A shunt active filter based on voltage detection for harmonic termination of a radial power distribution line

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A Shunt Active Filter Based on Voltage Detection for Harmonic Termination of a Radial Power Distribution Line

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***Abstract*—This paper is focused on a shunt active filter based on detection of harmonic voltages at the point of installation. The objective of the active filter is to attenuate harmonic propagation resulting from series/parallel resonance between capacitors for power factor correction and line inductors in a power distribution line. The active filter acts as a low resistor to the external circuit for harmonic frequencies, and it is installed on the end bus of the power distribution line, just like a 50-Ω terminator installed on the end terminal of a signal transmission line. Therefore, the function of the active filter is referred to as "harmonic termination" in this paper. Experimental results obtained from a laboratory system rated at 200 V and 20 kW verify that the active filter for the purpose of harmonic termination has the capability of harmonic damping throughout the power distribution line.**

***Index Terms*—Harmonic termination, power distribution systems, pulsewidth modulation inverters, shunt active filters, voltage detection.**

I. Introduction

NONLINEAR loads such as high-power diode/thyristor rectifiers, cycloconverters, and arc furnaces draw nonsinusoidal currents from utility grids. A single low-power diode rectifier used as a utility interface in an electric appliance produces a negligible amount of harmonic current. However, multiple low-power diode rectifiers can inject a large amount of current harmonics into power distribution systems. These harmonic-producing loads contribute to the degradation of power quality in transmission/distribution systems.

Oku, *et al.*, have reported the serious status of harmonic pollution in Japan [1], [2]. The maximum value of fifth harmonic voltage in the downtown area of a 6.6-kV power distribution system exceeds 7% under light-load conditions at night. The fifth 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. These observations, which are based on the actual measurements, suggest that the increase of fifth harmonic voltage on the 6.6-kV bus at night is due to "harmonic propagation" resulting from harmonic resonance between line inductors and shunt capacitors installed on the distribution system for power factor correction. This implies that harmonic damping would be as effective in solving harmonic pollution as harmonic compensation [3]. Hence, electric power utilities have the responsibility for harmonic damping throughout power distribution systems, while individual customers and end users are responsible for harmonic compensation of their own nonlinear loads.

Since their basic compensation principles were proposed around 1970, much research has been performed on active filters and their practical applications. In addition, the state-of-the-art power electronics technology has enabled us to put active filters into practical use. Active filters for solving harmonic pollution in power systems can provide the following functions:

- harmonic compensation [4]–[7];
- harmonic damping [7]–[11];
- harmonic isolation [8]–[10], [12], [13].

The purpose of a shunt active filter proposed and developed in this paper is to achieve harmonic damping throughout a radial power distribution line subjected to harmonic propagation. The active filter based on voltage detection is intended to be installed by electric power utilities on the distribution line. This paper pays much attention to experimental results which support and follow theoretical analysis and computer-simulated results presented in [3] and [14]. Harmonic mitigation of voltage and current is a welcome "byproduct," which stems from harmonic damping throughout the distribution line. The active filter is controlled in such a way as to present infinite impedance to the external circuit for the fundamental frequency, and as to exhibit low resistance for harmonic frequencies. When the active filter is installed on the end bus of the radial power distribution line, it successfully performs harmonic damping throughout the distribution line. This implies that the active filter acts as a "harmonic terminator," just like a 50-Ω terminator installed on the end terminal of a signal transmission line.

A laboratory system is designed and constructed, consisting of a shunt active filter based on voltage detection, seventh harmonic voltage and current sources, and a three-phase power distribution line simulator rated at 200 V, 60 Hz, and 20 kW. Experimental results obtained from the laboratory system verify the practical viability and effectiveness of the active filter having the function of "harmonic termination."

Paper IPCSD 99–03, presented at the 1998 Industry Applications Society Annual Meeting, St. Louis, MO, October 12–16, and approved for publication in the IEEE Transactions on Industry Applications by the Industrial Power Converter Committee of the IEEE Industry Applications Society. Manuscript released for publication January 13, 1999.

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Publisher Item Identifier S 0093-9994(99)03839-6.

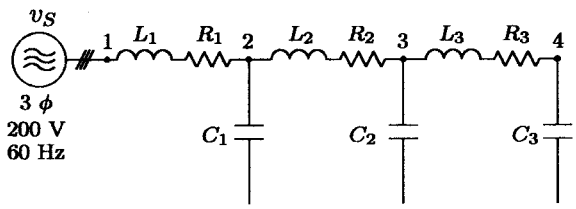

Fig. 1. Three-phase power distribution line simulator rated at 200 V, 60 Hz, and 20 kW.

TABLE I
CIRCUIT CONSTANTS ON A PER-PHASE BASE.

$L_1 = L_2 = L_3$	0.18 mH	3.4%
R_1	0.02 Ω	1.0%
$R_2 = R_3$	0.05 Ω	2.5%
$C_1 = C_2 = C_3$	150 μF	11.3%

note: 3ϕ 200-V, 60-Hz, 20-kVA base

II. SYSTEM CONFIGURATION

A. Power Distribution Line Simulator

Fig. 1 shows a three-phase power distribution line simulator used for the following laboratory experiments. Table I summarizes circuit constants of the line simulator on a per-phase base. The line simulator rated at 200 V, 60 Hz, and 20 kW is characterized by simplifying a real radial overhead distribution line rated at 6.6 kV and 3 MW in Japan [3], [14]. Hence, the line simulator is adequate to justify the effectiveness of the active filter for the purpose of harmonic termination.

The real overhead line between a bus and the adjacent bus can be represented by a lumped LR circuit, the parameters of which depend on the length and thickness of the line, because it is reasonable to neglect the effect of the stray capacitors of the line for the fifth and seventh harmonic voltage and current. In Fig. 1, L_1 corresponds to a leakage inductance of a primary distribution transformer, and L_2 and L_3 to line inductances. Eleven capacitors for power factor correction [3], [14], which are dispersed by high-power consumers on the real overhead line, are represented by three capacitors, C_1, C_2, and C_3 in the line simulator. The total capacity of the capacitors is 450 μF (7 kVA).

Harmonic propagation results from series and/or parallel resonance between the inductive reactances and the capacitive reactances. The most serious harmonic propagation in Fig. 1 occurs around the seventh harmonic frequency (420 Hz) under no-load conditions.

B. Implementation of the Active Filter

Fig. 2 shows a power circuit of the active filter used for experiment. The active filter is installed on a bus in the 200-V 20-kW line simulator via a three-phase transformer with turns ratio of 2:1. An electrolytic capacitor of 3300 μF is connected to the dc side, and the dc voltage is 260 V, while three inductors of $L_f = 1.0$ mH (1.8% on a 3ϕ 100-V 60-Hz 500-VA base) are connected to the ac side.

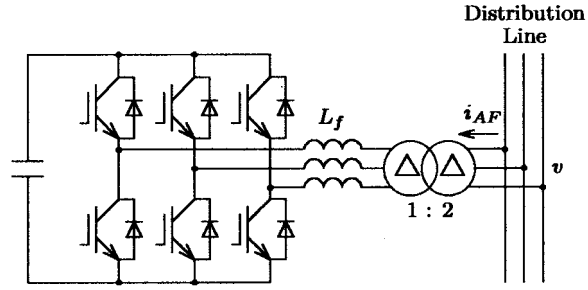

Fig. 2. Power circuit of the active filter.

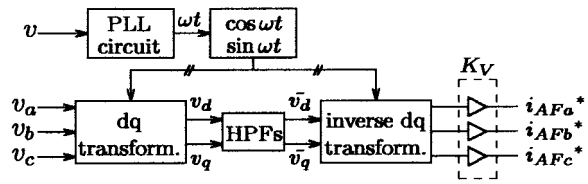

Fig. 3. Control circuit of the active filter.

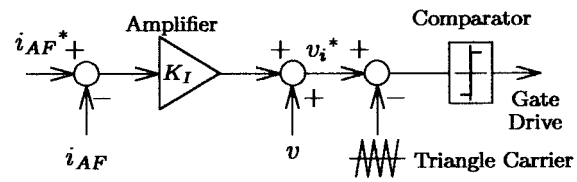

Fig. 4. Current control circuit per phase.

Fig. 3 shows a control circuit of the active filter. Three-phase voltages, which are detected at the point of installation, are transformed to v_d and v_q on the dq coordinates. Two first-order high-pass filters (HPF's) with the same cutoff frequency of 5 Hz as each other extract ac components $\tilde{v}_d$ and $\tilde{v}_q$ from v_d and v_q. The ac components are applied to the inverse dq transformation circuit, so that the control circuit yields three-phase harmonic voltages at the point of installation. Amplifying each harmonic voltage by a gain of K_V produces each current reference as follows:

$$i_{\mathrm{AF}}^* = K_V \cdot v_h. \tag{1}$$

The above equation implies that the active filter behaves like a resistor of $1/K_V$ Ω to the external circuit for harmonic frequencies, whereas the active filter makes no contribution to the external circuit for the fundamental frequency [3]. The gain K_V is set to 1 S, as discussed in the following section. Three-phase actual currents $i_{\mathrm{AF}a}$, $i_{\mathrm{AF}b}$, and $i_{\mathrm{AF}c}$ are controlled in such a way as to follow their current references.

Fig. 4 shows a current control circuit of the active filter. This circuit compares the reference current with its actual current and then amplifies the error signal between the two currents by a gain of K_I. Each phase voltage detected at the point of installation, v is added to each magnified error signal, thus constituting a feedforward compensation to improve current controllability. As a result, the current controller yields three-phase voltage references. Then, each reference voltage v_i^* is compared with a 10-kHz repetitive triangular waveform to generate the gate signals for the insulated gate bipolar

TABLE II
INSTALLATION SITE OF THE ACTIVE FILTER WITH $K_V = 1.0$, SEVENTH HARMONIC ADMITTANCES SEEN UPSTREAM AND DOWNSTREAM OF BUS 3, AND SEVENTH HARMONIC ADMITTANCE OF THE BRANCH LINE FROM BUS 3.

Installation site of active filter	7th-harmonic admittance [S]		
	upstream	downstream	branch
no installation	$0.07 - j0.94$	$0.01 + j0.49$	$j0.39$
bus 2	$0.35 - j0.99$	$0.01 + j0.49$	$j0.39$
bus 3	$0.07 - j0.94$	$0.01 + j0.49$	$1.0 + j0.39$
bus 4	$0.07 - j0.94$	$1.1 - j0.16$	$j0.39$

transistors (IGBT's). Here, a loop gain in the current feedback controller is set to 150 V/A.

III. SITE SELECTION OF THE ACTIVE FILTER

In this section, the installation site of the active filter with $K_V = 1.0$ is discussed when a seventh harmonic current source exists on bus 3 in the power distribution line shown in Fig. 1. Table II summarizes how the installation site of the active filter influences the seventh harmonic admittances seen from bus 3. The first column in the admittance table shows the seventh harmonic admittance seen "upstream" of bus 3, and the second column gives the seventh harmonic admittance seen "downstream" of bus 3. The last column shows the seventh harmonic admittance of the "branch" line from bus 3. Therefore, the first, second, and last terms from the top in the last column are equal to $j0.39$ S, which means the seventh harmonic susceptance of the 150-μF capacitor, because the capacitor is connected on bus 3, and no active filter is installed on bus 3. However, the third term is equal to $1.0 + j0.39$ S, which is given by the sum of the equivalent conductance of the active filter and the seventh harmonic susceptance of the 150-μF capacitor, because the active filter and the capacitor are connected in parallel on bus 3.

When no active filter is installed, the total seventh harmonic admittance seen from bus 3 is given by the sum of the three admittance values, $0.07 - j0.94$, $0.01 + j0.49$, and $j0.39$, and so it is nearly equal to zero. This implies that the distribution system seen from bus 3 forms a parallel resonant circuit with an impedance value as high as $8.0 + j6.0\ \Omega$ at the resonant frequency which is close to the seventh harmonic frequency, so that a seventh harmonic current injected by the harmonic-producing load existing on bus 3 is significantly magnified inside the distribution system.

Installation of the active filter on bus 2 changes the seventh harmonic admittance upstream of bus 3 from $0.07 - j0.94$ to $0.35 - j0.99$, as shown in Table II. However, the seventh harmonic impedance upstream of bus 3 is still "inductive," while that downstream of bus 3 remains "capacitive," and, therefore, the distribution system seen from bus 3, including the branch line, still forms a parallel resonant circuit with an impedance value as high as $2.5 + j0.77\ \Omega$ at the resonant frequency. Hence, the active filter has no capability of fully damping the harmonic propagation throughout the distribution system. However, installation of the active filter on bus 2 contributes to a slight mitigation of the harmonic propagation, compared with no installation, because the resonant frequency is mistuned from the seventh harmonic frequency.

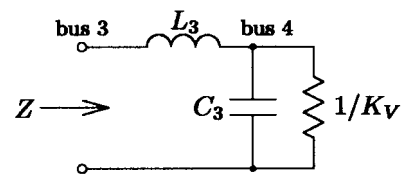

Fig. 5. Equivalent circuit for the distribution line with respect to harmonics when it is seen downstream of bus 3, where the active filter installed on bus 4 is represented by a resistor with resistance of $1/K_V\ \Omega$.

When the active filter is installed on bus 3, it can absorb the seventh harmonic current injected by the harmonic-producing load existing on bus 3. The reason is that the conductance of the active filter installed on bus 3 is larger than the admittances seen upstream and downstream of bus 3. Installation on bus 3 implies that the active filter is installed in the vicinity of the harmonic-producing load. Thus, the purpose of such an active filter is not harmonic damping throughout a radial power distribution line, but harmonic compensation of a harmonic-producing load.

As shown in Table II, installation on bus 4 makes the impedance downstream of bus 3 inductive, so that no parallel resonance occurs throughout the distribution line. As a result, the best site selection of installation is not the beginning terminal, but the end terminal of the distribution line [14]. This is the reason that the function of the active filter is referred to as "harmonic termination" in this paper.

IV. DESIGN OF GAIN K_V

This section discusses how to determine an optimal gain of K_V when the active filter is installed at the end terminal, that is, on bus 4.

A. When a Seventh Harmonic Current Source Exists on Bus 3

Fig. 5 depicts a circuit equivalent to the distribution line with respect to harmonics when it is seen downstream of bus 3, where the active filter installed on bus 4 is represented by a resistor with resistance of $1/K_V\ \Omega$. In order to achieve harmonic termination, K_V should be determined so that installation of the active filter on bus 4 makes the impedance downstream of bus 3 inductive. Referring to Fig. 5 yields the impedance downstream of bus 3, Z, as follows:

$$Z = \frac{K_V}{{K_V}^2 + (\omega C_3)^2} + j\omega\left\{L_3 - \frac{C_3}{{K_V}^2 + (\omega C_3)^2}\right\}. \tag{2}$$

The condition that Z has an inductive impedance produces

$$K_V > \sqrt{\frac{C_3}{L_3} - (\omega C_3)^2}. \tag{3}$$

Substitution of the circuit constants shown in Table I into (3) offers the following condition relevant to K_V:

$$K_V > 0.8 \text{ S}. \tag{4}$$

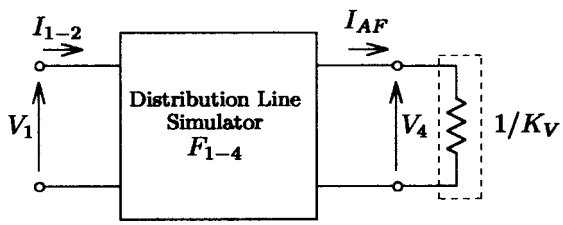

Fig. 6. Harmonic model equivalent to Fig. 1 when the active filter is installed on bus 4.

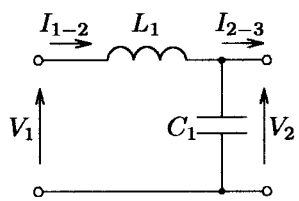

Fig. 7. Equivalent circuit between bus 1 and bus 2.

B. When a Seventh Harmonic Voltage Source Exists on Bus 1

Fig. 6 depicts a circuit equivalent to the distribution line with respect to harmonics, where the active filter with a gain of K_V is installed on bus 4. The circuit parameters between bus 1 and bus 4 is represented by an F matrix in the two-terminal pair circuit theory. The following equation exists in Fig. 6:

$$\begin{bmatrix} V_1 \\ I_{1-2} \end{bmatrix} = [F_{1-4}] \begin{bmatrix} V_4 \\ I_{\mathrm{AF}} \end{bmatrix}. \tag{5}$$

To achieve harmonic damping throughout the distribution line implies that V_4 should be smaller than V_1 because the highest seventh harmonic voltage appears in bus 4 when no active filter is installed. Thus, K_V should be determined so as to meet the above requirement. Fig. 7 shows an equivalent circuit between buses 1 and 2 under no-load conditions. The four-terminal constants in Fig. 7 are given by

$$\begin{bmatrix} V_1 \\ I_{1-2} \end{bmatrix} = \begin{bmatrix} 1-\omega^2 L_1 C_1 & j\omega L_1 \\ j\omega C_1 & 1 \end{bmatrix} \begin{bmatrix} V_2 \\ I_{2-3} \end{bmatrix}. \tag{6}$$

The distribution line simulator used for this experiment can be considered as a cascade connection of the equivalent circuit shown in Fig. 7. Hence, $[F_{1-4}]$ can be expressed as the product of the F matrix in (6)

$$[F_{1-4}] = \begin{bmatrix} 1-\omega^2 L_1 C_1 & j\omega L_1 \\ j\omega C_1 & 1 \end{bmatrix} \begin{bmatrix} 1-\omega^2 L_2 C_2 & j\omega L_2 \\ j\omega C_2 & 1 \end{bmatrix} * \begin{bmatrix} 1-\omega^2 L_3 C_3 & j\omega L_3 \\ j\omega C_3 & 1 \end{bmatrix}. \tag{7}$$

When attention is paid to the seventh harmonic frequency, the above equation and the circuit parameters in Table I yield the four-terminal constants of the F_{1-4} matrix in (5) as follows:

$$[F_{1-4}] = \begin{bmatrix} 0.04 & j1.08 \\ j0.90 & 0.47 \end{bmatrix}. \tag{8}$$

Equations (5) and (8) offer a transfer ratio of V_4 with respect to V_1 as follows:

$$\frac{V_4}{V_1} = \frac{1}{0.04 + j1.08K_V}. \tag{9}$$

The requirement that the voltage-transfer ratio is less than unity gives the other relationship related to K_V

$$K_V > 0.9 \text{ S}. \tag{10}$$

Equations (4) and (10) determine an optimal gain of K_V in this experimental system as follows:

$$K_V = 1.0 \text{ S}. \tag{11}$$

This implies that installation of the active filter with a gain of $K_V = 1.0$ S is equal to parallel connection of a 1-Ω resistor at bus 4, attention being paid to harmonic frequencies. Taking into account that the rated resistance is 2 Ω on the 3ϕ 200-V 60-Hz 20-kVA base, the active filter produces the same effect on harmonic damping as the 1-Ω resistor of 40 kW does, when the active filter is installed on bus 4 in the 200-V 20-kW distribution line simulator. Although installation of the 40-kW resistor is impossible, installation of the active filter is a viable and effective way of doing it for harmonic frequencies, but of doing nothing for the fundamental frequency. The reason is that the active filter is controlled in such a way as to present infinite impedance to the external circuit at the fundamental frequency, and to act as a 1-Ω resistor for voltage and current harmonics.

A real utility distribution line is not as simple as the distribution line shown in Fig. 1. Equation (11), however, suggests that the active filter for harmonic termination should be designed so that $1/K_V$ is less than half as low as the rated resistance of the actual distribution line.

V. Experimental Results

A. Experimental Conditions

In reality, harmonic-producing loads are dispersed on a power distribution line, and the distribution line itself is dynamic with the passage of time, day, season, and/or year, thus making it difficult to perform experiments under realistic conditions in the laboratory. Therefore, the following idealistic conditions, rather than realistic conditions, are taken, thus making it easier to evaluate the installation effect of the active filter with the gain of $K_V = 1.0$ S.

- Although the fifth harmonic voltage and current are the most dominant in a real 6.6-kV power distribution line in Japan, only the seventh harmonic voltage and current are taken into account because harmonic propagation occurs around the seventh harmonic frequency in Fig. 1.
- Experiments are performed under no-load conditions because no-load conditions cause more severe harmonic propagation than realistic light-load conditions.
- Either a seventh harmonic voltage source of 1.7 V (1.5%) or a seventh harmonic current source of 1.8 A (3.0%) is connected to the line simulator. Both harmonic sources

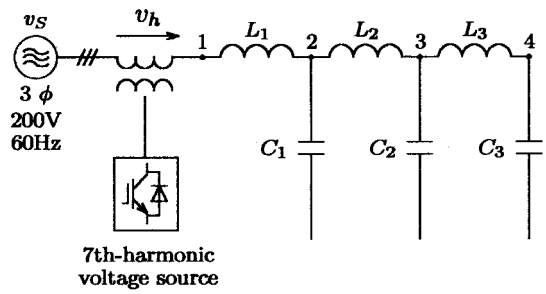

Fig. 8. Power distribution line simulator, where a seventh harmonic voltage source of $V_h = 1.7$ V (1.5%) exists upstream of bus 1.

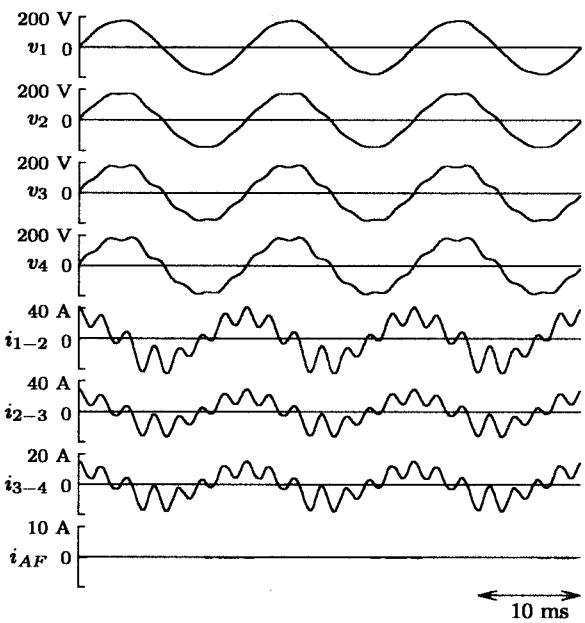

Fig. 9. Experimental waveforms when no active filter is connected.

are independent of each other, because the principle of superposition is applicable.

B. When a Seventh Harmonic Voltage Source Exists Upstream of Bus 1

Fig. 8 shows an experimental system where a seventh harmonic voltage source of 1.7 V (1.5%) is connected upstream of bus 1 in Fig. 1. Note that the seventh harmonic voltage source can be considered as a background harmonic voltage existing upstream of a primary distribution transformer in an actual power system. The seventh harmonic voltage source is implemented with a three-phase voltage-source pulsewidth modulation (PWM) inverter which is connected in series to the 200-V power system via three single-phase transformers, as if it were a series active filter [8]. Here, no harmonic-producing load exists in the power distribution line simulator.

Figs. 9–11 show experimental waveforms under the circuit configuration depicted in Fig. 8. Table III summarizes actual measurements of the seventh harmonic currents and voltages contained in the waveforms of Figs. 9–11. Table IV shows the ratio of the seventh harmonic voltage at each bus with respect to that at bus 1, which implies a voltage-magnifying factor at each bus.

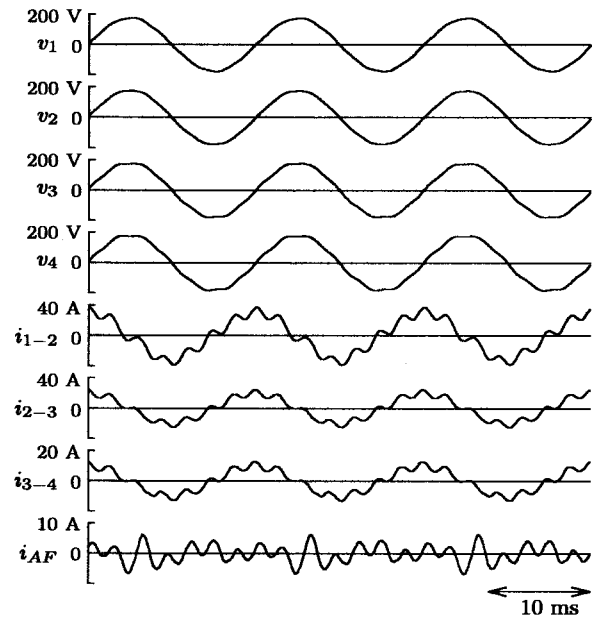

Fig. 10. Experimental waveforms when the active filter is connected to bus 2.

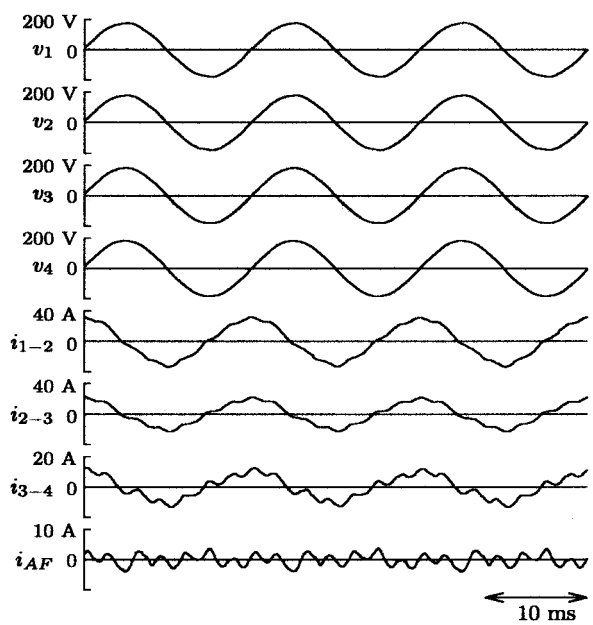

Fig. 11. Experimental waveforms when the active filter is connected to bus 4.

Fig. 9 shows experimental waveforms when no active filter is connected. Harmonic voltage propagation magnifies the seventh harmonic voltage at bus 4 by 5.7 times as large as that at bus 1.

Fig. 10 shows experimental waveforms when the active filter is installed on bus 2. The active filter attenuates the harmonic voltage propagation at bus 2. It, however, has no capability of harmonic damping throughout the power distribution line, because 4.0 V (3.5%) at bus 4 is much larger than 1.7 V (1.5%) at bus 1.

Fig. 11 shows experimental waveforms when the active filter is installed on bus 4. Tables III and IV verify that

TABLE III
ACTUAL MEASUREMENTS OF SEVENTH HARMONIC CURRENTS AND VOLTAGES WHEN THE ACTIVE FILTER IS DISCONNECTED OR CONNECTED.

[A]	dis-connection	connection	
		bus 2	bus 4
I_{1-2}	8.2	4.1	1.2
I_{2-3}	6.7	2.8	1.3
I_{3-4}	3.8	1.6	1.4
I_{AF}	—	1.8	1.3
[V]	dis-connection	connection	
		bus 2	bus 4
$V_1(=V_h)$	1.7	1.7	1.7
V_2	3.7	1.7	1.6
V_3	7.4	3.3	1.3
V_4	9.7	4.0	1.1

TABLE IV
MAGNIFYING FACTORS OF SEVENTH HARMONIC VOLTAGES WHEN THE ACTIVE FILTER IS DISCONNECTED OR CONNECTED.

	dis-connection	connection	
		bus 2	bus 4
V_2/V_1	2.2	1.0	0.9
V_3/V_1	4.4	1.9	0.8
V_4/V_1	5.7	2.4	0.6

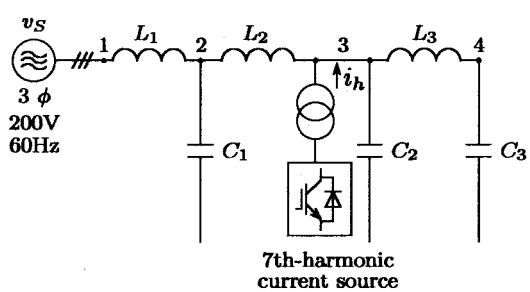

Fig. 12. Power distribution line simulator, where a seventh harmonic current source of $I_h = 1.8$ A (3.0%) exists on bus 3.

installation of the active filter on bus 4, that is, on the end bus of the power distribution line, leads to achieving harmonic damping throughout. Paying attention to the active filter current I_{AF} in Table III concludes that installation on bus 4 makes the required current rating of the active filter smaller than does installation on bus 2. In other words, the required voltampere rating of the active filter installed on bus 2 is 624 VA, whereas that of the active filter installed on bus 4 is 450 VA. When the active filter is installed on bus 4, it draws the following amount of seventh harmonic power from bus 4:

$$3 \times 1.3^2 \times 1/1.0 = 5.1 \text{ W} \tag{12}$$

which is only 1.1% of the active filter rating of 450 VA.

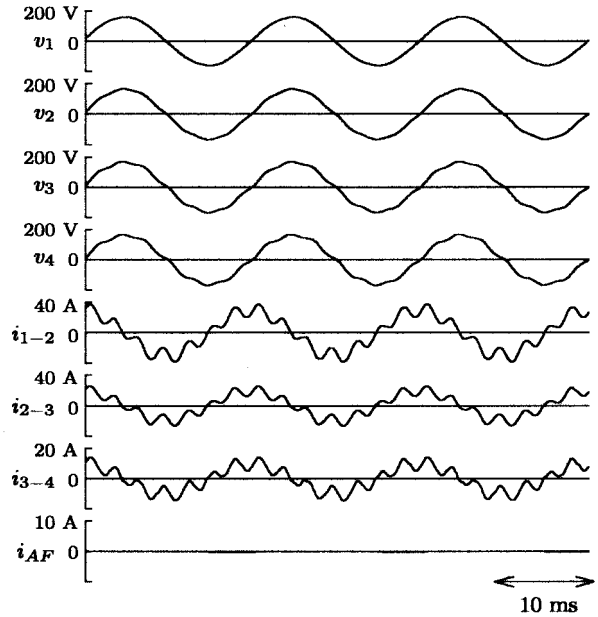

Fig. 13. Experimental waveforms when no active filter is connected.

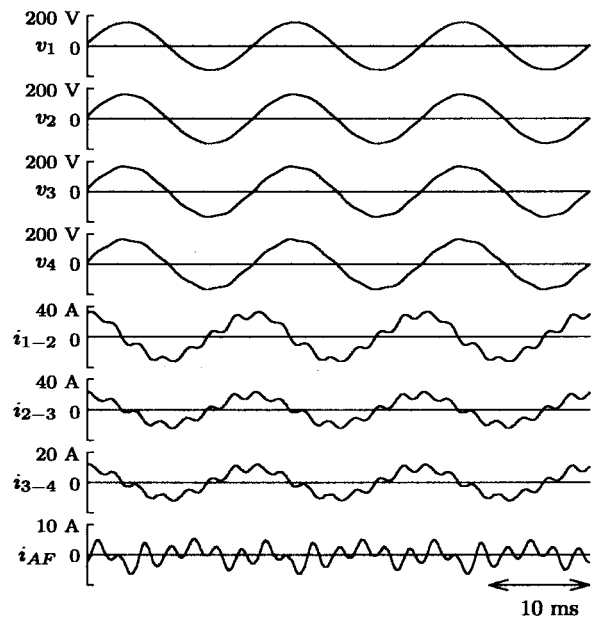

Fig. 14. Experimental waveforms when the active filter is installed on bus 2.

C. When a Seventh Harmonic Current Source Exists Downstream of Bus 2

Fig. 12 shows an experimental system in which a seventh harmonic current source of 1.8 A (3.0%) is connected to bus 3 in parallel. For the sake of simplicity, many harmonic-producing loads dispersed on the real power distribution line are represented by the single harmonic current source depicted in Fig. 12. The current source is implemented with a three-phase voltage-source PWM inverter with a current minor loop, as if it were a shunt active filter. Note that no harmonic voltage source is connected upstream of bus 1.

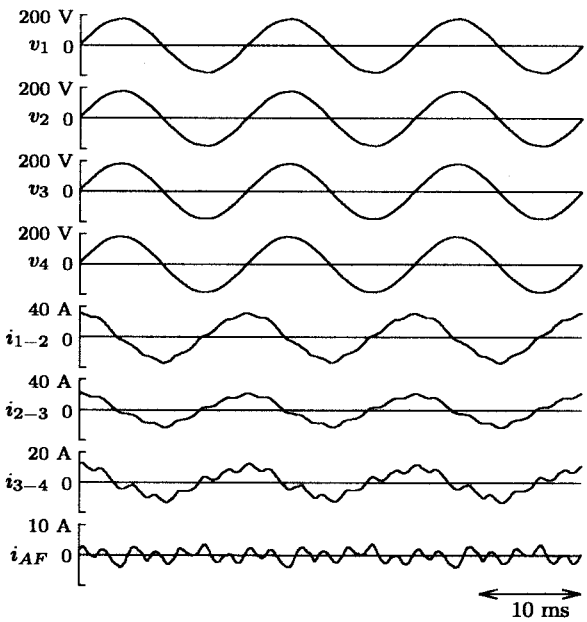

Fig. 15. Experimental waveforms when the active filter is installed on bus 4.

TABLE V
ACTUAL MEASUREMENTS OF SEVENTH HARMONIC CURRENTS AND VOLTAGES WHEN THE ACTIVE FILTER IS DISCONNECTED OR CONNECTED.

[A]	dis-connection	connection	
		bus 2	bus 4
I_{1-2}	5.8	3.5	1.3
I_{2-3}	4.5	3.4	1.0
I_{3-4}	2.8	1.6	1.6
I_h	1.8	1.8	1.8
I_{AF}	—	1.9	1.5
[V]	dis-connection	connection	
		bus 2	bus 4
V_2	2.8	1.6	1.0
V_3	5.0	3.1	1.3
V_4	6.3	3.8	1.3

TABLE VI
MAGNIFYING FACTORS OF SEVENTH HARMONIC CURRENTS WHEN THE ACTIVE FILTER IS DISCONNECTED OR CONNECTED.

	dis-connection	connection	
		bus 2	bus 4
I_{1-2}/I_h	3.2	1.9	0.7
I_{2-3}/I_h	2.5	1.9	0.6
I_{3-4}/I_h	1.6	0.9	0.9

Figs. 13–15 show experimental waveforms under the circuit configuration depicted in Fig. 12. Table V summarizes actual measurements of the seventh harmonic currents and voltages from the waveforms of Figs. 13–15. Table VI shows the ratio of the seventh harmonic current flowing between a bus and the adjacent bus with respect to $I_h = 1.8$ A, which implies a current-magnifying factor. Note that no seventh harmonic voltage exists on bus 1, that is, $V_1 = 0$.

Fig. 13 shows experimental waveforms when no active filter is connected. Harmonic current propagation makes each seventh harmonic current between a bus and the adjacent bus larger than 1.8 A.

Fig. 14 shows experimental waveforms when the active filter with the gain of $K_V = 1.0$ S is installed on bus 2. The seventh harmonic voltage at bus 2 or at the point of installation of the active filter is the smallest whereas the seventh harmonic current flowing between bus 1 and bus 2, that is, I_{1-2} is magnified by twice as large as 1.8 A. The seventh harmonic voltage at bus 4 reaches 3.8 V (3.3%).

Fig. 15 shows experimental waveforms when the active filter is installed on bus 4, that is, on the end bus of the distribution line. All of I_{1-2}, I_{2-3}, and I_{3-4} are smaller than 1.8 A. In other words, each current-magnifying factor is less than unity. The seventh harmonic voltage at bus 4 is reduced to 1.3 V (1.1%), which is one-third as low as that in the case of installing the active filter on bus 2. In addition, Table V concludes that installation on bus 4 makes the required current rating of the active filter, I_{AF}, smaller than does installation on bus 2. In this case, the required voltampere rating of the active filter installed on bus 2 is 658 VA, whereas that of the active filter installed on bus 4 is 520 VA.

VI. CONCLUSION

This paper has described a shunt active filter based on voltage detection, which is controlled in such a way as to present infinite impedance to the external circuit at the fundamental frequency, and as to exhibit low resistance for harmonic frequencies. A laboratory system rated at 200 V and 20 kW has been designed and constructed to verify the practical viability and justification of the active filter. Experimental results obtained from the laboratory system, along with theoretical results, are summarized as follows.

- Installation of the active filter on the end bus of a power distribution line is more effective in harmonic damping than installation on the beginning bus or in the vicinity of a primary distribution transformer.
- Installation on the end bus makes the required current rating of the active filter smaller than does installation on the beginning bus.
- Harmonic mitigation of voltage and current is a welcome "byproduct," as a result of harmonic termination.

The authors conclude that the voltage detection-based active filter intended for "harmonic termination" should be installed not on the beginning bus, but on the end bus of a radial power distribution line subjected to harmonic propagation.

ACKNOWLEDGMENT

The authors would like to thank K. Oku, Kansai Electric Power Company, and N. Shibamaru, Chugoku Electric Power Company, Inc., for their helpful and valuable suggestions. The authors would also like to thank Prof. S. Gardner, Okayama University, for his English language editing.

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