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A Hybrid Active Filter for Damping of Harmonic Resonance in Industrial Power Systems

Hideaki Fujita, *Member, IEEE*, Takahiro Yamasaki, and Hirofumi Akagi, *Fellow, IEEE*

Abstract—This paper proposes a hybrid active filter for damping of harmonic resonance in industrial power systems. The hybrid filter consists of a small-rated active filter and a 5th-tuned passive filter. The active filter is characterized by detecting the 5th-harmonic current flowing into the passive filter. It is controlled in such a way as to behave as a negative or positive resistor by adjusting a feedback gain from a negative to positive value, and vice versa. The negative resistor presented by the active filter cancels a positive resistor inherent in the passive filter, so that the hybrid filter acts as an ideal passive filter with infinite quality factor. This significantly improves damping the harmonic resonance, compared with the passive filter used alone. Moreover, the active filter acts as a positive resistor to prevent an excessive harmonic current from flowing into the passive filter. Experimental results obtained from a 20-kW laboratory model verify the viability and effectiveness of the hybrid active filter proposed in this paper.

Index Terms—Active filters, harmonic resonance, power quality, power systems, PWM inverters, voltage harmonics.

I. INTRODUCTION

NON-LINEAR loads such as diode or thyristor rectifiers and cycloconverters draw non-sinusoidal currents from utility grids, thus contributing to the degradation of power quality in utility or industrial power systems. Notably, voltage distortion or voltage harmonics in the power systems are becoming so serious that 5th- and 7th-harmonic voltages are barely acceptable at the customer-utility point of common coupling [1].

Oku, et al., have reported a serious status of harmonic pollution in Japan [2], [3]. 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. 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. These facts based on the actual measurement suggest that the increase of 5th-harmonic voltage on the 6.6-kV bus at night is due to harmonic resonance between line inductors and shunt capacitors for power factor correction installed on the distribution system. This harmonic resonance may occur, not only in utility power systems, but also in industrial power systems for factories, plants, office buildings and so on. Harmonic damping, therefore, would be as

cost-effective in mitigating harmonic voltages and currents as harmonic compensation [4], [5].

Hybrid filters consisting of active and passive filters connected in series or parallel with each other combine the advantages of both filters, thus leading to the best effectiveness in cost/performance [6]–[12]. Control schemes for the active filters have been presented to provide the required functions such as harmonic compensation, harmonic damping and/or harmonic isolation [1].

This paper proposes a hybrid active filter consisting of a small-rated active filter and a specially designed passive filter. The active and passive filters are connected in series with each other. The hybrid filter is connected in parallel with other loads in the vicinity of the secondary of a distribution transformer installed at the utility-consumer point of the common coupling (PCC). It is, therefore, different in the point of installation from pure active filters and hybrid active filters which have been installed in the vicinity of harmonic-producing loads. The purpose of installing the hybrid filter proposed in this paper is to damp the harmonic resonance in industrial power systems, as well as to mitigate harmonic voltages and currents. This paper describes the principle of operation of the hybrid filter and discusses three different harmonic detection methods for the active filter used in the hybrid filter. Experimental results obtained from a 20-kW laboratory model verify the viability of the hybrid filter and its effectiveness in harmonic damping and mitigation.

II. HARMONIC RESONANCE

Fig. 1 shows an industrial power system, in which linear and nonlinear loads, capacitors for power factor correction and passive filters are connected on a common bus. The primary of a distribution transformer installed by the consumer is connected to the PCC, while the secondary supplies the linear and nonlinear loads through the common bus. The power system may cause harmonic propagation as a result of series and/or parallel resonances between the power capacitors and the leakage inductor of the distribution transformer.

Fig. 2 shows a single-phase circuit equivalent to the power system under the assumption that only a 5th-harmonic voltage exists at the PCC. Here, L_T is the leakage inductance of the transformer; C is the capacitance of the capacitors for power factor correction; R_L is the resistance equivalent to the loads. The common bus voltage V_{BUS} includes a 5th-harmonic voltage V_{BUS5} which is given by

$$V_{BUS5} = \frac{1}{1 - (5\omega)^2 L_T C + \frac{j5\omega L_T}{R_L}} V_{S5} \quad (1)$$

where ω is the angular frequency of the line voltage.

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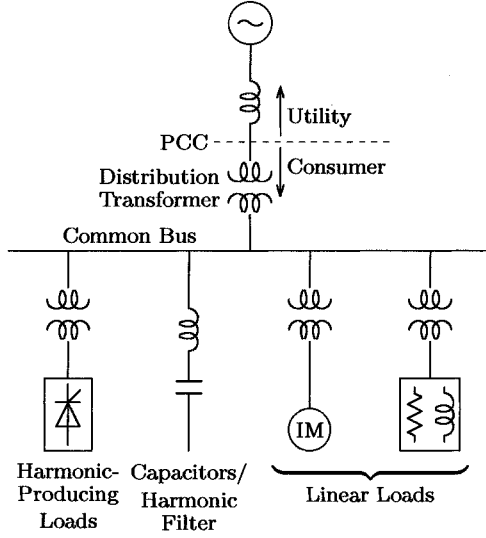


Fig. 1. Industrial power system.

A no-load condition of $R_L = \infty$ yields a relationship of $V_{BUS5} > V_{S5}$. This implies that harmonic propagation occurs in the industrial power system. When the resonant frequency between L_T and C coincides with the 5th-harmonic frequency, (1) is simplified as follows:

$$V_{BUS5} = \frac{R_L}{j5\omega L_T} V_{S5}. \quad (2)$$

The harmonic resonance may magnify the 5th-harmonic voltage by 4–10 times even in a full-load condition because L_T has an inductance value of 2–5%.

III. HYBRID ACTIVE FILTER

A. Experimental System

Fig. 3 shows a system configuration developed for this experiment. Table I summarizes the circuit constants in Fig. 3. The industrial power system is rated at 200 V, 60 Hz and 20 kVA, assuming no-load conditions under which the severest harmonic propagation occurs. The active filter consists of three single-phase voltage-source PWM inverters using twelve power MOSFETs. Each inverter is connected in series with the 5th-tuned passive filter via a single-phase matching transformer with a turns ratio of 1:10. Note that the rating of the active filter is 0.14 kVA, which is only 0.7% of 20 kVA, while the rating of the passive filter is 0.43 kVA or 2%. An inductor L_T (=7%) is connected in series downstream of the PCC, in order to represent a leakage inductor of a distribution transformer. A shunt capacitor C (=70%) is connected in parallel on the common bus. Combination of the inductor and capacitor forms a series and/or parallel resonant circuit, the resonant frequency of which is around the 5th-harmonic frequency. A 5th-harmonic generator consisting of a three-phase voltage-source PWM inverter is used to simulate a 5th-harmonic voltage existing upstream of the PCC.

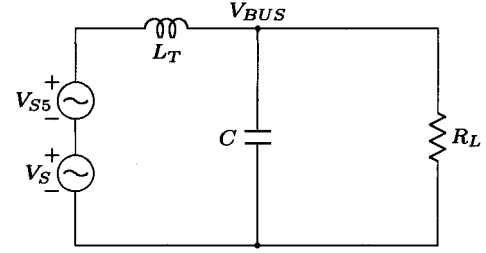


Fig. 2. Single-phase equivalent circuit.

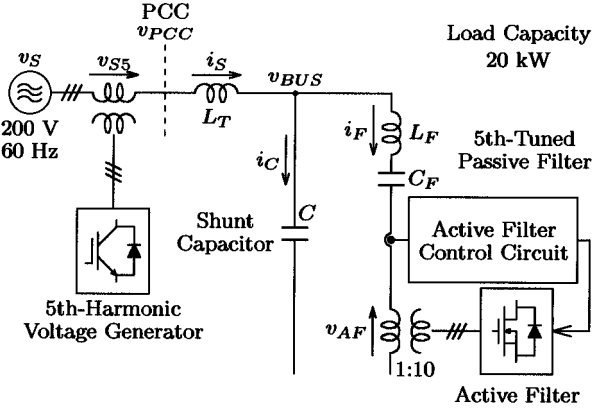


Fig. 3. Experimental system.

TABLE I
CIRCUIT CONSTANTS

5th-Tuned Passive Filter	$L_F = 12 \text{ mH}$, $C_F = 24 \text{ } \mu\text{F}$, $Q = 10$, 0.43 kVA (2%)
Active Filter	0.14 kVA (0.7%)
Shunt Capacitor	$C = 900 \text{ } \mu\text{F}$, 14 kVA (70%)
Leakage Inductance	$L_T = 360 \text{ } \mu\text{H}$ (7%)

3 ϕ , 200-V, 60-Hz, 20-kVA base

B. Operating Principle of the Active Filter

Fig. 4 shows a single-phase equivalent circuit for the industrial power system installing the hybrid filter on the common bus. The active filter detects the 5th-harmonic current flowing into the passive filter, i_{F5} , and then amplifying i_{F5} by a gain K determines its voltage reference as follows:

$$v_{AF}^* = K \cdot i_{F5}. \quad (3)$$

As a result, the active filter acts as a pure resistor of K [Ω] for the 5th-harmonic voltage and current. The impedance of the hybrid filter at the 5th-harmonic frequency, Z_5 is given by

$$Z_5 = j5\omega L_F + \frac{1}{j5\omega C_F} + r_F + K. \quad (4)$$

Here, r_F is a resistance value of a resistor inherent in the passive filter, and L_F and C_F are inductance and capacitance values. When the gain K is controlled in a range of $K < 0$, the active

filter presents a negative resistor to the external circuit, thus improving the quality factor of the passive filter, Q . Assuming that the passive filter is well tuned at the 5th-harmonic frequency, the impedance of the passive filter is equal to r_F .

Fig. 5 shows an equivalent circuit with the focus on the 5th-harmonic frequency. It is clear that Z_5 is 0 as long as $K = -r_F$. This implies that no 5th-harmonic voltage appears on the common bus. In general, V_{BUS5} , which is the 5th-harmonic voltage appearing on the common bus voltage, and I_{S5} , which is the 5th-harmonic current present in the supply current, are given by

$$V_{BUS5} = \frac{1}{1 - (5\omega)^2 L_T C + j5\omega L_T \left(\frac{1}{R_L} + \frac{1}{r_F + K} \right)} V_{S5} \quad (5)$$

$$I_{S5} = \frac{j5\omega C + \frac{1}{R_L} + \frac{1}{r_F + K}}{1 - (5\omega)^2 L_T C + j5\omega L_T \left(\frac{1}{R_L} + \frac{1}{r_F + K} \right)} V_{S5}. \quad (6)$$

Assuming that $K = -r_F$ yields

$$V_{BUS5} = 0 \quad (7)$$

$$I_{S5} = \frac{1}{j5\omega L_T} V_{S5}. \quad (8)$$

When an overcurrent flows into the passive filter, the active filter controls the gain K to be a positive value. Thus, the active filter acts as a positive resistor, preventing the passive filter from absorbing an excessive 5th-harmonic current. The 5th-harmonic current flowing into the passive filter, I_{F5} is given by

$$I_{F5} = \frac{\frac{1}{r_F + K}}{1 - (5\omega)^2 L_T C + j5\omega L_T \left(\frac{1}{R_L} + \frac{1}{r_F + K} \right)} V_{S5}. \quad (9)$$

Assuming no-load conditions of $R_L = \infty$ simplifies the above equation as follows:

$$I_{F5} = \frac{1}{(1 - (5\omega)^2 L_T C)(r_F + K) + j5\omega L_T} V_{S5}. \quad (10)$$

This indicates that adjusting the gain K is effective in reducing I_{F5} .

IV. THEORETICAL CONSIDERATIONS OF HARMONIC DETECTION METHODS

A. Stability Analysis

Three different harmonic detection methods for the active filter are considered and compared in view of system stability.

- Detecting the harmonic current flowing into the passive filter, I_{Fh}

$$V_{AF}^* = K \cdot I_{Fh}. \quad (11)$$

- Detecting the harmonic voltage appearing across the passive filter, V_{Fh}

$$V_{AF}^* = K \cdot V_{Fh}. \quad (12)$$

- Detecting the harmonic voltage appearing on the common bus voltage, V_{BUSh}

$$V_{AF}^* = K \cdot V_{BUSh}. \quad (13)$$

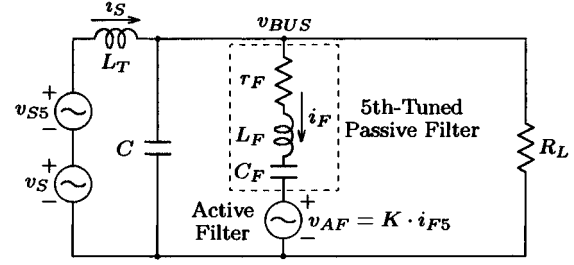


Fig. 4. Single-phase equivalent circuit.

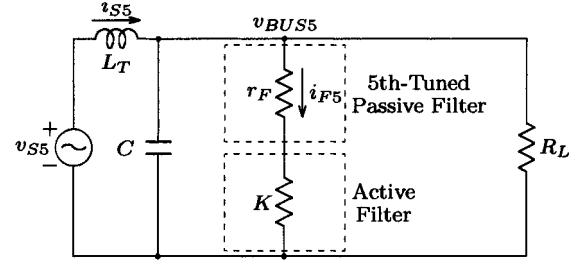


Fig. 5. Single-phase equivalent circuit for 5th harmonics.

In the following analysis, the harmonic-extracting circuit of the active filter is assumed to be ideal without time delay, so that the transfer function of the control circuit is simplified as the gain K . Fig. 6 shows a single-phase equivalent circuit from which the supply harmonic voltage is removed. The total impedance of the passive filter, $Z_F(s)$ is given by

$$Z_F(s) = r_F + sL_F + \frac{1}{sC_F}. \quad (14)$$

The external impedance seen from the installation point of the hybrid filter, $Z(s)$ is given by

$$Z(s) = \frac{1}{\frac{1}{R_L} + \frac{1}{sL_T} + sC}. \quad (15)$$

At first, it is necessary to calculate a loop transfer function of each harmonic detection method.

- I_F -detecting method

Fig. 6 allows us to calculate the transfer function from V_{AF} to I_{Fh} as follows:

$$\frac{I_{Fh}}{V_{AF}} = -\frac{1}{Z_F(s) + Z(s)}. \quad (16)$$

The product between (16) and the gain K offers the loop transfer function, $G_{I_{Fh}}(s)$

$$G_{I_{Fh}}(s) = K \cdot \frac{I_{Fh}}{V_{AF}} = -\frac{K}{Z_F(s) + Z(s)} \quad (17)$$

- V_F -detecting method

The loop transfer function of this method, $G_{V_{Fh}}(s)$ is also given by

$$G_{V_{Fh}}(s) = K \cdot \frac{V_{Fh}}{V_{AF}} = -\frac{K \cdot Z_F(s)}{Z_F(s) + Z(s)}. \quad (18)$$

Moreover, the harmonic voltage appearing on the common bus, V_{BUSh} is given by

$$V_{BUSh} = V_{Fh} + V_{AF} = (1 + K)V_{Fh}. \quad (19)$$

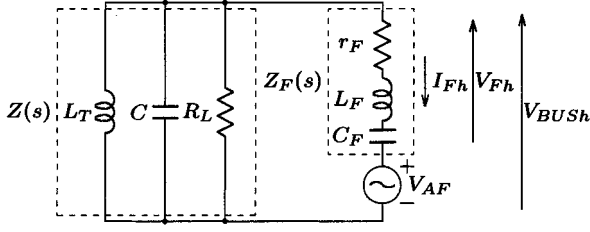


Fig. 6. Single-phase equivalent circuit when no harmonic voltage exists in the supply voltage.

Setting the gain to $K = -1$ yields an ideal condition of $V_{BUSh} = 0$.

c) V_{BUS} -detecting method

The loop transfer function of this method, $G_{V_{BUSh}}(s)$ is given by

$$G_{V_{BUSh}}(s) = K \cdot \frac{V_{BUSh}}{V_{AF}} = \frac{K \cdot Z(s)}{Z_F(s) + Z(s)}. \quad (20)$$

The harmonic voltage on the common bus, V_{BUSh} is given by

$$V_{BUSh} = \frac{V_{Fh}}{1 - K}. \quad (21)$$

An ideal gain of $K = -\infty$ results in a condition of $V_{BUSh} = 0$. However, such a realistic gain as $K = -100$ is taken in the following analytical results.

B. Analytical Results

Fig. 7 illustrates the Bode plots of the loop transfer functions obtained from (17), (18) and (20), where the circuit constants summarized in Table I are used for the analysis. A load resistor of $R_L = 2 \Omega$, which is rated at 20 kW, is connected on the common bus. Since each harmonic detection method is based on a positive-feedback system, the system is stable as long as the magnitude plot is below 0 dB at the phase crossover frequency of $\angle G(s) = 0$.

The I_F -detecting method with a gain of $K = -r_F$ has a gain margin of -6 dB at the phase crossover frequency around 300 Hz, as shown in Fig. 7(a), so that the system is stable. When the tuned frequency of the passive filter is 300 Hz, this system theoretically falls into being marginally stable under no-load conditions. A realistic system, however, is stable even in no-load conditions due to existing line resistors.

The V_F -detecting method with a gain of $K = -1$ has the magnitude of 0 dB and the phase angle of 0 in a frequency range of less than 200 Hz and of more than 400 Hz, as shown in Fig. 7(b), so that this system is marginally stable. Therefore, the gain should be set in a range of $0 > K > -1$, to provide a gain margin.

As shown in Fig. 7(c), the V_{BUS} -detecting method with a gain of $K = -100$ has a phase margin of more than 20° although the magnitude is over 0 dB in a frequency range of 150–600 Hz, so that this system is stable.

It is assumed in the above analysis that the transfer function of the harmonic-extracting circuit in the control circuit is a constant gain K , independent of frequency. If it is implemented to amplify only the extracted 5th-harmonic current or voltage

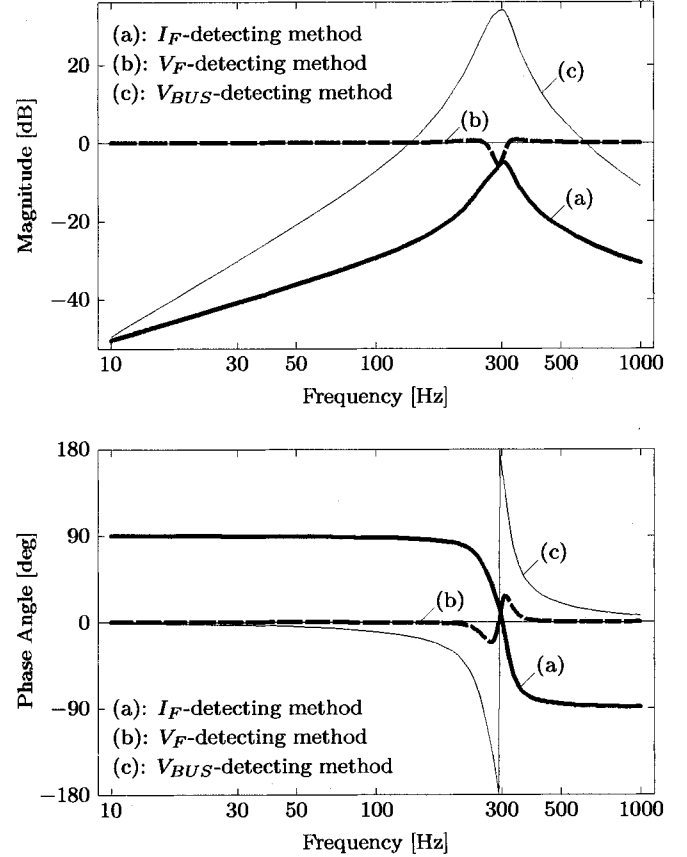


Fig. 7. Bode plots of each harmonic-extracting method under full-load conditions.

by the gain K and to lower the gain for other frequencies, the system stability of the three harmonic detection methods can be improved. In addition, the I_F -detecting method is superior in harmonic detection accuracy to the other methods because the ratio of the extracted harmonic component with respect to the fundamental component is the highest among the three methods. This experimental system, therefore, takes the I_F -detecting method from the viewpoint of stability and harmonic detection accuracy.

V. CONTROL CIRCUIT

Fig. 8 shows a block diagram of the control circuit for the active filter. It consists of two parts; a circuit for extracting the 5th-harmonic current from the passive filter current i_F and a circuit for automatically adjusting the gain K . The reference voltage for the active filter, v_{AF}^* is given by

$$v_{AF}^* = K \cdot i_{F5}. \quad (22)$$

where the gain K is determined in the gain-adjusting circuit.

A. Harmonic-Extracting Circuit

The extracting circuit detects three-phase currents flowing into the passive filter through three ac-CTs, and then the two-phase currents on the α - β coordinates are transformed to those on the d - q coordinates by using a unit vector $(\cos 5\omega t, \sin 5\omega t)$ with a rotating frequency of five times as

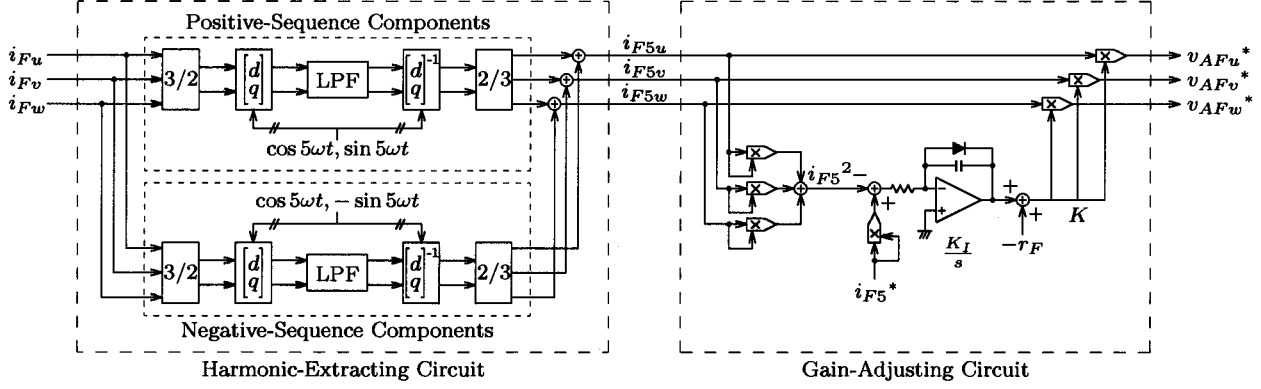


Fig. 8. Block diagram of control circuit.

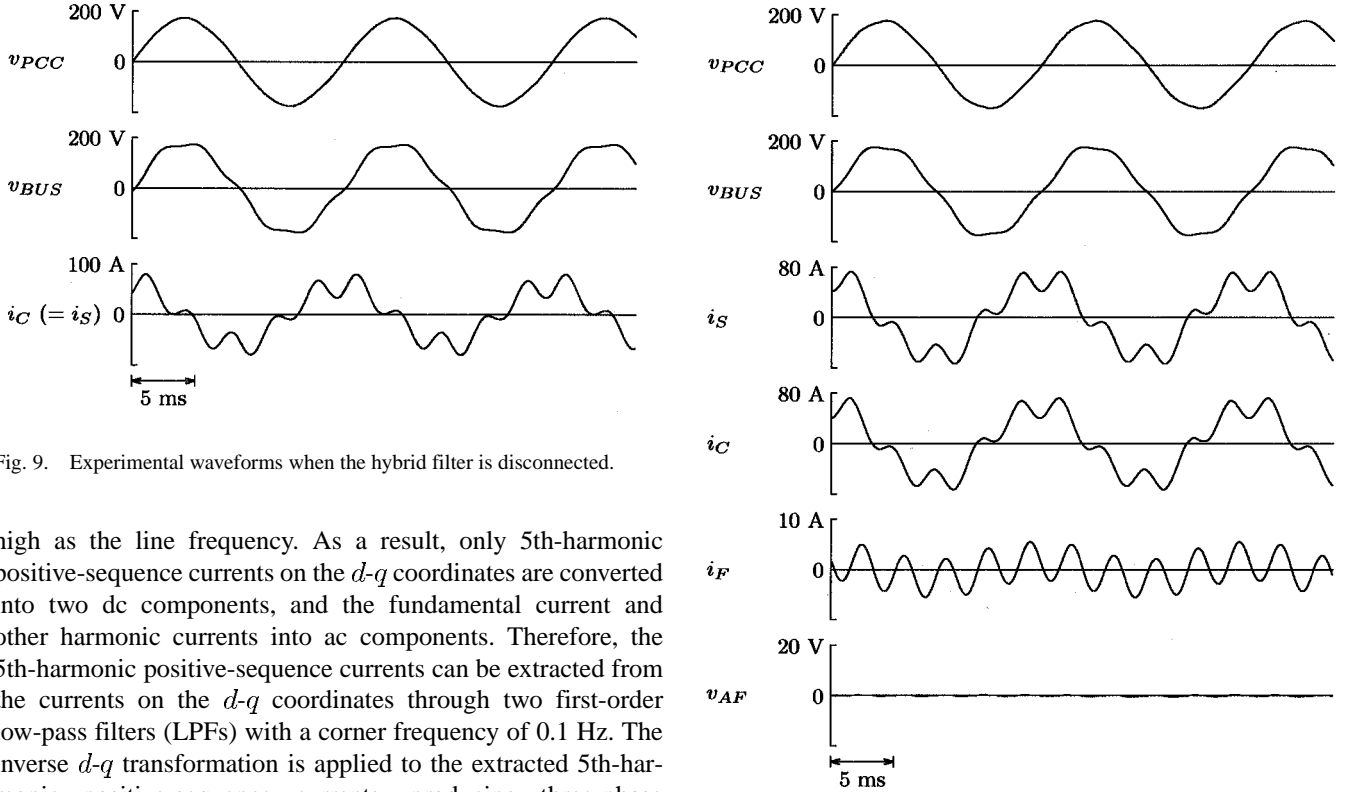


Fig. 9. Experimental waveforms when the hybrid filter is disconnected.

high as the line frequency. As a result, only 5th-harmonic positive-sequence currents on the d - q coordinates are converted into two dc components, and the fundamental current and other harmonic currents into ac components. Therefore, the 5th-harmonic positive-sequence currents can be extracted from the currents on the d - q coordinates through two first-order low-pass filters (LPFs) with a corner frequency of 0.1 Hz. The inverse d - q transformation is applied to the extracted 5th-harmonic positive-sequence currents, producing three-phase positive-sequence 5th-harmonic currents. To extract 5th-harmonic negative-sequence currents, the same signal processing as the 5th-harmonic positive-sequence currents is performed except for employing another unit vector ($\cos 5\omega t, -\sin 5\omega t$) with the opposite rotating direction. Finally, the extracted positive- and negative-sequence currents in each phase are added to obtain three-phase 5th-harmonic currents.

B. Gain-Adjusting Circuit

The gain-adjusting circuit calculates a square of the extracted 5th-harmonic current every phase, and then sums all of the three, producing i_{F5}^2 as follows:

$$i_{F5}^2 = i_{F5u}^2 + i_{F5v}^2 + i_{F5w}^2. \quad (23)$$

Fig. 10. Experimental waveforms when only the passive filter is installed.

The circuit compares i_{F5}^2 with a square of a limitation value i_{F5}^{*2} . When i_{F5}^2 is smaller than the square of i_{F5}^{*2} , the circuit sets the gain in such a way as $K = -r_F$. When i_{F5}^2 is larger, an integral feedback controller in the circuit adjusts the gain in such a way as to make i_{F5}^2 equal i_{F5}^{*2} . The purpose of the gain-adjusting circuit is to prevent the passive filter and the active filter from overheating and overcurrent, and therefore the circuit requires a control response as slow as 1–4 seconds. The integral gain is set to $K_I = 0.4 \Omega/(A^2s)$ in the following experiment. This implies that it takes about 2 seconds to adjust the gain K from -2Ω to 0, when an overcurrent being two times as large as the rated current of i_{F5} flows into the passive filter.

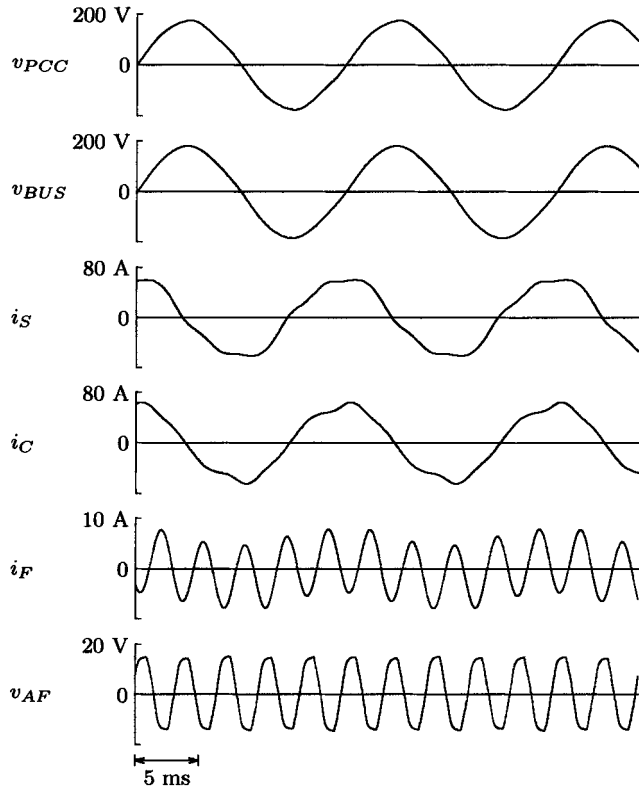


Fig. 11. Experimental waveforms when the hybrid active filter is installed.

TABLE II
FFT ANALYSIS OF WAVEFORMS IN FIGS. 9, 10, AND 11.

[%]	5th-harmonic voltages and currents		
	Fig. 9	Fig. 10	Fig. 11
v_{PCC}	1.3 (2.3)	2.3	2.3
v_{BUS}	8.1 (15.0)	6.3	1.1
i_S	27.0 (49.0)	23.0	4.4
i_C	27.0 (49.0)	22.0	3.7
i_F	—	4.7	7.8
v_{AF}	—	—	9.4

() : values referred to $v_{PCC} = 2.3\%$

3 ϕ , 200-V, 60-Hz, 20-kVA base

VI. EXPERIMENTAL RESULTS

A. Damping Effect of Harmonic Resonance

Figs. 9–11 show experimental waveforms obtained from Fig. 3. Table II summarizes FFT results of 5th-harmonic voltages and currents, where v_{PCC} , v_{BUS} and v_{AF} are given as the ratio of the 5th-harmonic voltage with respect to the rated phase voltage of $200/\sqrt{3}$ V, and i_S , i_C and i_F are as the ratio of the 5th-harmonic current with respect to the rated load current of 60 A. In Figs. 10 and 11, a 2.3% 5th-harmonic voltage is injected upstream of the PCC by the harmonic voltage generator, whereas a 1.3% 5th-harmonic voltage is intentionally injected in Fig. 9, in order to reduce the 5th-harmonic current flowing into the capacitor for power factor correction.

When the hybrid filter is disconnected, that is, neither the passive filter nor the active filter is installed, the 5th-harmonic voltage on v_{BUS} is magnified by 6.3 as a result of the harmonic resonance between L_T and C , as shown in Fig. 9. In other words, a 5th-harmonic voltage of 15% would appear on v_{BUS} if that of 2.3% existed on v_{PCC} .

When only the passive filter is installed, a 5th-harmonic voltage of 6.3% appears on v_{BUS} with a magnification factor of 2.7, as shown in Fig. 10 and Table II. Note that a much larger amount of 5th-harmonic current flows in the passive filter than the fundamental current because the capacity of the passive filter is as small as 2%.

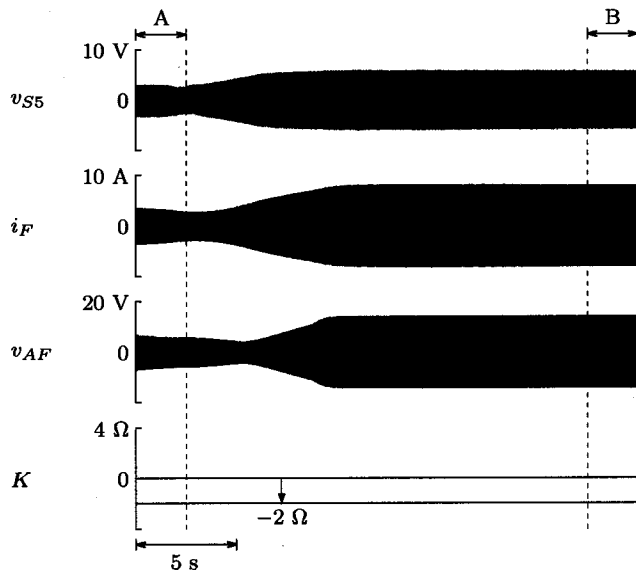
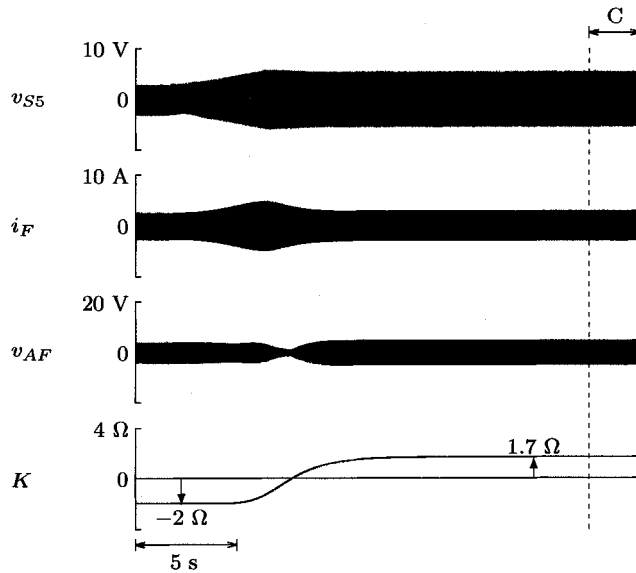
Fig. 11 shows the experimental waveforms when the hybrid filter is installed. No harmonic voltage magnification occurs even under the same conditions as Fig. 10, so that v_{BUS} is almost sinusoidal. The 5th-harmonic voltage and currents are reduced to one-sixth as small as those in Fig. 10. This indicates that the active filter connected in series with the passive filter makes a significant contribution to damping the harmonic resonance. The output voltage of the active filter, v_{AF} is opposite in phase to the 5th-harmonic current present in i_F . This implies that the active filter acts as a negative resistor for the 5th-harmonic voltage and current. Therefore, the 5th-harmonic current in i_F in Fig. 11 is 1.7 times as large as that in Fig. 10. The required peak rating of the active filter is 0.14 kVA, which is only 0.7% of the load rated at 20 kW.

Invoking equivalent transformation between a voltage source and a current source gives us that series connection of the 2.3% 5th-harmonics voltage source upstream of the PCC is equivalent to parallel connection of a 5th-harmonic current source on the common bus under the disconnection of the 5th-harmonic voltage source. The following relationship between the 2.3% 5th-harmonic voltage source V_{S5} and the 5th-harmonic current sources I_{BUS5} exists:

$$I_{BUS5} = \frac{V_{S5}}{5\omega L_T} = \frac{200 \text{ V}/\sqrt{3} \times 0.023}{5 \times 2\pi \times 60 \text{ Hz} \times 0.00036 \text{ H}} = 3.9 \text{ A}.$$

B. Experimental Results Against Overcurrent

Figs. 12 and 13 show experimental waveforms when the gain K is kept as a constant value of -2Ω , and when the gain is automatically controlled with the function of the gain-adjusting circuit, respectively. Figs. 14–16 illustrate close-up waveforms of periods A, B and C in Figs. 12 and 13. Note that the waveform of v_{S5} in Figs. 14, 15 or 16 includes a fundamental voltage component in addition to a 5th-harmonic voltage. The reason is that a fundamental current component of i_S , flowing through the matching transformer for connecting the 5th-harmonic voltage generator in series with the utility, induces the fundamental voltage component across the matching transformer due to the presence of a non-negligible leakage inductor. To realize overcurrent conditions in this experiment, the amplitude of the 5th-harmonic voltage injected by the harmonic voltage generator is increased at a constant rate of 0.5 V/s, and the limitation value of the 5th-harmonic current flowing into the passive filter is set to be 1.0 A. In Fig. 12, the 5th-harmonic current flowing into the passive filter finally reaches 4.3 A as the injected 5th-harmonic voltage is increased. The increased

Fig. 12. Waveforms when K is constant.Fig. 13. Waveforms when K is adjusted.

5th-harmonic current is accompanied by the increased output voltage of the active filter.

In Fig. 13, when the 5th-harmonic current i_{F5} is over the limitation value, the gain-adjusting circuit starts to vary the gain from a negative to positive value, finally approaching 1.7Ω . As a result of adjusting the gain, i_{F5} is eventually limited within 1.0 A. Note that a time delay of 1.3 s exists between the maximum point of the 5th-harmonic current in i_{F5} and the maximum point of a gain-rising rate of $1.2 \Omega/s$, because the first-order low-pass-filters with a corner frequency of 1.6 s are used in the harmonic-extracting circuit. In Fig. 16, the 5th-harmonic current in i_{F5} is in phase with the output voltage of the active filter v_{AF} , and thus the active filter acts as a positive resistor of 1.7Ω at the 5th-harmonic frequency.

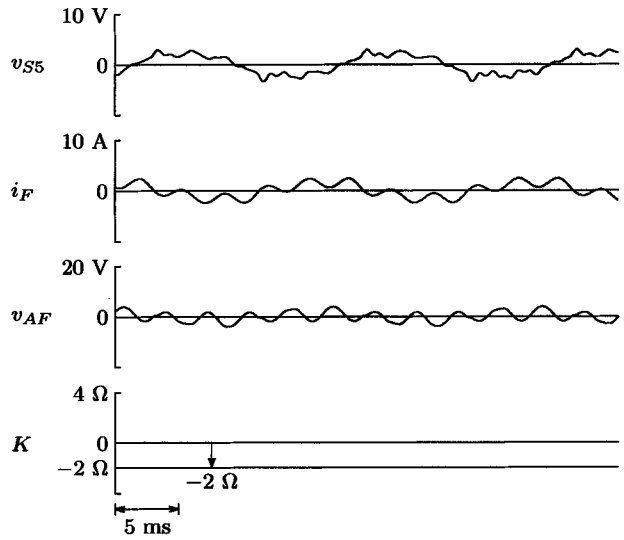


Fig. 14. Close-up of period A in waveforms in Fig. 12.

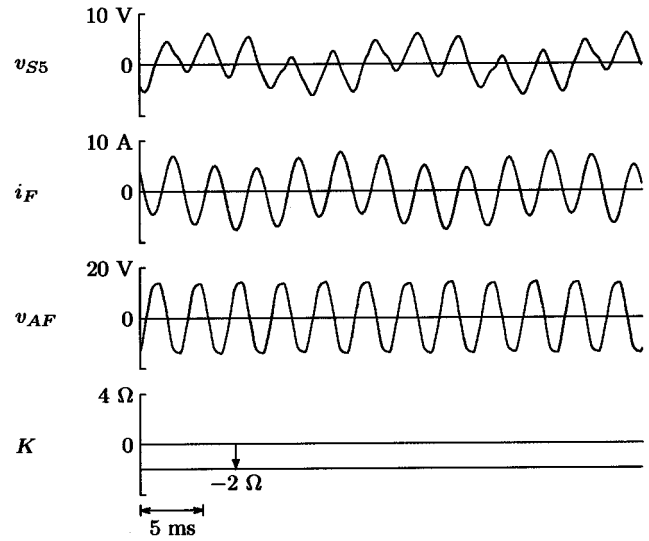


Fig. 15. Close-up of period B in waveforms in Fig. 12.

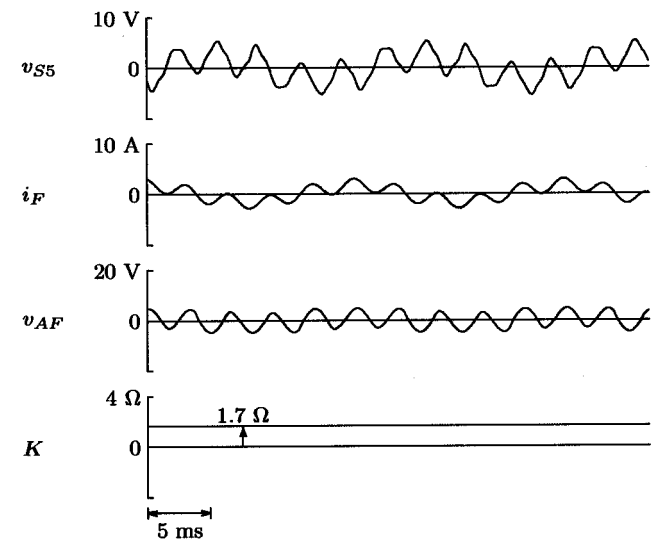


Fig. 16. Close-up of period C in waveforms in Fig. 13.

VII. CONCLUSION

This paper has proposed a hybrid active filter intended for damping of harmonic resonance in industrial power systems. The theoretical analysis and experiment developed in this paper have verified the viability and cost-effectiveness in the hybrid filter. This paper has led to the following conclusions.

- 1) The I_F -detecting method is much better in stability and detection accuracy than the other methods.
- 2) The hybrid filter can reduce the 5th-harmonic voltage appearing on the common bus to one-sixth as low as the passive filter used alone.
- 3) The required rating of the active filter is less than 1% of the rated load.
- 4) The active filter acting as a positive resistor at the 5th-harmonic frequency prevents the passive filter from overcurrent.

The hybrid active filter is expected to be installed in an industrial power system which is subjected to harmonic resonance.

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