Utility applications of power electronics in Japan

Hirofumi Akagi
Okayama University

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Hirofumi Akagi, *Fellow, IEEE*
Department of Electrical Engineering
Okayama University
Okayama-City, 700 Japan
Tel: +81-86-251-8117, Fax: +81-86-251-8259
E-mail: akagi@power.elec.okayama-u.ac.jp

Abstract—**Since the late 1950's, power electronics has been developing by leaps and bounds without saturation into the key technology essential to modern society and human life, as well as to electrical engineering. This paper is focused on utility applications of power electronics technology in Japan, and on the state of the art of power semiconductor devices for high power applications. For instance, attention is paid to a ±500 kV, 2.8 GW high-voltage dc transmission system being under construction, and to 8-kV, 3.5-kA light-triggered thyristors used for constituting its thyristor valves. This paper also presents future prospects and directions of power electronics technology in the 21st century, including the personal views and expectations of the author.**

I. Introduction

Power electronics has been initiated by the invention and production of thyristors or silicon-controlled rectifiers. In conjunction with microcomputers and digital signal processors (DSP's) brought by microelectronics technology, the following great leaps have been made in power electronics technology and utility applications:

- remarkable progress in capacity and switching speed of GTO thyristors and IGBT's;
- installation of an 80-MVA inverter-based static var generator (SVG) using GTO thyristors for stability improvement in power transmission systems;
- commercial operation of a 400-MW adjustable speed pumped-storage generator/motor system controlled by a naturally-commutated cycloconverter.

Applications of power electronics technology are now expanding, so that the term "power electronics" in the 21st century will have a much broader meaning than it did in the 1980's. For instance, the marriage of power electronics and power engineering will bear FACTS (Flexible AC Transmission Systems) in the near future unless power electronics gets a divorce from power 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.

This paper presents utility applications of power electronics in Japan, along with its future prospects and directions in the 21st century, including the personal views and expectations of the author. This paper is organized as follows: Section II describes the present status and future trends of high-power semiconductor devices in Japan. Sections III and IV describe two examples of practical utility applications; HVDC transmission systems using light-triggered thyristors, and adjustable speed pumped-storage generator/motor systems controlled by line-commutated cycloconverters or PWM rectifier/inverters. Section V presents shunt active filters intended for harmonic damping throughout power distribution systems, which will be dispersively installed by utilities in the near future.

II. Power Semiconductor Devices

Power semiconductor devices are indispensable to power electronic systems, like bread or rice is to the human system. No remarkable progress could be made in power electronic technology unless there were an emergence of new power devices or a significant improvement of already existing devices.

A. Light-Triggered Thyristors (LTT's)

Light-triggered thyristors rated at 8 kV and 3.5 kA (average current) have been developed with a on-voltage drop as low as 2.7 V at 3.5 kA [1]. The thyristors are fabricated on a silicon wafer 6 inches in diameter. The main reason for applying light-triggering technology to the thyristor is that light signals are not affected by electromagnetic interference (EMI). In addition, light is conducted through optical glass fibers which are one of the best insulation materials. This ensures sufficient insulation between a system controller operating at ground potential and a gate drive circuit operating at potentials as high as, or exceeding, 250 kV [2].

B. Gate Turn-Off (GTO) Thyristors and Gate Commutated Turn-off (GCT) Thyristors

A gate turn-off (GTO) thyristor rated at 6 kV and 6 kA, fabricated on a silicon wafer 6 inches in diameter, is now available to high-power inverters for utility/industry applications [3]. The GTO thyristor has the capability of shutting off an anode current of 6 kA with the help of a snubbing circuit, but the average anode current is designed to be about 2 kA in practical application. Extremely high voltage GTO thyristors rated at 9-12 kV will be developed in the near future, using leading edge semiconductor technology.

Gate commutated turn-off (GCT) thyristors with unity turn-off gain have been newly developed by the Mitsubishi Electric Corporation. Table I summarizes electric characteristics of a first generation 4.5-kV GCT thyristor (FG4000HX-90DS) and a second generation 4.5-kV

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TABLE I
ELECTRICAL CHARACTERISTICS OF 4.5-kV GCT THYRISTORS.

	First Generation GCT	Second Generation GCT
controllable turn-off current (snubber capacitor dependence)	3 kA at 3 μF	3 kA at 0 μF 4 kA at 3 μF
storage time	2 μs at 3 kA	2.5 μs at 3 kA
turn-on di/dt	500 A/μs	1000 A/μs
on voltage	3.5 V at 3 kA	3.8 V at 3 kA
gate trigger current	4 A at 25°C	4 A at 25°C
thermal resistance (junction to sink)	0.010°C/W	0.011°C/W

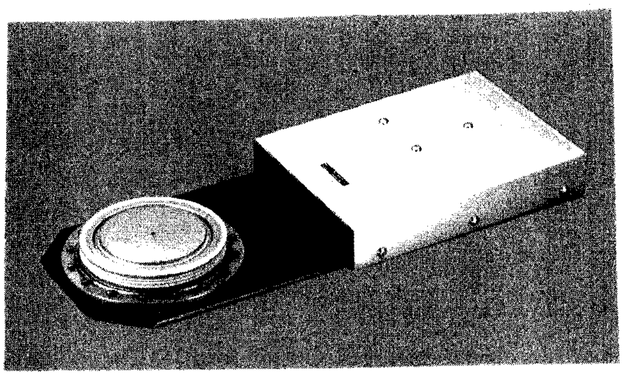


Fig. 1. The second generation 4.5-kV GCT thyristor.

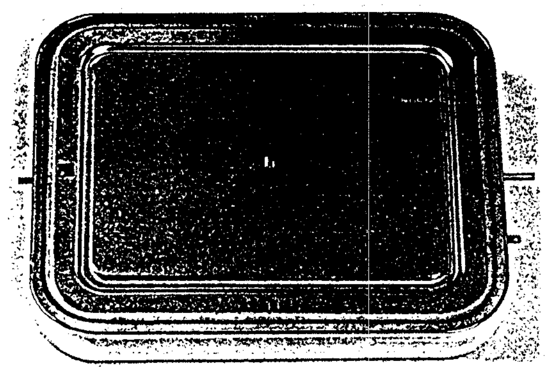


Fig. 2. Rectangular press pack reverse conducting IGBT rated at 2.5 kV and 1 kA.

GCT thyristor (FG4000AX-90DS) [4]. These devices have the following advantages over a conventional 4.5-kV GTO thyristor;

- the storage time is reduced to 2-2.5 μs, which is one-tenth as short as that of the GTO. This makes series connection viable and reliable, thus leading to implementation of static var generators (SVG's) for improving power stability and back-to-back converters intended for asynchronous ac linkage in power systems;
- the second generation GCT has the capability of snubber capacitor-less operation, so that it does not produce any snubber loss;
- the internal gate inductance of the GCT is one-tenth as low as that of the GTO;
- a combination of a specially developed gate circuit and the GCT makes the total gate inductance as low as 3 nH. This inductance value of the GCT is one-hundredth as low as that of the GTO.

Figure 1 is the photograph of the second generation GCT thyristor and its gate driver. The device is mounted in a package 130 mm in diameter. These GCT thyristors are now available from the Mitsubishi Electric Corporation.

The GCT thyristor is referred to as "the hard-driven GTO thyristor" in [5].

C. Static Induction (SI) Thyristors

A static induction (SI) thyristor rated at 4 kV and 200 A (average current) has been developed by the Toyo Electric Company. This device has the capability of shutting off an anode current of 1 kA or more. The SI thyristor equipped with a snubber capacitor of 0.1 μF can operate at 4 kHz, which is much higher than the switching frequency limitation of the same class of GTO thyristor [3]. However, the SI thyristor has not yet come on the market.

D. IGBT's (Insulated-Gate Bipolar Transistors)

Over the last ten years, a significant reduction in loss in IGBT's has been achieved in the process of transition from the first, via the second, to the third generation. At present, the third generation IGBT's rated at 600/1200/1700 V are widely used for general inverter applications with current ratings up to 600 A or more. They are packaged with soft-recovery free-wheeling diodes into power modules, so that they are often called "IGBT modules" in Japan. They have the advantage of not requiring any electric isolation from heat sinks, thus making inverters compact. Moreover, IGBT modules rated at 2000 V and 500 A are available and used mainly for electric traction.

The Fuji Electric Company has recently developed a reverse conducting IGBT rated at 2.5 kV and 1 kA [6]. The IGBT has the following electric characteristics:

- maximum turn-off collector current of 5 kA;
- saturation voltage of 4.4 V at $I_C = 1$ kA and 125°C;
- fall time of 0.85 μs;
- rise time of 1.6 μs.

Figure 2 shows the photograph of the IGBT. The size of the rectangular press pack is $133^W \times 110^H \times 20^D$ (mm). Nine IGBT chips and three diode chips are integrated into the package, and the size of either the single IGBT or diode

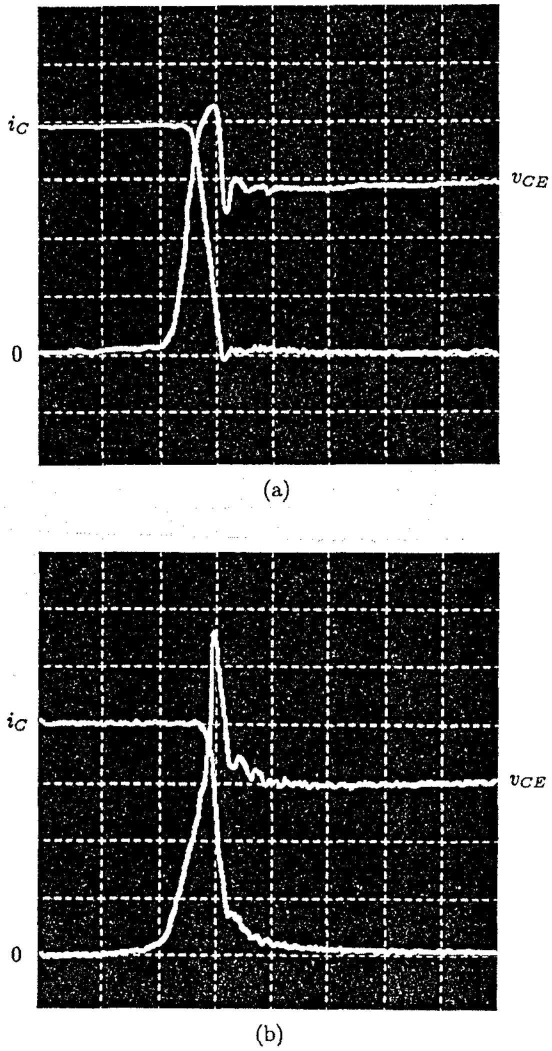


Fig. 3. Turn-off waveforms of the rectangular press pack reverse conducting IGBT rated at 1.2 kV and 2 kA (200 V/div, 500 A/div and 200 ns/div); (a) $T_j = 25°C$, and (b) $T_j = 125°C$.

chip is a square of 20 × 20 (mm). This package structure has the capability to efficiently remove heat from both top and bottom, so that the IGBT would be more suitable to electric traction applications requiring high reliability. The Fuji Electric Company has also developed a rectangular press pack reverse conducting IGBT rated at 1.2 kV and 2 kA for high-frequency resonant inverters. This IGBT has a on-voltage drop as low as 3.7 V at $I_C = 2$ kA and 125°C. Figure 3 shows the turn-off waveforms of v_{CE} and i_C in hard switching operation under the conditions of $V_{DC} =$ 600 V, $I_C = 2$ kA and $T_j = 25°C$ in (a), and $T_j = 125°C$ in (b). These IGBT's in rectangular press pack are now available on the market.

Hitachi has developed a 3.5-kV, 500-A IGBT module with a on-voltage drop as low as 5.6 V at $I_C = 325$ A [7]. Mitsubish has recently developed a 3.3-kV, 1.2-kA IGBT module. According to [3], 4.5 kV would be a final goal of IGBT's to reach, and therefore such a high voltage IGBT is expected to take the place of 4.5 kV GTO thyristors in

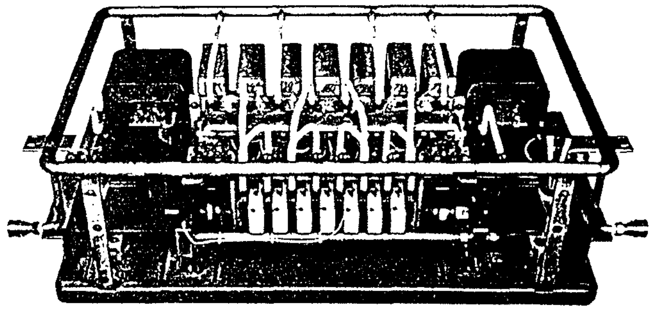


Fig. 4. Thyristor module for HVDC thyristor valves.

the near future.

To advance performance beyond the third generation IGBT's, the fourth generation devices will require exploiting fine line lithographic technology and/or employing the trench technology currently being used to produce a new power MOSFET with very low on-state resistance. The fourth generation IGBT will have a on-voltage drop as low as 1.5 V for a 600 V device or 2.0 V for a 1200 V device at each rated current.

An intelligent IGBT or an intelligent power module (IPM) is available, which is an attractive power device integrated with circuits to protect against overcurrent, overvoltage and/or over-temperature. The intelligent IGBT based on the fourth generation will take a few years to come on the market.

III. HVDC Transmission Systems and Back-To-Back Systems

A. HVDC Transmission Systems

In 1993, a high-voltage direct current (HVDC) transmission system rated at 300 MW (250 kV, 1.2 kA) was installed in commercial service to supply a submarine cable transmission system under the channel between the islands of Hokkaido and Honshu. Each high-voltage thyristor valve in this system consists of a series connection of several thyristor modules. Figure 4 is a photograph of a thyristor module consisting of a series connection of seven light-triggered thyristors rated at 6 kV and 2.5 kA. The introduction of the light-triggered thyristors makes a great contribution to the development of compact and reliable thyristor valves. Figure 5 shows a thyristor valve used in this HVDC transmission system [9].

An HVDC transmission system of 1.4 GW (±250 kV, 2.8 kA) at the first stage and then 2.8 GW (±500 kV, 2.8 kA) at the final stage is now under construction, aimed at commercial operation by the beginning of the 21st century [1]. Figure 6 and Table II show the main circuit and specifications of the HVDC system using light-triggered thyristors of 8 kV and 3.5 kA, respectively. The HVDC system will be able to control a bi-directional power flow of 2.8 GW through a 51 km-long submarine transmission cable and a 51 km-long overhead transmission line between the islands of Shikoku and Honshu. The main reason for intro-

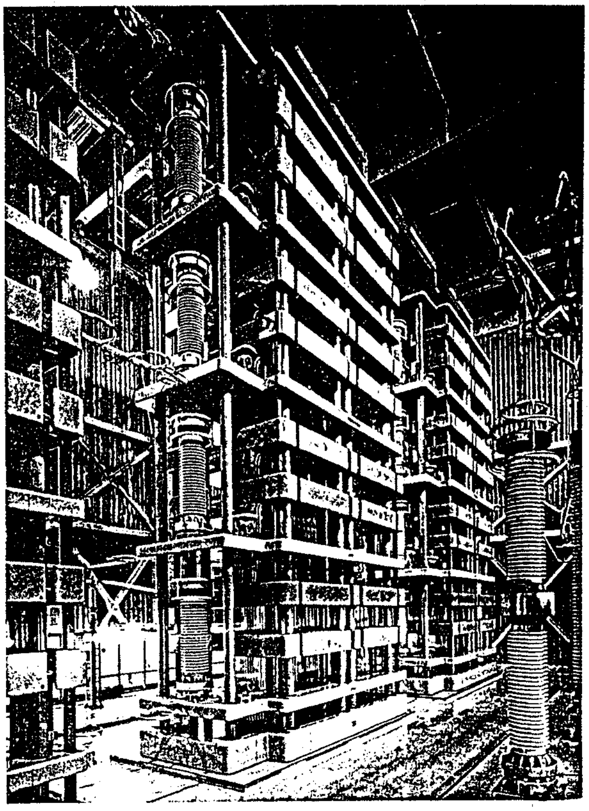


Fig. 5. Thyristor valve used for the 250-kV, 1.2-kA HVDC transmission system.

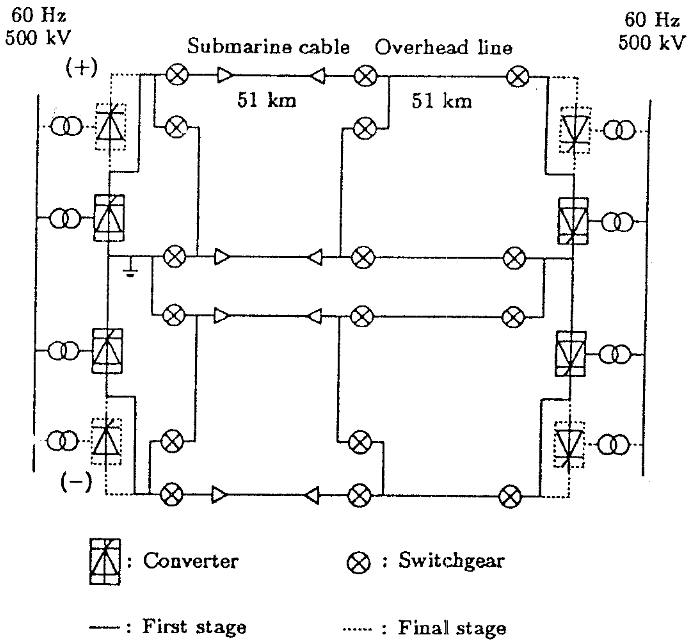


Fig. 6. Circuit configuration of the ±500-kV, 2.8-GW HVDC transmission system.

TABLE II
SPECIFICATIONS OF THE HVDC SYSTEM.

First Stage Rating	1.4 GW ±250 kV
Second Stage Rating	2.8 GW ±500 kV
Overload Capacity	125% (3.5 kA)
AC Power System	500 kV 60 Hz

ducing the HVDC system into such a short-distance power transmission system is that the 51 km-long submarine cable would impose restrictions on the sending power capacity in an HVAC system because a large amount of leading current would flow through non-negligible parasitic capacitors in the submarine cable. Thus the HVDC system is estimated to be lower in total construction costs than the HVAC system. The commercial operation of the HVDC system will result in achieving fast and precise power flow control irrespective of the difference between phase angles at the sending and receiving ac terminals, providing a higher degree of power stability in both power systems.

B. Back-To-Back Systems

A feasible study of a 1.5-GW back-to-back system using 6-kV, 6-kA GCT thyristors is going on [8]. This system is characterized by multiplicity of single-phase inverter cells. Each cell consists of an H-bridge voltage-fed inverter using the four GCT thyristors without snubber capacitors, where the dc link voltage of the inverter cell is 3 kV. According to [8], it is pointed out that the GCT thyristor-based system has potential advantages, not only in controllability and redundancy but also in not requiring either harmonic filters or capacitors for power factor improvement, over a back-to-back system using 8-kV, 3.5-kA light-triggered thyristors. In addition, the total operating loss of this system is reduced to 60% of that of a back-to-back system using 6-kV, 6-kA GTO thyristors, so that the total loss is estimated to be as low as that of the LTT-based system.

The GCT thyristor-based back-to-back system is also considered a promising and attractive device among various kinds of FACTS equipment.

IV. Adjustable Speed Pumped-Storage Generator/Motor Systems

Recent progress in power electronic technology has made it possible to achieve adjustable speed operation of 300-400 MW generators in hydroelectric power plants.

A. Based on a Line-Commutated Cycloconverter

In December 1993, an adjustable speed pumped-storage system of 400 MW was commissioned along with a conventional constant speed pumped-storage system of 400 MW at Ohkawachi hydroelectric power plant, owned and operated by the Kansai Electric Power Company in Japan [10]. Figure 7 shows the arrangement of the adjustable speed pumped-storage system. The field windings of the 20-pole generator/motor of 400 MW are excited with three-phase low-frequency ac currents which are supplied via slip rings by a 72 MVA three-phase twelve-pulse line-commutated cycloconverter. The armature terminals, rated at 18 kV, are connected to a 500-kV utility grid through a step-up

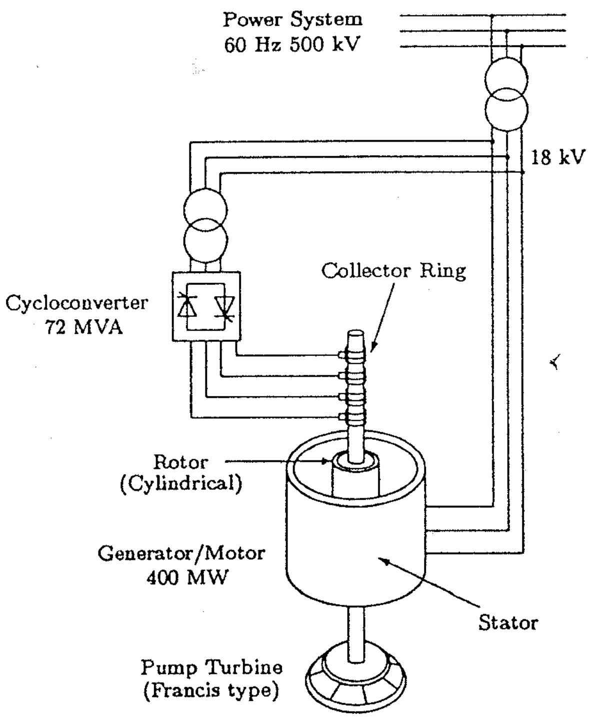


Fig. 7. Adjustable speed pumped-storage system.

transformer. The output frequency of the cycloconverter is controlled within ±5 Hz, and the line frequency is 60 Hz. This enables the application of the cycloconverter operating with *circulating current-free* mode into the adjustable speed system which has a synchronous speed of 360 rpm with a speed range from −8.3 % (330 rpm) to +8.3 % (390 rpm). Speed control provides the capability to control the input power in a range of ±80 MW in pump mode. This system was manufactured by Hitachi.

The adjustable speed pumped-storage generator/motor system of 400 MW has the following potential advantages over the conventional constant speed system:

- high speed active power control can be achieved by the combination of the cycloconverter and the inertia effect of rotating parts. For instance, the actual input active power follows its reference with the ramp response spending 20 seconds from 256 MW to 400 MW in pump mode without any time delay. This makes a significant contribution to the improvement of frequency control, especially in pump mode at night;
- the total operational efficiency of the system increases by 3 %;
- the stability of the adjustable speed system under line fault and reclosing conditions is far superior to the conventional constant speed system;
- the adjustable speed generator/motor system can be used as a FACTS device.

These excellent characteristics have been verified by field trials and the subsequent commercial operation.

B. Based on a GTO Rectifier/Inverter System

Another adjustable speed system of 300 MW is under construction at the Okukuyotu II power plant owned and operated by the Tokyo Electric Power Company. A voltage-source PWM rectifier/inverter using GTO thyristors rated at 4.5 kV and 3 kA is connected between the stator and rotor winding terminals of the generator/motor, instead of a line-commutated cycloconverter. The capacity of the GTO rectifier/inverter system is 40 MVA. The power circuit of each three-phase GTO rectifier is composed of three single-phase voltage-source PWM rectifiers, and six GTO rectifiers are connected to two excitation transformers, thus forming the GTO rectifier system having positive and negative dc terminals and a neutral terminal. The power circuit of each three-phase GTO inverter is a three-level voltage-source PWM inverter, and three GTO inverters are connected in parallel through ac reactors. This forms the GTO inverter system, the ac terminals of which are connected to the rotor terminals via three slip rings without transformers. The switching frequency of the GTO thyristors is 500 Hz. The adjustable speed system manufactured by Toshiba has been put into commercial operation since 1996.

V. Shunt Active Filters for Dispersed Installation on Power Distribution Systems

Shunt active filters for the purpose of harmonic damping will be dispersively installed on multiple feeders in power distribution systems by electric power companies or utilities in the near future, as voltage distortion and harmonics in distribution systems approach or exceed their allowable levels [12].

A. Power Distribution System

Figure 8 shows a radial distribution system in a residential area [13]. The rated bus voltage is 6.6 kV(line-to-line), and the rated frequency is 50 Hz. The equivalent inductive reactance upstream of bus 2, including the leakage reactance of a primary distribution transformer of 15 MVA, is to be estimated from the short circuit capacity of 110 MVA. The transformer supplies four distribution feeders numbered 1-4. For the sake of simplicity, only feeder 1 is considered under the assumption that feeders 2, 3 and 4 are disconnected from the transformer.

Overhead distribution lines are classified into the primary line and branch lines in feeder 1. A distribution line between a bus and the adjacent bus is assumed to be a lumped LR circuit dependent on the length and thickness of the line, because it is reasonable to neglect the effect of the stray capacitive reactances of the line for the 5th and 7th harmonic voltage and current. Feeder 1 delivers electric power to eleven medium-voltage consumers of 200-240 kW and six low-voltage consumers of 50-130 kW. Each medium-voltage consumer has a shunt capacitor without any series reactor for power factor correction, while the low-voltage consumers do not have shunt capacitors. The total capacity of the loads is 2.99 MW, and that of the shunt capacitors for power factor correction is 0.99 Mvar.

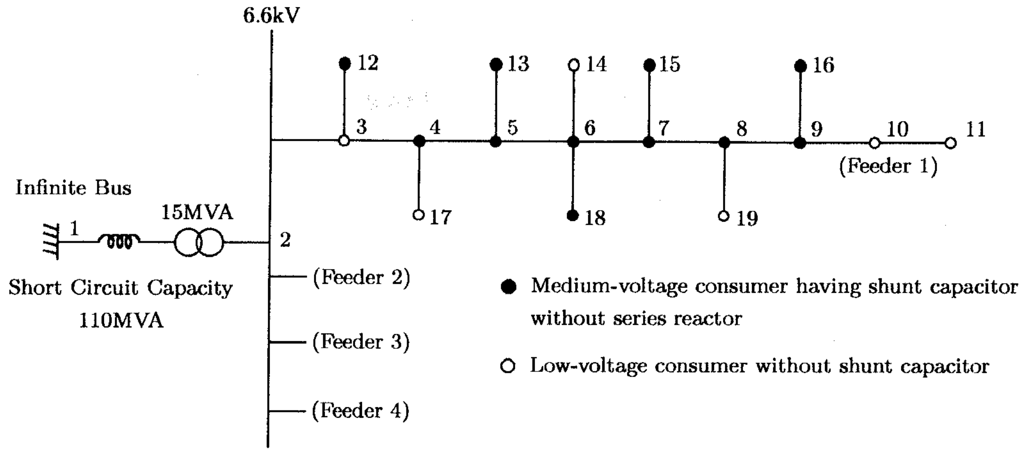


Fig. 8. Radial distribution system model.

Harmonic propagation occurs in feeder 1 around the 7th harmonic frequency (350 Hz), such that the 7th harmonic voltage is amplified by four times at the rated load of 2.99 MW and by eight times at no load. The harmonic propagation results from series and/or parallel harmonic resonance between the inductive reactances of the distribution lines, along with the equivalent inductive reactance upstream of bus 2, and the capacitive reactances of the shunt capacitors on feeder 1.

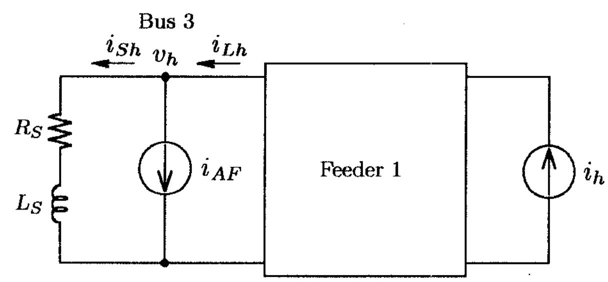


Fig. 9. Equivalent model for voltage and current harmonics.

B. Harmonic detection methods

Figure 9 shows an equivalent circuit for voltage and current harmonics on feeder 1, where a shunt active filter is installed on bus 3. The shunt active filter is assumed to be an ideal current source capable of "drawing" a compensating current i_{AF} from bus 3. A harmonic-producing load connected somewhere in feeder 1, downstream of bus 3, is also assumed to be an ideal current source "injecting" a harmonic current i_h into feeder 1. Note that the author distinguishes the two terms "drawing" and "injecting," considering the polarity of the ideal current sources shown in Figure 9.

The load current detection mentioned before is suitable for a shunt active filter installed in the vicinity of one or more harmonic-producing loads. However, depending on the point of installation, instability may occur as shown in [13]. A shunt active filter based on the supply current detection may cause instability as the phase margin is in the range of 10° to 90°. Adding differential compensation enables to improve the phase margin by 90°, because the principle of compensation is based on feedback control. A shunt active filter based on the voltage detection is extremely stable because the phase margin is over 90°, irrespective of the point of installation [13]. Hence, the voltage detection and the supply current detection with differential compensation are taken into consideration as they have the potential possibility applicable to the shunt active filter for installation on power distribution systems, while the other harmonic detection methods are excluded from discussion.

Assuming that the effect of the controller delay for extraction of the harmonic current or voltage is represented by a first-order lag system, the two harmonic detection methods are given as follows:

$$I_{AF}(s) = \frac{s \cdot K_S}{1+sT} I_{Sh}(s) \tag{1}$$

$$I_{AF}(s) = \frac{K_V}{1+sT} V_h(s) \tag{2}$$

where, K_S is a feedback gain with no dimension, and K_V is a feedback gain with the dimension of S.

C. Harmonic damping effect

Computer simulation is performed to verify the effect of the shunt active filter on damping of harmonic propagation under the following assumptions.

- Feeders 2, 3 and 4 are disconnected from bus 2.
- The 7th harmonic voltage and current are considered in feeder 1, because harmonic propagation occurs around the 7th harmonic frequency.
- All shunt capacitors for power factor correction remain connected to feeder 1, while all loads are disconnected, thus leading to the most severe harmonic propagation.
- The 7th harmonic current source of $I_h = 7.8$ A exists on bus 6.
- A single shunt active filter is installed at the beginning terminal or at the end terminal of the primary line, that is, bus 3 or bus 9, respectively.

TABLE III

EFFECT OF SHUNT ACTIVE FILTER ON HARMONIC DAMPING, WHERE 7TH HARMONIC CURRENT SOURCE OF 7.8A EXSISTS ON BUS 6.

(a) Supply current detection with differential compensation ($K_S = 20$).

[A]	installation of shunt active filter		
	no instal.	on bus 3	on bus 9
I_{2-3}	109.7	0	31.9
I_{3-4}	104.0	14.0	30.2
I_{5-6}	79.0	12.8	23.0
I_{6-7}	58.3	3.8	9.4
I_{8-9}	24.3	1.6	0
I_{AF}	–	14.0	6.4

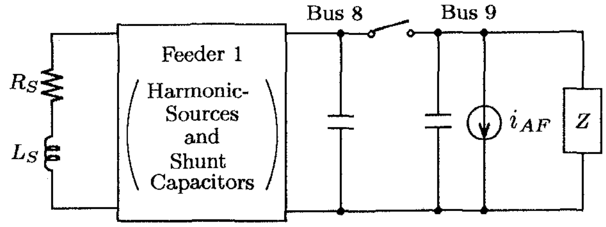
(b) Voltage detection ($K_V = 2\ \Omega^{-1}$).

[A]	installation of shunt active filter		
	no instal.	on bus 3	on bus 9
I_{2-3}	109.7	2.1	3.6
I_{3-4}	104.0	14.5	3.4
I_{5-6}	79.0	12.0	2.6
I_{6-7}	58.3	4.3	5.9
I_{8-9}	24.3	1.8	6.5
I_{AF}	–	13.7	6.5

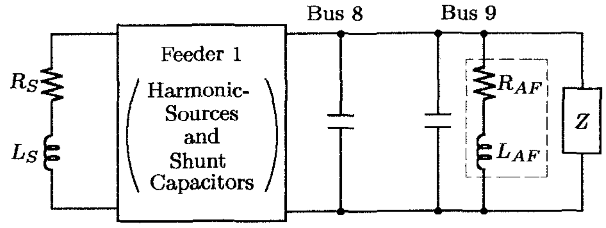
Table III shows the 7th harmonic current flowing between a bus and the adjacent bus in the primary line, and compensating current drawn by the shunt active filter, I_{AF}. For example, I_{2-3} means the 7th harmonic current flowing between buses 2 and 3. Table III (a) shows the 7th harmonic current and compensating current for the shunt active filter based on the supply current detection with differential compensation with a gain of K_S=20, while Table III (b) for the shunt active filter based on the voltage detection with a gain of K_V=2 S. A delay time of T=0.16 ms, which results from current or voltage detection and harmonic extraction, is considered for both harmonic detection methods.

The shunt active filter installed on bus 3 produces almost the same effect, independent of either harmonic detection method. The shunt active filter can compensate for the harmonic current flowing out upstream of bus 3. However, harmonic current propagation still occurs between buses 3 and 6. The shunt active filter installed on bus 6 fully compensates for the current harmonics throughout feeder 1, independent of either harmonic detection method, because it is installed in the vicinity of the harmonic current source existing on bus 6.

When the shunt active filter is installed on bus 9, there is a notable difference in the effect of shunt active filter between both harmonic detection methods. The shunt active filter based on the supply current detection with differential compensation can compensate for the harmonic current flowing upstream of bus 9, I_{8-9}, but it can not damp the harmonic current propagation upstream of bus 7. That is, $I_{2-3} \sim I_{6-7}$ are larger than 7.8 A. On the other hand, the shunt active filter based on the voltage detection reduces the harmonic current into less than 7.8 A throughout feeder 1. This means that the shunt active filter based on the voltage detection has the capability of harmonic damping throughout feeder 1, unlike the shunt active filter based on the supply current detection with differential compensation, when the shunt active filter is installed at the end terminal of the primary line, that is, on bus 9. The reason for the difference is clarified in the following section.



(a) Shunt active filter based on supply current detection with differential compensation.



(b) Shunt active filter based on voltage detection.

Fig. 10. Equivalent circuit models for shunt active filters with respect to 7th harmonic voltage and current.

D. Modeling of Shunt Active Filters

Figure 10 shows an equivalent circuit model for the shunt active filter based on either harmonic detection method.

When the shunt active filter based on the supply current detection with differential compensation is installed on bus 9, no harmonic current flows buses 8 and 9, that is, $I_{8-9} = 0$. With the focus on voltage and current harmonics upstream of bus 9, an equivalent circuit model for $I_{8-9} = 0$ is represented by an open switch connected in series between buses 8 and 9, as shown in Figure 10 (a). This means that the network upstream of bus 8 still has the potential possibility of causing harmonic propagation. In addition, opening the switch would change the resonant frequency in feeder 1. If a frequency of multiple harmonic current sources existing upstream of bus 8 coincided with the changed resonant frequency, installation of the shunt active filter on bus 9 would cause more severe harmonic propagation upstream of bus 8. Therefore, the supply current detection with differential compensation is not suitable for the shunt active filters intended for dispersive installation on power distribution systems by utilities.

On the other hand, equation (4) implies that the shunt active filter based on the voltage detection acts as a lumped series R_{AF}-L_{AF} circuit with $R_{AF} = 1/K_V$ and $L_{AF} =$

T/K_V, when it is seen from the point of installation. Note that the shunt active filter itself acts as a current source. Thus, the equivalent circuit model is represented by Figure 10 (b). It is clear from Table III (b) and Figure 10 (b) that installation of the shunt active filter on bus 9 is effective in harmonic damping throughout feeder 1. The reason is that installation of the shunt active filter on bus 9 makes the system impedance downstream of bus 6 inductive, so that the following equation exists in Table III (b).

$$I_{5-6} + I_{6-7} = 8.5 \simeq 7.8A$$

E. Best Site Selection of Installation

The best site selection of installation on a feeder is not the beginning terminal but the end terminal of the primary line [13], when a utility installs a "single" shunt active filter based on the voltage detection, in order to damp harmonic propagation throughout the feeder. Moreover, dispersive installation of "multiple" shunt active filters on multiple feeders in a power distribution system causes neither harmonic propagation nor harmonic interference among them, and thus it is a viable and effective way of actively damping harmonic propagation throughout a power distribution system which is subjected to harmonic pollution caused by harmonic resonance and a number of unidentified harmonic-producing loads [13].

VI. Conclusions

This paper has presented a survey of utility applications of power electronics in Japan. Power electronics technology has brought high performance, high efficiency, energy-savings, high reliability, maintenance-free operation and compactness to all electrical and electronic equipment. The author expects the continued efforts of power electronics researchers and engineers, including himself, to make more significant progress in power electronics technology by 2007 than that made in the last ten years.

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Hirofumi Akagi (M'87-SM'94-F'96) was born in Okayama-City, Japan, on August 19, 1951. He received the B.S. degree from Nagoya Institute of Technology in 1974 and the M.S. and Ph.D. degrees from Tokyo Institute of Technology in 1976 and 1979, respectively, all in electrical engineering. In 1979, he joined Nagaoka University of Technology as an assistant and then associate professor in the department of electrical engineering. In 1987, he was a visiting scientist at the Massachusetts Institute of Technology for ten months.

Since 1991, he has been a full professor in the department of electrical engineering at Okayama University. From March to August of 1996, he was a visiting professor at the University of Wisconsin-Madison and then the Massachusetts Institute of Technology. His research interests include ac motor drives, high frequency resonant inverters for induction heating and corona discharge treatment, and utility applications of power electronics such as active filters, static var compensators and FACTS devices. He has published 30 IEEE Transactions papers on power electronics and ac motor drives, and has made presentations as tutorial and keynote speaker internationally.

Dr. Akagi has received six IEEE/IAS society and committee prize paper awards, including the first-prize paper award in the IEEE Transactions on Industry Applications for 1991.