

Active Filters and Energy Storage Systems for Power Conditioning in Japan

Hirofumi Akagi, *Fellow, IEEE*

Department of Electrical and Electronic Engineering Tokyo Institute of Technology
2-12-1 O-okayama, Meguro-ku, Tokyo, 152-8554, JAPAN
Tel./Fax: +81-3-5734-3549, e-mail: akagi@ee.titech.ac.jp

Abstract – This paper describes advanced power electronics technology relevant to active filtering and energy storage for the purpose of power conditioning. The combination of active filtering and energy storage leads to a versatile system in terms of power conditioning. However, energy storage is much more difficult and costly in realization than active filtering because modern science offers only chemical action, electromagnetic or electrostatic field, and kinetic or potential energy as viable ways of energy storage. The author cannot survey the whole spectrum of active filtering and energy storage. Therefore, this paper is focused on the present status of active filters for power conditioning, along with a 200-MJ/20-MW flywheel energy storage system which has been commercially installed on a 66-kV power system for the purpose of line-frequency regulation in Japan.

Index Terms – Active filtering, energy storage, power conditioning, power conversion, power electronics, power quality.

I. INTRODUCTION

Over the last ten years, great leaps have been made in power electronics, in conjunction with microcomputers and digital signal processors (DSPs) brought by microelectronics.

Power electronics is now developing by leaps and bounds without saturation into the key technology essential to modern society and human life, as well as to electrical engineering. Generally, developments in power electronics yield needs of power electronics, so that the needs induce the developments in turn, as if to constitute a positive feedback system.

Recent remarkable progress in the capacity and switching speed of power semiconductor devices such as insulated gate bipolar transistors (IGBTs) has spurred interest in active filters for power conditioning. Since their basic compensation principles were proposed around 1970 [1]–[7], much research has been done on active filters and their practical applications. In addition, state-of-the-art power electronics technology has enabled to put active filters into practical use. More than one thousand sets of active filters consisting of voltage-source PWM inverters using IGBTs are operating successfully in Japan.

The term “power conditioning” has the following broad meanings in power systems [8]: reactive power

compensation, harmonic compensation, harmonic isolation, harmonic damping, harmonic termination, negative sequence/flicker compensation, voltage regulation, and/or frequency regulation. An active filter consisting of a voltage-source PWM inverter and a dc capacitor has the function of power conditioning. 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 as to 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 active filters and energy storage systems does not come from their circuit topology but depends on whether their energy storage capacity is small or large. For instance, when a current-source PWM inverter is used as an interface circuit between a utility grid and a dc inductor, this entire equipment is referred to as an “active filter” as long as it pays attention to an instantaneous active power with a frequency higher than 1 Hz.

When a superconductive magnetic coil takes the place of the dc inductor, this entire device is referred to as an “energy storage system,” because it provides the function of load leveling over a period range from one hour to one day.

The author attempts to individually deal with active filters and energy storage systems sharing a common base in advanced power electronics technology. This would make their functions clear, as well as would avoid their confusion.

Thus, this paper presents the present status of active filters for power conditioning, with emphasis on system configurations, control strategies, practical applications and research trends, and then describes a 200-MJ/20-MW flywheel energy storage system for line-frequency regulation of the 132-kV power system. In addition, the paper provides the future prospects and directions of active filters and energy storage systems in the 21st century, including the personal views and expectations of the author.

II. THEORETICAL BRIDGE BETWEEN ACTIVE FILTERING AND ENERGY STORAGE

A. The Theory of Instantaneous Power in Three-Phase Circuits

The theory of instantaneous power in three-phase circuits is referred to as the ‘‘Akagi-Nabae theory’’ or the ‘‘p-q theory’’ [9]. Fig. 1 shows a three-phase three-wire system on the a-b-c coordinates, where no zero-sequence component is included in the three-phase three-wire system. Applying the so-called three-to-two-phase transformation to Fig. 1 can transform three-phase voltages and currents on the a-b-c coordinates into two-phase voltages and currents

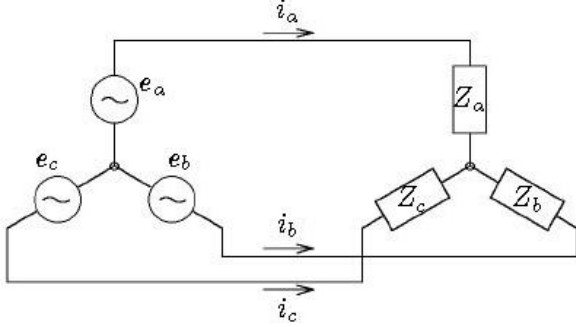


Fig. 1. Three-phase three-wire system.

on the α - β coordinates, as follows;

$$\begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} = \frac{\sqrt{3}}{2} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{\sqrt{3}}{2} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2)$$

As it is well known, the instantaneous real power either on the a-b-c coordinates or on the α - β coordinates is defined by

$$p = e_a i_a + e_b i_b + e_c i_c = e_\alpha i_\alpha + e_\beta i_\beta \quad (3)$$

To avoid confusion, p is referred to as three-phase instantaneous real power. According to the Akagi-Nabae theory [9], the three-phase instantaneous imaginary power, q is defined by

$$q = e_\alpha i_\beta - e_\beta i_\alpha \quad (4)$$

The combination of the above two equations bears the following basic formulation:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (5)$$

Here, $e_\alpha i_\alpha$ or $e_\beta i_\beta$ obviously means instantaneous power because either is defined by the product of the instantaneous voltage in one phase and the instantaneous current in the same phase. Therefore, p

has a dimension of [W]. Conversely, neither $e_\alpha i_\beta$ nor $e_\beta i_\alpha$ means instantaneous power because either is defined by the product of the instantaneous voltage in one phase and the instantaneous current in the other phase. Accordingly, q is quite different from p in dimension and electric property although q looks similar in formulation to p . A common dimension for q should be introduced from both theoretical and practical points of view. The author proposes a new dimension of [IW], that is, ‘‘imaginary watt.’’

Equation (5) is changed into the following equation:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p \\ q \end{bmatrix} \quad (6)$$

Note that the determinant with respect to e_α and e_β in (5) is not zero. The instantaneous currents on the α - β coordinates, i_α and i_β are divided into two kinds of instantaneous current components, respectively:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} p \\ 0 \end{bmatrix} + \begin{bmatrix} e_\alpha & e_\beta \\ -e_\beta & e_\alpha \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ q \end{bmatrix} \quad (7)$$

$$= \begin{bmatrix} i_{\alpha p} \\ i_{\beta p} \end{bmatrix} + \begin{bmatrix} i_{\alpha q} \\ i_{\beta q} \end{bmatrix}$$

Let the instantaneous powers in the α -phase and the β -phase be p_α and p_β , respectively. They are given by the conventional definition as follows:

$$\begin{bmatrix} p_\alpha \\ p_\beta \end{bmatrix} = \begin{bmatrix} e_\alpha i_\alpha \\ e_\beta i_\beta \end{bmatrix} = \begin{bmatrix} e_\alpha i_{\alpha p} \\ e_\beta i_{\beta p} \end{bmatrix} + \begin{bmatrix} e_\alpha i_{\alpha q} \\ e_\beta i_{\beta q} \end{bmatrix} \quad (8)$$

The three-phase instantaneous real power, p is given as follows, by using (7) and (8):

$$p = p_\alpha + p_\beta = \frac{e_\alpha^2}{e_\alpha^2 + e_\beta^2} p + \frac{e_\beta^2}{e_\alpha^2 + e_\beta^2} p + \frac{-e_\alpha e_\beta}{e_\alpha^2 + e_\beta^2} q + \frac{e_\alpha e_\beta}{e_\alpha^2 + e_\beta^2} q \quad (9)$$

The sum of the third and fourth terms of the right-hand side in (9) is always zero. From (8) and (9), the following equations are obtained:

$$p = e_\alpha i_{\alpha p} + e_\beta i_{\beta p} \equiv p_{\alpha p} + p_{\beta p} \quad (10)$$

$$0 = e_\alpha i_{\alpha q} + e_\beta i_{\beta q} \equiv p_{\alpha q} + p_{\beta q} \quad (11)$$

Inspection of (10) and (11) leads to the following essential conclusions:

- The sum of the power components, $p_{\alpha p}$ and $p_{\beta p}$, coincides with the three-phase instantaneous real power, p , which is given by (3). Therefore, $p_{\alpha p}$ and $p_{\beta p}$ are referred to as the α -phase and the β -phase instantaneous active powers.

III. SHUNT HYBRID AND PURE ACTIVE FILTERS

An inverter-driven motor requires neither fast speed response nor regenerative braking in many applications. As a result, a three-phase diode rectifier can be used as an ac-to-dc power converter, 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.

However, the diode rectifier produces a large amount of harmonic currents, and therefore it does not comply with the harmonic guidelines.

A. System Configurations

Fig. 3 shows a hybrid active filter integrated with a three phase six-pulse diode rectifier rated at 20 kW, which is directly connected to the 480-V line-to-line voltage system without any transformer [11][12]. The hybrid filter is designed to reduce the total harmonic distortion (THD) of i_s below 5%. The hybrid filter consists of a 1.6-kVA PWM inverter with a switching or carrier frequency of 10 kHz and a 5-kVA passive filter. It is connected in parallel with the 20-kW diode rectifier. The passive filter is a three-phase LC filter tuned at the 7th-harmonic frequency, through which i_F flows. The quality factor Q is set to 22. The LC filter and the PWM inverter are directly connected in series with each other. This “hybrid” configuration allows the inverter to have the dc voltage as low as 105 V. Moreover, no switching-ripple filter is required for the hybrid filter because the LC filter presents high impedance around 10 kHz.

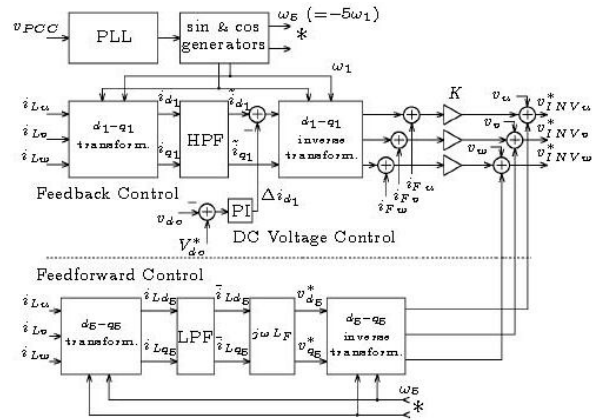


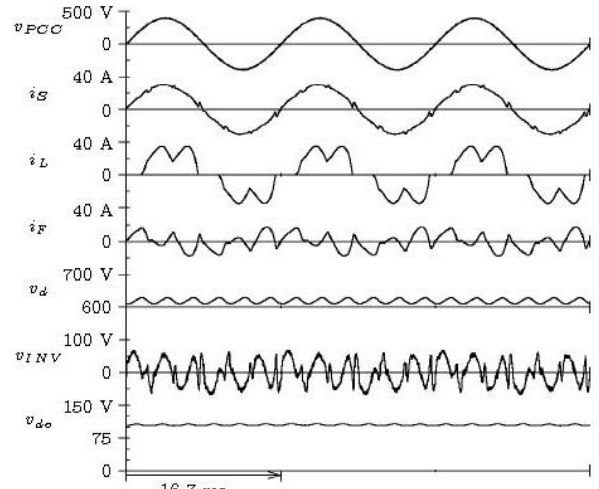
Fig. 6. Control system for the pure filter.

The ac inductance L_{AC} is designed to be 5% in order to prevent a large amount of fault current from flowing into the diode rectifier.

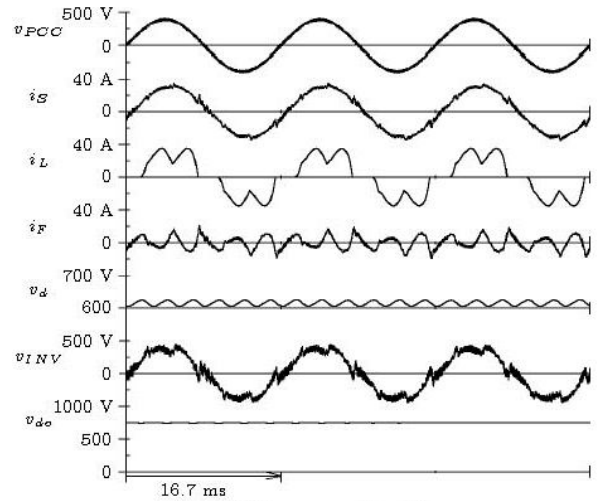
Fig. 4 shows the control system of the hybrid filter. The LC filter exhibits poor filtering characteristics in a range of low-order harmonic frequencies except around the 7th harmonic frequency. The PWM inverter is controlled in such a way as to mainly make the

5th-harmonic current in i_i flow into the hybrid filter, thus improving poor filtering characteristics of the LC filter when used alone. The feedforward control for the 5th-harmonic frequency is combined with the feedback control in Fig. 4. In addition, the PWM inverter can build up and regulate its dc capacitor voltage by itself without any external energy source. A proportional plus integral (PI) controller is used to do it.

Fig. 5 shows a pure active filter integrated with the same diode rectifier as that in Fig. 3. The pure filter is connected in parallel with the diode rectifier rated at 20 kW. It consists of the inductor L_F and a PWM inverter that are directly connected in series. Strictly speaking, this inductor is not a filter inductor but an ac-link inductor. However, it has the same inductance value as the filter inductor L_F in Fig. 3. It is worth noting the following consideration relevant to the circuit configurations shown in Figs. 3 and 5:



(a) The hybrid active filter



(b) The pure active filter

Fig. 7. Comparisons in waveform between the hybrid filter and the pure filter.

The hybrid filter can be divided into the following

two parts coupled with each other: One is the capacitor C_F , and the other is the pure filter consisting of the inductor L_F and the PWM inverter. This means that the hybrid filter in Fig. 3 can be considered as a series-connected capacitor and pure filter.

The pure filter in Fig. 5 is designed to reduce the total harmonic distortion of i_s below 5% like the hybrid filter.

This “pure” configuration makes the PWM inverter have the dc voltage as high as 750 V, so that the inverter requires 1.2-kV, or higher-voltage, IGBTs as power devices. The switching or carrier frequency of the pure filter is 10 kHz, which is the same as that of the hybrid filter. The other 4 parameters of the pure filter are the same as those of the hybrid filter.

TABLE I
HARMONIC COMPONENTS CONTAINED IN LOAD AND SUPPLY CURRENTS IN PERCENT OF FUNDAMENTAL CURRENT

	5th	7th	11th	13th	17th	19th	THD
i_L	31.4	9.2	6.6	3.4	2.5	1.9	33.9
i_s (Fig.7(a))	1.7	1.0	1.9	1.7	1.9	1.5	4.9
i_s (Fig.7(b))	0.8	1.7	2.1	1.6	1.2	1.5	4.9

Fig. 6 shows the control system of the pure filter. The control system is almost the same as that of the hybrid filter. The proportional and integral gains are the same as the hybrid filter. However, the following differences from the control system of the hybrid filter exist:

- The voltage at the point of common coupling, v_{PCC} is detected and added to the inverter voltage reference v_{INV} , in order to compensate for an effect of v_{PCC} on current controllability.

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

B. Comparisons between Hybrid and Pure Filters

Fig. 7 (a) shows simulated waveforms of the hybrid filter in steady state. The feedback gain of the PWM inverter, K is set to 39Ω so that the hybrid filter provides good stability. The waveform of v_{INV} contains a large amount of switching-ripple voltage that is caused by pulse-width modulation. Thereby, a first-order low-pass filter with a cut-off frequency of 2 kHz is used to eliminate the switching ripples from v_{INV} , thus making the waveform clear. Note that the low-pass filter for signal processing is integrated with the software package. The supply current i_s becomes a nearly-sinusoidal waveform. According to Fig. 5, the inverter dc capacitor voltage is set to 105 V, thus resulting in good filtering characteristics. The low-voltage MOSFETs used as switching devices are easily available in the market.

Fig. 7 (b) shows simulated waveforms of the pure filter under the same conditions as Fig. 7 (a). The

waveform of i_s in this case is also nearly sinusoidal. Note that the dc capacitor voltage of the PWM inverter in the pure filter is set to 750 V from a result of having achieved computer simulation. This means that the 1.2-kV, or higher-voltage, IGBTs are indispensable as the switching devices.

Table I summarizes the supply current THD and the ratio of each harmonic current with respect to the fundamental current. The THD value is calculated for harmonics up to the 31st order. The THD of i_L reached 33.9% because it contains a large amount of the 5-th harmonic current. On the other hand, when the hybrid filter is integrated, the THD of i_s decreases to 4.9%. Like the hybrid filter, the pure filter reduces the THD value to 4.9%.

The following significant difference exists in v_{INV} between Fig. 7 (a) and (b): No fundamental voltage is included in the waveform of v_{INV} in the hybrid filter because the voltage at the point of common coupling, v_{PCC} is applied across the filter capacitor C_F . On the other hand, the supply phase voltage as high as 277 V ($=480/\sqrt{3}$) is included in the waveform of v_{INV} in 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_{PCC} and i_s of Fig. 7 (a) and (b), it appears that the switching ripples in the hybrid filter are smaller than those in the pure filter. Note that no additional switching-ripple filter is installed in each case.

IV. AN INTEGRATED SERIES ACTIVE FILTER

A harmonic current-free ac/dc power conversion system integrates a series active filter with a diode rectifier. It takes both practical and economical advantages in high-power applications. Hence, it is expected to be used as a utility interface with large industrial inverter based loads such as multiple adjustable speed drives and uninterruptible power supplies in the range of 1—10 MW.

A. System Configuration

Fig. 8 shows a harmonic current-free ac/dc power conversion system which consists of a combination of a large rated double-series diode rectifier and a small-rated series active filter [13][14]. The ac terminals of a single-phase H-bridge voltage-source PWM inverter are connected in “series” with a power line through a single-phase matching transformer, so that the combination of the matching transformers and the PWM inverters forms the “series” active filter. For small to medium-power systems, it is economically practical to replace the three single-phase inverters with a single three-phase inverter using six IGBTs. The primary windings of the Y- Δ and Δ - Δ connected transformers are connected in “series” with each other,

so that the combination of the three-phase transformers and two three-phase diode rectifiers forms the “double-series” diode rectifier which is characterized as a three-phase twelve-pulse rectifier. The dc terminals of the diode rectifier and the active filter form a common dc bus equipped with an electrolytic capacitor. This results not only in eliminating any electrolytic capacitor from the active filter but also in reducing current ripples flowing into the electrolytic capacitor across the common dc bus.

B. Operating Principle

Fig. 9 shows an equivalent circuit for the power

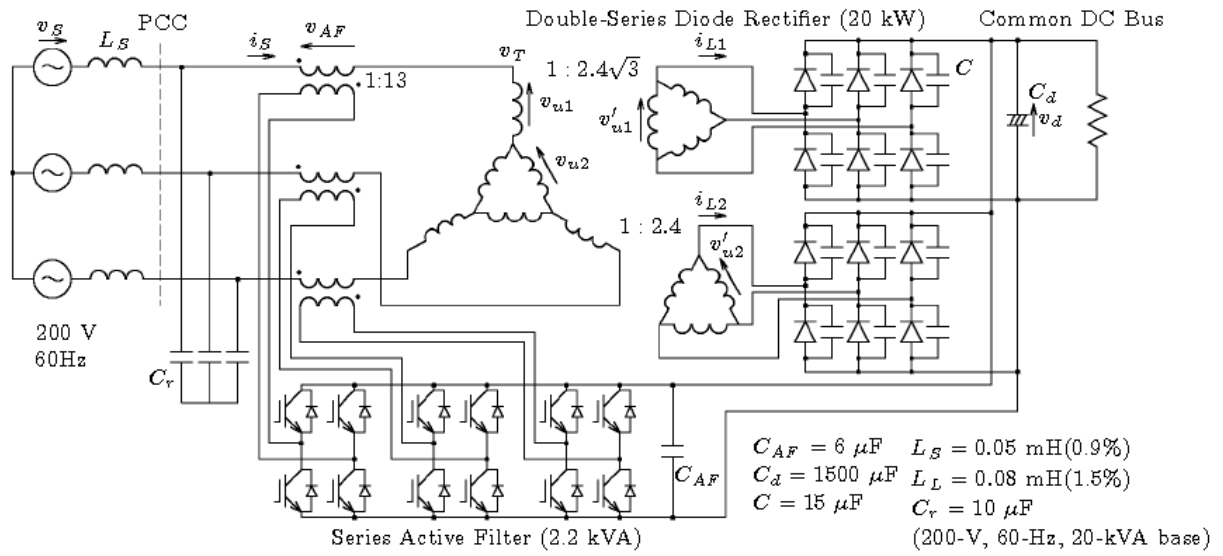


Fig. 8. Experimental system of the harmonic current-free ac/dc power conversion system.

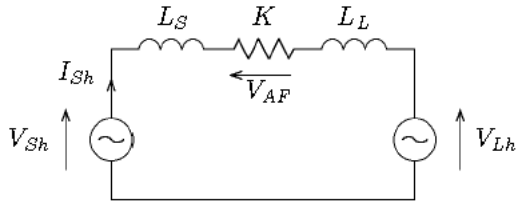


Fig. 9. Single-phase equivalent circuit with respect to harmonics.

The ac voltage of the active filter, which is applied to a power line through the matching transformer, is given by

$$v_{AF}^* = k \cdot i_{sh} \quad (15)$$

where i_{sh} is a supply harmonic current drawn from the utility. Note that v_{AF} and i_{sh} are instantaneous values. When attention is paid to current and voltage harmonics in Fig. 9, the following basic equations can be derived,

$$I_{Sh} = \frac{V_{Sh} - V_{Lh}}{Z_S + Z_L + K} \quad (16)$$

conversion system on a per-phase basis. The series active filter is represented as an ac voltage source v_{AF} , and the double-series diode rectifier as the series connection of a leakage inductor L_L of the transformers with an ac voltage source v_L . The reason for providing the ac voltage source to the equivalent model of the diode rectifier is that the electrolytic capacitor C_d is directly connected to the dc terminals of the diode rectifier, as shown in Fig. 8.

The active filter is controlled in such a way as to present zero impedance for the fundamental frequency and to act as a resistor with high resistance of $K [\Omega]$ for harmonic frequencies.

$$V_{AF} = \frac{K}{Z_S + Z_L + K} (V_{Sh} - V_{Lh}) \quad (17)$$

where V_{AF} is equal to the harmonic voltage appearing across the resistor K in Fig. 9.

If K is much higher than $Z_S + Z_L$, (16) and (17) are changed into the following simple equations.

$$I_{Sh} \approx 0 \quad (18)$$

$$V_{AF} \approx V_{Sh} - V_{Lh} \quad (19)$$

Equation (18) implies that an almost purely sinusoidal current is drawn from the utility. As a result, each diode in the diode rectifier continues conducting during a half cycle. Equation (19) suggests that the harmonic voltage V_{Lh} , which is produced by the diode rectifier, appears at the primary terminals of the transformers in Fig. 8, although it does not appear upstream of the active filter or at the utility-consumer point of common coupling (PCC).

Fig. 10 shows a block diagram of a control circuit based on hybrid analog/digital hardware implementation.

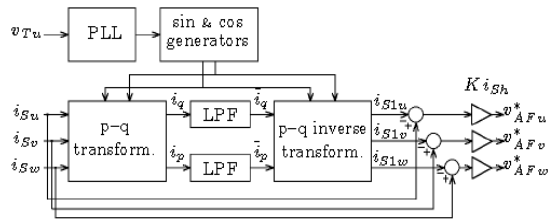


Fig. 10. The control circuit which is used in this paper.

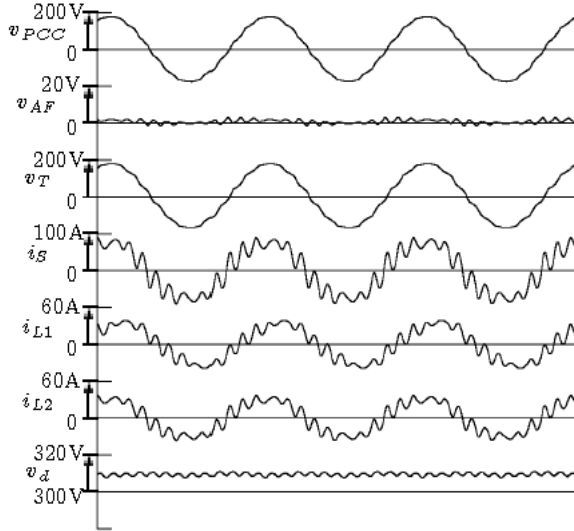


Fig. 11. Experimental waveforms before starting the active filter, in which v_{PCC} is a line-to-neutral voltage.

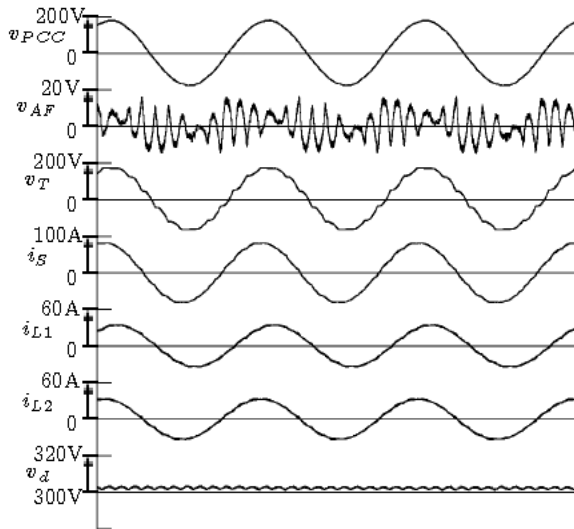


Fig. 12. Experimental waveforms after starting the active filter, in which v_{PCC} is a line-to-neutral voltage.

C. Experimental Results

The control gain of the active filter, K is set to 5Ω , which is equal to 2.5 p.u. on a three-phase 200-V, 20-kW, 60-Hz basis. Equation (16) suggests that the higher the control gain, the better the performance of the active filter. An extremely high gain, however, may make the control system unstable, and thereby a

trade-off between performance and stability exists in determining an optimal control gain. A constant load resistor is connected to the common dc bus.

Figs. 11 and 12 show experimental waveforms before and after starting the active filter. The supply 11th and 13th harmonic currents in Fig. 11 are slightly magnified due to resonance between the commutation capacitors C and the ac line and leakage inductors, L_s and L_L . Table II summarizes the THD values and harmonic currents of i_s in Figs. 11 and 12. Non-negligible amounts of 3rd, 5th and 7th harmonic currents, which are so-called “non-characteristic current harmonics” for the three-phase twelve-pulse diode rectifier, are drawn from the utility, as shown in Table II.

After starting the active filter, a sinusoidal current with a leading power factor of 0.96 is drawn because the active filter acts as a high resistor of 5Ω , having the capability of compensating for both voltage harmonics V_{Sh} and V_{LH} , as well as of damping out the resonance.

TABLE II
SUPPLY CURRENT THD AND HARMONICS BEFORE AND AFTER
STARTING THE ACTIVE FILTER EXPRESSED AS THE
HARMONIC-TO-FUNDAMENTAL CURRENT RATIO[%]

	3 rd	5 th	7 th	11 th	13 th	23 th	25 th	THD
Before	7.5	1.7	3.3	24.8	16.8	1.7	1.5	31.2
After	0.5	0.1	0.1	1.6	1.1	0.2	0.3	2.0

V. PRACTICAL APPLICATIONS OF ACTIVE FILTERS

Active filters for power conditioning have been put into practical use for harmonic compensation, reactive-power compensation flicker compensation, and so on. As a result of keen competition among Japanese companies, a good market is developing for active filters. Applications of active filters are expanding not only into industry and electric power utilities but also into office-buildings, hospitals, water supply utilities and rolling stock. At present, voltage source PWM inverters using IGBT modules are usually employed as the power circuits of active filters in a range from 10 kVA to 2 MVA, and dc capacitors are used as their energy storage components.

Toshiba has developed a 21-MVA shunt active filter using IEGTs (injection-enhanced gate transistors) for flicker compensation of arc furnaces. The press pack IEGT rated at 4.5 kV and 1.5 kA is fabricated on a silicon wafer with a 125-mm diameter, using 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 as small as a conventional GTO-thyristor leg in term of physical size. Moreover, the second generation IEGT-based active filter is reduced to 50% in power loss, compared to the first generation GTO based active filter [15].

Since a combined system of a series active filter and a shunt passive filter was proposed in 1988 [16], much

research has been achieved on hybrid active filters and their practical applications. The reason is that hybrid active filters are attractive from both practical and economical points of view, in particular, for high-power applications.

A hybrid active filter for harmonic damping has been installed at the Yamanashi test line for high-speed magnet levitation trains. The hybrid filter consists of a combination of a 5-MVA series active filter and a 25-MVA shunt passive filter [17]. The series active filter makes a great contribution to damping of harmonic resonance between the supply inductor and the shunt passive filter.

VI. FLYWHEEL ENERGY STORAGE SYSTEM

A 200-MJ/20-MW flywheel energy storage system has been installed in the vicinity of an arc furnace, and was commissioned in August of 1996 at the Chujowan substation of the Okinawa Electric Power Company in Japan [18].

Fig. 13 shows a cutaway view of the flywheel. This is not a trial application but is in commercial use for frequency regulation on a 132-kV bus.

A. System Configuration

Fig.14 shows the circuit configuration of the 200-MJ/20- MW energy storage system. It consists of a 26.5-MVA doubly-fed generator-motor coupled with a flywheel of 74,000 kg with a 4-m diameter, a three-phase twelve-pulse line-commutated cycloconverter, an excitation transformer and a controller.

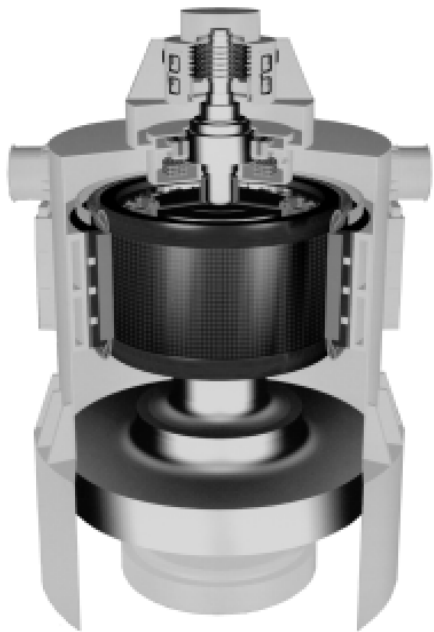


Fig. 13. Cutaway view.

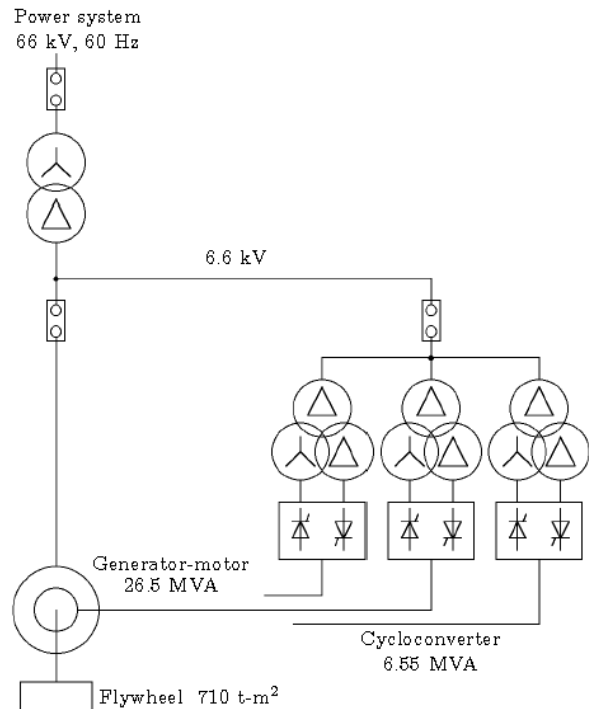


Fig. 14. System configuration.

TABLE III
SYSTEM SPECIFICATION.

Apparatus	Items	Ratings
Generator-motor	line-frequency	60Hz
	capacity	26.5 MVA
	primary voltage	6.6 kV
	pole number	12
	rotating speed	510–690 rpm
	flywheel effect (GD^2)	710 t-m ²
Cyclo-converter	capacity	6.55MVA
	output voltage	1930 V
	output current	1960 A
Transformer	output frequency	0.25—9.0 Hz
	capacity	4.2MVA×3
	primary voltage	6.6 kV
	secondary voltage	770 V

This flywheel energy storage system could be referred to as ROTES (ROTary Energy Storage)[18]. This newly developed generator-motor has a three-phase distributed wound rotor of 50,000 kg, equipped with collector rings. The rotor windings of the 12-pole generator-motor are excited with three-phase low-frequency ac currents which are supplied via the collector rings by a 6.55-MVA cycloconverter using light-triggered thyristors. The stator terminals rated at 6.6 kV are connected to the 66-kV utility grid through a step-up transformer. The output frequency of the cycloconverter is controlled within 0.25—9.0 Hz, and the line frequency is 60 Hz. This enables the cycloconverter to operate in a circulating current-free mode. The generator-motor with a synchronous speed of 600 rpm is adjusted in a speed range from -15% (510 rpm) to +15% (690 rpm).

The electric energy is stored as the rotating kinetic energy in the rotor and flywheel of the steel structure. Adjusting the rotor speed makes the generator-motor either release the energy to the power system or absorb it from the power system. The 26.5-MVA generator-motor coupled with the flywheel has a thrust bearing capable of withstanding its adjustable-speed operation. Note that the flywheel effect of $GD^2 = 710 \text{ t-m}^2$ in Table III includes the rotor inertia.

B. Dynamic Performance

The 200-MJ/20-MW flywheel energy storage system is the world's first commercial operation of such a large capacity flywheel energy storage system. The dynamic performance of the energy storage system has been confirmed by actual measurements. When the ROTES was disconnected from the 66-kV bus, frequency fluctuation over $\pm 0.4 \text{ Hz}$ often appeared in the line frequency, resulting from sudden and frequent load changes as large as 30 MW in a dc arc furnace. When the ROTES was connected, the frequency fluctuation was suppressed to within $\pm 0.3 \text{ Hz}$, thus meeting the goal of installation. The ROTES has been operating properly for more than four years, showing great promise as a FACTS device which has the capability of repetitively releasing or absorbing electric power with a response time as fast as less than 100 ms.

VII. FUTURE PROSPECTS AND DIRECTIONS OF ENERGY STORAGE SYSTEMS

With the help of power electronics technology, a large amount of electric energy may be stored in batteries based on chemical action, in the forms of an electromagnetic field in an inductor and an electrostatic field in a capacitor, or as the kinetic energy in a rotating part.

Among them, superconductive-magnetic energy storage, referred to as SMES, has the potential of being more efficient in terms of storing energy for a long period of time. It is also expected to be used as a repetitively-pulsed power generator. However, it takes a long period of time to put large-capacity SMES systems into practical use, although a small-capacity SMES system rated at 3.6 MJ (= 1 kWh) or "micro-SMES" is coming on the market in the United States and other countries. Universities or institutes and laboratories are performing research on superconductive magnet energy storage systems, whereas it is unfortunate that little literature has been published on practical applications of large-capacity SMES systems.

Battery energy storage systems intended for power conditioning are more viable and effective in terms of storing electric energy for a relatively long time, say, a few hours.

For example, in early 1988, a battery energy storage

system rated at 10 MW for 4 hours, was placed in service at the Chino Battery Energy Storage Facility in California [19]. This installation worked satisfactorily, and demonstrated the practicality of high performance power conversion for energy management, reactive power control, and power system stabilization. It was a benchmark for the size, cost, efficiency, and transient response which typifies this type of conversion installation.

Flywheel energy storage systems resulting from the marriage of power electronics and electric machine technologies show promise as "versatile power conditioners," in particular, being capable of repetitively absorbing and releasing electric energy for a short period of time, say, a few minutes. Here, the versatile power conditioners would be defined as advanced power electronic devices which are characterized by having the function of instantaneously controlling both active power and reactive power to improve power quality.

VIII. CONCLUSIONS

This paper has presented the state-of-the art of power electronics technology relevant to active filtering and energy storage. The difference in terminology between active filters and energy storage systems does not come from their circuit topology but depends on whether their energy storage capacity is small or large. The development of energy storage devices over the last two decades has been much less significant than the development of power semiconductor devices in terms of capacity, performance and cost effectiveness. No remarkable progress could not be made in energy storage systems unless there were an emergence of new energy storage devices or a significant improvement of already existing devices.

The author expects the continued efforts of power electronics researchers, including himself, physicists and chemists to make significant progress in active filters and energy storage systems for power conditioning.

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