-producing loads;
- active filters installed by *electric power utilities* in substations and/or on distribution feeders.

TABLE IV
COMPARISONS OF SHUNT AND SERIES ACTIVE FILTERS USED ALONE

	shunt active filter	series active filter
system configuration	Figure 1	Figure 2
power circuit of active filter	voltage-fed PWM inverter **with** current minor loop	voltage-fed PWM inverter **without** current minor loop
active filter acts as	current source: i_{AF}	voltage source: v_{AF}
harmonic-producing load suitable	diode or thyristor rectifiers with **inductive** loads, and cycloconverters	large capacity diode rectifiers with **capacitive** loads
additional function	reactive power compensation	ac voltage regulation
present situation	commercial stage	laboratory level

The main purpose of the active filters installed by individual consumers is to compensate for current harmonics and/or current imbalance of their own harmonic-producing loads. On the other hand, the primary purpose of active filters installed by utilities in the near future is to compensate for voltage harmonics and/or voltage imbalance, or to provide "harmonic damping" throughout power distribution systems. In addition, active filters have the function of harmonic isolation at the utility-consumer point of common coupling in power distribution systems.

B. Classification by System Configuration

1) Shunt Active Filters and Series Active Filters: Fig. 1 shows a system configuration of a shunt active filter used alone, which is one of the most fundamental system configurations. The shunt active filter is controlled to draw a compensating current, i_{AF}, from the utility, so that it cancels current harmonics on the ac side of a general-purpose thyristor rectifier with a dc link inductor [16], [17] or a PWM rectifier with a dc link capacitor for traction systems [33]. The shunt active filter has the capability of damping harmonic resonance between an existing passive filter and the supply impedance [12], [29].

Fig. 2 shows a system configuration of a series active filter used alone. The series active filter is connected in series with the utility through a matching transformer, so that it is applicable to harmonic compensation of a large capacity diode rectifier with a dc link capacitor. Table IV shows comparisons between the shunt and series active filters. This concludes that the series active filter has a "dual" relationship in each item with the shunt active filter [24].

2) Hybrid Active/Passive Filters: Figs. 3–5 show three types of hybrid active/passive filters, the main purpose of which is to reduce initial costs and to improve efficiency. The shunt passive filter consists of one or more tuned LC filters and/or a high-pass filter. Table V shows comparisons among the three hybrid filters, in which the active filters are different in function from the passive filters.

The combination of shunt active and passive filters has already been applied to harmonic compensation of large-rated cycloconverters for steel mill drives [12]. The combined filters, shown in Fig. 4 [19], [25], [44] and in Fig. 5 [21], [32], [45], will be practically applied in the near future, not only for harmonic compensation but also for harmonic isolation between supply and load, and for voltage regulation and imbalance compensation. They are considered prospective alternatives to shunt or series active filters used alone. Other combined systems of active filters and passive filters or LC circuits have been proposed in [31], [36], and [46].

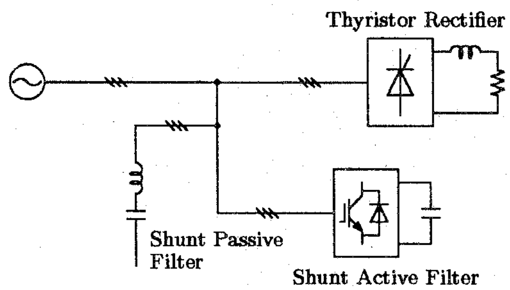


Fig. 3. Combination of shunt active filter and shunt passive filter.

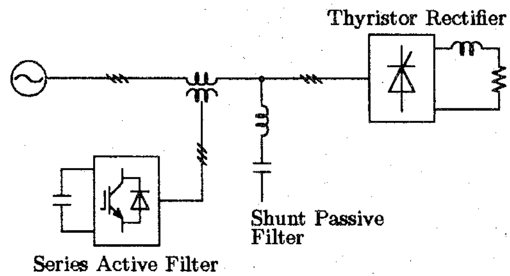


Fig. 4. Combination of series active filter and shunt passive filter.

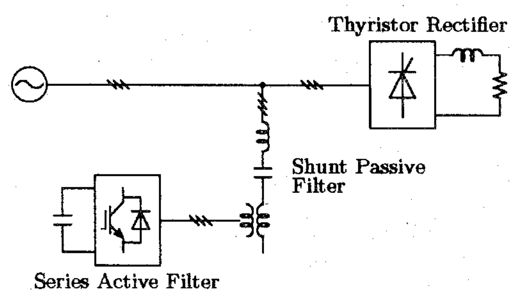


Fig. 5. Active filter connected in series with shunt passive filter.

C. Classification by Power Circuit

There are two types of power circuits used for active filters: a voltage-fed PWM inverter [10], [12] and a current-fed PWM inverter [7], [11]. These are similar to the power circuits used for ac motor drives. They are, however, different

TABLE V
COMPARISON OF HYBRID ACTIVE/PASSIVE FILTERS

	shunt active filter plus shunt passive filter	series active filter plus shunt passive filter	series active filter connected in series with shunt passive filter
system configuration	Figure 3	Figure 4	Figure 5
power circuit of active filter	• voltage-fed PWM inverter with current minor loop	• voltage-fed PWM inverter without current minor loop	• voltage-fed PWM inverter with or without current minor loop
function of active filter	• harmonic compensation or harmonic damping	• harmonic isolation and harmonic damping	• harmonic damping or harmonic compensation
advantages	• general shunt active filters applicable • reactive power controllable	• already existing shunt passive filters applicable • no harmonic current flowing through active filter	• already existing shunt passive filters applicable • easy protection of active filter
problems or issues	• share compensation in frequency domain between active filter and passive filter	• difficult to protect active filter against overcurrent • no reactive power control	• no reactive power control
present situation	• commercial stage	• field testing	• coming onto market

in their behavior because active filters act as nonsinusoidal current or voltage sources. The author prefers the voltage-fed to the current-fed PWM inverter because the voltage-fed PWM inverter is higher in efficiency and lower in initial costs than the current-fed PWM inverter [28]. In fact, almost all active filters, which have been put into practical applications in Japan, have adopted the voltage-fed PWM inverter as the power circuit.

D. Classification by Control Strategy

The control strategy of active filters has a great impact not only on the compensation objective and required kVA rating of active filters, but also on the filtering characteristics in transient state as well as in steady state [10].

1) Frequency-Domain and Time-Domain: There are mainly two kinds of control strategies for extracting current or voltage harmonics from the corresponding distorted current or voltage; one is based on the Fourier analysis in the frequency-domain [18], [22], and the other is based on the theory of instantaneous reactive power in three-phase circuits, which is called the "*p-q* theory" in Japan [8], [9]. The concept of the *p-q* theory in the time-domain has been applied to the control strategy of almost all the active filters installed by individual high-power consumers over the last five years in Japan.

2) Harmonic Detection Methods: Three kinds of harmonic detection methods in the time-domain have been proposed for shunt active filters acting as a current source i_{AF}.

load current detection $i_{AF} = i_{Lh}$;
supply current detection $i_{AF} = K_S \cdot i_{Sh}$;
voltage detection $i_{AF} = K_V \cdot v_h$.

Load current detection and supply current detection are suitable for shunt active filters installed in the vicinity of one or more harmonic-producing loads by individual high-power consumers. As discussed in Section V, voltage detection is suitable for a shunt active filter to be used as the shunt device of the "unified power quality conditioner" which will be concentratedly installed in primary distribution substations by utilities [41]. It is also suitable for shunt active filters described in Section VI, which will be dispersively installed on distribution systems by utilities [47].

Supply current detection is the most basic harmonic detection method for series active filters acting as a voltage source v_{AF}.

supply current detection $v_{AF} = G \cdot i_{Sh}$.

The series active filters, shown in Fig. 2 [24] and Fig. 4 [19], are based on supply current detection. It is also suitable for a series active filter to be used as the series device of the unified power quality conditioner.

IV. PRESENT STATUS OF ACTIVE FILTERS IN JAPAN

Since 1981, more than 500 shunt active filters have been put into practical applications mainly for harmonic compensation with or without reactive power compensation. A good market is developing for shunt active filters as the price gradually decreases mainly due to device cost reduction and power electronics integration strategies. In fact, the number of installed shunt active filters are increasing every year in Japan. Table VI shows ratings and application examples of shunt active filters classified by compensation objectives. At present, voltage-fed PWM inverters using IGBT modules are usually employed as the power circuits, and their rating ranges from 50 kVA to 2 MVA, although PWM inverters using bipolar junction transistors (BJT's) or GTO thyristors were more commonly employed in the past.

A. Harmonic Compensation

Fig. 6 shows a one-line diagram of office-building facilities in which a shunt active filter of 300 kVA, manufactured by Meidensha Corporation, Japan, has been installed to compensate for harmonic currents generated by eight adjustable-speed drives. Fig. 7 shows two waveforms of the supply current drawn from the 6.6-kV bus before and after compensation, with a current distortion factor of 38.4% and 7.4%, respec-

TABLE VI
SHUNT ACTIVE FILTERS ON COMMERCIAL BASE IN JAPAN

objective	rating	switching devices	applications
harmonic compensation with or without reactive/negative-sequence current compensation	50kVA ~ 2000kVA	IGBTs	diode/thyristor rectifiers and cycloconverters for industrial loads
voltage flicker compensation	5MVA ~ 50MVA	GTO thyristors	arc furnaces
voltage regulation	40MVA ~ 60MVA	GTO thyristors	Sinkansen (the Japanese "bullet" trains)

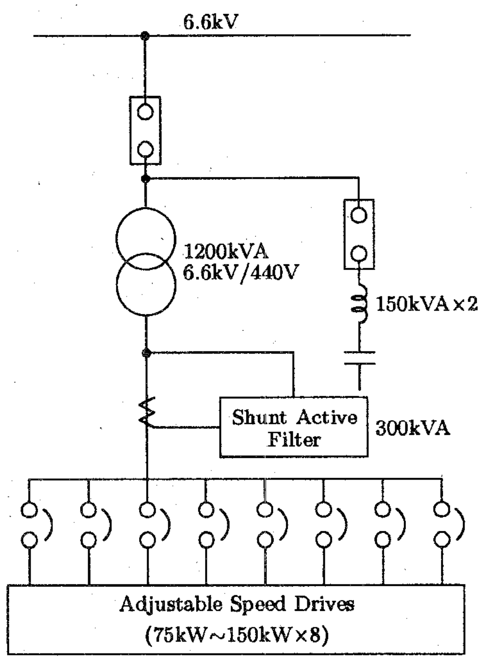


Fig. 6. Application to harmonic compensation.

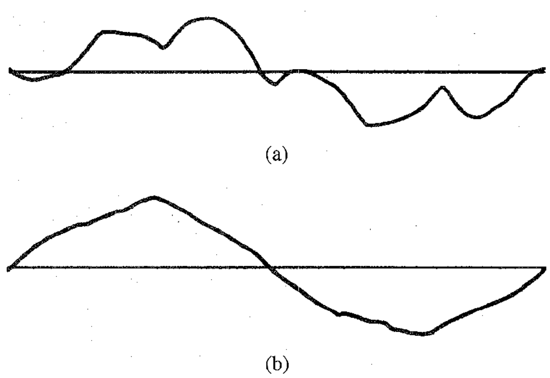


Fig. 7. Supply current drawn from 6.6-kV bus. (a) Before compensation. (b) After compensation.

tively. The most dominant 5th harmonic current is reduced from 33.4% to 5.3%. Voltage distortion factor on the 6.6-kV bus is reduced from 2.5% to 1.1%, and that on the 440-V bus from 7.3% to 2.7%.

As another example, 200-kVA/440-V and 75-kVA/210-V shunt active filters, designed and developed by Toyo Electric Manufacturing Company, Japan, have been installed for harmonic compensation at water supply facilities in Takatsuki-city, Japan. These filters have exhibited excellent filtering characteristics which would not be achieved by conventional shunt passive filters, although the active filters are currently more expensive than the passive filters.

B. Compensation for Voltage Impact Drop, Variation, and Imbalance

Fig. 8 shows a power system delivering electric power to the Japanese "bullet" trains on the Tokaido Sinkansen. Three shunt active filters for fluctuating reactive current/negative-sequence current compensation have been installed in Shintakatsuki substation by Central Japan Railway Company [38]. The shunt active filters, manufactured by Toshiba Corporation, Japan, consist of voltage-fed PWM inverters using GTO thyristors, each of which is rated at 16 MVA. A high-speed train with maximum output power of 12 MW draws unbalanced varying active and reactive powers from the Scott-transformer connected to the 154-kV utility grid and delivering the 25-kV 60-Hz electric power to the trains. More than 20 high-speed trains pass per hour during the daytime. This causes voltage impact drop, variation, and imbalance at the terminals of the 154-kV utility system, thus accompanied by a serious deterioration in the power quality of other consumers connected to the same power system. The purpose of the shunt active filters with the total rating of 48 MVA is to compensate for voltage impact drop, variation, and imbalance at the terminals of the 154-kV power system and to improve the power quality.

Fig. 9 shows voltage waveforms on the 154-kV bus and the voltage imbalance factor before and after compensation, measured at 14:20–14:30 on July 27, 1994. The shunt active filters are effective not only in compensating for the voltage impact drop and variation, but also in reducing the voltage imbalance factor from 3.6% to 1%. Here, the voltage imbalance factor is the ratio of the negative to positive-sequence component in the three-phase voltages on the 154-kV bus.

V. THE UNIFIED POWER QUALITY CONDITIONER

The "marriage" of a series active filter and a shunt active filter attracting each other makes both active filters much more charming than their "divorce."

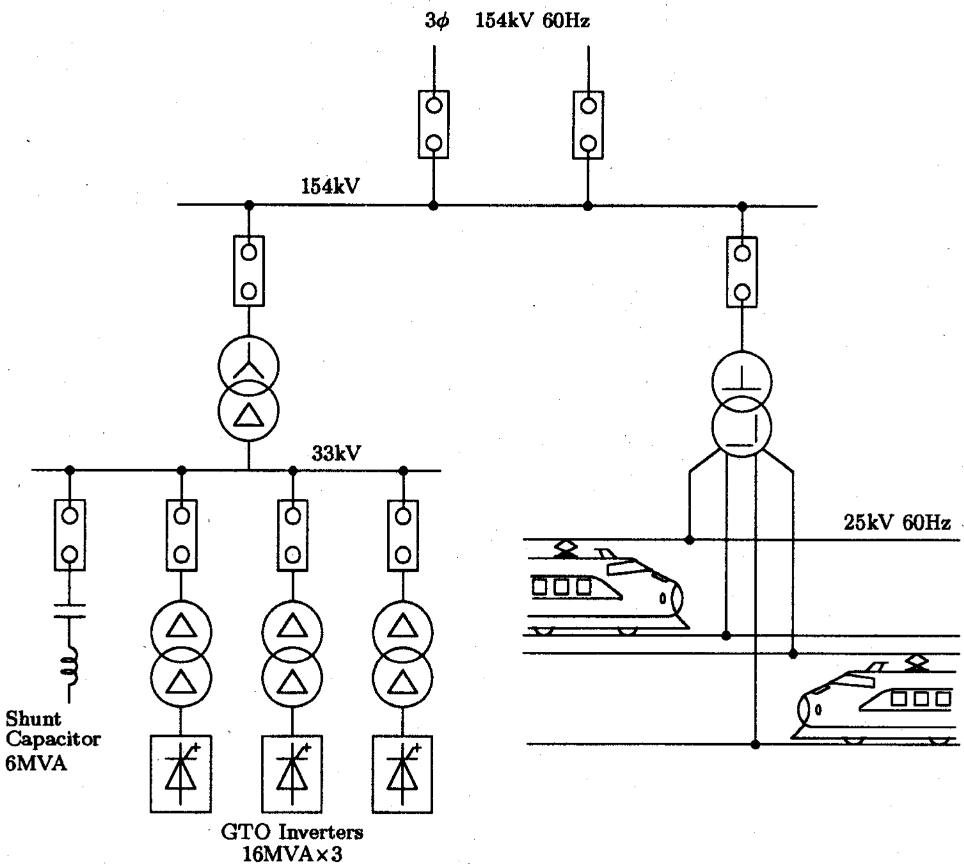
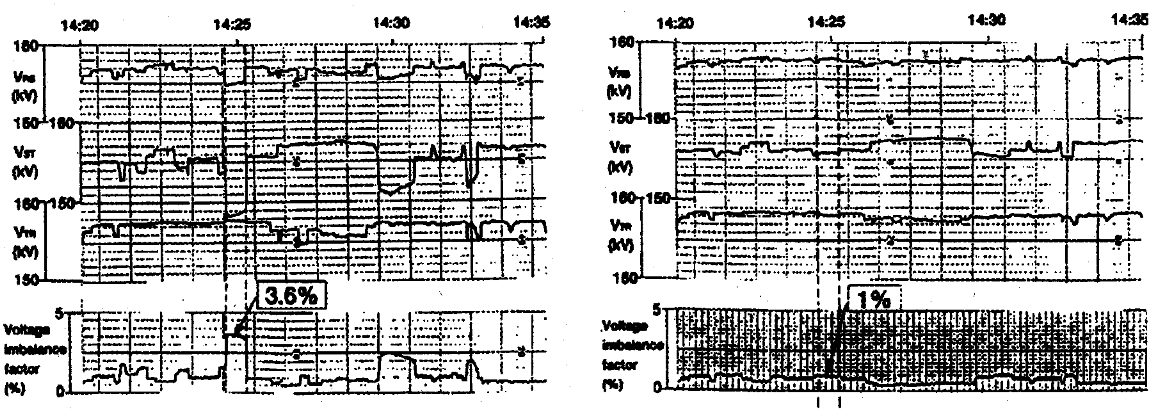


Fig. 8. Application to voltage regulation.



(a) (b)

Fig. 9. Compensation for voltage impact drop, variation, and imbalance. (a) Before compensation. (b) After compensation.

A. System Configuration

Fig. 10 shows the integration of a series active filter and a shunt active filter for concentrated installation in a substation by a utility in the near future [15], [40], [41], [48]. The integrated series and shunt active filter system is referred to as "the unified power quality conditioner" in this paper, and is due to its similarity in power circuit configuration to the "unified power flow controller" proposed by Gyugyi [23], [35]. However, the unified power quality conditioner for distribution systems is quite different in operation, purpose, and control strategy from the unified power flow controller for transmission systems.

B. Functions and Control of Series and Shunt Active Filters

A general unified power quality conditioner has the following functions shared by the series active filter and the shunt active filter. The functions being performed with the series active filter are harmonic isolation between the subtransmission system and the distribution system, voltage regulation, and voltage flicker/imbalance compensation at the point of

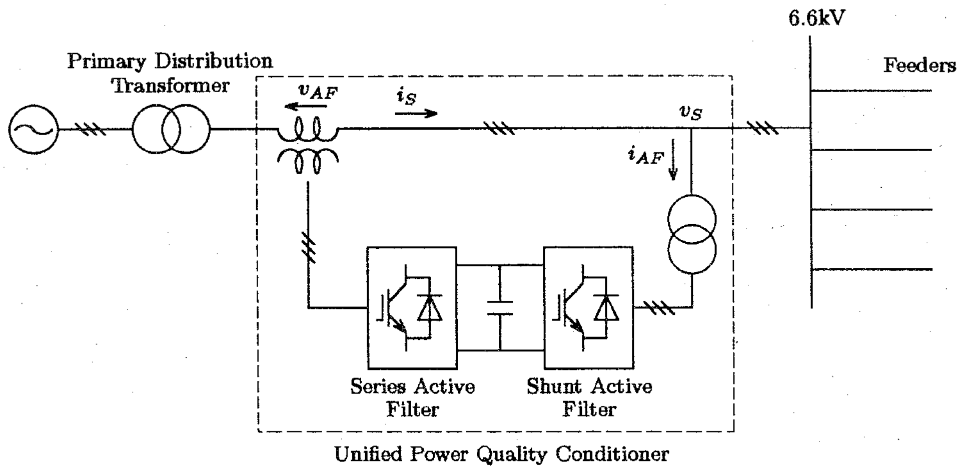


Fig. 10. Integration of series active filter and shunt active filter.

common coupling (PCC). The functions being performed with the shunt active filter are harmonic current and/or negative-sequence current compensation, and dc link voltage regulation between both active filters. In this paper, a basic control strategy is proposed for a specific unified power quality conditioner for solving harmonic pollution [42].

The purpose of the series active filter intended for harmonic isolation is to keep harmonic currents from flowing in and out of the distribution feeders. Thus, the series active filter detects the supply current i_S, and it is controlled in such a way to present zero impedance for the fundamental frequency and to act as a resistor with high resistance of G [Ω] for the harmonic frequencies

$$v_{AF} = G \cdot i_{Sh}. \tag{1}$$

The purpose of the shunt active filter intended for harmonic compensation is to absorb current harmonics generated from the feeders. Hence, the shunt active filter detects the bus voltage at the point of installation, v_S, and it is controlled to present infinite impedance for the fundamental frequency and to act as a resistor with low resistance of $1/K$ [Ω] for the harmonic frequencies

$$i_{AF} = K \cdot v_{Sh}. \tag{2}$$

In (1) and (2), i_{Sh} and v_{Sh} are the harmonic current and voltage which are extracted from the detected supply current i_S and the bus voltage v_S by calculation in the time-domain, and G and K are the feedback gains of the series and shunt active filters, respectively. Note that (1) and (2) have a dual relation in voltage and current. This implies that the unified power quality conditioner would not cause any harmonic interference or coupling between the two active filters. It is possible to add other feedback or feedforward control loops to (1) and (2), in order to achieve reactive power control, voltage flicker/imbalance compensation, and so on.

VI. Shunt Active Filters for Installation on Power Distribution Systems

One of the new trends in active filters is that the unified power quality conditioner shown in Fig. 10 will be "concentratedly" installed in primary distribution substations. Another is that shunt active filters for damping of harmonic propagation will be "dispersively" installed on multiple feeders in power distribution systems. The shunt active filters will be installed by electric power companies or utilities in the near future as voltage distortion and harmonics in distribution systems approach or exceed their allowable levels, as shown in Tables II and III.

A. Power Distribution System

Fig. 11 shows a radial distribution system in a residential area [47]. The rated bus voltage is 6.6 kV(line-to-line), and the rated frequency is 50 Hz. The equivalent inductive reactance upstream of bus 2, including the leakage reactance of a primary distribution transformer of 15 MVA, is to be estimated from the short-circuit capacity of 110 MVA. The transformer supplies four distribution feeders numbered 1 $\sim$ 4. For the sake of simplicity, only feeder 1 is considered under the assumption that feeders 2, 3, and 4 are disconnected from the transformer.

Overhead distribution lines are classified into the primary line and branch lines in feeder 1. A distribution line between a bus and the adjacent bus is assumed to be a lumped LR circuit dependent on the length and thickness of the line, because it is reasonable to neglect the effect of the stray capacitive reactances of the line for the 5th and 7th harmonic voltage and current. Feeder 1 delivers electric power to eleven medium-voltage consumers of 200 $\sim$ 240 kW and six low-voltage consumers of 50 $\sim$ 130 kW. Each medium-voltage consumer has a shunt capacitor without any series reactor for power factor correction, while the low-voltage consumers do not have shunt capacitors. The total capacity of the loads is 2.99 MW, and that of the shunt capacitors for power factor correction is 0.99 Mvar.

Harmonic propagation occurs in feeder 1 around the 7th harmonic frequency (350 Hz), such that the 7th harmonic voltage is amplified by four times at the rated load of 2.99 MW and by eight times at no load. The harmonic propagation results from series and/or parallel harmonic resonance between the inductive reactances of the distribution lines, along with

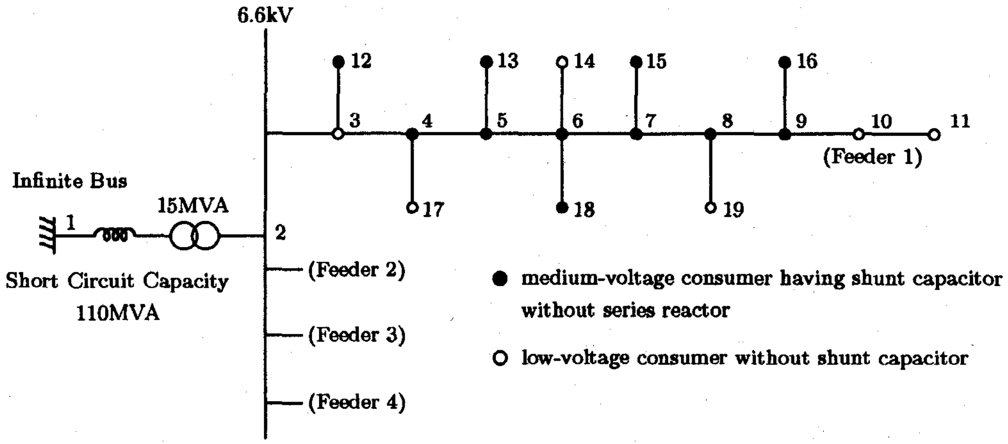


Fig. 11. Radial distribution system model.

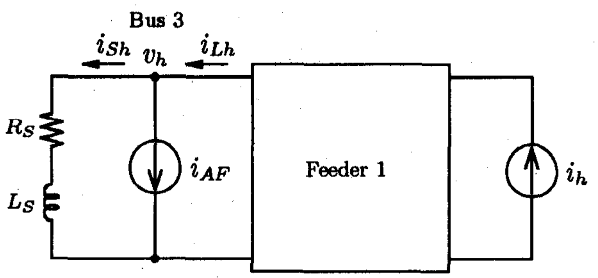


Fig. 12. Equivalent model for voltage and current harmonics.

the equivalent inductive reactance upstream of bus 2, and the capacitive reactances of the shunt capacitors on feeder 1.

B. Harmonic Detection Methods

Fig. 12 shows an equivalent circuit for voltage and current harmonics on feeder 1, where a shunt active filter is installed on bus 3. The shunt active filter is assumed to be an ideal current source capable of "drawing" a compensating current i_{AF} from bus 3. A harmonic-producing load connected somewhere in feeder 1, downstream of bus 3, is also assumed to be an ideal current source "injecting" a harmonic current i_h into feeder 1. Note that the author distinguishes the two terms "drawing" and "injecting," considering the polarity of the ideal current sources shown in Fig. 12.

The load current detection mentioned before is suitable for a shunt active filter installed in the vicinity of one or more harmonic-producing loads. However, depending on the point of installation, instability may occur as shown in [47]. A shunt active filter based on the supply current detection may cause instability as the phase margin is in the range of 10°–90°. Adding differential compensation enables to improve the phase margin by 90°, because the principle of compensation is based on feedback control. A shunt active filter based on the voltage detection is extremely stable because the phase margin is over 90°, irrespective of the point of installation [47]. Hence, the voltage detection and the supply current detection with differential compensation are taken into consideration as they have the potential possibility applicable to the shunt active filter for installation on power distribution systems, while the other harmonic detection methods are excluded from discussion.

Assuming that the effect of the controller delay for extraction of the harmonic current or voltage is represented by a first-order lag system, the two harmonic detection methods are given as follows:

$$I_{AF}(s) = \frac{s \cdot K_S}{1 + sT} I_{Sh}(s) \tag{3}$$

$$I_{AF}(s) = \frac{K_V}{1 + sT} V_h(s) \tag{4}$$

where K_S is a feedback gain with no dimension, and K_V is a feedback gain with the dimension of S.

C. Harmonic Damping Effect

Computer simulation is performed to verify the effect of the shunt active filter on damping of harmonic propagation under the following assumptions.

- Feeders 2, 3, and 4 are disconnected from bus 2.
- The 7th harmonic voltage and current are considered in feeder 1, because harmonic propagation occurs around the 7th harmonic frequency.
- All shunt capacitors for power factor correction remain connected to feeder 1, while all loads are disconnected, thus leading to the most severe harmonic propagation.
- The 7th harmonic current source of $I_h = 7.8$ A exists on bus 6.
- A single shunt active filter is installed at the beginning terminal or at the end terminal of the primary line, that is, bus 3 or bus 9, respectively.

Table VII shows the 7th harmonic current flowing between a bus and the adjacent bus in the primary line, and compensating current drawn by the shunt active filter, I_{AF}. For example, $I_{2\text{-}3}$ means the 7th harmonic current flowing between buses 2 and 3. Table VII(a) shows the 7th harmonic current and compensating current for the shunt active filter based on the supply current detection with differential compensation with a gain of $K_S = 20$, while Table VII(b) for the shunt active filter based on the voltage detection with a gain of $K_V = 2$ S. A delay time of $T = 0.16$ ms, which results from current or

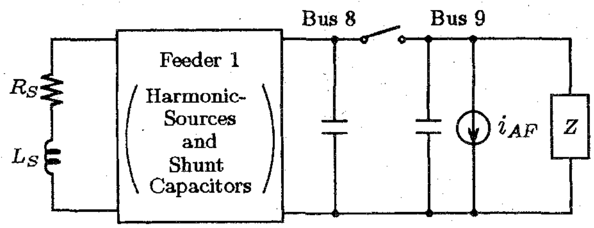
TABLE VII
EFFECT OF SHUNT ACTIVE FILTER ON HARMONIC DAMPING, WHERE 7TH HARMONIC CURRENT SOURCE OF 7.8A EXISTS ON BUS 6

[A]	installation of shunt active filter		
	no instal.	on bus 3	on bus 9
I_{2-3}	109.7	0	31.9
I_{3-4}	104.0	14.0	30.2
I_{5-6}	79.0	12.8	23.0
I_{6-7}	58.3	3.8	9.4
I_{8-9}	24.3	1.6	0
I_{AF}	–	14.0	6.4

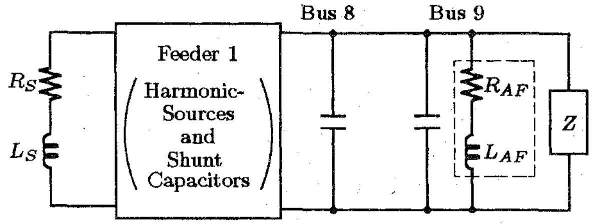
(a)

[A]	installation of shunt active filter		
	no instal.	on bus 3	on bus 9
I_{2-3}	109.7	2.1	3.6
I_{3-4}	104.0	14.5	3.4
I_{5-6}	79.0	12.0	2.6
I_{6-7}	58.3	4.3	5.9
I_{8-9}	24.3	1.8	6.5
I_{AF}	–	13.7	6.5

(b)



(a)



(b)

Fig. 13. Equivalent circuit model for shunt active filter with respect to 7th harmonic voltage and current. (a) Shunt active filter based on supply current detection with differential compensation. (b) Shunt active filter based on voltage detection.

voltage detection and harmonic extraction, is considered for both harmonic detection methods.

The shunt active filter installed on bus 3 produces almost the same effect, independent of either harmonic detection method. The shunt active filter can compensate for the harmonic current flowing out upstream of bus 3. However, harmonic current propagation still occurs between buses 3 and 6. The shunt active filter installed on bus 6 fully compensates for the current harmonics throughout feeder 1, independent of either harmonic detection method, because it is installed in the vicinity of the harmonic current/voltage source existing on bus 6.

When the shunt active filter is installed on bus 9, there is a notable difference in the effect of shunt active filter between both harmonic detection methods. The shunt active filter based on the supply current detection with differential compensation can compensate for the harmonic current flowing upstream of bus 9, I_{8-9}, but it cannot damp the harmonic current propagation upstream of bus 7. That is, $I_{2-3} \sim I_{6-7}$ are larger than 7.8 A. On the other hand, the shunt active filter based on the voltage detection reduces the harmonic current into less than 7.8 A throughout feeder 1. This means that the shunt active filter based on the voltage detection has the capability of harmonic damping throughout feeder 1, unlike the shunt active filter based on the supply current detection with differential compensation, when the shunt active filter is installed at the end terminal of the primary line, that is, on bus 9. The reason for the difference is clarified in the following section.

D. Modeling of Shunt Active Filters

Fig. 13 shows an equivalent circuit model for the shunt active filter based on either harmonic detection method.

When the shunt active filter based on the supply current detection with differential compensation is installed on bus 9, no harmonic current flows buses 8 and 9, that is, $I_{8-9} = 0$. With the focus on voltage and current harmonics upstream of bus 9, an equivalent circuit model for $I_{8-9} = 0$ is represented by an open switch connected in series between buses 8 and 9, as shown in Fig. 13(a). This means that the network upstream of bus 8 still has the potential possibility of causing harmonic propagation. In addition, opening the switch would change the resonant frequency in feeder 1. If a frequency of multiple harmonic current sources existing upstream of bus 8 coincided with the changed resonant frequency, installation of the shunt active filter on bus 9 would cause more severe harmonic propagation upstream of bus 8. Therefore, the supply current detection with differential compensation is not suitable for the shunt active filters intended for dispersive installation on power distribution systems by utilities.

On the other hand, equation (4) implies that the shunt active filter based on the voltage detection acts as a lumped series R_{AF}-L_{AF} circuit with $R_{AF} = 1/K_V$ and $L_{AF} = T/K_V$, when it is seen from the point of installation. Note that the shunt active filter itself acts as a current source. Thus, the equivalent circuit model is represented by Fig. 13(b). It is clear from Table VII(b) and Fig. 13(b) that installation of the shunt active filter on bus 9 is effective in harmonic damping throughout feeder 1. The reason is that installation of the shunt active filter on bus 9 makes the system impedance downstream of bus 6 inductive, so that the following significant equation exists in Table VII(b):

$$I_{5-6} + I_{6-7} = 8.5 \simeq 7.8 \text{ A}.$$

E. Best Site Selection of Installation

The best site selection of installation on a feeder is not the beginning terminal but the end terminal of the primary line [47], when a utility installs a "single" shunt active filter based on the voltage detection, in order to damp harmonic propagation throughout the feeder. Moreover, dispersive installation of "multiple" shunt active filters on multiple feeders in a power distribution system causes neither harmonic propagation nor harmonic interference among them, and thus it is a viable and effective way of actively damping harmonic propagation throughout a power distribution system which is subjected to harmonic pollution caused by harmonic resonance and a number of unidentified harmonic-producing loads [49].

VII. Conclusions

The efforts of researchers and engineers in the automobile industry to comply with the Clean Air Act Amendments of 1970 has led to success in suppressing CO, HC, and NOx contained in automobile exhaust. As a result, the reduction is achieved by 90% when gasoline-fueled passenger cars in the 1990's are compared with the same class of cars at the beginning of the 1970's. It is interesting that the development of the automobile industry, along with the proliferation of cars, has made a great contribution to absorbing the increased cost related to the reduction of harmful components in exhaust emitted by gasoline-fueled vehicles.

Guidelines or regulations for harmonic mitigation are essential and would be effective in overcoming "harmonic pollution." Customers pay for the cost of high efficiency, energy-savings, high performance, reliability, and compactness brought by power electronic technology. But they are unwilling to pay for the cost of suppressing or eliminating the current harmonics generated by power electronic equipment unless guidelines or regulations are enacted. It is expected that the continuous efforts of power electronics researchers and engineers will achieve significant development of advanced active filters for power conditioning, such as:

- voltage regulation with voltage flicker/imbalance compensation;
- fluctuating reactive current/negative-sequence current compensation;
- harmonic compensation, harmonic isolation, and/or harmonic damping.

The advanced active filters characterized by low-cost, high-efficiency, high-performance, and value-added functions for the customers will come onto the market in the near future, thus being viable and cost-effective in power conditioning.

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