Control strategy and site selection of a shunt active filter for damping of harmonic propagation in power distribution systems

Hirofumi Akagi
Okayama University

IEEE Transactions on Power Delivery, Vol. 12, No. 1, January 1997

Control Strategy and Site Selection of a Shunt Active Filter for Damping of Harmonic Propagation in Power Distribution Systems

Hirofumi Akagi, Senior Member, IEEE
Department of Electrical Engineering
Okayama University
Okayama-city, 700 Japan

Abstract—**This paper deals with a shunt active filter which will be installed by an electric utility, putting much emphasis on the control strategy and the best point of installation of the shunt active filter on a feeder in a power distribution system. The objective of the shunt active filter is to damp harmonic propagation, which results from harmonic resonance between many capacitors for power factor improvement and line inductors in the feeder, rather than to minimize voltage distortion throughout the feeder. Harmonic mitigation is a welcome "by-product" of the shunt active filter, which comes from damping of harmonic propagation.**

This paper concludes that the shunt active filter based on detection of voltage at the point of installation is superior in stability to others, and that the best site selection is not the beginning terminal but the end terminal of the primary line in the feeder. Computer simulation is performed to verify the validity and effectiveness of the shunt active filter by means of an analog circuit simulator, which is characterized by installing it on a feeder of a radial distribution system in a residential area.

I. Introduction

A number of electronic-based appliances such as TV sets, personal computers, and adjustable speed heat pumps generate a large amount of harmonic current in power systems even though a single low-power electronic-based appliance, in which a single-phase diode rectifier with a dc link capacitor is used as a utility interface circuit, produces a negligible amount of harmonic current. Three-phase diode or thyristor rectifiers and cycloconverters for industry applications also generate a large amount of harmonic current. Voltage distortion resulting from the harmonic currents produced by power electronic equipment has become a serious problem to be solved in many countries.

The guidelines for harmonic mitigation, announced on Sept. 30, 1994 in Japan, are currently applied on a voluntary basis to keep harmonic levels in check and promote better practices in both power systems and equipment design. In general, individual low-power end-users and high-power consumers are responsible for limiting current distortion caused by power electronic equipment, while electric utilities are responsible for limiting voltage distortion at the point of common coupling in distribution systems.

Shunt active filters, or active power line conditioners, have been researched since the basic principle was proposed in the beginning of the 1970's [1]–[12]. Based on state-of-the-art power electronics technology, they have been put into practical applications, not only for harmonic compensation [4][6], but also for flicker compensation [7] and voltage regulation of impact drop at the end terminal of a power system feeding the Shinkansen, i.e., the Japanese "bullet" trains [11][12].

Many shunt active filters, consisting of PWM inverters using IGBTs or GTO thyristors, have been operating properly in Japan, the capacity or rating of which ranges from 50kVA to 48MVA. All of them have been installed by the individual high-power consumers on their own premises near large capacity nonlinear loads. They have presented much more satisfactory filtering characteristics than conventional shunt passive filters and/or static var compensators consisting of thyristor-controlled reactors do. However, no shunt active filters for harmonic compensation in power systems have been installed by electric utilities.

Grady, et al., presented a new procedure based on nonlinear optimization theory for computing the compensating currents injected by a shunt active filter, aiming at minimizing voltage distortion throughout a distribution network [13]. It is, however, assumed that the shunt active filter is provided with measurements of voltage distortion throughout the network. It is also assumed that the network impedance matrix is known by means of either measurement or calculation. Their paper has spurred theoretical interest in shunt active filters installed on power distribution systems by electric utilities, but the assumptions would make the procedure impractical.

This paper deals with a shunt active filter which will be installed on a distribution feeder in a power system, not by an electric consumer but by an electric utility. The major objective of the shunt active filter is to damp harmonic propagation, rather than to minimize voltage distortion throughout the feeder. Harmonic mitigation is a welcome by-product, which comes from damping of harmonic propagation. Stability analysis based on the phase

96 WM 087-7 PWRD A paper recommended and approved by the IEEE Transmission and Distribution Committee of the IEEE Power Engineering Society for presentation at the 1996 IEEE/PES Winter Meeting, January 21-25, 1996, Baltimore, MD. Manuscript submitted July 20, 1995; made available for printing November 13, 1995.

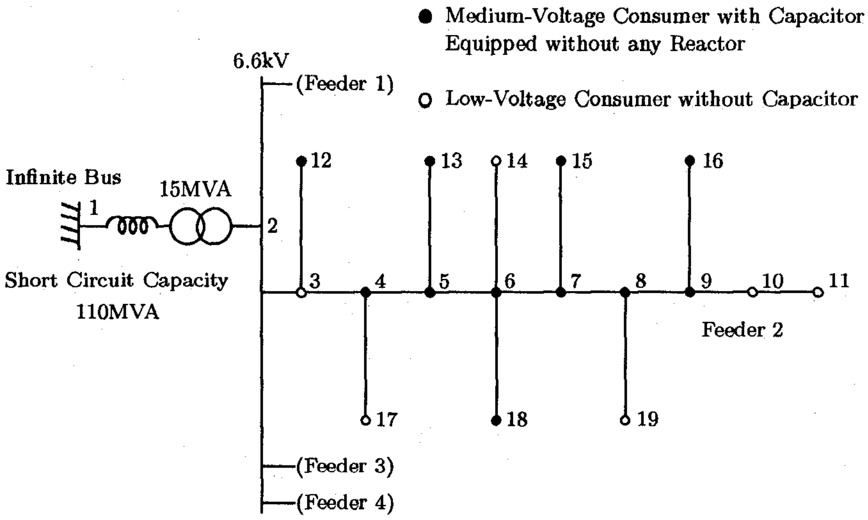


Fig. 1. Model for radial distribution system in residential area.

margin of open-loop transfer functions is done with the focus on the control strategy of the shunt active filter. This paper also proposes a basic concept of the best point of installation of the shunt active filter on a feeder of a virtual distribution system in a residential area. The validity and effectiveness of the control strategy and site selection is verified by theory and computer simulation.

II. Model for Power Distribution System

Fig.1 shows a model for a power distribution system in a residential area, which is used for analysis and computer simulation. The rated bus voltage is 6.6kV(line-to-line), and the rated frequency is 50Hz. The equivalent inductive reactance upstream of bus 2, including the leakage reactance of a primary distribution transformer of 15MVA, is to be estimated from the short circuit capacity of 110MVA. The transformer supplies four distribution feeders consisting of feeders 1 $\sim$ 4. For the sake of simplicity, only feeder 2 is considered under the assumption that feeders 1, 3 and 4 are disconnected from bus 2. Overhead distribution lines, which are classified into a primary line and branch lines in feeder 2, are assumed to be LR circuits because it is reasonable to neglect the effect of stray capacitors of the distribution lines on the 5th and 7th harmonic voltage and current. The primary line is from bus 3 to bus 9 and the branch lines are from bus 9 to bus 11, from bus 9 to bus 20, and so on. Feeder 2 supplies electric power to eleven medium-voltage consumers of 200 – 240kW, which install shunt capacitors without any reactor, and to six low-voltage consumers of 50 – 130kW, which have no shunt capacitor. The total capacity of the loads is 2.99MW, and that of the shunt capacitors for power factor improvement is 0.99MVAr.

Fig.2 shows a Bode diagram of the transfer function of $V_1(s)/V_3(s)$ in feeder 2. For instance, the subscript of 1 in the transfer function means bus 1. It is assumed that bus 1 is an infinite bus and the turn ratio of the primary distribution transformer is 1:1. Fig.2 shows that harmonic propagation occurs around the 7th harmonic frequency (350Hz) so that the 7th harmonic voltage is amplified between bus 1 and bus 3 by four times at the rated load of 2.99MW and by eight times at no load. This results from resonance between inductive reactances of the distribution lines, along with the equivalent inductive reactance upstream of bus 2, and capacitive reactances of the shunt capacitors on feeder 2.

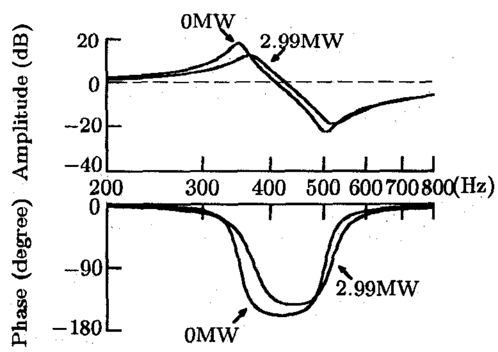


Fig. 2. Bode diagram of $V_3(s)/V_1(s)$.

III. Control Strategy and Stability

It is essential to discuss how the stability of a shunt active filter is affected by the control strategy and the point of installation on the primary line in feeder 2. Fig.3 shows a circuit equivalent to current and voltage harmonics, in which the shunt active filter is installed on bus 3. A harmonic-producing load is assumed to be a current source i_h and the shunt active filter to be an ideal current source capable of injecting a compensating current i_{AF}. There are

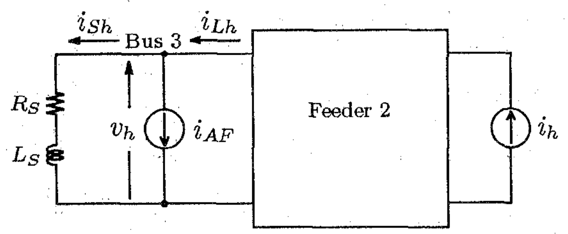


Fig. 3. Equivalent circuit to current and voltage harmonics.

three types of harmonic detection methods which play an important role in the control strategy of the shunt active filter.

- Load current detection: This method detects the load current i_L, which flows downstream of the point of installation, and then extracts harmonic current i_{Lh} from i_L.
- Supply current detection: This method detects the supply current i_S, which escapes upstream of the point of installation, and then extracts harmonic current i_{Sh} from i_S.
- Voltage detection: This method detects the bus voltage at the point of installation, v and then extracts harmonic voltage v_h from v.

A. Control Strategy

Taking into account the polarity of voltage and current in Fig.3, Kawahira, et al., presented the compensating current of i_{AF} in time domain as follows [4]:

Load current detection: $i_{AF} = i_{Lh}$

Supply current detection: $i_{AF} = K_S \cdot i_{Sh}$

Voltage detection: $i_{AF} = K_V \cdot v_h$.

Here, K_S has no dimension while K_V has the dimension of $(1/\Omega)$. The shunt active filter itself, in each method, acts as the current source of i_{AF}, as shown in Fig.3. As for the voltage detection method, it behaves as a pure resistor of $1/K_V(\Omega)$ in the relationship between the bus voltage and the compensating current at the point of installation. In a real shunt active filter, it is impossible to neglect the delay time caused by the calculation to extract the harmonic current or voltage from the detected current or voltage in time domain. Assuming that the effect of the delay time is represented by a first-order lag system, the compensating current of the shunt active filter in each detection method is given as follows:

Load current detection: $I_{AF}(s) = \frac{1}{1+sT} \cdot I_{Lh}(s)$

Supply current detection: $I_{AF}(s) = \frac{K_S}{1+sT} \cdot I_{Sh}(s)$

Voltage detection: $I_{AF}(s) = \frac{K_V}{1+sT} \cdot V_h(s)$.

The following relation exists in the shunt active filter

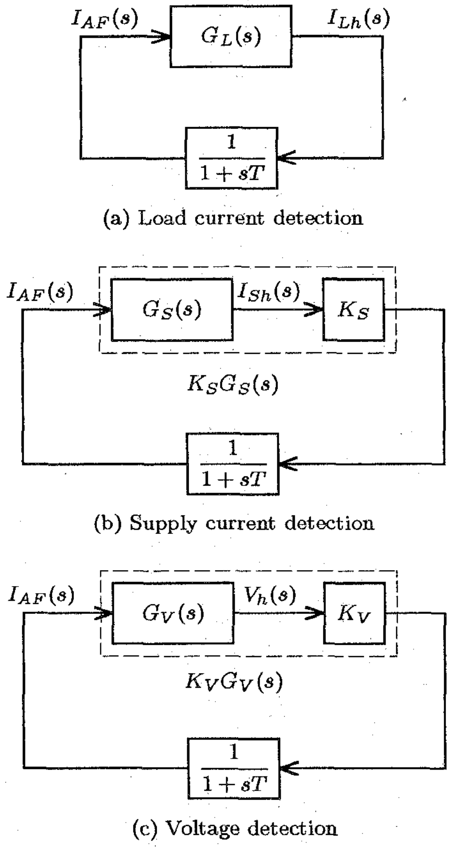


Fig. 4. Block diagram of control system.

based on the voltage detection:

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

Eq.1 means that it acts as an inductive load of an RL series circuit when the delay time is taken into account. The circuit constants are:

$$R_{AF} = 1/K_V\ (\Omega) \qquad L_{AF} = T/K_V\ (\text{H}). \tag{2}$$

B. Open-Loop Transfer Function and Stability

The stability analysis of the shunt active filter installed on bus 3 results in the positive feedback system shown in Fig.4. To describe the feedback system, attention is paid to the polarity of voltage and current in Fig.3 and all of the harmonic current sources are removed from Fig.3. The open-loop transfer function of the shunt active filter in each detection method is given as follows:

Load current detection: $G_L(s) = \frac{I_{Lh}(s)}{I_{AF}(s)}$

Supply current detection: $G_S(s) = \frac{I_{Sh}(s)}{I_{AF}(s)}$

Voltage detection: $G_V(s) = \frac{V_h(s)}{I_{AF}(s)}$.

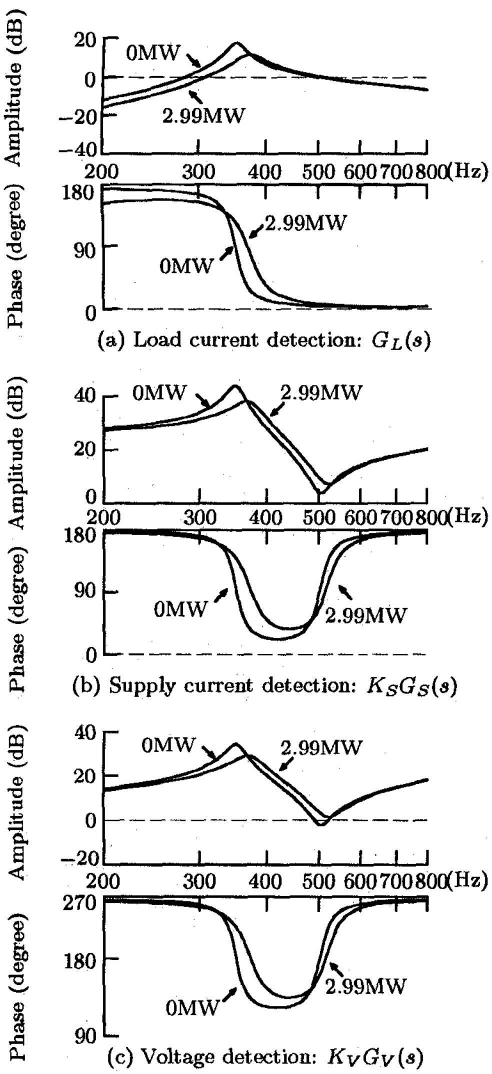


Fig. 5. Bode diagram of transfer function.

Fig.5 shows Bode diagrams of the transfer functions of $G_L(s)$, $K_S G_S(s)$, and $K_V G_V(s)$, where $K_S = 20$ and $K_V = 2$. Instability occurs because the phase is equal to 0° and the amplitude is over 0 dB. Note that the phase characteristic of $K_S G_S(s)$ in Fig.5 is independent of K_S and that of $K_V G_V(s)$ is also independent of K_V.

Fig.5(a) reveals that the load detection method has only the phase margin of 6° ~ 7°, thus resulting in instability in an actual system which is subjected to the delay time. In the supply current method shown in Fig.5(b), the phase margin is 37° at the rated load of 2.99MW but it decreases to 22° at no load, thus causing instability in the actual system. To verify the stability analysis based on Fig.5, computer simulation was performed by applying the "transient analysis", which is one of the functions in an analog circuit simulator (Micro-Cap IV). As a result, no instability occurs in either the load current detection method or the supply current method in the case of neglecting the delay time. The simulated results agree well with those of

TABLE I

RELATIONSHIPS IN EACH DETECTION METHOD BETWEEN POINT OF INSTALLATION AND PHASE MARGIN.

(a) Installation on bus 3

MW	load current	supply current	voltage
0	6°	22°	110°
2.99	7°	37°	125°

(b) Installation on bus 6

MW	load current	supply current	voltage
0	unstable	9°	93°
2.99	unstable	16°	96°

(c) Installation on bus 9

MW	load current	supply current	volatge
0	27°	48°	94°
2.99	stable	83°	98°

the theoretical. However, the computer simulation reveals that both methods become unstable when the delay time of $T = 0.16$ms (cutoff frequency=1kHz) is taken into account. Instability or sustained oscillation appears in a frequency range from 400Hz to 450Hz.

On the other hand, Fig.5(c) suggests that the shunt active filter based on the voltage detection is a stable system because the phase margin is over 90°. In fact, the computer simulation shows that the shunt active filter is quite stable even if it has the delay time of $T = 0.16$ms.

C. Relationship between Point of Installation and Phase Margin

Table 1 shows how the phase margin in each detection method is affected by the point of installation, for instance, on bus 3, bus 6 or bus 9. Here, bus 3 is at the beginning terminal of the primary line in feeder 2, bus 6 is at the midpoint, and bus 9 is at the end terminal. The shunt active filter installed on bus 6 has a negative phase margin in the load current detection. This means that it is unstable even if no delay time is taken into account. However, installation on bus 9 makes the shunt active filter based on the load current detection stable at the rated load of 2.99MW, because the amplitude characteristic of $G_L(s)$ is under 0dB against all frequencies. In general, a shunt active filter based on either the load current or supply current detection operates properly and stably, if neither shunt capacitor nor shunt passive filter is connected to a network downstream of the point at which the shunt active filter is installed. Thus, these two methods have already been applied to shunt active filters installed in the vicinity of one or more harmonic-producing loads.

The voltage detection method has a phase margin over 90° regardless of location. From the viewpoint of stability, it is the most suitable for shunt active filters which are intended to be dispersed throughout power distribution systems or industrial power systems.

TABLE II

7TH HARMONIC IMPEDANCES SEEN FROM EACH HARMONIC SOURCE.

connection of harmonic source	impedance (Ω)	
	upstream	downstream
to bus 3	$0.13 + j3.52$	$0.32 - j3.57$
to bus 4	$0.27 + j4.82$	$0.28 - j5.25$
to bus 5	$0.43 + j6.30$	$0.19 - j7.00$
to bus 6	$0.76 + j8.81$	$0.15 - j10.2$
to bus 7	$1.50 + j12.9$	$0.13 - j16.2$
to bus 8	$4.00 + j21.6$	$0.18 - j33.2$
to bus 9	$8.46 + j31.8$	$0.25 - j68.2$

IV. Effect on Damping of Harmonic Propagation

This chapter reveals the best site selection of a single shunt active filter based on the voltage detection with the delay time of $T = 0.16$ms, and the effect on damping of harmonic propagation.

A. Simulation Conditions

The following assumptions are made in the power distribution system shown in Fig.1.

- All of the capacitors for power factor improvement remain connected to feeder 2, but all of the loads remain disconnected, so that the most severe harmonic propagation occurs.
- Feeders 1, 3 and 4 are disconnected from bus 2.
- Although the 5th harmonic voltage and current are the most dominant harmonic components in power distribution systems, only the 7th harmonic voltage and current are taken into consideration in feeder 2, because harmonic propagation occurs around the 7th harmonic frequency, as shown in Fig.2.

Table 2 shows the 7th harmonic impedance upstream and downstream of each bus on the primary line.

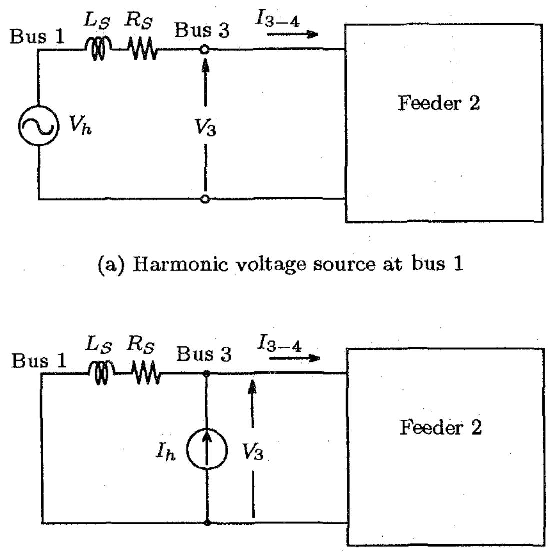
As for a background harmonic voltage in the power system, it is assumed that a 7th harmonic voltage source of 184V(=4.8%) exists on bus 1. This means that a 7th harmonic current source of 52.4A is connected to bus 3, as shown in Fig.6. The following relationship exists between V_h and I_h:

$$V_h = (R_S + j7\omega L_S) \cdot I_h. \quad (3)$$

A single 7th harmonic current source of 52.4A is connected to bus 6 to represent seventeen unidentified harmonic-producing loads on feeder 2 for the sake of simplicity. On the other hand, the shunt active filter may be installed on bus 3, bus 6, or bus 9. Computer simulation is performed to verify the effect of the shunt active filter on the damping of harmonic propagation. The 7th harmonic voltage source on bus 1 and the 7th harmonic current source on bus 6 are independent of each other, because the principle of superposition is applicable to Fig.1.

B. Damping of Harmonic Propagation Caused by the 7th Harmonic Voltage Source on Bus 1

Table 3 shows the 7th harmonic currents flowing in the primary line, compensating current injected by the shunt active filter I_{AF}, and the 7th harmonic voltages appearing on buses 3, 6 and 9. For example, I_{2-3} means the 7th harmonic current flowing between buses 2 and 3, and V_3 means the 7th harmonic voltage appearing on bus 3. Note that the 7th harmonic current source is disconnected from bus 6.



(a) Harmonic voltage source at bus 1

(b) Harmonic current source at bus 3

Fig. 6. Equivalent conversion between harmonic voltage source and harmonic cuurent source.

Serious propagation of harmonic voltage and current occurs when no shunt active filter is connected, that is, $K_V = 0$. The reason is clarified in the following: The 7th harmonic impedance *upstream* of bus 3 is an inductive RL series circuit of $0.13 + j3.52$, while the 7th harmonic impedance *downstream* of bus 3 is a capacitive RC series circuit of $0.32 - j3.57$. These form a series resonant circuit, in which the resonant frequency is near the 7th harmonic frequency. Thus, a large amount of 7th harmonic current is drawn from bus 1, so that the 7th harmonic voltage at bus 3 is amplified by eight times as large as that at bus 1.

When the shunt active filter with a gain of $K_V \geq 1$ is installed, it is capable of damping harmonic propagation throughout feeder 2, irrespective of the installation point. The 7th harmonic voltage at the point of installation becomes the lowest value, as shown in Table 3. Installation of the shunt active filter on bus 3 results in the best mitigation of harmonics, but in the largest amount of compensating current. Therefore, the best site selection is bus 9 from the economical down-to-earth point of view that the shunt active filter injects a minimum compensating current.

C. Damping of Harmonic Propagation Caused by the 7th Harmonic Current Source on Bus 6

Table 4 shows the effect of the shunt active filter when the 7th harmonic current source is on bus 6. Here, the 7th harmonic voltage source is removed from bus 1, that

TABLE III

EFFECT ON DAMPING OF HARMONIC PROPAGATION, WHERE 7TH HARMONIC VOLTAGE SOURCE OF 184V IS ON BUS 1.

(a) Installation of shunt active filter on bus 3

(A)	K_{V3}=0	K_{V3}=0.1	K_{V3}=0.2	K_{V3}=0.5	K_{V3}=1.0	K_{V3}=1.5	K_{V3}=2.0
I_{2-3}	407 (7.77)	100 (1.91)	69.5 (1.33)	50.2 (0.95)	49.0 (0.94)	49.6 (0.95)	50.0 (0.95)
I_{3-4}	386 (7.42)	107 (2.04)	62.0 (1.18)	27.4 (0.52)	14.2 (0.27)	9.6 (0.18)	7.2 (0.14)
I_{5-6}	293 (5.59)	81 (1.55)	47.1 (0.90)	20.8 (0.40)	10.8 (0.21)	7.3 (0.14)	5.5 (0.10)
I_{6-7}	217 (4.14)	60 (1.15)	34.9 (0.67)	15.4 (0.29)	8.0 (0.15)	5.4 (0.10)	4.1 (0.08)
I_{8-9}	90 (1.71)	25 (0.48)	14.5 (0.28)	6.4 (0.12)	3.3 (0.06)	2.2 (0.04)	1.7 (0.03)
I_{AF3}	–	38 (0.73)	44 (0.84)	48.7 (0.93)	50.5 (0.96)	51.1 (0.98)	51.4 (0.98)

(V)	$K_{V3}=0$	$K_{V3}=0.1$	$K_{V3}=0.2$	$K_{V3}=0.5$	$K_{V3}=1.0$	$K_{V3}=1.5$	$K_{V3}=2.0$
V_3	1455 (7.93)	404 (2.20)	234 (1.28)	103 (0.56)	54 (0.29)	36.1 (0.20)	27.2 (0.15)
V_6	2600 (14.2)	723 (3.94)	419 (2.28)	185 (1.01)	96 (0.52)	64.7 (0.35)	48.8 (0.27)
V_9	3090 (16.8)	860 (4.69)	498 (2.72)	220 (1.20)	114 (0.62)	76.9 (0.42)	58.0 (0.32)

(b) Installation of shunt active filter on bus 6

(A)	K_{V6}=0	K_{V6}=0.1	K_{V6}=0.2	K_{V6}=0.5	K_{V6}=1.0	K_{V6}=1.5	K_{V6}=2.0
I_{2-3}	407 (7.77)	42.0 (0.80)	27.5 (0.52)	23.9 (0.46)	24.3 (0.46)	24.7 (0.47)	24.9 (0.48)
I_{3-4}	386 (7.42)	40.4 (0.77)	27.8 (0.53)	25.1 (0.48)	25.7 (0.49)	26.1 (0.50)	26.3 (0.50)
I_{5-6}	293 (5.59)	33.6 (0.64)	27.1 (0.52)	27.0 (0.52)	27.7 (0.53)	28.1 (0.54)	28.3 (0.54)
I_{6-7}	217 (4.14)	23.0 (0.44)	12.1 (0.23)	5.0 (0.10)	2.5 (0.05)	1.7 (0.03)	1.3 (0.02)
I_{8-9}	90 (1.71)	9.6 (0.18)	5.0 (0.10)	2.1 (0.04)	1.1 (0.01)	0.7 (0.01)	0.5 (0.01)
I_{AF6}	–	26.1 (0.50)	27.4 (0.52)	28.3 (0.54)	28.7 (0.55)	28.8 (0.55)	28.8 (0.55)

(V)	$K_{V6}=0$	$K_{V6}=0.1$	$K_{V6}=0.2$	$K_{V6}=0.5$	$K_{V6}=1.0$	$K_{V6}=1.5$	$K_{V6}=2.0$
V_3	1455 (7.93)	210 (1.15)	148 (0.81)	113 (0.28)	103 (0.56)	99.7 (0.54)	98.4 (0.53)
V_6	2600 (14.2)	276 (1.50)	145 (0.79)	60 (0.33)	30 (0.17)	20.3 (0.11)	15.3 (0.08)
V_9	3090 (16.8)	328 (1.79)	173 (0.94)	71 (0.39)	36 (0.69)	24.1 (0.13)	18.1 (0.10)

(c) Installation of shunt active filter on bus 9

(A)	K_{V9}=0	K_{V9}=0.1	K_{V9}=0.2	K_{V9}=0.5	K_{V9}=1.0	K_{V9}=1.5	K_{V9}=2.0
I_{2-3}	407 (7.77)	30.5 (0.58)	17.8 (0.34)	13.0 (0.25)	12.8 (0.24)	12.9 (0.25)	13.0 (0.25)
I_{3-4}	386 (7.42)	29.1 (0.56)	18.1 (0.35)	14.6 (0.28)	14.7 (0.28)	14.9 (0.28)	14.9 (0.28)
I_{5-6}	293 (5.59)	24.3 (0.46)	19.1 (0.36)	18.8 (0.36)	19.3 (0.37)	19.5 (0.37)	19.6 (0.37)
I_{6-7}	217 (4.14)	22.0 (0.42)	20.4 (0.39)	21.1 (0.40)	21.7 (0.41)	21.9 (0.42)	22.0 (0.42)
I_{8-9}	90 (1.71)	21.3 (0.41)	22.5 (0.43)	23.5 (0.45)	23.9 (0.46)	24.0 (0.46)	24.1 (0.46)
I_{AF9}	–	22.5 (0.43)	23.9 (0.46)	23.9 (0.46)	24.1 (0.46)	24.2 (0.46)	24.2 (0.46)

(V)	$K_{V9}=0$	$K_{V9}=0.1$	$K_{V9}=0.2$	$K_{V9}=0.5$	$K_{V9}=1.0$	$K_{V9}=1.5$	$K_{V9}=2.0$
V_3	1455 (7.93)	209 (1.14)	170 (0.93)	149 (0.81)	143 (0.78)	141 (0.77)	140 (0.76)
V_6	2600 (14.2)	242 (1.32)	154 (0.84)	104 (0.57)	90 (0.49)	86 (0.47)	84 (0.46)
V_9	3090 (16.8)	239 (1.30)	124 (0.68)	51 (0.28)	26 (0.14)	17 (0.09)	13 (0.07)

Note that the value in ( ) is amplification factor, which is the ratio of each 7th harmonic current to 52.4A, or that of each 7th harmonic voltage to 184V.

is, no background harmonic voltage appears on the infinite bus. The 7th harmonic current source of 52.4A on bus 6 produces both the 7th harmonic current flowing *upstream* of bus 6, I_{5-6}, and the 7th harmonic current flowing *downstream* of bus 6, I_{6-7}.

When no shunt active filter is connected to feeder 2, I_{5-6} and I_{6-7} are severely propagated because the 7th harmonic impedance *upstream* of bus 6 is an inductive RL series circuit of $0.76 + j8.81$, while the 7th harmonic impedance *downstream* of bus 6 is a capacitive RC circuit of $0.15 - j10.2$. These form a parallel resonant circuit, in which the resonant frequency is near the 7th harmonic frequency. The 7th harmonic current flowing *upstream* of bus 6 continues to increase gradually as it approaches the beginning terminal of feeder 2 or bus 3, because eleven shunt capacitors installed by the individual medium-voltage consumers remain connected to feeder 2. As a result, the 7th harmonic current escaping *upstream* of bus 3, I_{2-3}, reaches 737A: This is about fourteen times as large as the 7th harmonic current source of 52.4A on bus 6. The 7th harmonic current flowing *downstream* of bus 6 continues to decrease gradually as it approaches the end terminal of feeder 2 or bus 9, whereas the 7th harmonic voltage becomes the highest value at bus 9 due to the so-called "Feranti effect."

The shunt active filter installed on bus 3 can mitigate the 7th harmonic current escaping *upstream* of bus 3, I_{2-3},

TABLE IV

EFFECT ON DAMPING OF HARMONIC PROPAGATION, WHERE 7TH HARMONIC CURRENT SOURCE OF 52.4V IS ON BUS 6.

(a) Installation of shunt active filter on bus 3

(A)	K_{V3}=0	K_{V3}=0.1	K_{V3}=0.2	K_{V3}=0.5	K_{V3}=1.0	K_{V3}=1.5	K_{V3}=2.0
I_{2-3}	737 (14.1)	205 (3.91)	119 (2.27)	52 (1.00)	27 (0.52)	18.3 (0.35)	13.8 (0.26)
I_{3-4}	699 (13.3)	228 (4.35)	159 (3.03)	115 (2.19)	103 (1.97)	99.2 (1.89)	97.7 (1.86)
I_{5-6}	531 (10.1)	181 (3.45)	131 (2.50)	101 (1.93)	92 (1.76)	90.0 (1.72)	88.9 (1.70)
I_{6-7}	392 (7.48)	118 (2.25)	74 (1.42)	43 (0.82)	33 (0.63)	30.0 (0.57)	28.7 (0.55)
I_{8-9}	163 (3.11)	49 (0.94)	31 (0.59)	18 (0.34)	14 (0.27)	12.5 (0.25)	11.9 (0.23)
I_{AF3}	–	68 (1.30)	79 (1.51)	87 (1.67)	90 (1.73)	91.6 (1.75)	92.1 (1.76)

(V)	$K_{V3}=0$	$K_{V3}=0.1$	$K_{V3}=0.2$	$K_{V3}=0.5$	$K_{V3}=1.0$	$K_{V3}=1.5$	$K_{V3}=2.0$
V_3	2600 (14.2)	723 (3.94)	419 (2.28)	185 (1.01)	96 (0.52)	65 (0.35)	49 (0.27)
V_6	4710 (25.7)	1411 (7.69)	892 (4.86)	518 (2.82)	397 (2.16)	361 (1.97)	344 (1.88)
V_9	5600 (30.5)	1678 (9.15)	1060 (5.78)	816 (4.45)	471 (2.57)	429 (2.34)	409 (2.23)

(b) Installation of shunt active filter on bus 6

(A)	K_{V6}=0	K_{V6}=0.1	K_{V6}=0.2	K_{V6}=0.5	K_{V6}=1.0	K_{V6}=1.5	K_{V6}=2.0
I_{2-3}	737 (14.1)	78.3 (1.49)	41.2 (0.79)	17.0 (0.32)	8.6 (0.16)	5.8 (0.11)	4.3 (0.08)
I_{3-4}	699 (13.3)	74.2 (1.42)	39.1 (0.75)	16.1 (0.31)	8.2 (0.16)	5.5 (0.10)	4.1 (0.08)
I_{5-6}	531 (10.1)	56.3 (1.07)	29.6 (0.56)	12.2 (0.23)	6.2 (0.12)	4.1 (0.08)	3.1 (0.06)
I_{6-7}	392 (7.48)	41.6 (0.79)	21.9 (0.42)	9.0 (0.17)	4.6 (0.09)	3.1 (0.06)	2.3 (0.04)
I_{8-9}	163 (3.11)	17.3 (0.33)	9.1 (0.17)	3.8 (0.07)	1.9 (0.04)	1.3 (0.02)	1.0 (0.02)
I_{AF6}	–	47.1 (0.90)	49.6 (0.95)	51.2 (0.98)	51.8 (0.99)	52.0 (0.99)	52.1 (0.99)

(V)	$K_{V6}=0$	$K_{V6}=0.1$	$K_{V6}=0.2$	$K_{V6}=0.5$	$K_{V6}=1.0$	$K_{V6}=1.5$	$K_{V6}=2.0$
V_3	2600 (30.5)	276 (1.50)	145 (0.79)	60 (0.33)	30.4 (0.17)	20.3 (0.11)	15.3 (0.08)
V_6	4710 (25.7)	499 (2.72)	263 (1.43)	109 (0.59)	54.9 (0.30)	36.7 (0.20)	27.6 (0.15)
V_9	5600 (14.2)	593 (3.23)	312 (1.70)	129 (0.70)	65.2 (0.36)	43.7 (0.24)	32.8 (0.18)

(c) Installation of shunt active filter on bus 9

(A)	K_{V9}=0	K_{V9}=0.1	K_{V9}=0.2	K_{V9}=0.5	K_{V9}=1.0	K_{V9}=1.5	K_{V9}=2.0
I_{2-3}	737 (14.1)	68.7 (1.31)	43.6 (0.83)	29.5 (0.56)	25.5 (0.49)	24.4 (0.47)	23.8 (0.45)
I_{3-4}	699 (13.3)	65.2 (1.24)	41.4 (0.79)	27.9 (0.53)	24.2 (0.46)	23.1 (0.44)	22.6 (0.43)
I_{5-6}	531 (10.1)	49.4 (0.94)	31.4 (0.60)	21.2 (0.40)	18.4 (0.35)	17.5 (0.33)	17.1 (0.33)
I_{6-7}	392 (7.48)	39.8 (0.76)	36.9 (0.70)	38.2 (0.73)	39.2 (0.75)	39.5 (0.75)	39.7 (0.75)
I_{8-9}	163 (3.11)	38.5 (0.73)	40.6 (0.77)	42.5 (0.81)	43.2 (0.82)	43.5 (0.83)	43.6 (0.83)
I_{AF9}	–	40.8 (0.78)	42.3 (0.81)	43.3 (0.83)	43.6 (0.83)	43.7 (0.83)	43.8 (0.84)

(V)	$K_{V9}=0$	$K_{V9}=0.1$	$K_{V9}=0.2$	$K_{V9}=0.5$	$K_{V9}=1.0$	$K_{V9}=1.5$	$K_{V9}=2.0$
V_3	2600 (14.2)	242 (1.32)	154 (0.84)	104 (0.57)	90 (0.49)	86 (0.47)	84 (0.46)
V_6	4710 (25.7)	438 (2.39)	278 (1.52)	188 (1.03)	163 (0.89)	155 (0.85)	152 (0.83)
V_9	5600 (30.5)	432 (2.36)	224 (1.22)	92 (0.50)	46 (0.25)	31 (0.17)	23 (0.13)

Note that the value in ( ) is amplification factor, which is the ratio of each 7th harmonic current to 52.4A, or that of each 7th harmonic volatge to 184V.

whereas the 7th harmonic currents flowing between bus 3 and bus 6, that is, I_{3-4} and I_{5-6} in Table 4(c) are larger than 52.4A. This means that the shunt active filter has no capability of damping harmonic propagation throughout feeder 2. The required rating of the shunt active filter with a gain of $K_{V3} = 2$ is 1.76 times as large as the rating of the harmonic current source at bus 6.

The shunt active filter installed on bus 6 can absorb the 7th harmonic current effectively because it is installed in the vicinity of the harmonic-producing load. The 7th harmonic currents flowing *upstream and downstream* of bus 6, I_{5-6} and I_{6-7} are reduced to only $6 \sim 4\%$ if $K_{V6} = 2$. The 7th harmonic voltage at bus 6 is 28V ($\approx I_h/K_{V3} = 52.4/2$). Table 4(b) shows that the shunt active filter can greatly mitigate both the 7th harmonic voltages and currents throughout feeder 2. The required rating of the shunt active filter is equal to the rating of the harmonic current source.

Table 4(c) reveals that the shunt active filter installed on bus 9 can damp the propagation of harmonic current if $K_{V9} \geq 0.2$, and it can also damp the propagation of both harmonic current and voltage throughout feeder 2 if $K_{V9} \geq 0.5$. The 7th harmonic currents flowing *upstream and downstream* of bus 6 continue to increase as they approach the beginning and end terminals of feeder 2. However, both the ratio of I_{2-3} and that of I_{8-9} to 52.4A are

TABLE V

RELATIONSHIPS BETWEEN POINT OF INSTALLATION OF SHUNT ACTIVE FILTER WITH $K_V = 2$ AND 7TH HARMONIC IMPEDANCES SEEN FROM BUS 6.

point of installation	impedance (Ω)	
	upstream	downstream
no installation	$0.76 + j8.81$	$0.15 - j10.2$
on bus 3	$0.94 + j3.75$	$0.15 - j10.2$
on bus 6	$0.76 + j8.81$	$0.15 - j10.2$
on bus 9	$0.76 + j8.81$	$1.12 + j3.88$

less than unity. The 7th harmonic voltage is the highest at bus 6, while it is the lowest at bus 9. The required rating of the shunt active filter is the smallest among the three, i.e., about 80% of the rating of the harmonic current source.

V. Best Site Selection and Optimal Gain of K_V

A. Best Site Selection

It is well-known that the installation of a shunt active filter in the vicinity of an identified harmonic-producing load is the best way of harmonic mitigation or compensation. However, it may be impossible for an electric power company to identify all of harmonic-producing loads on power distribution systems. Even if it is possible, it would be economically impractical to install a shunt active filter in the vicinity of each harmonic-producing load.

Installation of the shunt active filter on bus 9, or the end terminal of the primary line is the most effective and practical way to damp harmonic propagation throughout feeder 2. Table 5 shows the effect of the shunt active filter with a gain of $K_V = 2$ on system impedances *upstream and downstream* of bus 6. Fig.7 shows the principles of generation and damping of harmonic propagation, paying attention to the system impedances. Installation of the shunt active filter on bus 9 makes both the system impedances *upstream and downstream* of bus 6 inductive, so that the following relationship exists:

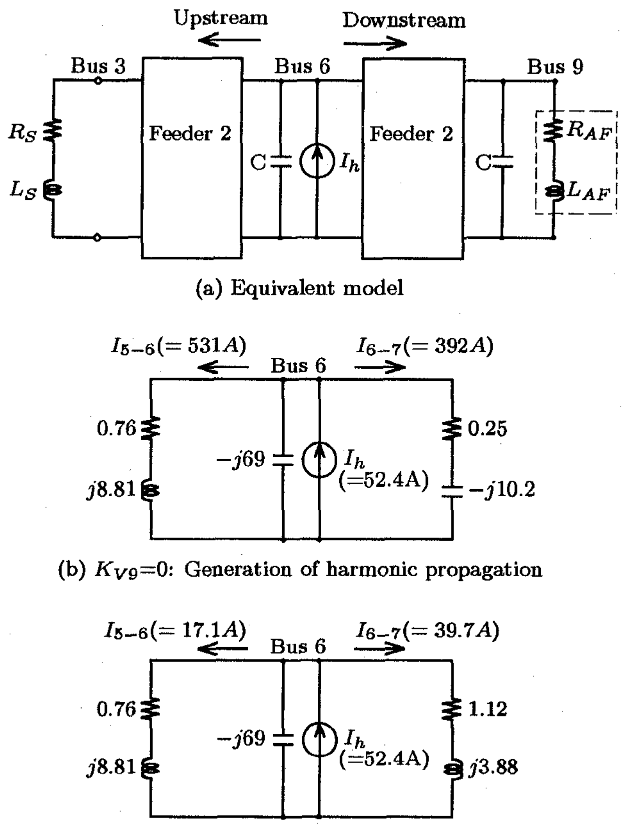
$$I_{5-6} + I_{6-7} = 56.8 \approx 52.4A. \quad (4)$$

Eq.4 indicates that no harmonic propagation occurs at bus 6. However, installation of the shunt active filter on bus 3 has no effect on the system impedance *downstream* of bus 6. In other words, the system impedance *downstream* of bus 6 remains capacitive. This results in amplification of the 7th harmonic currents flowing between bus 3 and bus 6, as shown in I_{3-4} and I_{5-6} in Table 4(a).

Installation of the shunt active filter on bus 9 is also effective in damping the harmonic propagation caused by a background voltage on bus 1, because the installation makes the system impedance *downstream* of bus 3 inductive. In addition, the required rating of the shunt active filter installed on bus 9 is the smallest among the three, as shown in Table 3.

B. Optimal gain of K_{V9}

Since the load capacity of feeder 2 is 6.6kV, 2.99W, the resistance at the rated load is 14.6Ω. Installation of the



(a) Equivalent model

(b) K_{V9}=0: Generation of harmonic propagation

(c) K_{V9}=2: Damping of harmonic propagation

Fig. 7. Damping of harmonic propagation by installing shunt active filter on bus 9, where 7th harmonic current source be on bus 6.

shunt active filter on bus 9 is equivalent to connection of the RL series circuit with respect to the 7th harmonic frequency, the circuit constants of which are given by (2). The equivalent resistance of the shunt active filter, R_{AF} is $2 \sim 0.5$ (Ω), when K_{V9} is set between 0.5 and 2 (1/Ω). Therefore, the shunt active filter acts as a damping resistor, the resistance of which is much smaller than 14.6Ω. The above discussion, along with Tables 3 and 4, leads to the conclusion that an optimal gain of the shunt active filter installed on bus 9, K_{V9} is between 0.5 and 2(1/Ω) in order to carry out the damping of harmonic propagation throughout feeder 2.

VI. Conclusions

This paper has discussed the control strategy and site selection of a shunt active filter which is intended to be installed on a feeder in a power distribution system. The effectiveness and validity of the basic concept proposed in this paper have been verified by theory and computer simulation. The basic concept is summarized as follows:

- Voltage detection in time domain is the most suitable in stability for the shunt active filter installed in power distribution systems.

- The shunt active filter based on the voltage detection, which is installed in the vicinity of a harmonic-producing load, is effective in the mitigation of harmonic voltage at the point of installation.
- The shunt active filter based on the voltage detection, which aims at damping harmonic propagation throughout a feeder, should be installed at the end terminal of the primary line in the feeder. In other words, the best point of installation is bus 9 in Fig.1.

The author believes that the basic concept makes a great contribution to the damping of harmonic propagation and to the improvement of power quality throughout power distribution systems.

References

[1] H. Sasaki, and T. Machida, "A new method to eliminate ac harmonic currents by magnetic compensation–Consideration on basic design," *IEEE Trans. Power Appl. Syst.*, vol. 90, no. 5, pp. 2009-2019, 1971

[2] L. Gyugyi, and E. C. Strycula, "Active ac power filters," in *Proceedings of the 1976 IEEE/IAS Annual Meeting*, pp. 529-535, 1976

[3] J. Uceda, F. Aldana, and P. Martinez, "Active filters for static power converters," *IEE Proceedings*, vol. 130, pt. B, no. 5, pp. 347-354, 1983

[4] H. Kawahira, T. Nakamura, S. Nakazawa and M. Nomura, "Active power filters," in *Proceedings of the 1983 International Power Electronics Conference*, Tokyo, Japan, pp. 981-992, 1983

[5] H. Akagi, A. Nabae, and S. Atoh, "Control strategy of active power filters using multiple voltage-source PWM converters," *IEEE Trans. Ind. Appl.*, vol. 22, no. 3, pp. 460-465, 1986

[6] M. Takeda, K. Ikeda, and Y. Tominaga, "Harmonic current compensation with active filter", in *Proceedings of the 1987 IEEE/IAS Annual Meeting*, pp. 808-815, 1987

[7] Y. Tanoue, F. Aoyama, and K. Terashima, "5MVA flicker suppression equipment based on voltage-source PWM inverters using GTO thyristors," *Toshiba Rev.*, vol. 43, no. 4, pp. 339-342, 1988

[8] W. M. Grady, M. J. Samotyj, and A. H. Noyola, "Survey of active power line conditioning methodologies," *IEEE Trans. Power Deliv.*, vol. 5, no. 3, pp. 1536-1542, 1990

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

[10] H. Akagi, "Trends in active power line conditioners," *IEEE Trans. Power Electronics*, vol. 9, no. 3, pp. 263-268, 1994

[11] M. Takeda, S. Murakami, et al., "Development of an SVG series for voltage control over three-phase unbalance caused by railway load," in *Proceedings of the 1995 International Power Electronics Conference*, Yokohama, Japan, pp. 603-698, 1995

[12] A. Iizuka, M. Kishida, et al., "Self-Commutated Static Var Generators at Shintakatuki Substation," in *Proceedings of the 1995 International Power Electronics Conference*, Yokohama, Japan, pp. 609-614, 1995

[13] W. M. Grady, M. J. Samotyj, and A. H. Noyola, "The application of network objective functions for actively minimizing the impact of voltage harmonics in power systems," *IEEE Trans. Power Deliv.*, vol. 7, no. 3, pp. 1379-1386, 1992

Hirofumi Akagi (M'87, SM'94) was born in Okayama-city, Japan, on August 19, 1951. He received the B.S. degree from Nagoya Institute of Technology in 1974 and the M.S. and Ph.D. degrees from Tokyo Institute of Technology in 1976 and 1979, respectively, all in electrical engineering. In 1979, he joined Nagaoka University of Technology as assistant and then associate professor in the department of electrical engineering. In 1987, he was visiting scientist at the Massachusetts Institute of Technology for ten months.

Since 1991, he has been professor in the department of electrical engineering at Okayama University. His research interests are utility applications of power electronics such as active filters and FACTS equipment, ac motor drives, and high frequency inverters and their applications. He has received five IEEE/IAS Society and Committee Prize Paper Awards including the First Prize Paper Award in the IEEE Transactions on Industry Applications for 1991.

Discussion

Z. Yao, V. Rajagopalan (CPEE, Département de génie électrique, Université du Québec à Trois-Rivières, Trois-Rivières, Qc., G9A 5H7/Canada), and **S. Lahaie** (LTEE–Hydro Québec, Shawinigan, Qc., G9N 7N5, Canada):

In this paper, the author proposes an interesting concept : damping of harmonic propagation in power systems.

However, the basic models which the author uses for theoretical analysis and simulations are too simplified in comparison with real systems. First of all, the impedances viewed from nonlinear loads cannot be calculated simply by their short-circuit level [1-2]. Secondly, the model of a shunt active filter [3-4] would be more sophisticated than that used in this paper.

Since the damping of harmonic propagation and best site selection depend principally on these two models (harmonic impedances and shunt active filter), we would like to know if the conclusions of this paper are always valid in the case where a more realistic system model is used, e.g., in the case when the filter must be installed at the end of the distribution system (see the third point of the section VI. CONCLUSIONS). Further, if several shunt active filters are installed in the other feeders for the same purpose, we wonder how to examine damping of harmonic and select best site of installation. In other words, is the proposed method always valid in this case ?

[1] E. W. Kimbark, Direct Current Transmission, Wiley Interscience, 1971.
[2] J. Arrillaga, D. A. Bradley and P. S. Bodger, Power System Harmonics, John Wiley & Sons, 1985.
[3] H. Akagi, A. Nabae and S. Atoh, "Control Strategy of Active Power Filters Using Voltage-Source PWM Converters", IEEE Trans. on Industry Applications, Vol. 22, No. 3, 1986, pp. 460-465.
[4] Z. Yao, S. Lahaie and V. Rajagopalan, "Robust Compensator of Harmonics and Reactive Power", IEEE Power Electronics Specialist Conference PESC'95, June 18-22, 1995, Atlanta, USA, pp. 215-221.

Manuscript received February 8, 1996.

H. Akagi:

First of all, I deeply thank the discussers for taking a great interest in the paper. I am also glad to have the opportunity of responding to the siginficant discussions.

I quite agree with the discussers about the distribution system model used for analysis and simulation, and about the impedances viewed from nonlinear loads. As for a shunt active filter, an ideal model is used except for considering a controller delay time of $T = 0.16$ms which produces little effect on operation. Thus, the model for the shunt active filters in [3] [4] cited by the discussers would not be more sophisticated than that used in this paper. The simplified models for the distribution system and the shunt active filter are effective in clarifying the physical meaning of harmonic propagation and harmonic damping, as shown in Fig.7. Generally speaking, a detailed model for real distibution systems is too complicated as the first step for such a basic research as performed in this paper. But, the closure author is not satisfied by using the simplified models but is due to expand the basic concepts of the control strategy and the best site selection proposed in this paper to a more realistic system model.

I would like to say that such a significant conclusion that a single shunt active filter based on the voltage detection should be installed at the end terminal of the primary line in a feeder, is only valid in a shunt active filter intended for damping of harmonic propagation throughout the feeder. As is well-known, installation of a shunt active filter in the vicinity of an identified harmonic-producing load is the best way of harmonic compensation, as shown in [3] [4] listed in the discussion. However, it may be impossible for utilities to identifiy all harmonic-producing loads on power distribution systems. Even if it is possible, it would be economically impractical to install a shunt active filter based on either load detection or supply detection in the vicinity of each harmonic-producing load.

In the near futur, utilities will dispersively install multiple shunt active filters on multiple feeders in a power distribution system which is subjected to harmonic pollution caused by harmonic propagation and a number of unidentifed harmonic-producing loads. I think that the proposed concepts are valid even in this case as long as utilities install the shunt active filters, not for harmonic compensation, but for harmonic damping. However, no one verifies the validity of the concepts from either theoretical or practical point of view. I hope that many researchers and engineers involved in power electronics and power engineering take an intereset in utility level issues concerning harmonics in power systems.

Finally, the closure author would like to thank the discussers again.

Manuscript received April 8, 1996.