

Modern active filters and traditional passive filters

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Abstract. Unlike traditional passive filters, modern active filters have the following multiple functions; harmonic filtering, damping, isolation and termination, reactive-power control for power factor correction and voltage regulation, load balancing, voltage-flicker reduction, and/or their combinations. Significant cost reductions in both power semiconductor devices and signal-processing devices have inspired manufactures to put active filters on the market. This paper deals with general pure active filters for power conditioning, and specific hybrid active filters for harmonic filtering of three-phase diode rectifiers, as well as traditional passive filters.

Key words: active filters, harmonics, passive filters, power quality, power semiconductor devices.

1. Introduction

Since their basic operating principles were firmly established in the 1970s [1–5], active harmonic filters – active filters,¹ for short – have attracted the attention of power electronics researchers/engineers who have had a concern about harmonic pollution in power systems [6–14]. Moreover, deeper interest in active filters has been spurred by

- the emergence of semiconductor switching devices such as IGBTs (insulated-gate bipolar transistors) and power MOSFETs (metal-oxide-semiconductor field-effect transistors), which are characterized by fast switching capability and insulated-gate structure,
- the availability of digital signal processors (DSPs), field-programmable gate arrays (FPGAs), analog-to-digital (A/D) converters, Hall-effect voltage/current sensors, and operational and isolation amplifiers at reasonable cost [15–22].

Modern active filters are superior in filtering performance, smaller in physical size, and more flexible in application, compared to traditional passive filters using capacitors, inductors and/or resistors. However, the active filters are slightly inferior in cost and operating loss, compared to the passive filters, even at present. Active filters intended for power conditioning are also referred to as “active power filters,” “active power line conditioners,” “active power quality conditioners,” “self-commutated SVCs (static var compensators),” etc. The term “power conditioning” used in this paper has much broader meanings than the term “harmonic filtering.” In other words, the power conditioning is not confined to harmonic filtering, but it contains harmonic damping, harmonic isolation, harmonic termination, reactive-power control for power factor correction and voltage regulation, load balancing, voltage-flicker reduction, and/or their combinations.

Active filters can be divided into single-phase active filters and three-phase active filters. Research on single-phase active

filters has been carried out, and the resultant papers have appeared in technical literature. However, single-phase active filters would attract much less attention than three-phase active filters because single-phase versions are limited to low-power applications except for electric traction or rolling stock.

Moreover, the active filters can be classified into pure active filters and hybrid active filters in terms of their circuit configuration. Most pure active filters can use as their power circuit either a voltage-source pulsewidth-modulated (PWM) converter equipped with a dc capacitor or a current-source PWM converter equipped with a dc inductor. At present, the voltage-source converter is more favourable than the current-source converter in terms of cost, physical size and efficiency. Hybrid active filters consist of single or multiple voltage-source PWM converters and passive components such as capacitors, inductors and/or resistors. The hybrid filters are more attractive in harmonic filtering than the pure filters from both viability and economical points of view, particularly for high-power applications [23–33].

This paper describes both pure and hybrid active filters, along with traditional passive filters. These pure and hybrid filters have a wide range of spectrum, ranging from those available in the market to those under research and development. They are based on leading-edge power electronics technology that includes power conversion circuits, power semiconductor devices, analog/digital signal processing, voltage/current sensors, and control theory. In addition, active filters act as a powerful bridge between power electronics and power engineering in electrical engineering. Attention, therefore, is paid to basic circuit configurations and operating principles of pure active filters intended for power conditioning. Then, emphasis is put on the principle, design and filtering performance of low-cost transformerless hybrid filters for harmonic filtering of low- and medium-voltage diode rectifiers. Finally, this paper gives some examples of practical pure and hybrid active filters, including

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¹The term “active filters” are also used in the field of analog signal processing. These active filters usually consist of operational amplifiers, capacitors and resistors. The active filters for power conditioning in this paper are quite different in circuit and principle from the active filters for analog signal processing.

the 300-kVA pure active filter installed in a water-processing plant, and the 21-MVA active filter using the 4.5-kV 1.5-kA IEGTs (injection-enhanced gate transistors) for voltage-flicker reduction of electric arc furnaces.

2. Voltage harmonics in power systems

2.1. Harmonic-producing loads. Nonlinear loads drawing nonsinusoidal currents from three-phase sinusoidal voltages are classified into identified and unidentified loads. High-power diode or thyristor rectifiers, cycloconverters, and arc furnaces are typically characterized as identified harmonic-producing loads, because electric power utilities identify the individual nonlinear loads installed by high-power consumers on power distribution systems in many cases. Each of these loads produces a large amount of harmonic current. The utilities can determine the point of common coupling (PCC) of high-power consumers who install their own harmonic-producing loads on power distribution systems. Moreover, they can determine the amount of harmonic current drawn by an individual consumer.

A “single” low-power diode rectifier produces a negligible amount of harmonic current if it is compared with the system total current. However, multiple low-power diode rectifiers can produce a significant amount of harmonics into the power distribution system. A low-power diode rectifier used as a utility interface in an electric appliance is typically considered as an unidentified harmonic-producing load. So far, less attention has been paid to unidentified loads than identified loads. Harmonic regulations or guidelines such as IEEE 519-1992, IEC61000, etc. are currently applied to keep current and voltage harmonic levels in check. The final goal of the regulations or guidelines is to promote better practices in both power systems and equipment design at the minimum social cost.

2.2. Voltage THD and 5th-harmonic voltages. Tables 1 and 2 show the maximum and minimum values of total harmonic distortion (THD) in voltage and the most dominant 5th-harmonic voltage in a typical power system in Japan, which were measured in October 2001 [34]. Note that Japanese electric utilities have been traditionally introducing three-phase three-wire ungrounded systems without neutral line to their 6.6-kV distribution networks. The individual harmonic voltages and the resulting voltage THD in high-voltage power transmission systems tend to be less than those in the 6.6-kV power distribution system. The primary reason is that the expansion and interconnection of high-voltage power transmission systems has made the systems stiffer with an increase of short-circuit capacity. For the distribution system, the maximum value of 5th-harmonic voltage in a commercial area has exceeded its allowable level of 3%, considering Japanese guidelines, while the maximum voltage THD was marginally lower than its allowable level of 5%.

According to [35], the maximum value of 5th-harmonic voltage in the downtown area of a 6.6-kV power distribution system in Japan exceeds 7% under light-load conditions at night. They also have pointed out another significant phe-

nomenon. The 5th-harmonic voltage increases on the 6.6-kV bus at the secondary of the power transformer installed in a substation, whereas it decreases on the 77-kV bus at the primary, under light-load conditions at night. These observations 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 amplification” as a result of series and/or parallel harmonic resonance between line inductors and shunt capacitors for power-factor correction installed on the distribution system. This implies that not only harmonic compensation, but also harmonic damping is a viable and effective way to solve harmonic pollution in power distribution systems. Hence, electric power utilities should have responsibility for harmonic damping throughout power distribution systems. Individual consumers and end-users are responsible for keeping the harmonic currents produced by their own equipment within specified limits.

Table 1
Voltage THD and 5th-Harmonic Voltage in a High-Voltage Power Transmission System

	Over 154 kV		154–22 kV	
	THD	5th-harm.	THD	5th-harm.
Max	2.8%	2.8%	3.3%	3.2%
Min	1.1%	1.0%	1.4%	1.3%

Table 2
Voltage THD and 5th-Harmonic Voltage in a 6.6-kV Power Distribution System

	6.6 kV			
	Residential		Commercial	
	THD	5th-harm.	THD	5th-harm.
Max	3.5%	3.4%	4.6%	4.3%
Min	3.0%	2.9%	2.1%	1.2%

3. Traditional passive filters

3.1. Circuit configurations. Passive filters consisting of capacitors, inductors and/or resistors can be classified into tuned filters and high-pass filters. They are connected in parallel with nonlinear loads such as diode/thyristor rectifiers, ac electric arc furnaces, and so on. Figures 1 and 2 show circuit configurations of the passive filters on a per-phase base. Among them, the combination of four single-tuned filters to the 5th-, 7th-, 11th- and 13th-harmonic frequencies and a second-order high-pass filter tuned around the 17th-harmonic frequency has been used in a high-power three-phase thyristor rectifier.

Installation of such a passive filter in the vicinity of a nonlinear load is to provide low-impedance paths for specific harmonic frequencies, thus resulting in absorbing the dominant harmonic currents flowing out of the load. The actual value of the low-impedance path for each single-tuned filter is affected by the quality factor of the filter inductor Q , which determines the sharpness of tuning. Usually, a value of Q ranges between 20 and 100 [36]. Although a second-order high-pass filter provides good filtering performance in a wide frequency range, it produces higher fundamental-frequency loss than its corresponding single-tuned filter.

Passive filters have a value-added function of achieving power-factor correction of inductive loads. This function brings an advantage to passive filters in many cases, but not in all cases.

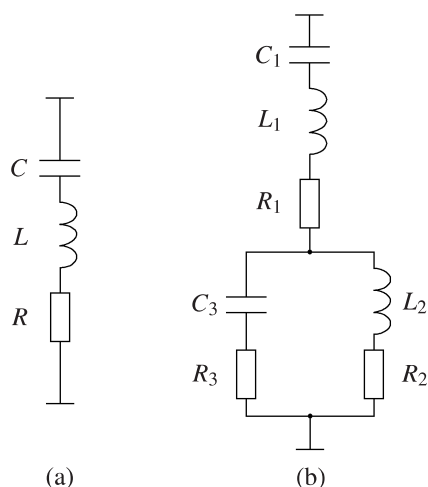


Fig. 1. Passive tuned filters: (a) single tuned, and (b) double tuned

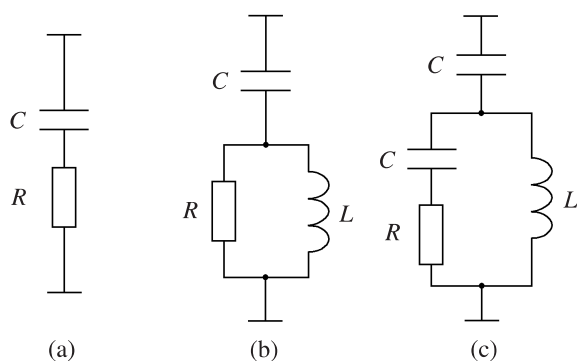


Fig. 2. Passive high-pass filters: (a) first-order, (b) second-order and (c) third-order

3.2. Consideration to installation. The background power system impedance seen upstream of the point of installation of a passive filter can be represented by a simple inductive reactance in a range of low-order harmonic frequencies. Harmonic series and/or parallel resonances between the passive filter and the power system impedance may occur at a lower frequency than each tuned frequency.² Moreover, a passive filter may sink specific harmonic currents from other nonlinear loads on the same feeder and/or from the power system upstream of the passive filter.³ This may make the passive filter overloaded and ineffective. Before installing a passive filter, engineers should make elaborate investigations into the possibility of harmonic resonance and overloading on a case-by-case basis. However, these investigations may be accompanied by relatively high engineering cost.

²See the waveforms of i_S and i_F in Fig. 10 where a severe parallel resonance occurred at the 4th-harmonic frequency before starting the active filter.
³See the waveforms of i_S and i_F in Fig. 11 where some harmonic currents flow from the supply to the passive filter before starting the active filter.

In addition, the final design of a passive filter should allow for component tolerance and variations. For example, initial inductor/capacitor tolerance typically ranges within 5%, and their variations occur due to temperature and other operating conditions [37].

4. Pure active filters for power conditioning

Pure active filters can be classified into shunt (parallel) active filters and series active filters from their circuit configurations. At present, shunt active filters are more preferable than series active filters in terms of form and function, and therefore series active filters are suitable exclusively for harmonic filtering.

4.1. Circuit configurations of shunt and series active filters.

Figure 3 shows a system configuration of a single-phase or three-phase shunt active filter for harmonic-current filtering of a single-phase or three-phase diode rectifier with a capacitive dc load. This active filter is one of the most fundamental system configurations among various types of pure and hybrid active filters. The dc load may be considered as an ac motor driven by a voltage-source PWM inverter in many cases. This active filter with or without a transformer is connected in parallel with the harmonic-producing load. The active filter can be controlled on the basis of the following “feedforward” manner:

- The controller detects the instantaneous load current i_L .
- It extracts the harmonic current i_{Lh} from the detected load current by means of digital signal processing.
- The active filter draws the compensating current i_{AF} ($= -i_{Lh}$) from the utility supply voltage v_S , so as to cancel out the harmonic current i_{Lh} .

Note that the ac inductor L_{ac} , that is installed at the ac side of the diode rectifier, plays an important role in operating the active filter stably and properly.

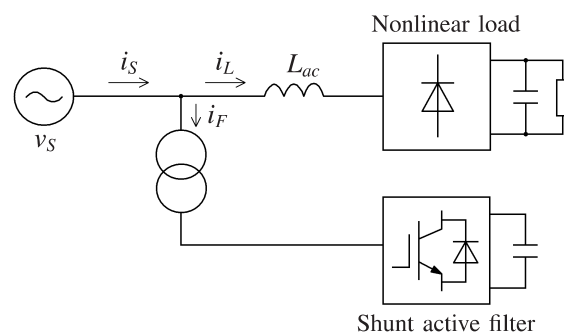


Fig. 3. Single-phase or three-phase shunt active filter

Figure 4 shows a system configuration of a single-phase or three-phase series active filter for harmonic-voltage filtering of a single-phase or three-phase diode rectifier with a capacitive dc load. The series active filter is connected in series with the utility supply voltage through a three-phase transformer or three single-phase transformers. Unlike the shunt active filter,

the series active filter is controlled on the basis of the following “feedback” manner:

- The controller detects the instantaneous supply current i_S .
- It extracts the harmonic current i_{Sh} from the detected supply current by means of digital signal processing,
- The active filter applies the compensating voltage v_{AF} ($= K i_{Sh}$) across the primary of the transformer. This results in significantly reducing the supply harmonic current i_{Sh} when the feedback gain K is set to be enough high.

The above considerations suggest that “dual” relationships exist in some items between the shunt active filter and the series active filter.

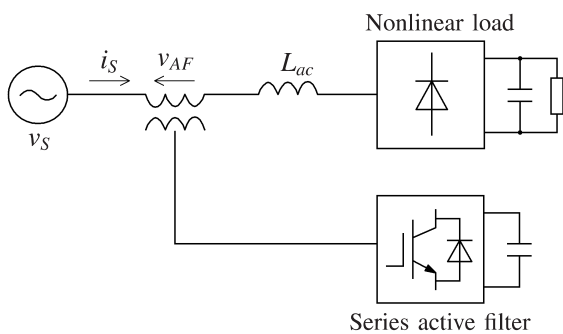


Fig. 4. Single-phase or three-phase series active filter

4.2. Three-phase voltage-source and current-source PWM converters. There are two types of power circuits applicable to three-phase active filters; a voltage-source PWM converter equipped with a dc capacitor, which is shown in Fig. 5 (a), and a current-source PWM converter equipped with a dc inductor, which is shown in Fig. 5 (b). These are similar to the power circuits used for ac motor drives. They are, however, different in their behaviour because active filters act as nonsinusoidal current or voltage sources. The author prefers the voltage-source to the current-source PWM converter because the voltage-source PWM converter is higher in efficiency, lower in cost, and smaller in physical size than the current-source PWM converter, particularly in terms of comparison between the dc capacitor and the dc inductor.

Moreover, the IGBT module that is now available from the market is more suitable for the voltage-source PWM converter because a free-wheeling diode is connected in anti-parallel with each IGBT. This means that the IGBT does not need to provide the capability of reverse blocking in itself, thus bringing more flexibility to device design in a compromise among conducting and switching losses and short-circuit capability than the reverse-blocking IGBT. On the other hand, the current-source PWM converter requires either series connection of a traditional IGBT and a reverse-blocking diode as shown in Fig. 5 (b), or the reverse-blocking IGBT that leads to more complicated device design and fabrication, and slightly worse device characteristics than the traditional IGBT without reverse-blocking capability. In fact, almost all active filters that have been put into practical applications in Japan have adopted

the voltage-source PWM converter equipped with the dc capacitor as the power circuit.

The authors of [22] describe shunt active filters using a voltage-source PWM converter and a current-source PWM converter with focus on their comparisons from various points of view.

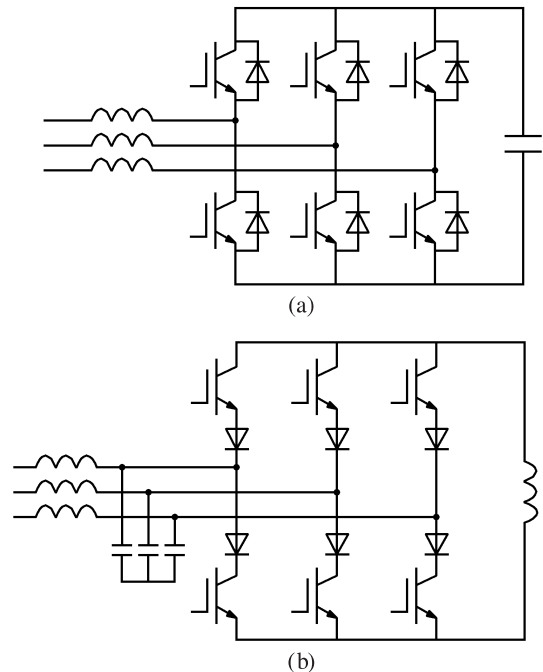


Fig. 5. Power circuits applicable to three-phase active filters: (a) voltage-source PWM converter and (b) current-source PWM converter

4.3. Three-phase pure active filters. Figure 6 shows a detailed circuit configuration of a three-phase shunt active filter. This active filter consists of the following three parts; a three-phase voltage-source PWM converter equipped with a dc capacitor, a control circuit, and a switching-ripple filter. The control circuit is based on a leading-edge digital controller using DSPs, FPGAs, and A/D converters for digital signal processing, together with operational and isolation amplifiers for analog signal processing, and Hall-effect voltage/current sensors. The desirable device characteristics for the active filter can be summarized as follows:

- The voltage-source PWM converter with a current minor loop should provide the capability of controlling the compensating current i_{AF} with a frequency bandwidth up to 1 kHz. This leads to harmonic filtering in a range of the most dominant 5th-harmonic current to the 25th-harmonic current. The carrier frequency of the PWM converter is desirable to be as high as 10 kHz.
- The control circuit should extract the harmonic current i_{Lh} from the detected load current i_L with as small errors as possible in amplitude and phase, not only in steady states but also in transient states. As for three-phase active filters, the instantaneous active and reactive power theory or the so-called “p-q theory,” [9,10], and the d-q transformation [6,30]

are usually applied to their control circuits for harmonic extraction. The p-q theory is required to take the three-phase voltage v in the control circuit, as shown in Fig. 6. The d-q transformation needs a phase-locked-loop (PLL) circuit to synchronize the transformation with the line frequency and phase. Note that the p-q theory comprehends wider concepts than the d-q transformation.

- The small-rated switching-ripple filter designed appropriately should be connected in parallel as close as possible to the voltage-source PWM converter. The task of the small-rated filter is to eliminate switching ripples caused by PWM operation from the compensating current i_F .

The active filter shown in Fig. 6 is still referred to as a “pure active filter,” because the small-rated switching-ripple filter provides no capability of mitigating the dominate 5th- and 7th-harmonic currents produced by the diode rectifier. Forming an appropriate dc-voltage feedback loop enables to build up and regulate the dc voltage without any power supply [13]. (See Fig. 13.)

Generally, the dc capacitor can be considered as an energy storage element from a theoretical point of view. However, the active filter is usually not referred to as an energy storage system from a practical point of view, because the amount of energy stored in the dc capacitor is much smaller than that in a battery or a superconductive magnetic coil. In other words, the difference in terminology between the active filter and the energy storage system does not come from their circuit configuration but depends mainly on whether their energy storage capacity is small or large.

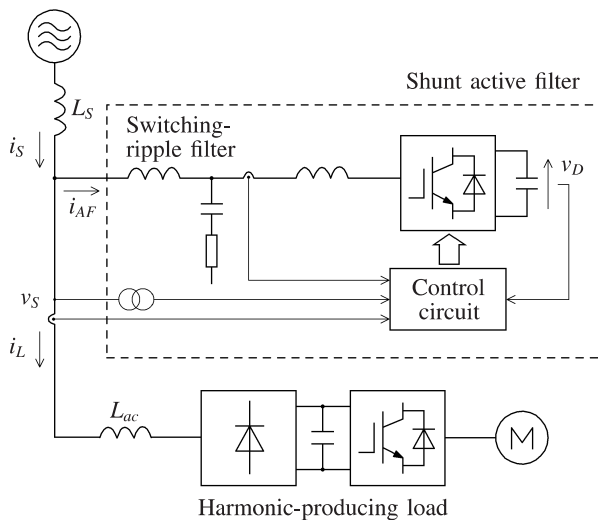


Fig. 6. Single-line system configuration of a three-phase active filter

4.4. Trends in pure active filters. As a result of keen competition in cost and performance among Japanese manufactures, a good market has developed for pure active filters for power conditioning. At present, the pure active filters are becoming affordable due to cost reductions in power semiconductor devices (IGBTs), their auxiliary parts, and integrated digital con-

trol circuits. However, the actual price of active filters on the market depends strongly on purchase conditions.

For example, Fuji Electric in Japan has already put pure active filters in a capacity range of 10 to 400 kVA on the market. An active filter can be directly installed on a low-voltage industrial power system in a voltage range from 200 to 440 V. On the other hand, another active filter requires a step-down transformer when it is installed on a medium-voltage power system. Practical applications of active filters are expanding into and electric power utilities, industry, office-buildings, hospitals, water supply utilities and transportation.

References [38–43] deal with a shunt active filter intended for installation on a power distribution system suffering from harmonic amplification due to series and/or parallel resonances between line inductances and capacitors for power-factor correction. The active filter based on detection of voltage at the point of installation 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 of a radial power distribution feeder, it successfully performs harmonic damping throughout the distribution feeder. 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.

Reference [44] describes a three-phase series active filter consisting of three single-phase H-bridge converters operated at a PWM carrier frequency of 10 kHz, and a small-rated high-frequency dc capacitor. The dc terminals of the active filter is connected to the dc terminals of a three-phase diode rectifier equipped with a dc capacitor, thus forming a common dc capacitor between the active filter and the diode rectifier. Satisfactory filtering performance has been verified by a three-phase experimental system rated at 200 V, 20 kW and 50 Hz.

5. Hybrid active filters for harmonic-current filtering

5.1. Circuit configurations. Two types of hybrid active filters for harmonic-current filtering of nonlinear loads were proposed in 1988 [24] and in 1990 [26], respectively. Figure 7 [24,25] and Fig. 8 [26] show the simplified circuit configurations of the hybrid active filters. The proposal of the two hybrid filters has encouraged power electronics researchers/engineers to do further research on various hybrid active filters, concentrating on their practical use [27–33].

The two hybrid filters are based on combinations of an active filter, a three-phase transformer (or three single-phase transformers), and a passive filter consisting of two single-tuned filters to the 5th- and 7th-harmonic frequencies and a second-order high-pass filter tuned around the 11th-harmonic frequency. Although these hybrid filters are slightly different in circuit configuration, they are almost the same in operating principle and filtering performance. Such a combination with the passive filter makes it possible to significantly reduce the rating of the active filter. The task of the active filter is not to compensate for harmonic currents produced by the thyris-

tor rectifier, but to achieve “harmonic isolation” between the supply and the load [24]. As a result, no harmonic resonance occurs, and no harmonic current flows in the supply.

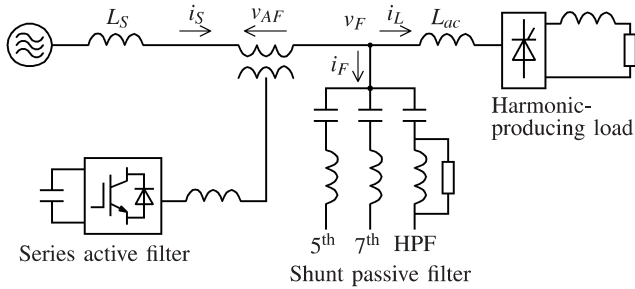


Fig. 7. Combination of a series active filter and a shunt passive filter

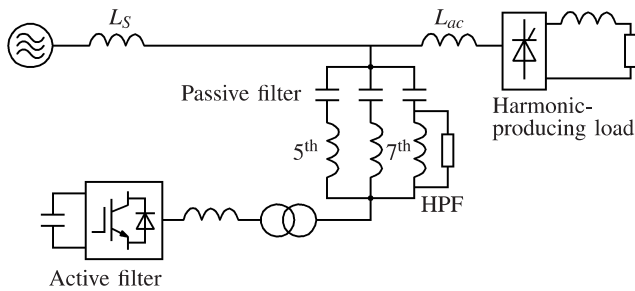


Fig. 8. Series connection of an active filter and a passive filter

5.2. Experimental waveforms. Figures 9 to 11 show experimental waveforms obtained from the hybrid filter shown in Fig. 7. A three-phase six-pulse thyristor rectifier with an inductive dc load was used as a harmonic-producing load. The thyristor rectifier is rated at 200 V, 20 kVA and 50 Hz. From the top of the five waveforms, v_F is the voltage at the terminals of the shunt passive filter, i_S is the supply current, i_F is the current flowing into the passive filter, i_L is the load current, and v_{AF} is the voltage across the series active filter, which was observed in the primary of the transformer, as shown in Fig. 7.

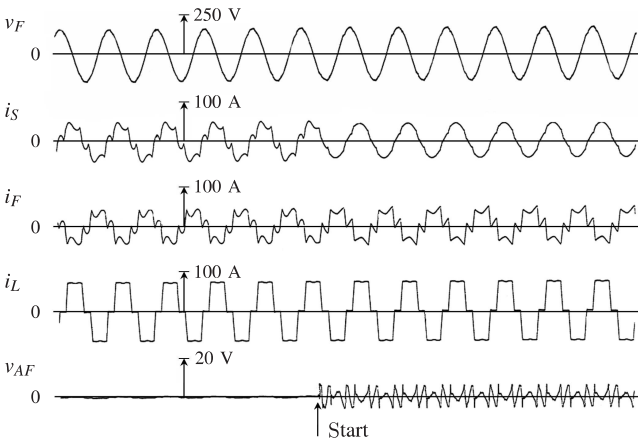


Fig. 9. Experimental waveforms with $L_S = 2\%$ in Fig. 7

Figure 9 shows experimental waveforms on the transient state at the start of the series active filter in the case of $L_S =$

2% on a three-phase 200-V, 20-kVA and 50-Hz base. Before the active filter was started, a large amount of harmonic current still remained in i_S . This means that the “pure” passive filter provides unsatisfactory performance in terms of harmonic-current filtering. After the active filter was started, i_S became almost sinusoidal, showing that the active filter improves the filtering performance of the passive filter.

Figure 10 shows experimental waveforms in the case of $L_S = 5.6\%$. Before the active filter was started, a severe parallel resonance at the 4th-harmonic frequency occurred in the whole system. This resonance significantly amplified a small amount of the 4th-harmonic current in i_L . However, no harmonic resonance appeared after the active filter was started.

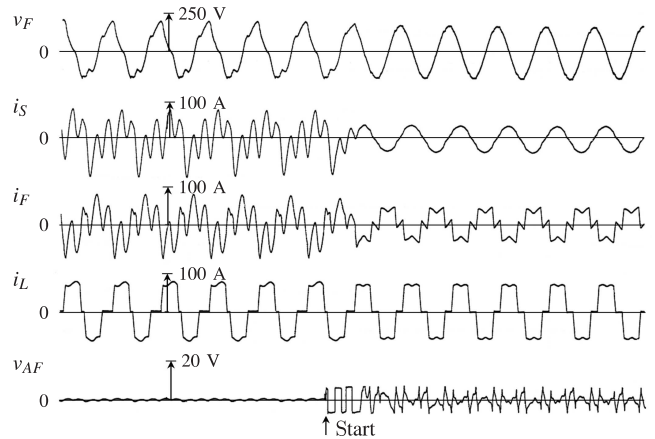


Fig. 10. Experimental waveforms with $L_S = 5.6\%$ in Fig. 7

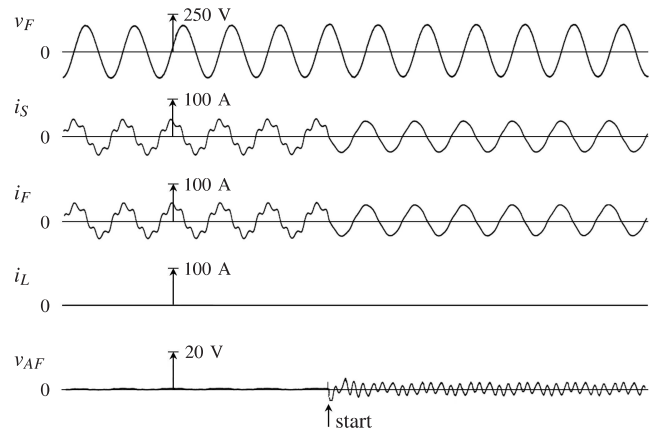


Fig. 11. Experimental waveforms with $L_S = 2\%$ under no-load condition ($i_L = 0$) in Fig. 7

Figure 11 shows experimental waveforms with no load ($i_L = 0$) in the case of $L_S = 2\%$. Although an amount of background harmonic voltage existing upstream of the passive filter was only 1%, the harmonic current contained in i_S reached about 10% before the active filter was started. This means that the passive filter may absorb an unexpected amount of harmonic current from the power system upstream of the passive filter and other nonlinear loads on the same feeder. After the

active filter was started, no harmonic current flowed in the passive filter. Moreover, no harmonic voltage appeared at the terminals of the passive filter because the background harmonic voltage was blocked by the active filter [24].

These hybrid filters provide viable and effective solutions to harmonic-current filtering of high-power thyristor rectifiers. However, they have difficulty in finding a good market because of the necessity of the transformer and the complexity of the passive filter.

6. Low-voltage transformerless hybrid active filters

Adjustable-speed drive systems based on leading-edge voltage-source PWM converters using IGBTs have been used in industrial drives, home appliances, and transportation. In many applications, however, an inverter-driven motor requires neither fast speed response nor regenerative braking. As a result, a three-phase diode rectifier can be used as the front-end converter of the inverter, instead of a three-phase PWM rectifier. The diode rectifier is much more efficient and reliable as well as much less expensive than the PWM rectifier in low- and medium-voltage drive systems. However, the diode rectifier produces a large amount of harmonic currents, and therefore it does not comply with the harmonic guidelines.

This section deals with a low-cost transformerless hybrid active filter [45,47], comparing it with a pure active filter.

6.1. The 480-V hybrid active filter. Figure 12 (a) shows the circuit configuration of a hybrid active filter connected in parallel with a three-phase diode rectifier rated at 480-V and 20 kW [47]. The hybrid filter is directly connected to the 480-V industrial distribution feeder without any transformer. It is designed to reduce the total harmonic distortion (THD) of i_S below 5%. The hybrid filter consists of an active filter based on a 1.6-kVA voltage-source PWM converter with a carrier frequency of 10 kHz, and a 5-kVA passive filter. The passive filter is a three-phase single-tuned filter to the 7th-harmonic frequency with a quality factor of $Q = 22$. The passive filter exhibits poor filtering performance in a range of low-order harmonic frequencies except around the 7th-harmonic frequency.

The passive filter and the active filter are directly connected in series with each other. This “hybrid” configuration results in a dc voltage as low as 105 V across the dc bus of the active filter. Moreover, no switching-ripple filter is required for the hybrid filter because the passive filter presents high impedance around 10 kHz. The diode rectifier has an ac inductor of $L_{ac} = 5\%$ at its ac side. This ac inductor is indispensable to achieve proper operation of the hybrid filter because no inductor is installed on the dc side of the diode rectifier.

Figure 12 (b) shows the control system of the hybrid filter. The control system has the following three control functions; feedback control, feedforward control and dc-voltage control.

The feedback control forces all the harmonic currents contained in i_L to flow into the hybrid filter, whereas it forces no harmonic current to flow from the power system into the hybrid filter. This improves the filtering performance of the pas-

sive filter, and prevents the passive filter from being overloaded and ineffective. Moreover, the feedback control makes the active filter act as a damping resistor for low-order harmonic frequencies, so that no harmonic resonance occurs between the passive filter and the power system inductance L_S . As a result, this hybrid filter gets free from elaborate investigations into the possibility of harmonic resonance and overloading before installing it.

The feedforward control forces the 5th-harmonic current contained in i_L to flow actively into the hybrid filter. The dc-voltage control makes the active filter build up and regulate its dc capacitor voltage by itself without any external power supply. A proportional plus integral (PI) controller is used to do it. Reference [46] describes in detail the control system.

This paper defines the volt-ampere rating required for the active filter in the 480-V hybrid filter as follows:

$$\begin{aligned} P_{HF} &= \sqrt{3} \times \frac{V_{dc}}{\sqrt{2}} \times \frac{I_{Fmax}}{\sqrt{2}} \\ &= \sqrt{3} \times 74^V \times 13.0^A \\ &= 1.6 \text{ kVA}, \end{aligned}$$

where I_{Fmax} is a maximum value of the filter current i_F .

6.2. The 480-V pure active filter. Figure 13 (a) shows a pure active filter integrated into the same diode rectifier as that in Fig. 12 (a). The pure active filter consists of an inductor L_F and a PWM converter that are directly connected in series. Strictly speaking, this inductor is not a filter inductor but an ac inductor. However, it has the same inductance value as the filter inductor L_F in Fig. 12 (a).

The hybrid filter in Fig. 12 (a) can be divided into the following two parts connected with each other: One is the capacitor C_F , and the other is an pure active filter consisting of the inductor L_F and the PWM converter. This means that the hybrid filter in Fig. 12 (a) can be considered as a series connection of the capacitor and the pure active filter.

The pure filter is designed to reduce the total harmonic distortion of i_S below 5%, like the hybrid filter. Unfortunately, this “pure” configuration results in a dc voltage as high as 750 V across the dc bus of the active filter, and so the active filter requires the 1.2-kV, or higher-voltage, IGBT as a power device. The carrier frequency of the pure filter is 10 kHz, which is the same as that of the hybrid filter. The other parameters of the pure filter are the same as those of the hybrid filter. The required rating of the 480-V pure filter, P_{PF} is given by

$$\begin{aligned} P_{PF} &= \sqrt{3} \times 530^V \times 13.7^A \\ &= 12.6 \text{ kVA}. \end{aligned}$$

Figure 13 (b) shows the control system of the pure filter. The control system is almost the same as that of the hybrid filter. The pure filter has the same proportional and integral gains as the hybrid filter. However, the following differences exist, compared to the control system of the hybrid filter:

- The supply voltage v_S is detected and added to the voltage reference of the pure filter, v_{AF}^* , in order to compensate for

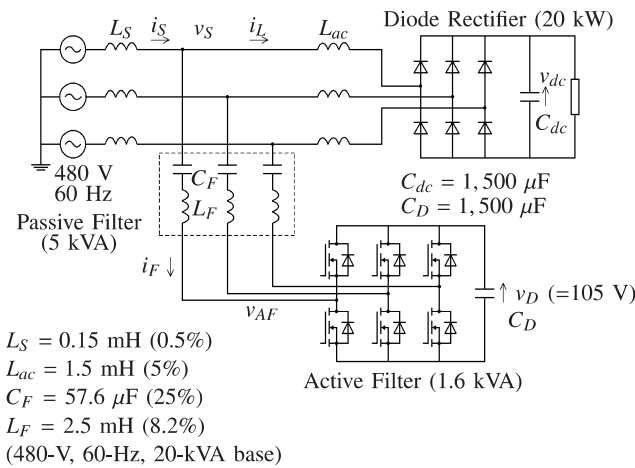
an effect of v_S on current controllability.

- The electrical quantity controlled in the dc voltage control is not Δi_{q1} but Δi_{d1} , because precise adjustment of a small amount of active power enables to regulate the dc voltage of the pure filter.

The feedforward control in the pure filter has the same task as that in the hybrid filter. It calculates the voltage appearing across the ac inductor L_F , assuming that all of the 5th-harmonic current included in the load current flows into the pure filter.

6.3. Design of the 480-V hybrid active filter. The resonant frequency of the passive filter in the hybrid filter is given by

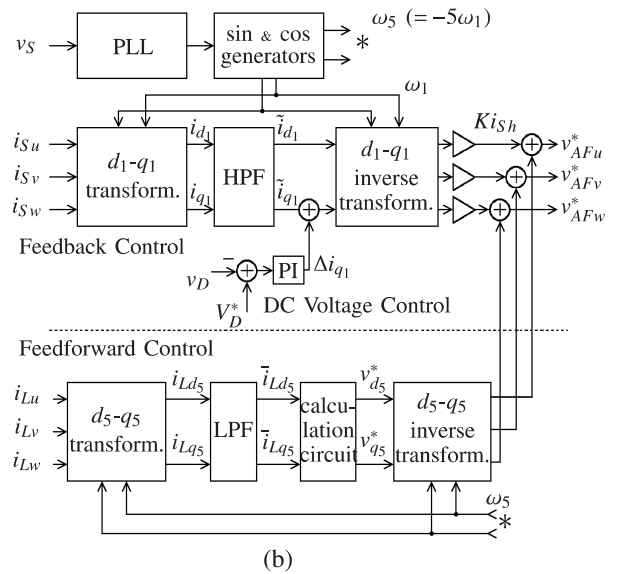
$$f = \frac{1}{2\pi\sqrt{L_F C_F}} \quad (1)$$



(a)

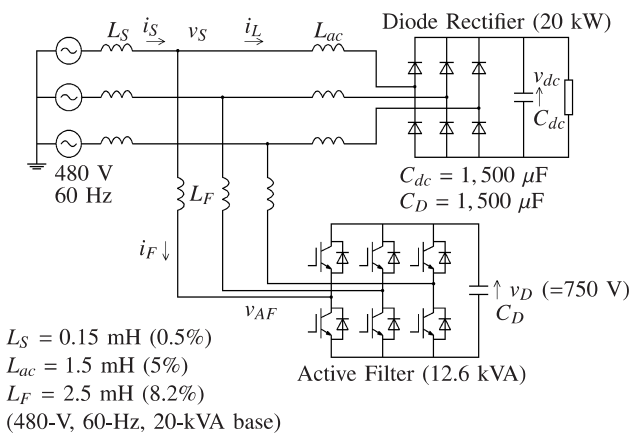
It is a well-known fact that the passive filter presents good filtering characteristics around the resonant frequency. This paper selects not the 5th-harmonic frequency but the 7th-harmonic frequency as the resonant frequency for the following lucid reasons:

- The passive filter tuned to the 7th-harmonic frequency is less expensive and less bulky than that tuned to the 5th-harmonic frequency as long as both filters have the same filter inductor L_F .
- The passive filter tuned to the 7th-harmonic frequency offers less impedance to the 11th- and 13th-harmonic components, compared to that tuned to the 5th-harmonic frequency.
- The feedforward control combined with the feedback control makes a significant contribution to improving the filtering performance at the most dominant 5th-harmonic frequency.

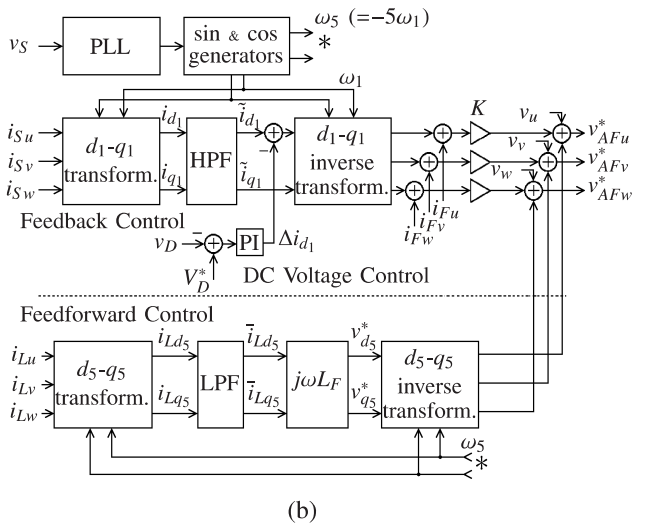


(b)

Fig. 12. The 480-V hybrid active filter: (a) circuit configuration and (b) control system



(a)



(b)

Fig. 13. The 480-V pure active filter: (a) circuit configuration and (b) control system

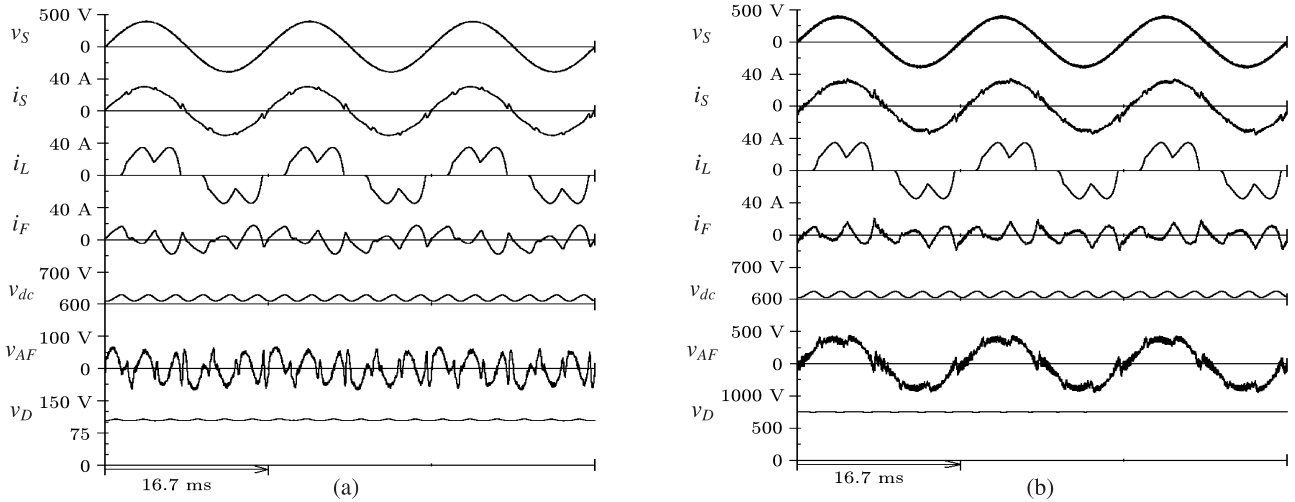


Fig. 14. Simulated waveforms of the 480-V hybrid and pure filters: (a) hybrid filter and (b) pure filter

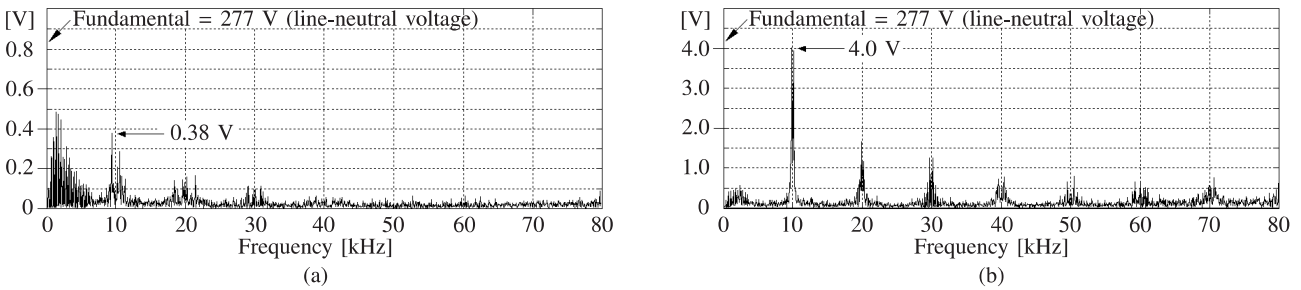


Fig. 15. Spectra (rms) of v_S in the 480-V hybrid and pure filters: (a) hybrid filter and (b) pure filter

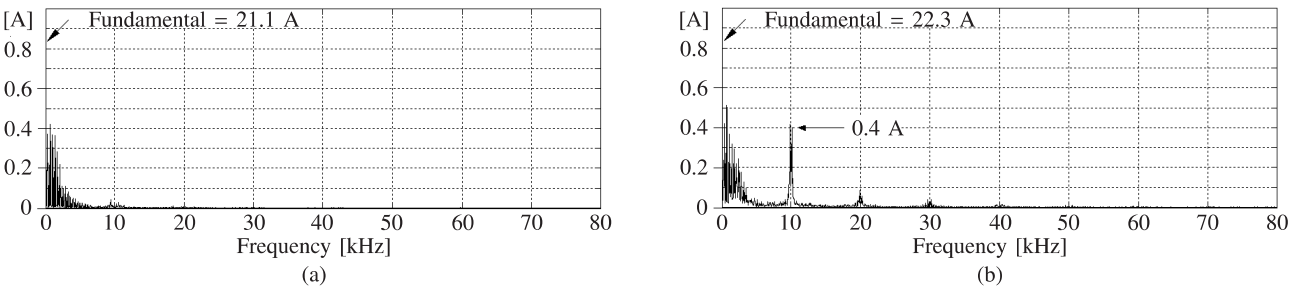


Fig. 16. Spectra (rms) of i_S in the 480-V hybrid and pure filters: (a) hybrid filter and (b) pure filter

The characteristic impedance of the passive filter, Z is given by

$$Z = \sqrt{\frac{L_F}{C_F}} \quad (2)$$

This impedance determines filtering performance at harmonic frequencies except for the resonant frequency. Generally speaking, the characteristic impedance should be as low as possible to obtain better filtering performance. This implies that the capacitance value of C_F should be as large as possible, and the inductance value of L_F should be as small as possible. A lower characteristic impedance reflects a lower dc capacitor voltage as well as lower EMI emissions by the hybrid filter.

This allows the hybrid filter to use low-voltage MOSFETs that are less expensive and more efficient than high-voltage ones. On the other hand, a low characteristic impedance has the following disadvantages:

- A large capacitance value of C_F makes it bulky and expensive.
- A large amount of leading reactive current flows into the hybrid filter.
- A smaller inductance value of L_F increases switching ripples. The ratio of the switching-ripple voltage contained in the supply voltage, v_{Ssw} , with respect to that at the ac side of

the active filter, v_{AFsw} can be calculated under an assumption of $L_S \ll L_{ac}$ as follows:

$$\frac{v_{Ssw}}{v_{AFsw}} \approx \frac{L_S}{L_S + L_F}.$$

Hence, a trade-off or a compromise exists in the design of the characteristic impedance. In other words, the above-mentioned criteria should also be considered when selecting the value of L_F .

6.4. Comparisons between the 480-V hybrid and pure filters. Figure 14 (a) shows simulated waveforms⁴ of the 480-V hybrid filter in a steady state. The feedback gain of the active filter, K is set to 39Ω (340%) so that the hybrid filter provides good stability [46]. The supply current i_S becomes nearly sinusoidal. The dc capacitor voltage of the active filter is set to 105 V. The low-voltage MOSFETs used here are easily available from the market at low cost.

Figure 14 (b) shows simulated waveforms of the 480-V pure filter under the same conditions as Fig. 14 (a). The waveform of i_S is also nearly sinusoidal. Note that the dc capacitor voltage for the 480-V pure filter is observed to be 750 V from computer simulation. This means that the 1.2-kV, or higher-voltage, IGBTs are required as the power devices in the pure-filter configuration.

The following significant difference exists in the waveforms of v_{AF} between Fig. 14 (a) and (b): No fundamental voltage appears across the ac terminals of the active filter in the hybrid filter because the supply voltage v_S is applied across the filter capacitor C_F . On the other hand, the supply line-to-neutral voltage as high as $277 \text{ V} (= 480/\sqrt{3})$ appears in the waveform of v_{AF} in the case of the pure filter. This is an essential difference in operating principle and performance between the hybrid filter and the pure filter.

When attention is paid to switching ripples contained in v_S and i_S of Fig. 14, it is clear that the switching-ripples in the hybrid filter are much smaller than those in the pure filter. Note that no additional switching-ripple filter is installed in both cases. Figure 15 (a) and (b) shows frequency spectra of v_S in the hybrid and pure filters. The 10-kHz ripple voltage contained in v_S is 0.38 V (0.14%) in the hybrid filter, whereas it reaches 4.0 V (1.4%) in the pure filter. Figure 16 (a) and (b) shows frequency spectra of i_S in the hybrid and pure filters. The 10-kHz current ripple present in i_S is small enough to be neglected in the hybrid filter, whereas it reaches 0.4 A (1.8%) in the pure filter [47].

7. The 400-V hybrid active filter

7.1. System configuration. Figure 17 shows the experimental system integrating the 400-V hybrid active filter into the 400-V, 15-kW diode rectifier. This hybrid filter consists of the 0.73-kVA active filter with a PWM carrier frequency of 10 kHz, and the 5-kVA single-tuned passive filter. Both are directly con-

nected in series without transformer. A proportional plus integral (PI) controller can regulate the dc voltage of the active filter to its reference voltage of 80 V.

The capacitor C_F and the inductor L_F were assigned to $100 \mu\text{F}$ and 2 mH, respectively. As a result, their resonant frequency was 356 Hz, that was not equal, but close, to the 7th-harmonic frequency of 350 Hz. The characteristic impedance was 4.5Ω , and the quality factor was 25.

The diode rectifier acting as a nonlinear load produces a large amount of harmonic current, mainly including the 5th- and 7th-harmonic components. The ac inductance L_{ac} (5%), that is connected at the ac side of the diode rectifier, should be designed to be larger than the supply inductance L_S (1.8%), that is an equivalent inductance seen upstream of the point of installation of the hybrid filter. The dc inductor L_{dc} (1%)⁵ is connected to the dc side of the diode rectifier.

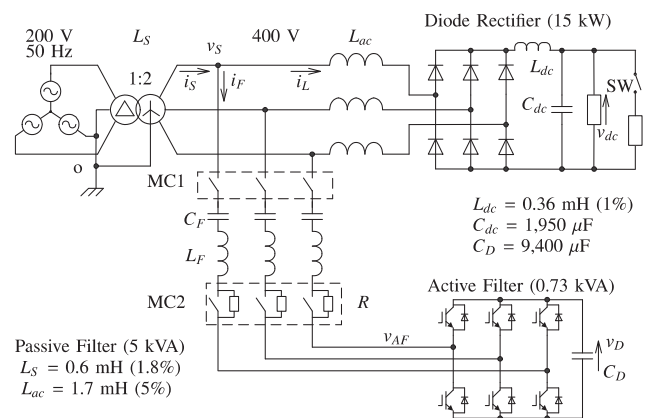


Fig. 17. The 400-V, 15-kW experimental system

7.2. Start-up procedure. Magnetic contactors MC1 and MC2, and a resistor R per phase are used for starting the hybrid filter in Fig. 17. The start-up procedure is as follows:

1. Before starting, the three upper IGBTs of the active filter remained turned on, while the three lower IGBTs remained turned off. The active filter formed a short circuit when it was seen from the ac side. Moreover, both MC1 and MC2 remained turned off.
2. When MC1 was switched on, the hybrid filter was connected to the ac mains through the resistor R , keeping a large amount of in-rush current from flowing into the hybrid filter.
3. After the passage of 12 cycles ($= 240 \text{ ms}$), MC2 was switched on. At this moment, the filter current i_F was transferred from R to MC2. Hence, the hybrid filter was directly connected to the ac mains.
4. After the above-mentioned procedure was completed, the active filter controller started providing PWM gate signals to the six IGBTs, thus building up the dc-capacitor voltage to 80 V by itself.

⁴A first-order low-pass filter with a cut-off frequency of 2 kHz is used to eliminate the switching ripples from v_{AF} , thus making the waveform clear. Note that the low-pass filter for signal processing is integrated into the software package.

⁵Although the dc inductor is connected to the dc side of the rectifier, this per-unit value is on a three-phase, 400-V, 15-kW base, like the other per-unit values.

Table 3

Harmonic currents and THD values with a DC load rated at 15 kW, expressed as the harmonic-to-fundamental current ratio (%)

Passive filter	3rd	5th	7th	11th	13th	17th	19th	23rd	25th	29th	31st	35th	37th	THD
i_S	0.7	32.1	1.4	2.8	2.7	0.9	1.1	0.6	0.5	0.5	0.4	0.3	0.3	32.4
i_L	0.9	25.7	6.8	4.5	3.3	1.3	1.5	0.8	0.7	0.6	0.5	0.3	0.4	27.3
Hybrid filter	3rd	5th	7th	11th	13th	17th	19th	23rd	25th	29th	31st	35th	37th	THD
i_S	0.9	1.0	1.0	1.2	1.4	1.0	0.9	0.8	0.7	0.5	0.5	0.5	0.3	3.6
i_L	1.5	30.8	7.7	4.9	3.2	1.9	1.7	0.9	0.9	0.6	0.5	0.5	0.4	32.5

Figure 18 shows the transient waveforms of the u-phase line-to-neutral supply voltage v_{Su} , and the three-phase passive filter currents i_{Fu} , i_{Fv} and i_{Fw} during the start-up procedure. When MC1 was switched on, the peak in-rush current reached 40 A. When MC2 was switched on, it was 15 A.

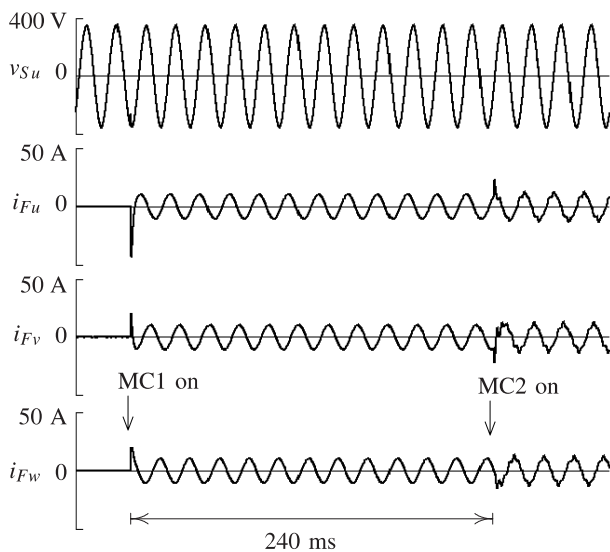


Fig. 18. Experimental waveforms when MC1 and MC2 were turned on with a time difference of 240 ms

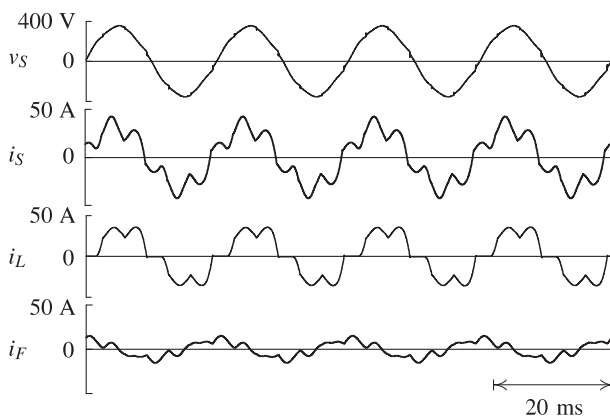


Fig. 19. Experimental waveforms with a dc load rated at 15 kW when the single-tuned passive filter was used alone

7.3. Steady-state performance of the passive filter used alone. Figure 19 shows experimental waveforms with a dc

load rated at 15 kW when the single-tuned passive filter was used alone. Table 3 summarizes harmonic currents and THD values of i_S and i_L , which were obtained from their experimental waveforms. Here, each THD value was calculated up to the 37th-harmonic currents. The THD value of i_L was 27.3%, whereas that of i_S was 32.5%. The most dominant 5th-harmonic current included in i_L was 25.7%, whereas that in i_S was 32.1%. The reason is that installation of the single-tuned passive filter was accompanied by increased supply harmonic currents in a frequency range of 200 to 340 Hz.

7.4. Steady-state performance of the hybrid filter. Figure 20 shows experimental waveforms with a dc load rated at 15 kW when the hybrid filter was used. The feedback gain of the active filter, K was set to 21 Ω (200%). The voltage waveform at the ac side of the active filter, v_{AF} was observed through a first-order low-pass filter with a cut-off frequency of 4 kHz, thus making the waveform clear. The peak voltage of v_{AF} was as low as 50 V because no fundamental voltage was included in v_{AF} , unlike a pure active filter. The dc capacitor voltage was well regulated to its reference voltage of 80 V.

Table 3 indicates that the THD value of i_S was as low as 3.6%, whereas that of i_L was as high as 32.5%. Moreover, each harmonic current contained in i_S was reduced below 2%. These experimental results conclude that the hybrid filter provides satisfactory filtering performance in steady states.

7.5. Transient-state performance of the hybrid filter. Figure 21 shows transient waveforms of the hybrid filter when a step change occurred in the dc load from 15 kW to 10 kW. The supply current i_S was slightly distorted for about 10 ms after the load change occurred. However, such a supply current would not produce any bad effect on other loads connected on the same feeder. The dc voltage of the active filter was well regulated, even during the transient state. The overvoltage appearing in the transient state was as low as 5.2 V, that is 6.5% of 80 V.

8. Medium-voltage transformerless hybrid active filters

Figure 22 shows a possible circuit configuration of a transformerless hybrid active filter applicable to the 6.6-kV 1,000-kW diode rectifier. The 50-kVA active filter uses a three-level diode-clamped PWM converter with a dc voltage of 1.2 kV and a PWM carrier frequency of 10 kHz. The 250-kVA passive fil-

ter is tuned to the 7th-harmonic frequency. The active filter and the passive filter are directly connected in series without transformer. The ac inductor of $L_{ac} = 10\%$ is usually preferred for better current protection than a value of $L_{ac} = 5\%$, particularly in such a medium-voltage diode rectifier.

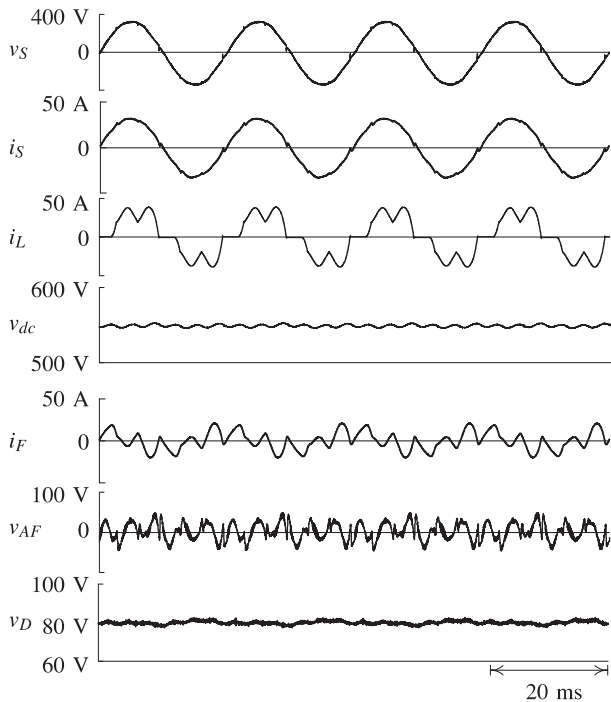


Fig. 20. Experimental waveforms with a dc load rated at 15 kW when the hybrid filter was used

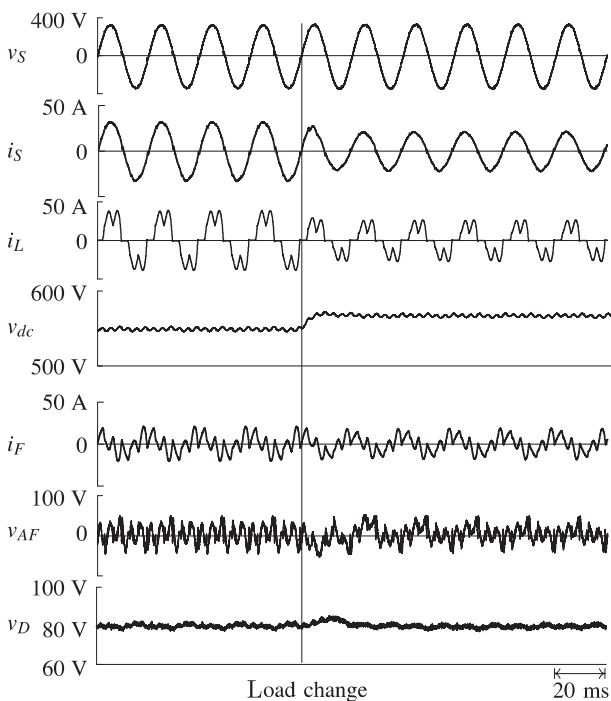


Fig. 21. Experimental waveforms by the hybrid filter when a step load change occurred from 15 kW to 10 kW

⁶This active filter is referred to as a self-commutated SVC (static var compensator) in [52].

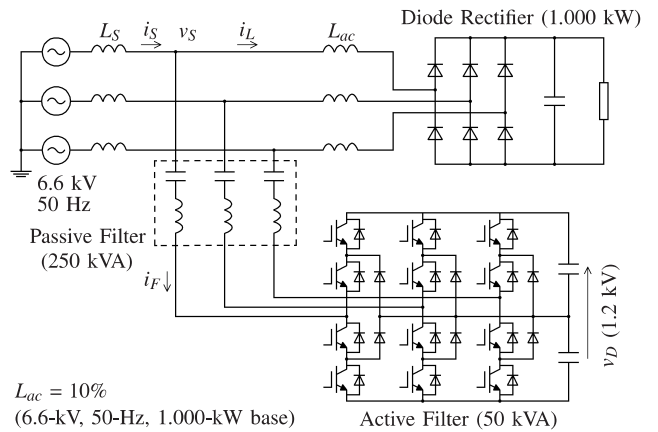


Fig. 22. System configuration of the 6.6-kV transformerless hybrid filter

The 6.6-kV hybrid filter has less flexibility in assigning the dc voltage of the active filter than the 400-V hybrid filter presented in the previous section. In other words, the 6.6-kV hybrid filter imposes the following constraint on its active filter: The dc voltage should be assigned to range from 1,200 to 1,500 V when the three-level converter uses 1.2-kV or 1.4-kV IGBTs. These IGBTs are easily available from the market at reasonable cost. The three-level converter produces less switching ripple and loss, and less EMI emission than the two-level converter when both converters has the same PWM carrier frequency as 10 kHz [48–50].

9. Practical applications of active filters

9.1. Application to harmonic-current filtering. Water supply utilities in Japan have been actively introducing adjustable-speed inverter-driven pumps to their water-processing plants for energy conservation.

Figure 23 shows an example of a practical application of a pure active filter for power conditioning to a water-processing plant. The use of the four inverter-driven pumps brings optimal system operation and energy savings to the plant. However, the inverter-driven pumps draw a large amount of harmonic current, and other inductive and imbalanced loads connected to the same feeder deteriorate power quality. The 300-kVA shunt active filter has been installed at the secondary of the 6.6-kV/440-V transformer rated at 750 kVA. The functions of this active filter are mainly harmonic-current filtering, as well as power-factor correction, and load balancing [51].

9.2. Application to voltage-flicker reduction. Toshiba Mitsubishi-Electric Industrial Systems Corporation (TMEIC) in Japan has developed a 21-MVA active filter⁶ using 4.5-kV 1.5-kA IEGTs (injection-enhanced gate transistors) for voltage-flicker reduction of two ac arc furnaces [52]. Each IEGT has a press package with a diameter of 125 mm, and it is based on leading-edge semiconductor technology. It may be considered as an advanced IGBT in terms of device structure and characteristics. The IEGT leg in each phase is one

third the physical size of its corresponding GTO (gate-turn-off thyristors) leg. Moreover, the IEGT-based active filter has lower power loss by 50% than the GTO-based active filter. The IEGTs used here are planar-gate devices. Toshiba will soon release a trench-gate version of the IEGT that has lower conducting and switching losses [45].

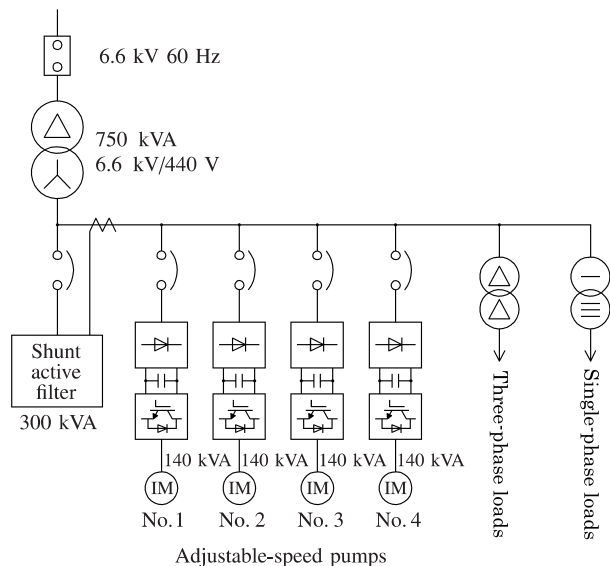


Fig. 23. Single-line diagram of water-processing plant in water supply utility

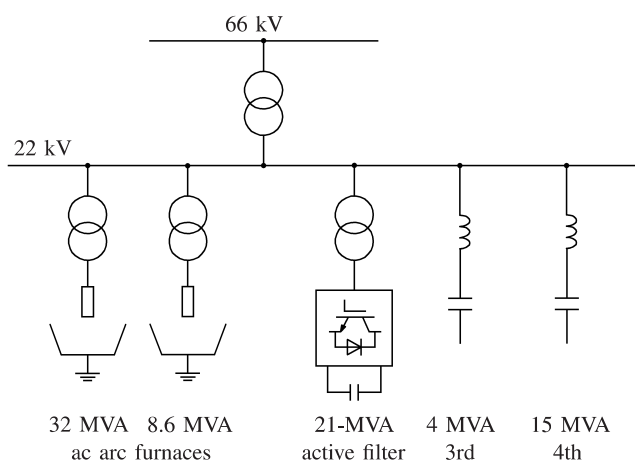


Fig. 24. Single-line diagram of the whole system including ac arc furnaces, along with active and passive filters

Figure 24 shows the simplified single-line diagram of the whole system including two ac arc furnaces, the active filter, and two single-tuned filters to the 3rd- and 4th-harmonic frequencies. The two arc furnaces draw a reactive current, a negative-sequence current and low-order harmonic currents from the 22-kV bus. All the currents fluctuate with time. In collaboration with the two single-tuned filters, the active filter compensates for the randomly-fluctuating reactive, negative-sequence, and harmonic currents.

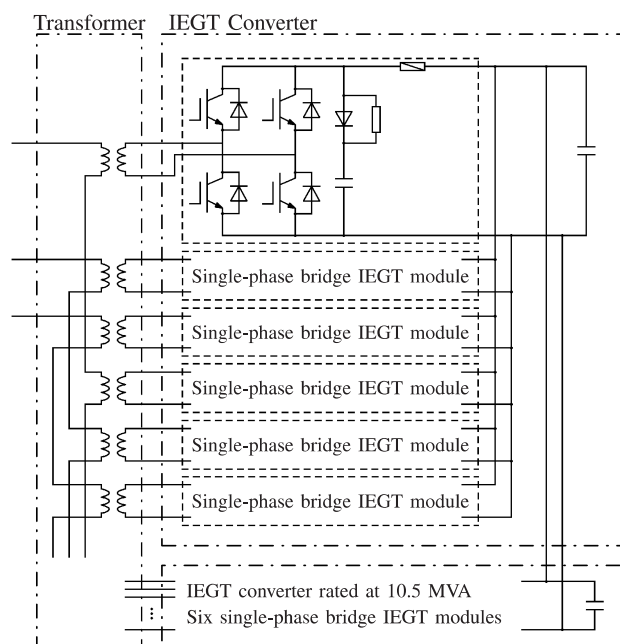


Fig. 25. Circuit configuration of the 21-MVA shunt active filter

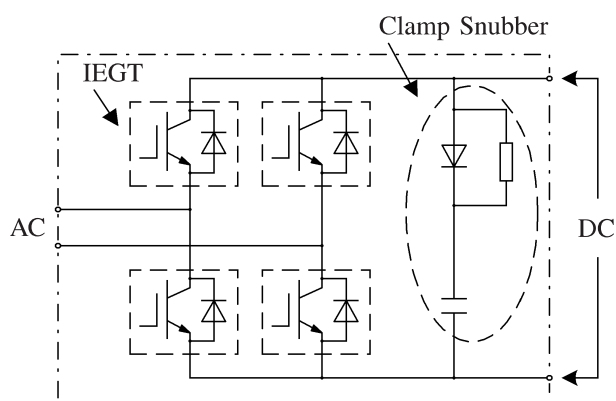


Fig. 26. Circuit configuration of each IEGT converter

Figure 25 shows the detailed circuit configuration of the 21-MVA active filter consisting of 12 single-phase H-bridge converters and a transformer with multi-windings.

Figure 26 shows the detailed circuit configuration of each single-phase H-bridge converter. Neither turn-on nor turn-off snubber is required for each IEGT. However, each IEGT leg needs a simple and efficient clamp snubber that is connected between the positive and negative buses. The carrier frequency of PWM is 390 Hz.

Table 4 summarizes the ratings of the active filter. The symbol “1S-1P-2L” means the one-series, one-parallel, two-leg configuration. In other words, the single-phase H-bridge converter consists of four IEGTs with neither series nor parallel connection. The total number of the IEGTs used here is 48, so that the MVA rating per power switching device is 0.44 MVA/device [53].

Japan has been using the so-called “ $\Delta V10$ ” as an index for evaluating voltage flicker. This index considers the sensitivity

of human eyes to flicker frequencies with the largest weight assigned to flicker at 10 Hz. When the active filter was disconnected, the maximum value of the ΔV_{10} was 1.3 V. When the active filter was operated, it was reduced to 0.5 V [52]. Note that these values of the ΔV_{10} are referred to 100 V. The active filter made a significant contribution to mitigating the voltage flicker caused by the arc furnaces to acceptable levels.

Table 4
Ratings and specifications of the 21-MVA shunt active filter

Power device	IEGT 4.5 kV-1.5 kA
Capacity	21 MVA
Converter configuration	(1S-1P-2L) \times 3 \times 4
Rated dc voltage	2.500 V
Rated ac voltage	1.350 V
Rated ac current	1.296 A
Carrier frequency	390 Hz

10. Conclusions

Active filters based on leading-edge power electronics technology can be classified into pure active filters and hybrid active filters. The reader may ask the following simple question in his/her mind, "Which is preferred, a pure active filter or a hybrid active filter?" Fortunately or unfortunately, engineering has no versatile techniques in terms of cost and performance, and it is based on a compromise or a trade-off between cost and performance. Therefore, a comprehensive answer of the author to the question depends strongly on the function(s) of active filters intended for installation.

A pure active filter provides multiple functions such as harmonic filtering, damping, isolation and termination, load balancing, reactive-power control for power-factor correction and voltage regulation, voltage-flicker reduction, and/or their combinations. A cluster of the above functions can be represented by "power conditioning." Hence, the pure active filter is well suited to "power conditioning" of nonlinear loads such as electric ac arc furnaces, and utility/industrial distribution feeders. On the other hand, a hybrid active filter consists of an active filter and a single-tuned filter that are directly connected in series without transformer. This hybrid filter is exclusively devoted to "harmonic filtering" of three-phase diode rectifiers, because it has no capability of reactive-power control from a practical point of view although it has from a theoretical point of view.

Some manufactures have already put active filters for power conditioning on the market. However, they should strive for cost reductions, as well as better filtering performance and higher efficiency, to compete well with traditional passive filters. In addition to the harmonic guidelines or recommendations, sincere efforts by the manufactures would accelerate installation of active filters in the vicinity of nonlinear loads. This in turn would bring greater cost reductions to the active filters due to the economy of large-scale production. Constituting such a positive feedback loop would encourage wide acceptance of the active filters, resulting in solving harmonic pollution and improving power quality.

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