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FUJI ELECTRIC REVIEW

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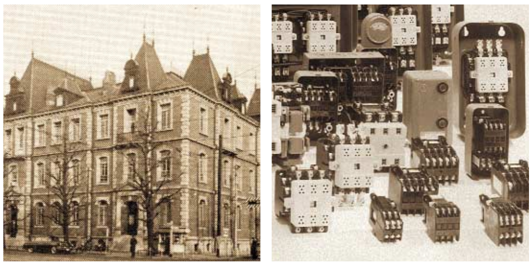
2004 VOL.50

New Technologies for Globalization



Fuji Electric Group


e-Front runners

FUJI ELECTRIC
REVIEW

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New Technologies for Globalization

CONTENTS

Cover photo:

For the 80 years since its founding in 1923, Fuji Electric has contributed to society through providing technology, products and services as an electric and electronic equipment manufacturer. The manufacturing expertise acquired ever since and the spirit for integrity and hard work has been passed down generation-to-generation.

The cover image shows a photo of Fuji Electric’s original office building as well as former models of magnetic contactors and silicon rectifier diodes and present products suited for globalization such as inverters, low-voltage circuit breakers, programmable controllers, digital camera-use power ICs, intelligent power modules, magnetic disks and autofocus modules. In the center of the cover image a photo of a DNA strand is shown that represents the unbroken chain of inheritance of manufacturing techniques that have been passed down since the founding of the company.

Fuji Electric Holdings Co., Ltd. Head Office : No.11-2, Osaki 1-chome, Shinagawa-ku, Tokyo 141-0032, Japan

INTRODUCTORY REMARKS

Inheriting "Genes" of Manufacturing

Kunihiko Sawa
President and Representative Director
Fuji Electric Holdings Co., Ltd.

Fuji Electric Co., Ltd. was founded in 1923 as a joint venture between The Furukawa Electric Co., Ltd. and Germany's Siemens AG. Over the past 80 years since the founding of the company we have received warm praise and encouragement from customers of Fuji Electric's technologies, products and services. At the same time, through our individual and corporate activities, and our technologies, products and services, we have continued efforts to contribute to society.

At its inception, Fuji Electric was fostered based on Siemens' technology. Japan and Germany are similar in that both are poor in industrial raw materials but have highly educated citizens who have a strong work ethic. Also, both countries were defeated in World War II and had their lands reduced to ashes, but faced with starvation, their citizens rose up and rebuilt their countries into major economic powers. German technology which was able to apply knowledge and know-how to extract the maximum functionality from the minimum quantity of materials and which always sought the highest efficiency, was the most appropriate model for resource-poor Japan.

Moreover, Fuji Electric's technologies and skills, which were fostered based on a model of logical thinking characteristic of the German people and the refined skills inherited from German "Meister," were welcomed in the marketplace as being distinctive from that of other companies which followed American technical trends.

Incorporating extensive knowledge and know-how and supported by expert skills, this technology was hailed as "proven technology" by the general public, and it is not an exaggeration to say that we lived up to our motto of "be always number one."

Today, Fuji Electric has no relation to Siemens, except in the fields of thermal power, hydroelectric power and energy management. However, we have inherited "genes" for resource-saving and energy-saving "manufacturing" techniques and a "spirit for integrity and hard work" that have been passed down since the founding of the company and are most desired in this age. On this occasion of the 80th anniversary of our company's founding, I would like our employees, our customers and the general public to acknowledge this.

The year before last the Fuji Electric Group adopted "*Fe*" as its group symbol and "*e-Front runners*" as its group statement. The "*F*" in the group symbol is the first letter of "Fuji" and represents our conviction that we continue to place importance on the technical capability, trust, diligence and good corporate culture that we have fostered since the company's earliest days. The "*e*" is the first letter of "electric" which is the foundation for our technology and also expresses our dedication to continuous "evolution" in harmony with the global "environment" so that we can realize the "enrichment" of society. The group statement is our pledge for each and every employee at his or her workplace to continue to "be a *Front runner*" in pursuit of the values embraced in the "*e*." Our "genes," as mentioned above, are the key for realizing this stated goal.

Fuji Electric Group's Corporate Governance

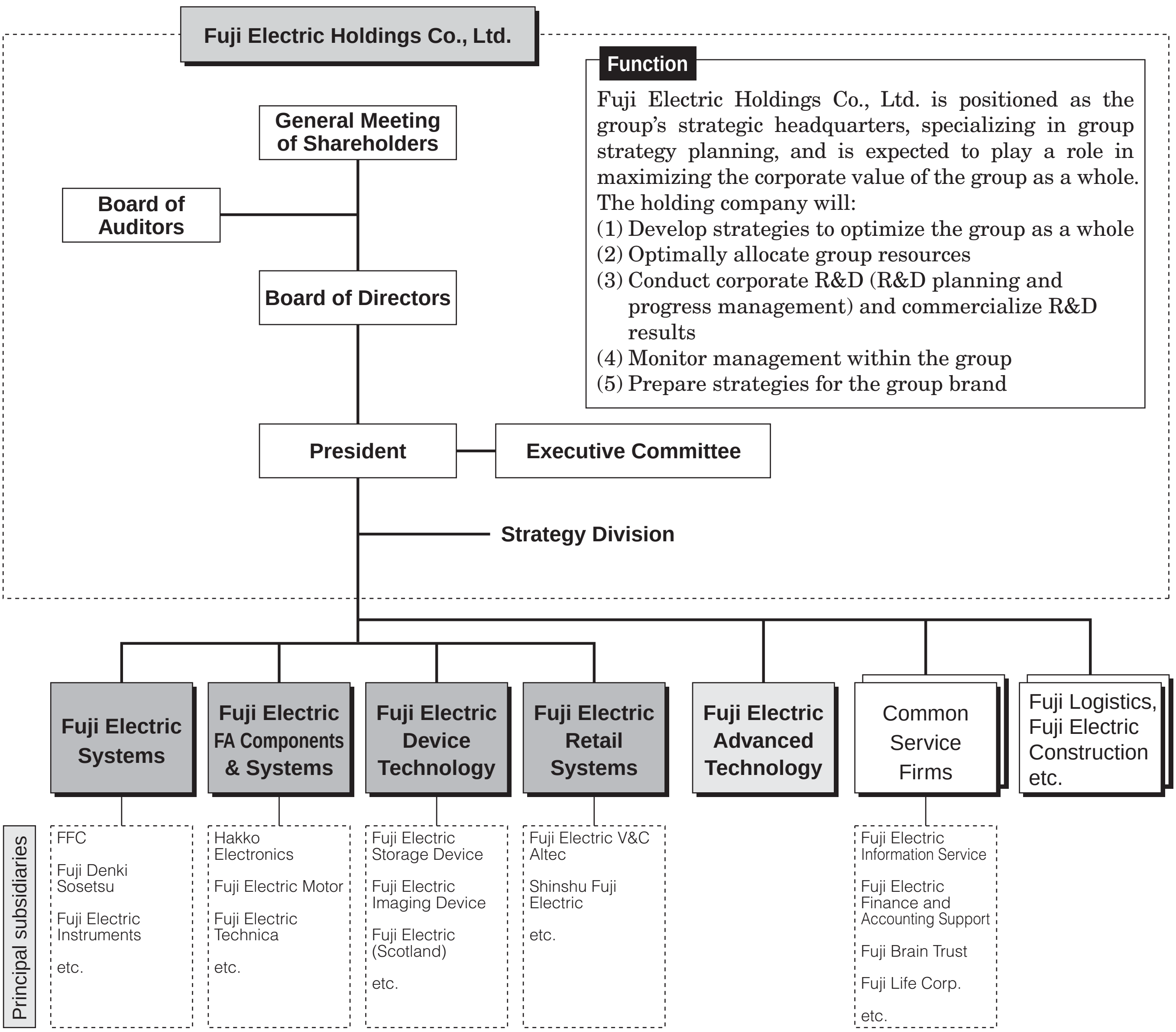
By separating the functions of supervising and executing business, the areas of authority and responsibility will be clearly defined. This will strengthen group management and allow operating companies to exercise speedy management as well as self-responsibility.

(1) From the understanding that supervision and execution functions will naturally be separated in the transition to a holding company structure, the holding company's form of corporate governance will be based on the board of auditors system.

(2) Directors of the holding company will be barred from holding directorships at group operating companies. The term of office for the directors of holding companies and those of operating companies is one year.

(3) An executive committee will be established to give advice to the president of the holding company on such issues as management strategy and policies for the group as a whole.

Group Management Structure under the Pure Holding Company System (As of October 1, 2003)



Note: Fuji Electric Retail Systems was established on April 1, 2003.

Mission and Future Role as a Core Operating Company for Next Progress

Shigeaki Hori
President and Representative Director
Fuji Electric FA Components & Systems Co., Ltd.

The Fuji Electric Group reached its 80-year anniversary in September 2003. Since its founding, many senior company employees have worked passionately in their respective era and industrial generation to achieve technical innovation, develop new products, expand the sales network, boost customer satisfaction and increase Fuji's branding strength. I am profoundly aware that the success of the Fuji Electric Group is due to the service of these senior employees and to our customers' patronage to Fuji Electric brand products over a long period, and accordingly I deeply appreciate this. Moreover, current employees who aim at further growth and expansion of the business, as well as future employees of this business, cannot forget the huge responsibility, as described above, that we have inherited.

As a result of the Fuji Electric Group's reorganization into a pure holding company system, the Fuji Electric FA Components & Systems Co., Ltd. (Fuji Electric FA) began functioning as a core operating company as of October 1, 2003. We recognized that this was a historical and revolutionizing change, and we sought answers to the question of "what should the Fuji Electric FA do as a core operating company of the Fuji Electric Group?" The answer, we believe, is to emphasize the following five points, especially in our company operations, in order to expand our business for the future.

1. Creation of a business structure for steady high profitability

The Fuji Electric FA aims "customer satisfaction and value creation by providing components used in the fields of power electronics, distribution & control, and drive control, as well as for the small or medium-sized systems formed from combinations of those components" with the world's highest level of quality, performance and service. Namely, as a key business of the Fuji Electric group, our company has a large responsibility to contribute both to corporate and also to society. We intend to create a company structure that is not affected by changes in market conditions or sales quantities and always remains profitable, even under deflationary economic conditions when the future economic environment is uncertain.

2. Proactive business operation for sales increase and expansion into the Chinese market

Our main business activity concerns the route-sales of individual FA components and systems, and it is so vital that we sustain and increase customer trust through a persistent effort. However, in addition to such single-unit sales model, it will not be possible to realize sales increase as a manufacturer in drastically changing market today, unless each individual salesperson takes the initiative to perform consulting with full use of the advanced systems technology that has been acquired thus far by the System Technology Integration Group. We intend to transform ourselves into a professional sales force who can interact directly with our customers and provide them with optimal solutions. We will also implement a sales strategy for the Chinese market which has potential market needs, and high economic growth.

3. Development acceleration for worldwide strategic products

Our business focus is not limited to Japan, and we also aim to be victorious in the tough technology and market share competition with overseas top manufacturers. Thus we can increase overseas sales rate to 30 % or more of our total sales. In order to realize this goal, we are putting our full effort into the refinement of constituent technologies and the development of new products, and we plan to advance a global strategy considering worldwide market steadily.

4. Formation of alliances to increase business efficiency

Efforts to expand our business will not only be undertaken by ourselves, but also through a proactive initiative to form alliances with other companies. We intend to operate our business efficiently through such alliances that offer higher productivity with regard to sales increase, cost reduction of development and manufacturing, and promotion of mutual complementary products.

5. Establishment of QCM activities and elimination of loss cost

In order to generate a profit in today's severe economic climate, it is necessary to raise quality further and to minimize loss cost to the extent possible. Analyzing the failures that cause less quality thoroughly by QCM (quality chain management) techniques, the causes are classified to human factors or organization factors and then each cause is corrected to stop the failures. Loss cost has been reduced year by year, and we are reaching the era in which loss cost is reduced by fifty-percent, and may be finally targeted for extermination.

While emphasizing the above five goals, we not only concentrate on our individual work activities, but also we aim to become the "industry's strongest specialist" by surveying the general flow of whole work processes and considering ways to make particular sequences of processes "more efficiently," "more rapidly" and "more precisely."

Innovative Power Electronics Technology

Hidetoshi Umida

1. Introduction

Modern society is demanding solutions to the environmental problems such as global warming by reducing CO_2 emissions and protecting the environment. These and other problems must be solved, however, while securing a source of energy. The society is based on an infrastructure that uses electric energy and therefore, the appropriate and waste-free use of this electric energy must be realized and highly efficient and reliable electric power sources must be secured.

Power electronics technology has already been fulfilling that role, and is widely used in applications ranging from social infrastructures such as generators and traction control equipment to industrial, automotive, and home electronic equipment, and cellular phones.

This paper presents Fuji Electric's recent activities concerning power electronics.

2. Missions of Power Electronics

Figure 1 shows the representative product families of Fuji Electric's power electronic products and power devices. Fuji Electric has pioneered efforts to increase the efficiency and performance, bringing IGBT (insulated gate bipolar transistor) technology into the inverters and UPSs (uninterruptible power systems), and replacing switching devices for static var compensators and static flicker compensators from thyristors or GTOs (gate turn off thyristors) to high power IGBTs, and has commercialized low loss, high performance devices. Recently in the field of the medium-power products such as high-voltage inverters, there is a trend to increase the operating voltage.

Figure 2 shows the changes in volume of inverters over time. The size of the inverter has reached almost the same level as that of the motor, due to the remarkable reduction in loss achieved by power devices. Moreover, improvements in high-speed MOSFET switches contributed in size reduction and performance enhancement in the areas of information processing and mobile equipment.

In the 1990's, one of the major tasks of power electronics has been to replace the function of the engine, the machine system, the generator or the battery with an equivalent electronics system to achieve higher performance. Progress in downsizing, cost reduction, performance enhancement, and network system connectivity has expanded the range of power electronics applications to various fields.

The new challenge of power electronics in the 21st century is to achieve harmony between the desire for more sophisticated information technology and the need to conserve resources and protect the environ-

Fig.1 Power devices and power electronics products

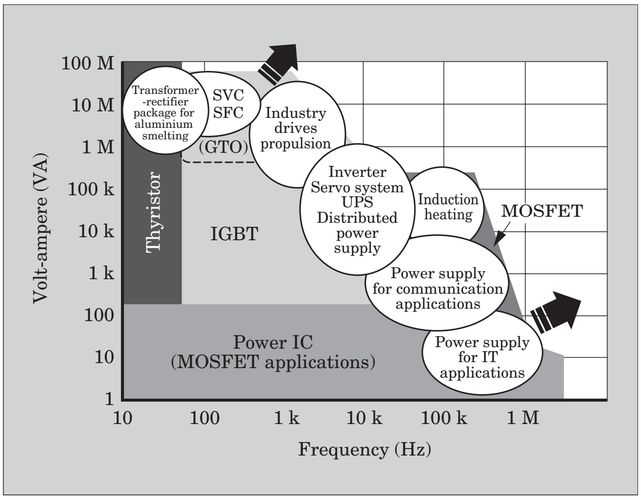
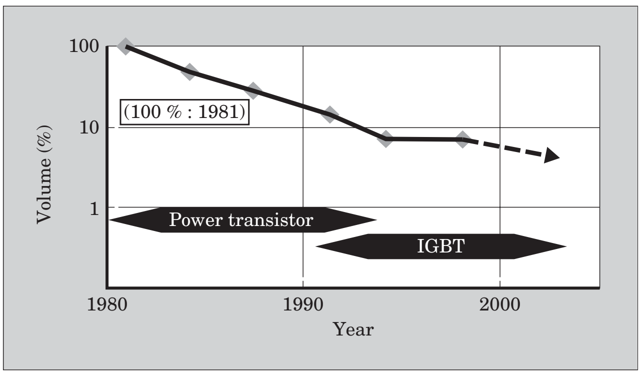


Fig.2 Changes in volume of general-purpose inverter



ment. To accomplish this, Fuji Electric is working toward the following technological goals.

(1) Technical innovation enabled by new key components
(2) Downsizing and loss reduction enabled by new technology
(3) Improvement of intelligent functions

3. New Technological Trends

Fuji Electric is developing new technologies to achieve maximum performance while reducing power loss. Several examples of these new technologies are introduced below.

3.1 Technical innovation enabled by new key components

New power devices have brought about breakthroughs in power electronics. The latest one of these innovative devices from Fuji Electric is a unique key device, the RB-IGBT (reverse blocking IGBT) [1].

Table 1 compares the functions and circuitry comparison of the RB-IGBT and conventional power devices.

Most conventional power devices have no reverse blocking capability, and therefore require a flywheel diode (indicated as Di in the table) connected in parallel as shown in Table 1. Circuit topologies that required reverse-blocking devices have long been ignored because conventional high-speed power devices such as most GTOs, bipolar power transistors, MOS FETs, and IGBTs, can not block a reverse voltage. Moreover, conventional power conversion circuits have a limitation in that a desired function must be realized by a multiple stage combination of AC-DC and/or DC-DC converters. The RB-IGBT has no such limitation, which greatly increases its capability to realize various new circuit topologies and achieve significant loss reduction.

The matrix converter, which is a typical AC-AC direct converter, requires bi-directional switches. The conventional bi-directional switch was composed of two pairs of an IGBT and diode as shown in Table 2.

Table 1 Controllability of power devices

Power devices & circuits		Current controllability: Forward	Current controllability: Reverse
Conventional power devices	GTO, Power transistor, IGBT	Available	Prohibited
Conventional power devices	GTO (Di), Power transistor (Di), IGBT (Di), MOSFET	Available	Conduction
RB-IGBT		Available	Block

However, a new bi-directional switch can be realized with only two RB-IGBTs in an anti-parallel connection.

Figure 3 shows the three-phase matrix converter, composed of nine bi-directional switches, and its input and output waveforms. The matrix converter directly converts the input voltage into an AC output voltage with arbitrary frequency and amplitude, and the input current becomes sinusoidal. The voltage drop across the new switch is reduced to 1/2 and the loss is reduced to 2/3 that of the conventional switch. The control method of this matrix converter is usually complex and much different from that of the inverter. To solve this

Table 2 Bi-directional switches

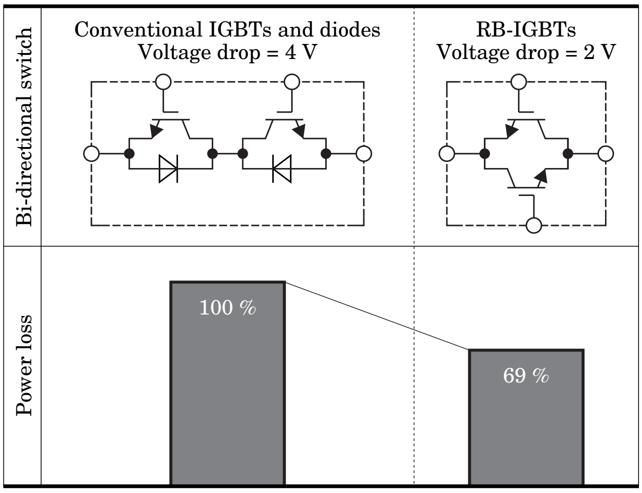


Fig.3 Matrix converter circuit and its waveforms

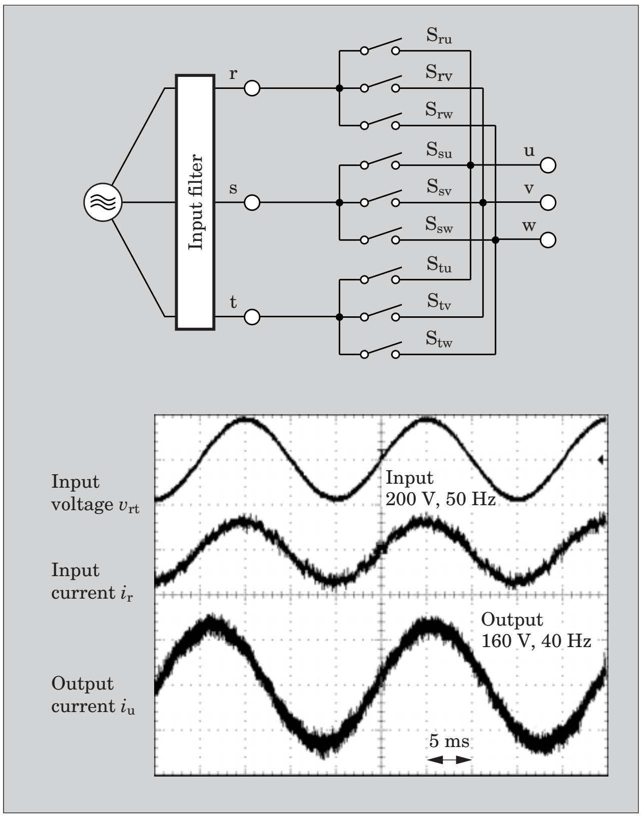
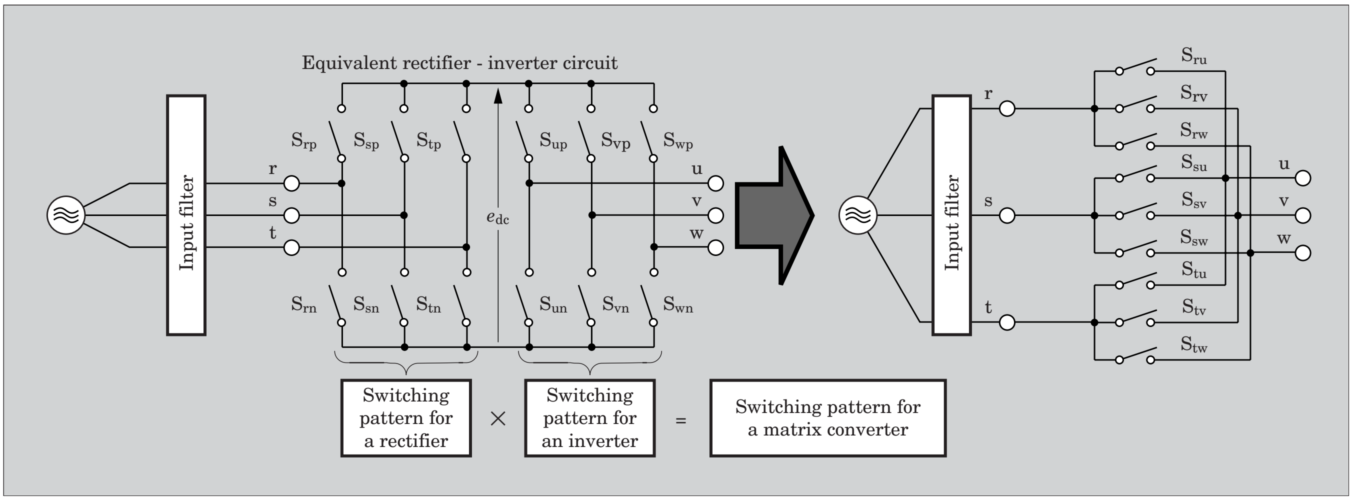


Fig.4 Virtual indirect control method



problem, a virtual indirect control method has been developed and employed.

The switching patterns for the matrix converter are synthesized mathematically from the switching patterns for a PWM rectifier and an inverter. This method enables the latest inverter control technologies to be applied to the matrix converter. (Refer to Fig. 4.)

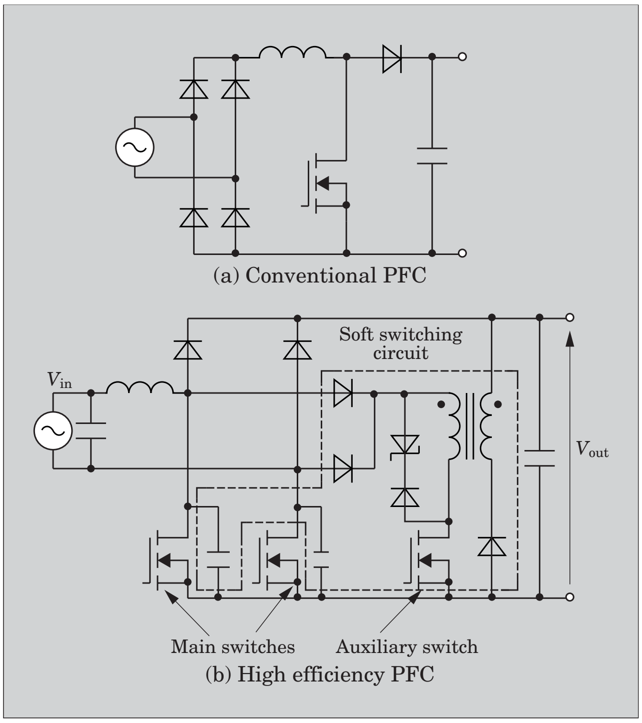
3.2 Downsizing and loss reduction enabled by new technology

Equipment for converting and controlling electric energy is required to have high controllability and low loss. Fuji Electric has control technology capable of providing high-speed response and high accuracy. In order to achieve high performance and high efficiency to conquer old theoretical limits, Fuji concentrated on the development of conversion technologies. Several new achievements in the field of power supplies are presented here.

As the AC-DC conversion circuit for power supplies, the diode rectifier has been recognized as the most efficient and advantageous device in terms of noise emission. The diode rectifier, however, has a major drawback of generating high levels of current harmonics, which prevents its use for regulating power supply harmonics. Because of this problem, PFCs (power factor compensators) are becoming popular, but they too have problems as loss and noise emissions due to the switching action.

Figure 5 shows examples of single-phase PFCs. Figure 5(a) is the most common circuit. The efficiency of this circuit is at most 95 %. The majority of the loss is due to the conduction loss of the diodes and the switching loss of the MOSFETs. Figure 5(b) shows a new PFC circuit in which the loss is much lower than in the circuit of Fig. 5(a). The total loss decreases remarkably to 1/2 that of Fig. 5(a), and the noise is suppressed at the same time by employing the forward gate bias during the reverse-conduction period of the main MOSFET switch and combining a soft-switching

Fig.5 Single phase PFC circuits



technology using auxiliary switches. Technology to reduce channel resistance is being developed rapidly in the field of the power MOSFETs, and in the near future, a remarkable reduction of resistance can be expected to achieve higher efficiency than that of the diode rectifier.

Next, an example of the three-phase PFC[(2)] is shown in Fig. 6. The proposed method reduces the IGBT's rated voltage to half that of the general three-phase PWM converter by skillfully applying a bi-directional switch circuit. As a result, compatibility with power-supply voltages of 200 V and 400 V can be achieved by using low-cost IGBTs with low voltage ratings. In addition, due to the low switching loss of the IGBT having a low voltage rating, the efficiency of

Fig.6 Worldwide three phase PFC circuit

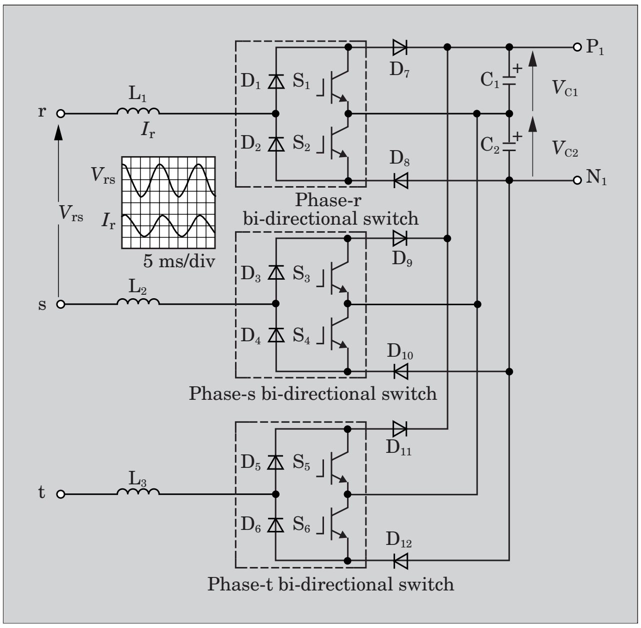
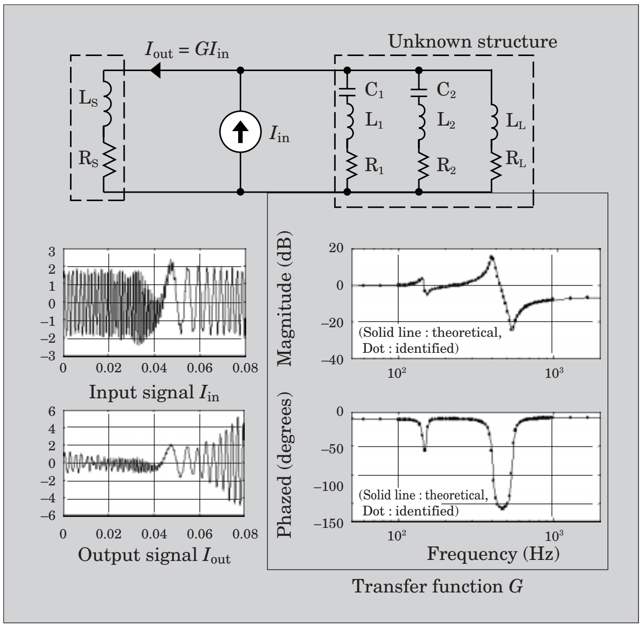


Fig.7 Plant identification result of the singular value decomposition method

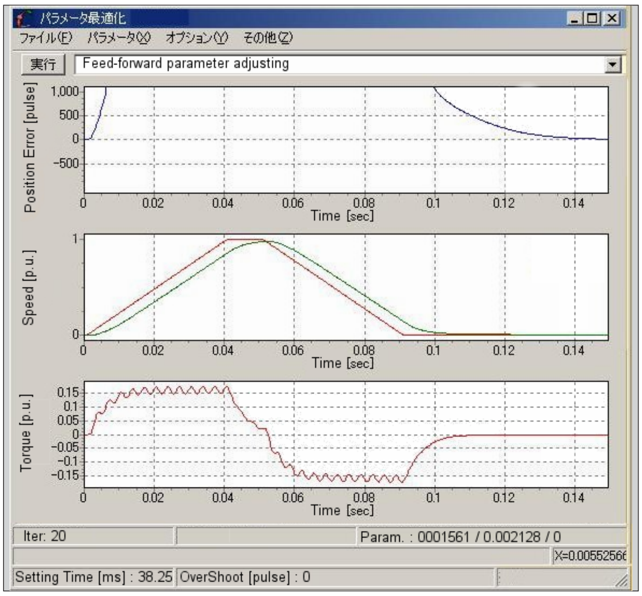


the converter is 97.4 % at 400 V operation and the size is reduced to half that of Fuji Electric's past product.

3.3 Improvement of intelligent functions

Recent power electronic equipment has functions for connecting to standard networks and meeting the requirements of IT systems. One aim for future technical innovation is to achieve a built-in intelligent function. The theory of optimization based on specific rules has been defined and an algorithm has been established. However, the optimization of the process for making judgments has not been systematized and its algorithm is complex.

Fig.8 Control parameter adjustment using a meta-heuristic technique



In some areas, auto-tuning techniques have been widely used to adjust the control parameters. However, manual-tuning by skilled experts is still needed in most areas where higher performance is required, thereby presenting an obstacle to easy optimization of the control system.

Therefore, application technologies of a mathematical method and a meta-heuristic technique are developed as parts of the research for a solution. One example of automation technology relating to adjustment is discussed below.

The identification of an unknown structure at a plant, which is the intended target for control, is one of the tasks to require an expert's judgment ability. One result of a trial to automate the identification is shown in Fig. 7. This is an example in which the structure identification utilizes the singular value decomposition method. The structure can be specified by adding the order determination into the identification process of the structure's transfer function.

After the identification of the system structure has been finished, an appropriate control system can be selected and its parameters adjusted.In actual plants, however, there are many adjustable elements having complicated interdependencies, and the adjustment of these elements is extremely difficult. Therefore, one approach is to apply a meta-heuristic technique for parameter adjustment instead of a human operator who can adjust only 1 or 2 parameters at a time.

Figure 8 shows an example of the results of the adjustment.

Because the meta-heuristic technique can manipulate many parameters simultaneously, the adjustment result can be obtained without repeating many trials.

While the above-described technique has not yet reached the level of human experts, translating the "experiences" of those experts into the algorithms is expected to lead to new intelligent systems to aid or substitute for humans in the adjustment of complicated control systems.

4. Conclusion

As a leading company in the field of power electronics and power devices, Fuji Electric will continue to develop new frontiers, especially in Fuji Electric's strong fields such as inverters, UPSs, and distributed power sources using fuel cells or solar cells. Through those efforts, Fuji Electric would like to contribute to the realization of an advanced and comfortable society that lives in harmony with the environment.

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Fuji Electric's General-purpose Inverter Aims to be No. 1

Masaru Yamazoe

1. Introduction

In 1977, Fuji Electric developed and began to sell the first general-purpose transistor inverter for industrial use, thereby paving the way for variable-speed drives that use inexpensive standard motors. In the 27 years since then, as the consistent leader in the industry, the Fuji Electric Group has worked to innovate the technology of general-purpose inverters and has established the general-purpose inverter as an indispensable equipment for industrial applications. The progress of the general-purpose inverter can be described in terms of advances toward smaller size, higher performance and lower prices.

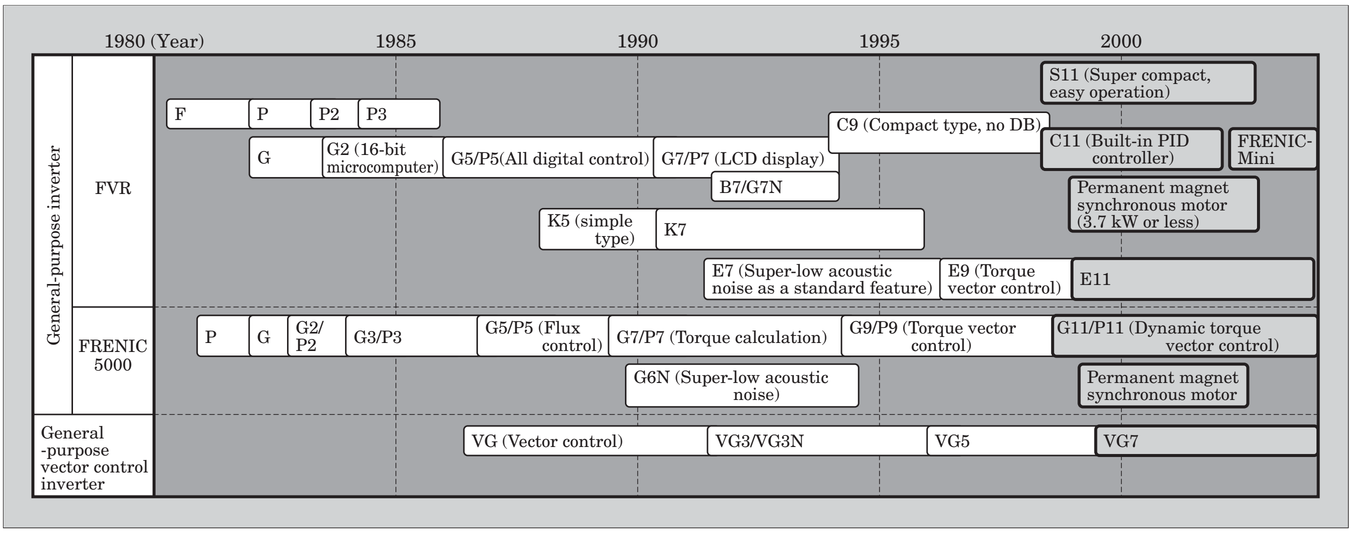
This paper looks back on the progress of Fuji Electric's general-purpose inverters, describes future technologies to provide the functionality and performance required for future general-purpose inverters, and also discusses future goals of Fuji Electric's general-purpose inverters.

2. Progress of Fuji Electric's General-purpose Inverters

In 1977, Fuji Electric introduced the world's first general-purpose inverter that used a bipolar junction power transistor (BJT). The development of this device was enabled by breakthroughs that increased the voltage and current levels of power transistors and also by advances in the technology for power transistor applications. Thereafter, general-purpose inverters have continued their development in tandem with the progress in technical innovation.

Figure 1 summarizes the progress of Fuji Electric's general-purpose inverters. In 1982, Fuji developed the FRENIC5000G and FVR-G series of general-purpose inverters that utilized sinewave PWM (pulse width modulation) control. Originally, we only provided a 200 V power supply series, but after a 1,000 V power transistor was developed, we commercialized a 400 V power supply series in 1982 as our basic series. This is said to be the beginning of the history of modern general-purpose inverters. Because a general-purpose inverter is capable of easily operating a standard motor at variable speeds, the use of general-purpose inverters quickly became popular in various industrial applications including woodworking machines, conveyance machinery such as conveyors and dollies, fans and pumps, food processing machines, and the like. Noticing that general-purpose inverters are highly

Fig.1 Progress of Fuji Electric's general-purpose inverters



effective in saving energy, especially in variable torque drive applications for fans, pumps and the like, we developed and brought to market the FRENIC5000P and FVR-P series, one after another. Our product line initially had a capacity up to 70 kVA, but following the development of a 1,200 V, 300 A power transistor, we increased the capacity of our product line to enable the driving of up to a 280 kW motor. In 1986, we brought to market the FRENIC5000G5 and FVR-G5 series, one after another. The FRENIC5000G5 series uses flux control-type PWM control to reduce the torque ripple of a motor. The FVR-G5 series is not only suitable for performing motor control, but it is series of fully digital control inverters that feature digital operation and settings, and was the first inverter series to utilize a 7-segment LED (light emitting diode) display and a key pad panel equipped with key switches. The FVR-G5 enables necessary parameters for the inverter to be displayed and set as digital values, which lead to a dramatic increase in multi-functionality and ease of operation.

Introduced to the market in 1994, the FRENIC 5000G9 series was the first general-purpose inverter to incorporate the concept of vector control, and this series realized a dramatic improvement in performance. Thereafter, we introduced the industry's smallest inverter, the FVR-C9 series, which was the leading product in the industry. Then in 1998, we introduced the present FRENIC5000G11 series, whose performance surpassed that of the initial vector controlled inverters. In 2002, we brought to market the most recent and extremely cost effective series, the FRENIC-Mini.

3. Progress of General-purpose Inverter Technology

The progress of inverter technology is the same as the progress of power electronics technology. Inverter technology can roughly be classified into the categories of main circuit technology, control circuit technology, and motor control technology.

3.1 Main circuit technology

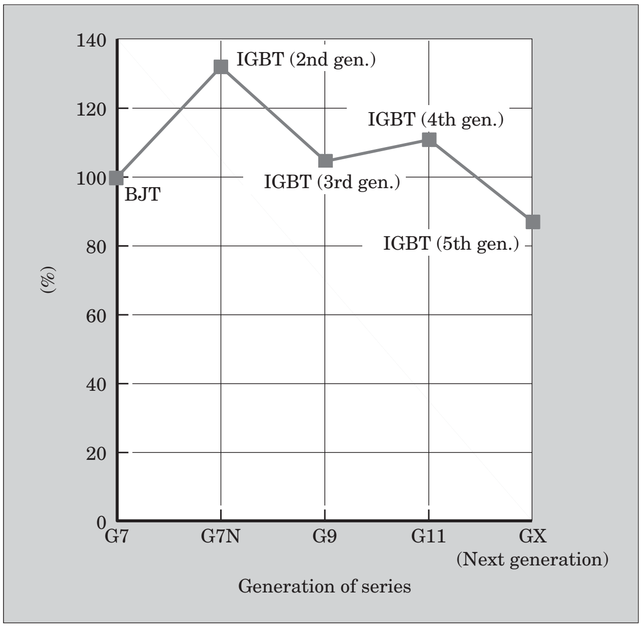
Main circuit technology has progressed along with advances in power devices. By applying PWM control to a full bridge-type inverter that uses a BJT, a compact and low-cost general-purpose inverter was realized. When a BJT was utilized, however, the carrier frequency, which was the switching frequency of the power device, was several kHz and the motor noise generated by switching at this frequency was audible as a harsh and unpleasant sound. Moreover, the current ripple was large, and from the present day perspective, this resulted in large loss by the motor. The problems were resolved by the development of an IGBT (insulated gate bipolar transistor) that enabled high-speed switching and in 1988, by the introduction of a general-purpose inverter that utilized this IGBT.

Fuji Electric introduced the FRENIC5000G6N series, which utilized an IGBT, in 1989. By using an IGBT, the carrier frequency was increased to 10 kHz or greater, thereby eliminating the harsh, unpleasant motor noise and consequently there was an increase in general-purpose inverter usage at locations where people were nearby. Thereafter, IGBTs have continued to be used as the power devices for general-purpose inverters. The increase in carrier frequency, however, created a new problem of electromagnetic noise, which was higher than when BJTs were used, and this noise affected peripheral devices. Measures to reduce electromagnetic noise became a serious problem for general-purpose inverters. Moreover, power device loss was also greater than when BJTs were used, and the measures to reduce this loss are linked to advances in cooling technology such as the development of heat sinks and the like.

Figure 2 shows the trend of loss generated by general-purpose inverters. The majority of loss generated by a general-purpose inverter is the loss attributed to the power device, and there was a dramatic increase in loss when BJTs were replaced by IGBTs. Advances in IGBT technology enabled the next generation of IGBTs to achieve approximately the same level of loss as BJTs. Moreover, in the G11 series, which used the 4th generation of IGBTs, magnetic noise was reduced but, as a consequence, loss increased to a level greater than that of the G9 series which used 3rd generation IGBTs. Our next generation inverter series, which will use 5th generation IGBTs, is designed to provide dramatic improvement by reducing both magnetic noise and loss.

In order to reduce the size and cost of small-

Fig.2 Loss in general-purpose inverters



capacity inverters, Fuji Electric has independently developed a power module specifically for inverters. By integrating the inverter's main circuit terminal with the power module, the circuitry has been simplified and made smaller with lower cost. Fuji's power module for inverters uses our proprietary compound metal printed circuit board to simplify the cooling of the miniaturized power module.

3.2 Control circuit technology

Control circuit technology underwent its largest change during the transition from analog to digital circuitry. In particular, in 1986, Fuji Electric was the first in the industry to apply fully digital control using a 16-bit CPU (central processing unit) to create the prototype for the modern general-purpose inverter. The higher performance and multi-functionality of general-purpose inverters could not have been realized without advances in CPU technology.

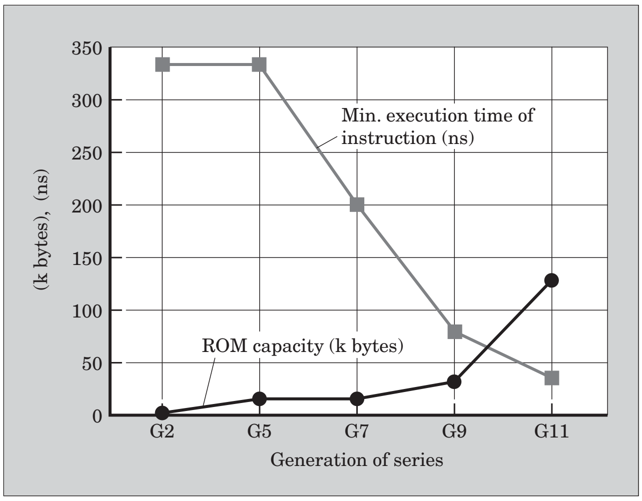
Figure 3 shows the history of improvement in the performance of CPUs used in general-purpose inverters. Performance improvements have resulted in approximately 10 times the computational processing speed and 30 times the program capacity, thereby making it possible to realize inverters having higher levels of performance and multi-functionality. Moreover, control circuit technology is characterized by an appropriate balance between the hardware using LSI (large scale integrated circuit) and the software.

3.3 Motor control technology

Motor control technology is based on the *V/f* control of induction motors and enables standard motors to be operated at variable speeds. The FRENIC5000VG series, introduced in 1986 as the industry's highest precision inverter, uses vector control to realize performance comparable to that of a DC motor, and enables the use of inverters in new applications such as cranes, car parking facilities, winding machines, extruders and the like that require highly responsive and highly accurate speed control performance. Based on this, vector control began to be applied to general-purpose inverters in 1990, enabling the high performance control of standard motors.

With the advances in control technology, applications for general-purpose inverters have increased. Figure 4 shows the markets in which drive equipment are utilized. Recently, general-purpose inverters have also been used in gear-equipped elevators and cranes.

Fig.3 History of CPU performance improvements



4. Future Requirements for General-purpose Inverters

In looking back at the progress of inverters, progress has been made in response to requirements for smaller size, higher performance and multi-functionality. The expected future requirements of general-purpose inverters are listed below.

(1) Miniaturization has achieved an inverter size that is approximately 1/10 that of an original-stage equivalently functional inverter. Figure 5 shows the volumetric changes in size of general-purpose inverters. Demands for miniaturization are not as strong as in the past, but in the future, miniaturization will be requested for general-purpose inverter systems that include peripheral devices.

(2) Performance and multi-functionality have increased with each successive generation of inverter, and with the increase in general-purpose inverter applications, there are strong demands for higher performance and greater multi-functionality. The increase in multi-functionality of general-purpose inverters has been amazing, but it can also be said that the utilization of this multi-functionality has become complicated for the end user. Because it is sufficient to provide just the required functions for a particular application, demand will likely increase for inverters that allow functions to be selected according to the application and for user-programmable inverters.

(3) The market for general-purpose inverters originated in Japan, but now this market has spread worldwide and is reportedly valued at approximately 3 billion dollars. Requirements vary somewhat according to country and region, and the problem of supporting these differences is a challenge for the future. Such considerations include, for example, protective structures, terminal structures, anti-noise filters, as well as considerations for an open field bus. Moreover, there has been an increase in various regulations, and compliance with Europe's CE marking and RoHS (restriction on hazardous substances) regulations or the equivalent are being required throughout the world. These various regulations are indications of the heightening environmental concern. Even in Japan, users are increasingly calling for

Fig.4 Example applications for general-purpose inverters

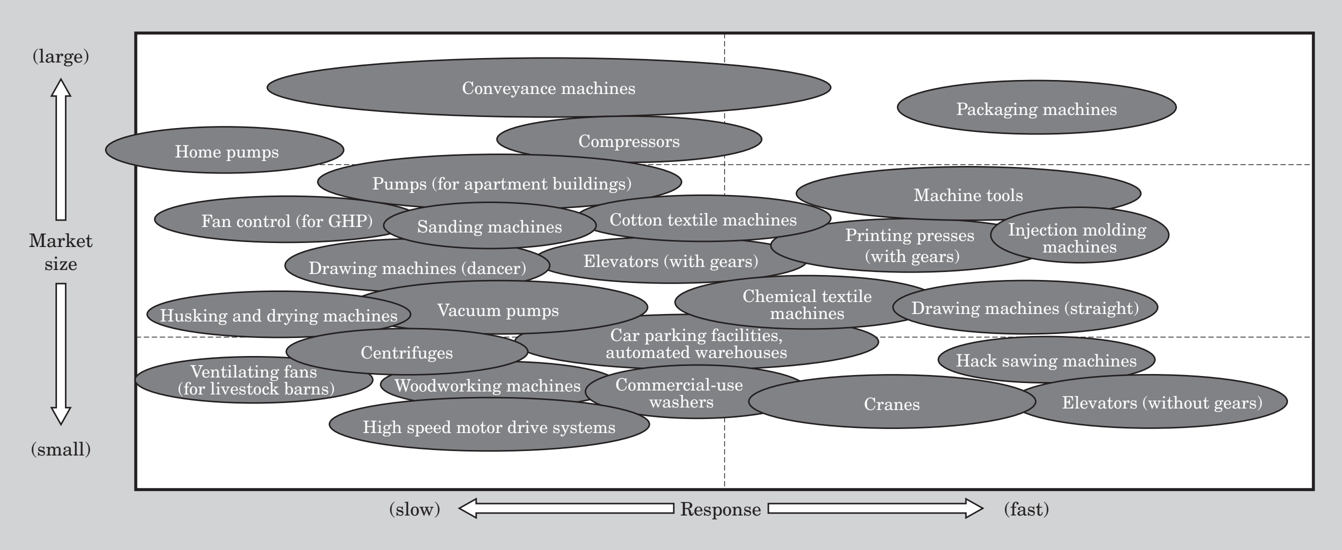
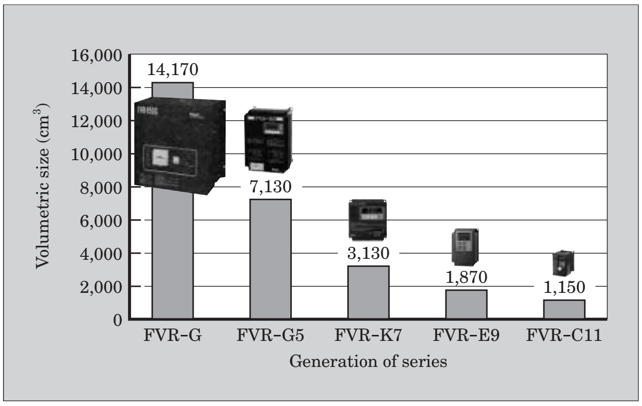


Fig.5 Changes in size of general-purpose inverters (750 W)



"green procurement" and this will likely be an important factor for future inverters.

5. Outlook for Future Technology

5.1 Main circuit technology

IGBTs will likely continue to be used for some time as the basic power devices for inverters. The main circuits most commonly employ a full bridge inverter using PWM control. Some inverters are trending toward commercialization as 3-level inverters, but since the cost is high, applications for these inverters will be limited. A reverse-blocking IGBT has been developed and circuits are being designed to best utilize its features, but applications will likely be limited due to the high cost.

The most important trend of main circuit technology is toward noiseless circuitry. The increase in magnetic noise caused by switching at a high carrier frequency has been described above, but in a broad sense, the development of technology to solve the problem of noise (magnetic noise, harmonic current emissions, leakage current, etc.) is crucial and Fuji Electric is advancing technical development to realize a completely noiseless inverter.

5.2 Control circuit technology

The use of highly integrated LSI chips containing a CPU core is expected to increase in response to demands for miniaturization and for the application of high-speed CPUs in order to achieve higher performance and increased multi-functionality. Requests for connection to an open field bus have also resulted in the emergence of inverters containing built-in interface functions as a standard feature.

5.3 Control method

As performance levels increase, it becomes necessary to adjust the characteristics of the drive motor, and automatic tuning technology and robust control technology are expected to evolve as control methods.

A shift in control methods, from inductive motor driving to synchronous motor driving has been observed. In particular, synchronous motor driving has already begun to be used in pump applications that aim to achieve energy savings, higher speed and smaller size. This trend is expected to continue.

5.4 Maintenance

General-purpose inverters use components such as electrolytic capacitors and cooling fans that have a finite lifespan, and therefore, maintenance is essential. Efforts are underway to extend the useful lifespan of these components and to develop technology that does not use these finite-lifespan components and ultimately general-purpose inverters will not require any maintenance. For the time being, however, functions for displaying lifespan information and for outputting lifespan prediction signals will likely be improved to simplify maintenance and to increase reliability.

In addition, internet-based servicing can be used to perform maintenance in the case of a malfunction or the like. The ease of use is expected to increase.

6. Future Aims of Fuji Electric's General-purpose Inverters

Fuji Electric first began selling its FRENIC5000G series 27 years ago, and has continued to provide cutting-edge general-purpose inverters that utilize the most advanced technology of the time. Based on the requirements for general-purpose inverters and the outlook for future technical innovation, future aims of Fuji Electric's general-purpose inverters are described below.

(1) Wide range of model types

As the leading manufacturer of general-purpose inverters, Fuji Electric aims to have a complete line of products, from low-end inverters to high-end inverters, and to continue to provide the best-suited inverter for each particular application. Also, in view of the global market, Fuji Electric intends to create a line of different models that range from small to large capacity and that support different voltages as in the case of overseas manufacturers.

(2) Environmentally-friendly inverters

Fuji Electric aims to make its general-purpose inverters become noise-free. Although previously considered a source of noise, the development of inverters that do not adversely affect the peripheral devices is an important issue.

As represented by the concept of "green procurement," there is demand for products manufactured without certain hazardous substances. Lead-free products have already begun to be used in household electrical appliances, and there are similar demands for making industrial-use general-purpose inverters lead-free as well. Fuji Electric is already endeavoring to develop general-purpose inverters that do not contain certain hazardous substances, and expects to be compliant by 2005 with its newly developed products. The FRENIC-Mini, introduced to the market in 2002, is already using lead-free solder in some parts of its construction.

As described above, Fuji Electric's general-purpose inverters aim to become "environmentally-friendly inverters."

(3) Support of diverse applications

In the past, general-purpose inverters were controlled by a concentrated control system whereby commands were received from a host controller or the like. On the other hand, there are also requests for distributed control systems in which the information of adjacent inverters is captured and an inverter operates by evaluating and controlling its own actions. Fuji Electric's general-purpose inverters aim to be able to support these types of requests too.

Required specifications are diverse and depend on the particular application. The operation and specifications of a general-purpose inverter are determined by a user's selection of parameters with the integrated function group. In order to support diversification, one solution is to provide the user with programmable functions. In other words, one realization of this concept is a general-purpose inverter provided with a built-in programmable controller (PLC) function.

(4) Pursuit of cost effectiveness

The trends for general-purpose inverters are diverging toward the extremes of either single function, low cost products or high-performance, multi-function products. However, from the perspective of an application, there is no need for performance and functions in excess of what is appropriate for that application. In other words, users are requesting that cost effective inverters be provided. For this reason, it is important that there be a standard inverter, which is situated between the two extremes. Such an inverter is required to be capable of easily supporting user requested specifications, and Fuji Electric intends to develop such a standard general-purpose inverter. Moreover, the vector inverter that previously used a special motor has recently become able to use a standard motor, and the boundary between general-purpose inverters and vector inverters is becoming blurred. Fuji Electric intends to remove this boundary and provide users with lower cost and higher performance inverters.

7. Conclusion

This paper has looked back on the advances of Fuji Electric's general-purpose inverters, and discussed the future requirements for general-purpose inverters and Fuji's aims for its general-purpose inverters.

Fuji Electric intends to continue to promote the evolution of general-purpose inverters and to provide the latest general-purpose inverters to the worldwide market. Constant technology development and product development are essential for this purpose. Fuji Electric is committed to developing new general-purpose inverters by adding new technology to its base of cultivated technology, and to respond to user needs.

Low-voltage Switching Devices for the Global Market

Yasutoshi Ide

1. Introduction

As society has become more industrialized over the last half-century, low-voltage switching devices such as magnetic contactors and circuit breakers have evolved greatly as the main components for electrical equipment. Recent conditions such as full-scale global deployment and an upsurge in environmental protection measures are requiring new advances in these components.

Fuji Electric has always produced and provided distinctive products that have pioneered technical trends and have met market demands.

This paper introduces Fuji Electric's recent series of low-voltage switching devices and our efforts to satisfy the latest market demands and to incorporate new technical trends.

2. Trends of Low-voltage Switching Devices and Fuji Electric's Activities

2.1 Market trends

The size of the global market for low-voltage switching devices, assumed to consist mainly of circuit breakers, earth leakage circuit breakers, magnetic contactors (MCs) and overload relays, was approximately 700 billion yen in the year 2001. In China where economic condition is especially good, market growth is continuing at a rate of several percent or more.

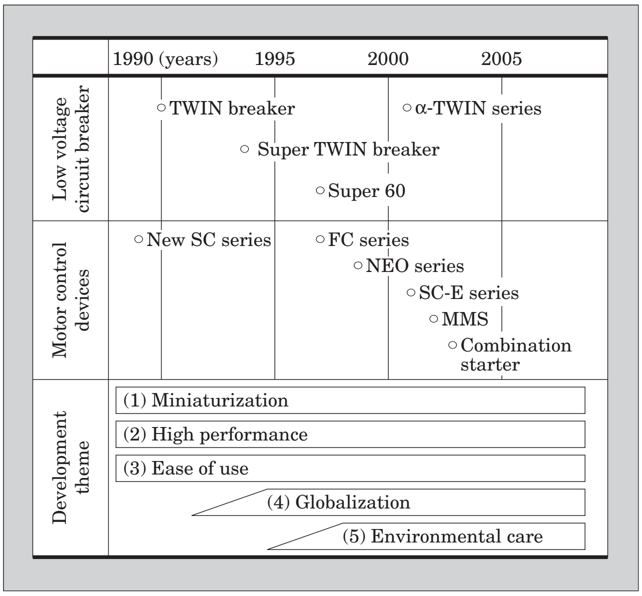
In response to these international market trends, customers' business is rapidly expanding into global markets. Therefore, the necessity for products that comply with global standards and specifications is increasing rapidly.

2.2 Technical trends and Fuji Electric's activities

Figure 1 shows the history of development of our main products in the field of low-voltage switching devices and their underlying development themes.

Until now, development pursued the main three themes of: ① miniaturization, ② high performance and quality, and ③ ease of use. These of course are all universal themes that are still continued to be pursued.

Fig.1 New product development and development theme



The TWIN Breaker and the new SC series of magnetic contactors announced in 1990 were innovative products which pursued, to the extent possible, miniaturization, high performance and ease of use. These devices are still popular today. Meanwhile, over the past several years themes such as ④ globalization and ⑤ environmental care have rapidly been increasing in importance.

Below, we introduce specific examples of Fuji Electric's efforts in the low-voltage circuit breaker and motor control fields.

3. Fuji Electric's Efforts Relating to Low-voltage Circuit Breakers

Fuji Electric has long been providing circuit breakers and earth leakage circuit breakers.

These devices have been marketed under the name of the Fuji auto breaker (FAB) and the Fuji earth leakage breaker (ELB), respectively, and have been well received in the market.

The TWIN breaker put on the market in 1990 (shown in Fig. 1) was an innovative series that featured, for the first time in the industry, the same external dimensions for FAB and ELB. The concept of standardized external dimensions has been inherited as a basic concept for FABs and ELBs, and has also become a market standard in the Japanese market.

3.1 Characteristic of α-TWIN series

Fuji Electric's FAB and ELB series are shown in Fig. 2. The TWIN breaker concept unifies the whole region from 30 A to 800 A. Within this region, the α-TWIN covers the range from 30 A to 100 A, which is the region of most usage. The α-TWIN has been designed not only to achieve ultimate miniaturization, but also to comply with the increasing demands for globalization and environmental consideration on an advanced level. The external appearance of the α-TWIN is shown in Fig. 3.

(1) Ultimate miniaturization

Figure 4 shows a cross-sectional view of the α-TWIN ELB together with a superimposed rendering of the dimensions of the previous TWIN breaker and a former model. Over the past ten years, the length of the ELB has been reduced from 200 mm (former model) to 130 mm (TWIN) and then to 100 mm (α-TWIN). There is no doubt that this 50 % reduction achieved by the α-TWIN can be called the ultimate miniaturization.

Figure 5 shows accessories for the α-TWIN. Since panel specifications may change during manufacture and operation, the α-TWIN has been designed for flexibility and most of its accessories can easily be attached by the customer.

(2) Globalization of the α-TWIN

The α-TWIN complies with major international and domestic standards (such as JIS, IEC, and UL/CSA), and as such, displays CE and UL markings.

Fig.2 FAB and ELB series

		Ampere frame size (AF)							
		30	50	60	100	225	400	600	800
Short circuit breaking capacity I_{cu} at 440 V IEC947-2 (kA)	1.5								
	2.5			α-TWIN series					
	7.5								
	10								
	15								
	25					Super 60			
	35							Super TWIN breaker	
	50								

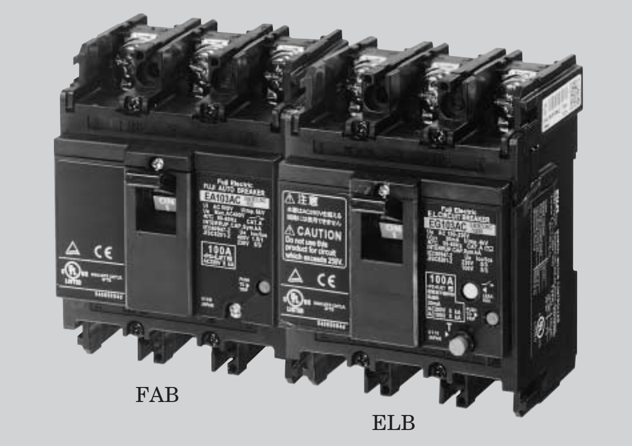


Fig.3 Appearance of MMS α-TWIN

Fig.4 Cross-sectional view of α-TWIN

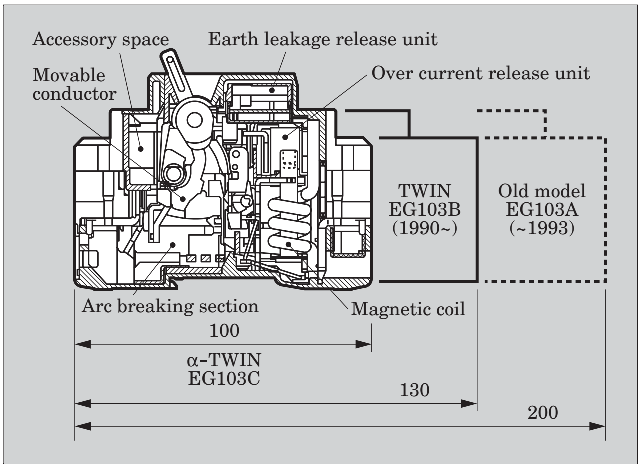
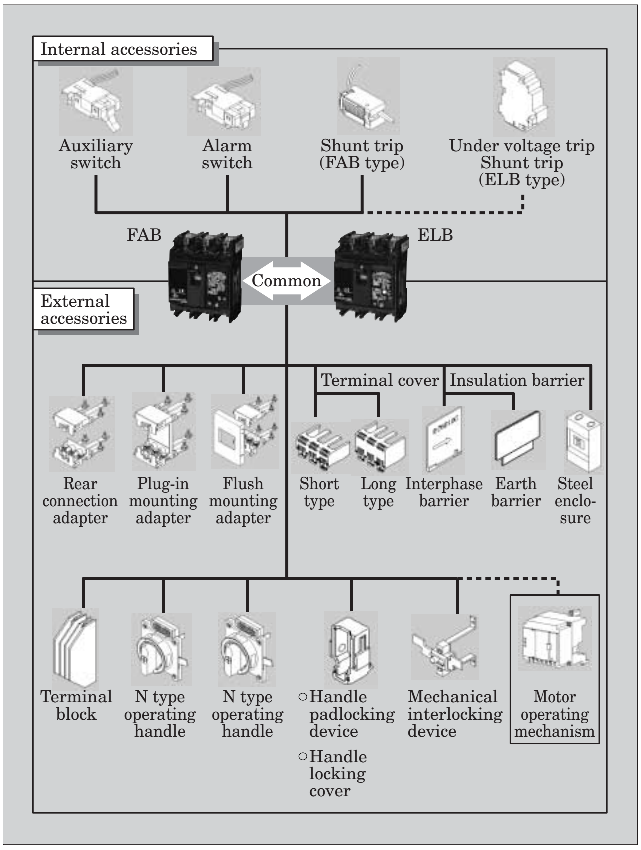


Fig.5 α-TWIN accessories



Therefore, the α-TWIN has been designed in response to customer demands for equipment suitable for deployment overseas. Moreover, environmental measures (such as the use of lead-free material, for example) have also been applied.

3.2 Design and manufacturing technology to achieve miniaturization

The ultimate miniaturization of the α-TWIN is a result of marginal design of each component such as the short circuit breaking mechanism, arc extinguishing chamber, overcurrent detection, and earth-leakage detection units, while making full use of simulations based on previously accumulated characteristic technology.

4. Efforts to Develop Motor Control Devices

For nearly 50 years, Fuji Electric has been providing motor control and switchgear equipment such as magnetic contactors (for motor control) and thermal overload relays (for overload protection). In this paper we will focus on the new MC and TOR series which target the global market, the MMS, and the combination starter that combines the MC and MMS into a single compact unit.

4.1 Product series targeting the global market

In Japan, the process of unifying the JIS standard with the IEC standard is being undertaken in every field. Since the JIS standard for MCs and TORs did not differ greatly with the corresponding IEC standard, a unified JIS standard was announced in 1999, thereby eliminating any remaining barrier due to international standards. Moreover, although the unification of standards is advancing globally at a quick pace, the standard specifications created by the industrial culture of a market are actually difficult to unify. A good example is the difference in electric wire connecting systems for different markets. Fuji Electric's MC and TOR series are available in two series of differing terminal structures, one that connects ring-shaped terminals and another for direct wiring. These structures enable the devices to be useable in any market in the world. The MC, TOR, and MMS series are shown in Fig. 6, and the terminal structures of the MC are compared in Fig. 7.

4.2 Support of advanced motor circuit protection functions

In Japan, most power supplies for a motor circuit are 200 V, and 400 V systems are very rare and account for only about 10 % of all systems. The 400 V system, however, is the most common system overseas, and the difference in circuit voltage has led to differences in the degree of protection perceived to be required for short circuit and electric shock accidents. A short circuit accident in a 400 V system involves a much larger amount of energy than in a 200 V system,

Fig.6 MC, TOR and MMS series

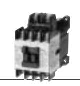
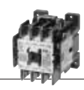
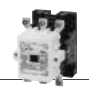
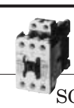
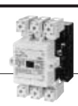
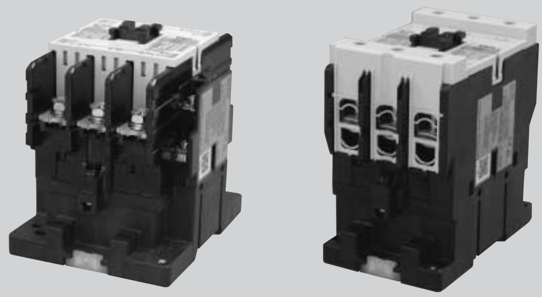
		Small capacity	Middle capacity	Large capacity
AC-3, 400 V (A)		up to 25	32 to 65	80 to 150 to 800
Ring terminal wiring type	CTT			
	TOR	New SC series	NEO series	
Direct wiring type	CTT			
	TOR	SC–E series		
	MMS			

Fig.7 MC terminal structure comparison



NEO series (SC-N3) SC-E series (SC-E3)

thus leading to the requirement for a short circuit protector with a large breaking capacity. Nowadays, technical competition for short circuit protection is focused on developing ways to reduce the energy during a short circuit accident and thereby prevent damage to a MC and TOR.

The manual motor starter (MMS), introduced below, is a newly developed product series that satisfies the safety requirements of overseas 400 V motor circuits.

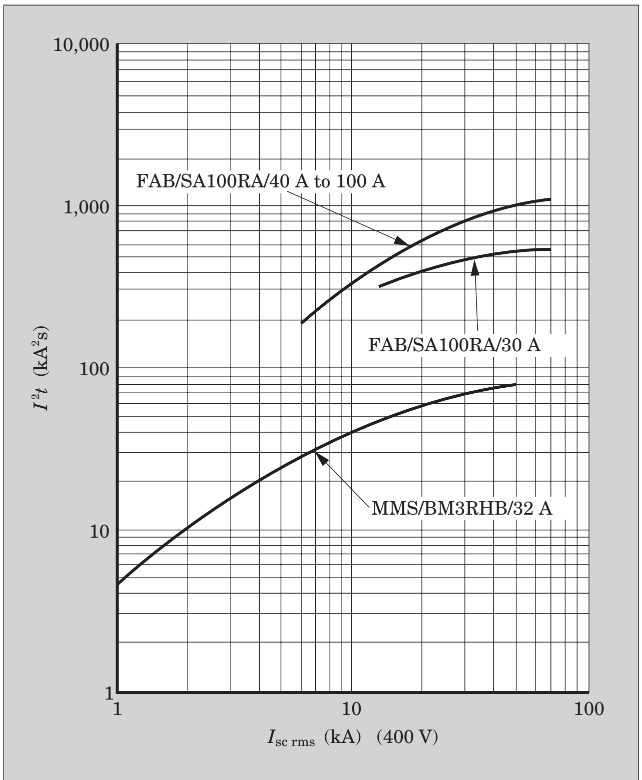
(1) MMS

The MMS is a product that combines the short circuit function of a low voltage circuit breaker and the overload function of a TOR into a single compact component. The external appearance of the MMS series is shown in Fig. 8. One of the greatest features of the MMS is its enormous current limiting performance during the breaking of a short circuit current. Figure 9 shows the current limiting characteristic of the MMS. It can be seen that the MMS suppresses the energy generated during a short circuit to about ten times lower than that of an ordinary circuit breaker.

The structure of the MMS is shown in Fig. 10. The main feature is the current breaking section. The aim

Fig.8 Appearance of MMS series

Fig.9 Current limiting characteristic



to rapidly increase the arc voltage and to limit the let through current at the time of a short circuit has been achieved by positioning two arc chambers in series per pole.

Of course, the MMS can be used independently as a manual switch for an electric motor, but generally, it is used in combination with an MC. The high current limiting capability prevents damage to the MC in the case of a short circuit accident. The level of short circuit coordination is defined in IEC 60947-4-1 as either “type 1” in which the MC cannot be re-used, or “type 2” in which re-use of the MC is possible.

In the design of modernistic automation equipment, specifications calling for “type 2” coordination are expected to increase in order to reduce the maintenance downtime of the equipment after an accident. Fuji Electric’s MMS is just the right product to fulfill these specifications.

Fig.10 Internal structure of MMS

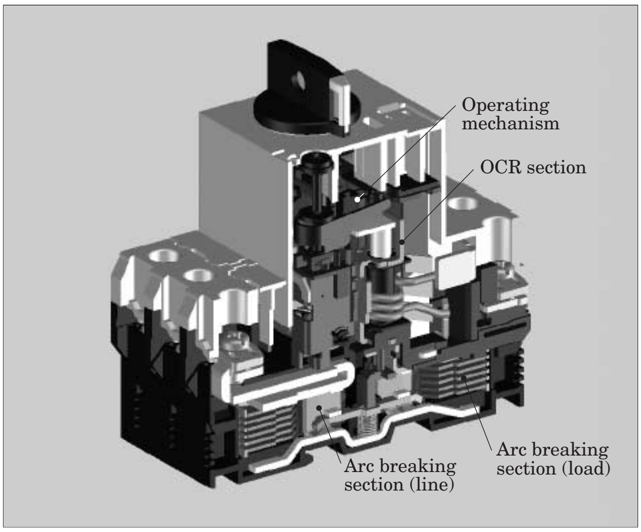
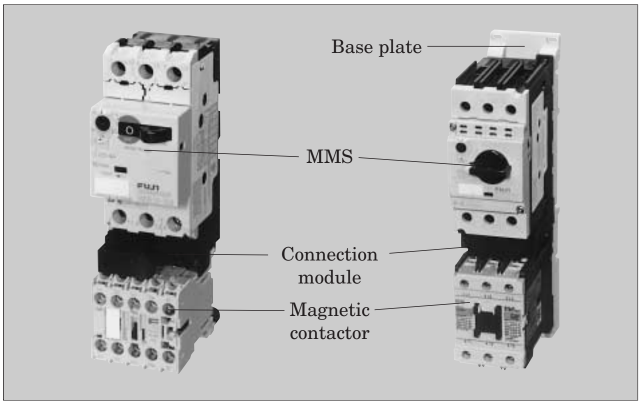


Fig.11 Combination starter



(2) Combination starter

The combination starter shown in Fig. 11 is an MMS and MC combined by a special interconnect component. The advantage of combining both an MMS and MC into a single unit is that it simplifies the selection of the coordination level and additional wiring is unnecessary, it also reduces the wiring work and requires less space for installation.

5. Conclusion

This paper has introduced Fuji Electric’s efforts in response to market and technical trends, and the main new series of low-voltage switching components recently put on the market. It is thought that market demands will become increasingly diversified in the future and will become much more complicated.

Fuji Electric intends to utilize leading edge technology as well as its accumulated experience and technical know-how to continue to function as a valuable component provider for the world market.

Customer Satisfaction Through the Pursuit of High Quality
"*Quality is our message*"

Akira Takai
President and Representative Director
Fuji Electric Device Technology Co., Ltd.

Fuji Electric Device Technology Co., Ltd. is organized into separate business units for semiconductor, storage device and photoconductor products. The operation of these business units is supported by high quality products, all of which are quick to incorporate new technology innovations, and are subjected to the business processes of technology development, product development, manufacturing, quality assurance and after-sales service. Fuji Electric Device Technology Co., Ltd. has the following goals,

- ○ The abovementioned business units shall be the world-leading specialized manufacturer in their field
- ○ The business units shall achieve high business performance by providing high-quality products

and is promoting its business with the slogan, "***Quality is our message***."

Based on its core technologies of high-voltage, high precision analog CMOS, and digital control, Fuji Electric is expanding its product lines mainly around power supply ICs, FPD (flat panel display) driver ICs, and the like. The product concept for power supply IC is based on the aims of achieving lower power consumption, higher precision, smaller size and a greater combination of functions. Using its proprietary analog CMOS technology, Fuji Electric is working to develop specific products that will be useful for its customers, in the fields of cellular phone, personal digital assistant (PDA), and digital audio portable devices. With regard to PDP (plasma display panel) driver ICs, C/DMOS technology is being commercialized for medium voltage-low current address ICs and SOI substrates for high voltage-high current scan ICs. The camera market is shifting rapidly from conventional film cameras to digital cameras, and products based on the auto-focus IC, which realizes the advantage of a short shutter release time, are being developed to meet the needs of the digital camera market based.

In the field of discrete power semiconductors, we are focusing on the four markets of industrial, automotive, information, and consumer applications, and are deploying IGBT modules, power MOSFETs and power diode products worldwide. IGBT modules are used in industrial applications, and we are developing technology and products to meet the needs for energy savings and smaller size of these modules. Achieving a lower on-voltage through utilizing FZ wafers, thin-wafer technology used to realize non-punch-through construction, and fine pattern lithography technology to trench formation, and by developing a field stop construction, we have developed the "U Series" of 5th generation IGBT modules. In the field of power supplies for information and consumer devices, there is demand for lower power consumption during light load and standby operation, smaller size, lighter weight and higher efficiency power supplies and devices.

We are working to propose new circuits and to develop super junction devices in accordance with desired applications. In the automotive field, in addition to supplying products such as high-performance MOSFETs, intelligent power supplies for ignition systems, pressure sensors, and the like that incorporate Fuji Electric's distinctive technology, we are also working to develop IGBT modules for propulsion.

Magnetic hard disks primarily use a 3.5-inch Al-substrate and have a capacity of 80 Gbytes per platter. The main use of these disks is in PCs and servers. This technology requires nanometer-level processing, however, and uniform control in a highly clean environment is necessary to manufacture low-noise recording media that supports high-speed revolution rates. Recording densities are increasing at an extremely rapid pace; a density of 150 Gbits/in^2 has been realized at the R&D phase and recording technology will soon transition from longitudinal recording, which is presently the mainstream, to perpendicular recording. Through the use of SiO_2–composite granular technology, Fuji Electric has already reached this level of achievement and is now targeting practical applications. As recording densities increase, the bit unit-price is decreasing, and the application of recording media to game devices, video recorders, car navigation systems and the like is expected to increase suddenly. We are also working to develop small-diameter glass disk media suitable for this market.

In the field of photoconductors, we are developing new products to meet the needs of a diverse market by using high-precision processing technology for the aluminum tube and the like to develop new OPC (organic photoconductor) materials such as an OPC having high-speed response, high durability and gradation suitable for a digital multi-function machine, and positively-charged OPC that produces low levels of ozone and promises to deliver high resolution. In the field of on-demand printing, which is well suited for the onsite printing of small quantities, we are aware of the popularity of electro-photographic printing and are developing a color printer-use OPC for this application.

Fuji Electric Device Technology Co., Ltd. intends to continue advancing the quality of its business operations by providing new products based on our core technologies in order to raise the level of customer satisfaction even further.

Fuji Electric's Power Semiconductor Devices Aim for Higher Performance and Higher Functionality

Hisao Shigekane

1. Introduction

Ever since Fuji Electric first began to manufacture selenium rectifiers in 1953, our company has continued to introduce new types of power devices, one-after-another, to the market with the silicon diode in 1959, the thrysistor in 1961, the discrete BJT (bipolar junction transistor) in 1975, the BJT module in 1980, the power MOSFET (metal oxide semiconductor field effect transistor) in 1986, the discrete IGBT (insulated gate bipolar transistor) in 1987, the IGBT module in 1988, the BJT-IPM (BJT-intelligent power module) in 1989, and the IGBT-IPM in 1993.

Since 1991, Fuji Electric has been working to increase the performance and functionality of these devices. At present, Fuji's distinctive and abundant product lineup includes typical power devices for industrial power electronics machinery such as IGBT modules and IGBT-IPM, typical power devices for information and consumer devices such as power MOSFETs and rectifier elements, and typical power devices for vehicle-mounted electronic equipment such as smart MOSs and IPDs (intelligent power devices). This product lineup has received high praise from the market.

Also, as will be discussed later, power devices and power electronics technology have a close and cooperative relationship, and both fields have developed while mutually promoting each other. Fuji Electric places special emphasis on this close relationship, and has advanced its research and development of power devices based on close cooperation with its customers.

This paper describes the relationship between the power devices and variable speed driving of electric motors in the industry as the typical example, and presents the history and recent trends of their development.

2. Development of Power Devices and Power Electronics

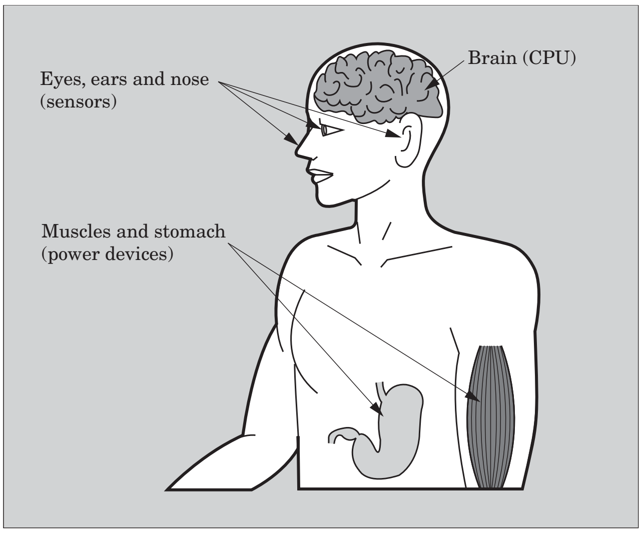
2.1 Relationship between power devices and related technologies

It is no exaggeration to say that requests for the development of electronic equipment in recent years has been based on a desire to remove the limitations of machines and make them more human in form. Such human desires as the ability to be able "to see further," "to converse from any location," and "to be stronger," have given rise to televisions, cellular phones and robots and the like.

Electronic devices have played a large role in enabling machines to more closely approximate the human body. As shown in Fig. 1, machines are approximating the human body through the use of microprocessors and memory that function as the brain, semiconductor sensors that function as the eyes, ears and nose, and so on. Not to be forgotten are the power devices which correspond to the muscles and stomach of the human body. Power devices have a behind-the-scenes-like existence, but this rapidly developing technology is no less important than that of cutting-edge LSI (large scale integrated) circuit technology.

Power devices have established three major elemental technologies of power device design technology, power device application technology and micro-fabrication technology for semiconductors for power device-use. In other words, as shown in Fig. 2, device design

Fig.1 Role of power devices



technology and micro-fabrication technology can be considered to have been developed in order to satisfy various requirements of power electronics technology, or conversely, it can be considered that advances in device design technology and micro-fabrication technology have enabled the development of new power devices which were then used to develop power electronics technology. In this manner, power devices and power electronics technology are closely related and have developed while mutually promoting each other.

In various power electronics equipment fields, a common theme relating to the progress of recent power devices is the transition from thyristors (SCRs (silicon controlled rectifiers) and GTOs (gate turn-off thyristors)) to power transistors (BJTs, IGBTs and MOSFETs).

Figure 3 shows the applicable range of various power devices. IGBTs and MOSFETs are rapidly expanding their applicable range and are becoming the mainstream power devices.

Fig.2 Power devices and related technologies

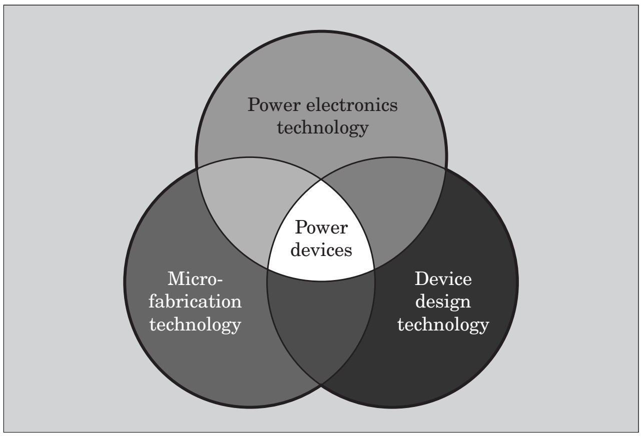
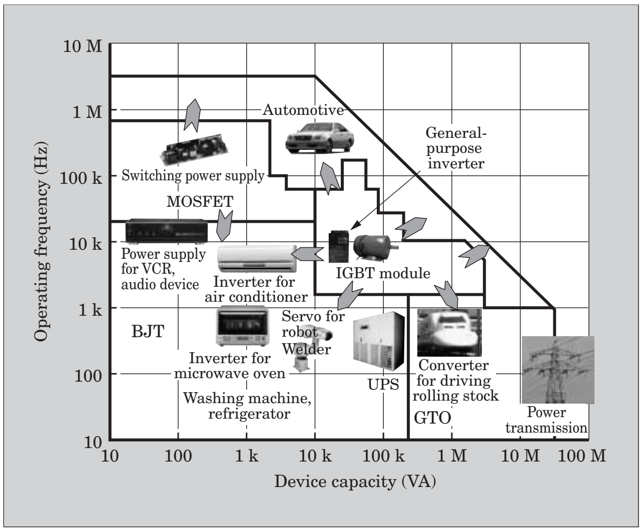


Fig.3 Power device applications



2.2 Development and history of the variable speed driving of electric motors

As can be seen in Fig. 4, in the history of the variable speed driving of electric motors, there was a drastic change in 1970 with the transition from DC motors to AC motors, and the power electronics equipment for driving those motors changed from thryistor Leonard systems to transistor inverters.

1979 was the year in which Japan experienced a second oil crisis, and under the circumstances of that time, there was growing demand for the use of inverter-based variable speed driving of AC motors in order to satisfy requirements for energy savings, maintenance-free operation and the like. The practical application of an inverter system requires a high-voltage, large-capacity, self-commuting device capable of relatively high speed switching. The BJT module was introduced as a device capable of satisfying those requirements, and a drastic changeover to BJT modules occurred. similarly to the case above.

Figure 5 shows a comparison of the thyristor inverter and transistor inverter. The power devices used in an inverter system subsequently changed from BJTs to IGBTs. At present, high voltage and high frequency PWM (pulse wave modulation) control inverters are most prevalent.

Ever since Fuji Electric led the industry to intro-

Fig.4 History of variable speed driving systems and power devices

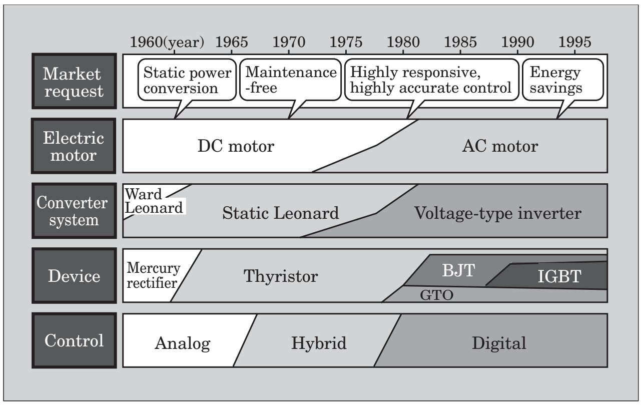
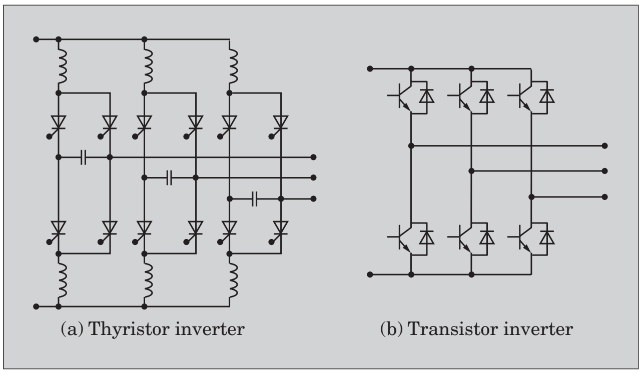


Fig.5 Comparison of inverter main circuits



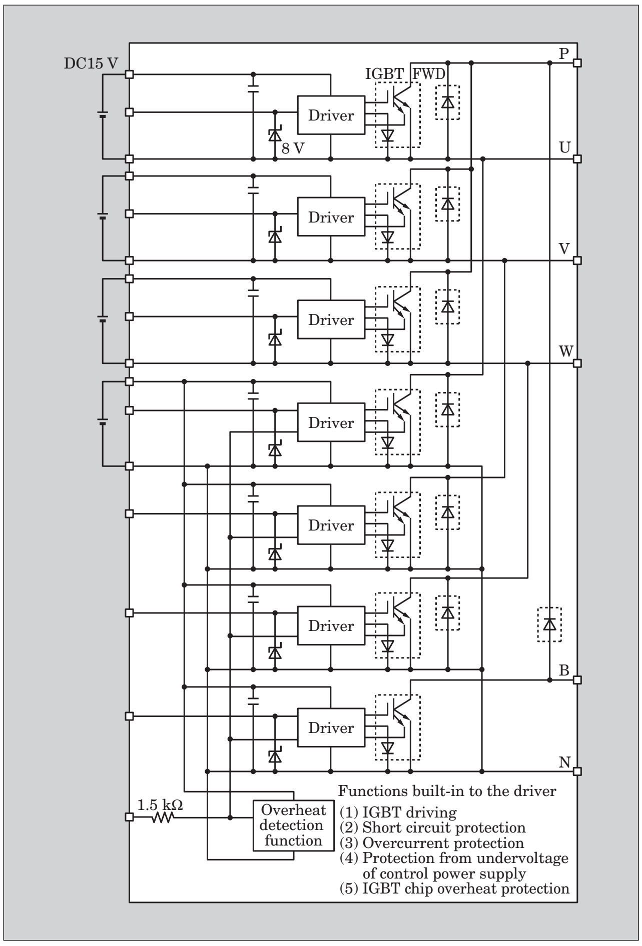
duce the BJT module, we have made great strides in increasing the capacity and intelligence of power devices, and the introduction of our new IGBT modules in 1988 initiated a changeover to these new generation devices.

The changeover from BJTs to IGBTs was supported by the capability for high speed switching and for the manufacture of low loss IGBTs that would enable inverter systems to be made lighter, more compact and quieter, as would be increasingly requested.

Meanwhile, to increase the functionality of power devices, Fuji Electric was early to develop and bring to market IPMs that contained built-in drive circuits, overheat detection circuits, self-diagnosis circuits and the like. When the main device transitioned from BJTs to IGBTs thereafter, in conjunction with improvements in IGBT characteristics, Fuji Electric made progress in reducing the size and increasing the performance of power devices. With the power transistor modules thus far, an application engineer had to design a peripheral circuit in order to use the module in a system, and the function of power devices approximated that of a single muscle tendon of the human body. Desiring to change this functionality to the level of reflexive muscles (that will stop in case an accident occurs), Fuji Electric continued its development work. At present, IPMs are used not only in such industrial fields as machine tools and robotics, but also a wide range of fields including home air conditioners and electric automobiles.

Figure 6 shows an internal block diagram of Fuji Electric's latest IGBT-IPM (R-IPM3).

Fig.6 Block diagram of the R-IPM3



3. Recent IGBT Development Trends

Figure 7 shows the history of changes in Fuji Electric's IGBT application technology. Figure 8 shows, as a typical example, the changes in the cross-sectional structure of a 1,200 V IGBT chip. Figure 9 shows a comparison of 1,200 V IGBT chip tradeoff characteristics. In Fig. 9, the vertical axis indicates turn-off loss which is representative of switching loss, and the horizontal axis indicates saturation voltage which is representative of saturation loss. A tradeoff point that approaches zero on both axes indicates a high performance device capable of realizing a low loss system.

At present, 5th generation IGBTs are being produced as commercial products and the family of these products is being expanded. The 1st through 3rd

Fig.7 History of Fuji Electric's IGBT chip application technology

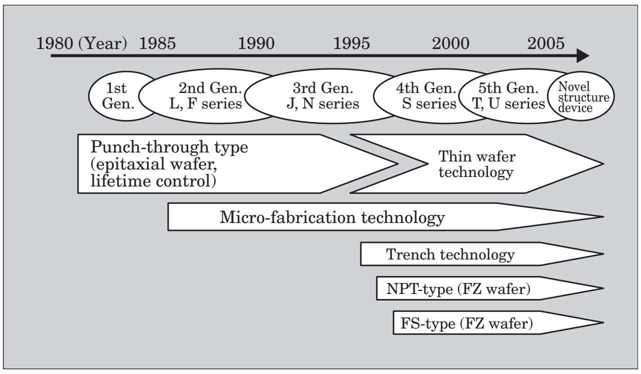


Fig.8 Changes in the cross-sectional structure of a 1,200 V IGBT chip

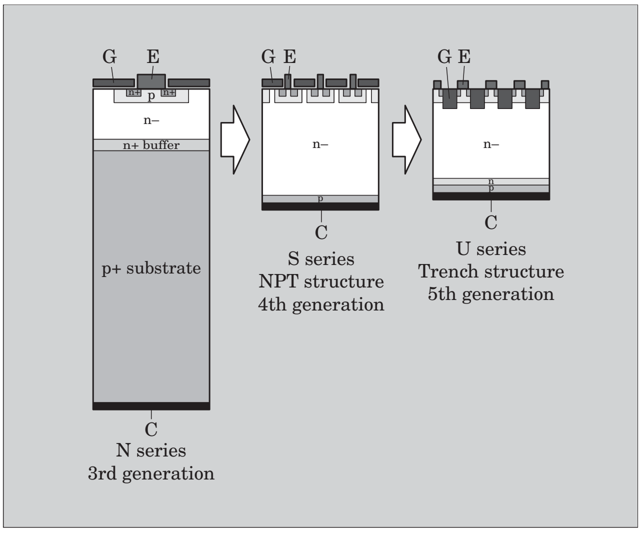


Fig.9 Comparison of 1,200 V IGBT chip tradeoff characteristics

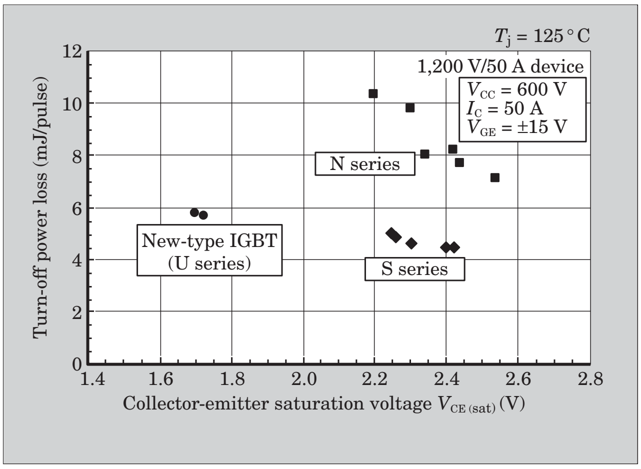
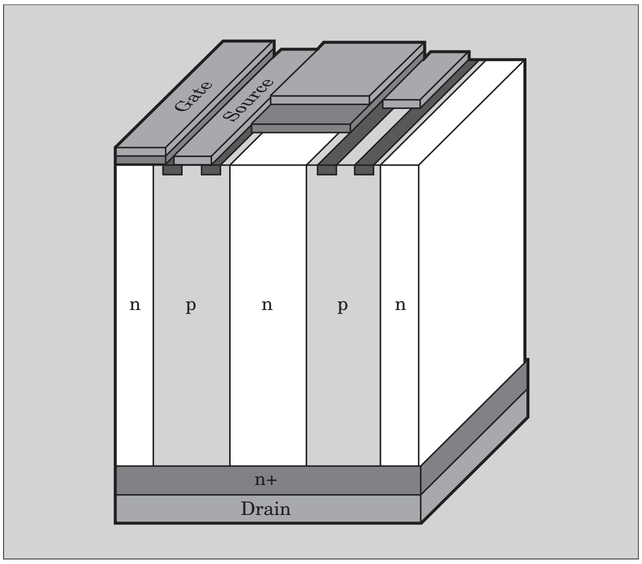


Fig.10 Cross-sectional structure of SJ-MOSFET chip



generation IGBTs sought to achieve a high performance construction by using epitaxial wafers, implementing lifetime control and micro-fabricating the surface gate structure. The 4th and subsequent generations sought to improve performance by adopting drastic design changes such as the use of FZ (floating zone) wafers and a NPT (non-punch through) structure. In order to realize an NPT structure, it was necessary to establish technology for making the wafer thinner. Consequently, not only was performance improved, but also the need for lifetime control was eliminated and the fluctuation in device characteristics during manufacture was reduced. The 5th generation additionally uses a trench structure at the surface gate and an FS (field stop) to achieve further improvement in performance. Fuji Electric is presently advancing products that use a trench-and-FS structure in its 1,200 V-and-above class of IGBT chips, and products that use an NPT structure in its 600 V-class of IGBT chips.

The key technologies for these devices are the technology for thinning the wafers to approximately 100 µm and the technology for forming a layer having a diffused junction on the backside of the wafers. These technologies can be said to be unique to power devices.

The 5th generation U series IGBT module is presently making great contributions to reducing the size and weight and increasing the efficiency of various types of systems.

4. Research and Development Trends for Next Generation Power Devices

4.1 SJ-MOSFETs

The theoretical performance limit for a high-voltage power MOSFET that uses silicon (Si) material was thought to have been reached with the Super FAP-G series introduced by Fuji Electric in 2000, but an SJ (super junction)-MOSFET, which also uses Si material, achieves a performance level that sufficiently exceeds that of the so-called theoretical performance.

As can be seen in the cross-section of the chip construction shown in Fig. 10, the SJ-MOSFET has structure in which consecutive pnpn ··· impurity regions are sandwiched by drift regions in the body of the device. Consequently, the depletion layer is extended horizontally, making it possible for all drift regions to become depleted at the same time, which was not possible with a conventional structure. As a result, the SJ-MOSFET can achieve a higher impurity concentration and lower ON-resistance than a conventional structure.

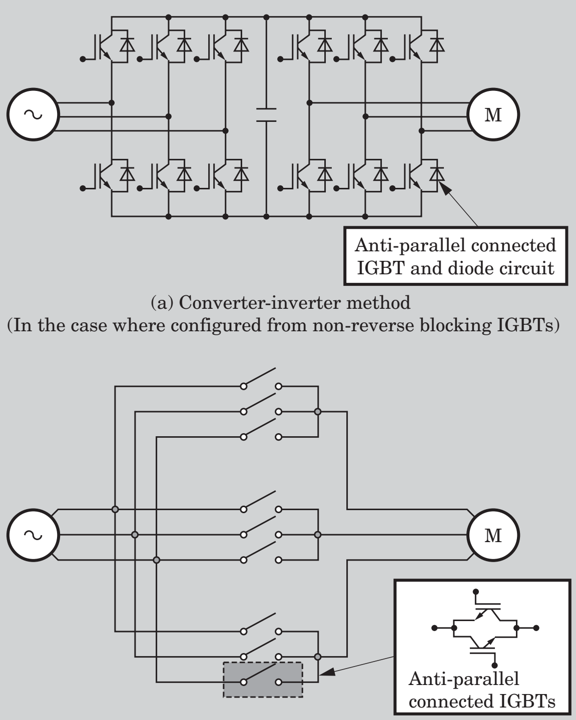
Commercial SJ-MOSFET devices have already appeared on the market and Fuji Electric is continuing its development efforts in the aim of commercializing a SJ-MOSFET device in the near future.

4.2 Reverse blocking IGBTs

Fuji Electric led the industry in introducing a reverse blocking IGBT, for which Fuji developed proprietary technology for a thin wafer IGBT process, and through the close-knit exchange of information and cooperation between power device engineers and power electronics engineers, a new method for power conversion is about to be proposed.

As described above, the most common method at present for the variable speed driving of electric motors is AC motor control based on a voltage-type high-frequency PWM inverter. In this method, as shown in Fig. 11(a), commercial AC current is first converted into a DC current, and then is reconverted by the inverter into a variable-frequency variable-voltage AC current and then output. Application of this method to voltage-type high-frequency PWM inverters was one goal of the abovementioned power device research and development. Alternatively, as shown in Fig. 11(b), a method in which commercial AC current is converted directly into a variable-frequency variable-voltage AC current has also been suggested, but practical applica-

Fig.11 Comparison of main circuits of converter



(a) Converter-inverter method
(In the case where configured from non-reverse blocking IGBTs)

(b) Matrix converter method
(In the case where configured from reverse-blocking IGBTs)

tion has been difficult as this method requires a bi-directional high-speed switching device.

In a conventional IGBT, the breakdown voltage (reverse blocking voltage) between the emitter and collector is not high. However, if an IGBT having high reverse blocking voltage could be realized and such devices were connected in a anti-parallel connection, the realization of a bi-directional switching device is thought to be possible. This is the context for the development of reverse blocking IGBTs.

Compared to a converter system configured from non-reverse blocking IGBTs, a converter system that uses reverse blocking IGBTs has the following characteristics.

(1) Because current flows through two IGBTs, instead of flowing through four non-reverse blocking IGBTs in the other method, the amount of generated power loss can be reduced.

(2) Because a DC smoothing capacitor is unnecessary, the system can be made smaller and lighter in weight.

The matrix converter, a direct AC-AC converter system that uses high-frequency PWM control with reverse blocking IGBTs, is soon to be commercially practical.

5. Conclusion

Based on our policies of “realizing high-performance power devices with the world’s most advanced technology to develop products that are number-one worldwide” and “working in concert with the customer to integrate power device and IC technology and to realize and provide solution-proposing-type smart devices and intelligent devices,” Fuji Electric has developed and provided new products based on the desires of our customers.

This paper has discussed the development history and trends of representative products developed based on the above policies.

There is no end in sight for the progress of power devices, and research and development continues to be fiercely competitive. Devices such as the reverse blocking IGBT are being proposed that urge reconsideration of long-established mainstream power conversion methods.

Fuji Electric is committed to working to develop even more advanced power electronics products and will press on with efforts to decrease the power loss and to increase the performance of power devices further.

Power Supply IC Technology Contributes to Smaller Size and Lower Power Consumption of Electronic Equipment

Eiji Kuroda

1. Introduction

Power supply technology is a basic technology that supports all types of electronic equipment. Switching power supplies, in particular, are characterized by small size, light weight and high efficiency and are the mainstream technology used in power supplies at present. In recent years, with the advent of an advanced information and communications-oriented society, trends toward personalization and mobilization have accelerated and demands are increasing for electronic devices that are smaller, lighter in weight and consume less power. Power supply technology is also entering an era of change.

Having a long history of involvement with semiconductor devices for switching power supplies, Fuji Electric is now concentrating on power supply ICs (integrated circuits) as core devices that perform control functions. Fuji Electric's power supply ICs fall into the two categories of AC-DC power supply-use devices that take a commercial AC line input and DC-DC converter-use devices that are mainly used in battery-driven applications. These devices had previously been produced as commercial products using bipolar technology, but in response to market demands for lower power consumption and a combination of functions, a change to high-voltage CMOS (complementary metal oxide semiconductor) analog technology was initiated several years ago and at present, nearly all of Fuji Electric's power supply ICs have completed the transition to CMOS technology.

This paper introduces the technical and product development for power supply ICs and also discusses Fuji Electric's future outlook for this field.

2. High-voltage CMOS Analog Technology of Power Supply ICs

2.1 Process device technology

Table 1 compares the IC process technologies used in power supply ICs. Bipolar technology is commonly used throughout the industry and to date Fuji Electric has commercialized many power supply ICs using this technology. A power supply IC that uses bipolar technology will feature high accuracy of the control circuit (offset voltage of error amplifier, accuracy of reference voltage, and the like) and a low process cost since only a few mask steps are required during the manufacturing process, but since it is a current controlled device, the degree to which power consumption can be decreased will be limited. Moreover, because each transistor is isolated by a p-n junction, the parasitic capacitance with the substrate will be large and since the storage time during transistor switching will be long, a bipolar process is considered to be disadvantageous for high frequency operation. Additionally, the technique of isolation by p-n junction is difficult to miniaturize and is ill-suited for high levels of integration. As a power supply IC process, bipolar technology became unable to satisfy the requirements of the market.

Table 1 Comparison of power supply IC process technology

Item \ Process	Bipolar	Bi-CMOS	CMOS
Power consumption	Poor	Fair	Excellent
Miniaturization	Poor	Fair	Excellent
Circuit accuracy	Excellent	Excellent	Fair → Excellent
Built-in power MOS	Poor	Excellent	Excellent
Process cost	Excellent	Poor	Fair

CMOS process technology has previously been widely used in digital ICs. MOS (metal oxide semiconductor) devices are voltage controlled devices and are extremely effective in reducing current consumption, however, their compatibility with analog circuitry is poor and in the past, power supply ICs almost never used CMOS technology. For this reason, products were commercialized using Bi-CMOS (bipolar-CMOS) process technology that combined the advantages of bipolar and CMOS processes into a single chip. However, the Bi-CMOS process was disadvantageous because its bipolar portion was inherently difficult to miniaturize and it had a high processing cost due to the use of epitaxial wafers and the use of at least twice as many mask steps as in a bipolar process. To resolve these problems, Fuji Electric developed several CMOS process technologies specifically for power supply ICs and has promoted the commercialization of products using those technologies. Figure 1 shows the product map of Fuji Electric's CMOS power supply ICs. Fuji Electric provides a wide range of products whose operating voltages span from 1 or 2 dry-cell batteries to worldwide AC power supply input levels.

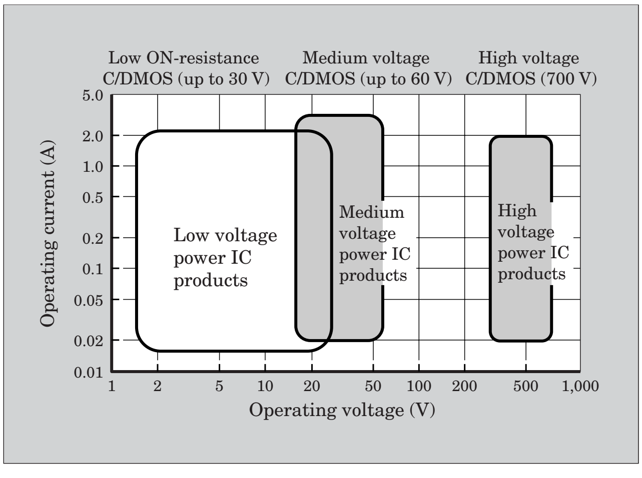
2.2 Analog circuit accuracy with CMOS technology

In the case where CMOS technology is used in a power supply IC, the circuit accuracy generally presents a problem and is less than that of a bipolar process. Circuit accuracy depends on the absolute fluctuations of device characteristics and on the relative accuracy. In response, Fuji Electric has optimized wafer process conditions and strengthened process control to reduce fluctuation in device characteristics, developed device design techniques, and developed circuit technology specifically for CMOS circuits, that when used together with on-chip trimming technology, realize circuit accuracy which exceeds that of bipolar process technology.

2.3 Built-in power elements

In order to reduce the size of power supply circuits and the space they occupy, there is a growing trend to embed the power MOSFET (metal oxide semiconductor field effect transistor), which had been attached as a separate external component in the past, into the power supply IC. Fuji Electric uses a lateral DMOS (double diffused MOS) structure to realize low ON-resistance, which as shown in Fig. 2, is in the top class of the industry. By using a lateral DMOS device with its low gate-drain capacitance and by optimizing the device size for each IC product, operation at higher frequencies with lower current consumption is possible. As an example, Fig. 3 shows a photograph of a 3-channel control IC chip having a built-in n-channel power MOSFET rated at 1 MHz operation and 50 V breakdown voltage.

Fig.1 Product map of CMOS power supply ICs



3. Product Line Up of CMOS Power Supply ICs

3.1 AC-DC power supply ICs

Fuji Electric was quick to adopt CMOS technology in its power supply control ICs designed for a commercial AC line input. An overview is presented below.

3.1.1 PWM control ICs for low standby power

Efforts to reduce the load on the global environment have intensified in recent years. For AC-DC power supplies, the trend toward lower standby power is accelerating because devices for the remote control of an always-on connection, devices built-into a timer, various types of AC adapters and the like are in a standby state for a much longer time than at rated operation. In response to this trend, Fuji Electric has commercialized power supply ICs that feature reduced standby power consumption. As shown in Fig. 4, low standby power consumption has been realized by combining the drastic reduction in low current consumption enabled by the use of CMOS technology and a variable frequency function that reduces switching loss by lowering the switching frequency during light loads. Figure 5 shows the input power characteristic of

Fig.2 Breakdown voltage vs. $R_{on} \cdot A$ (NMOS)

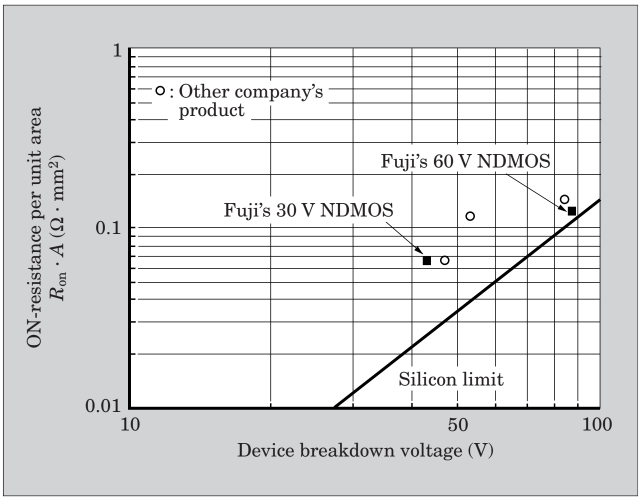


Fig.3 Die photo of power supply IC with a built-in power MOSFET

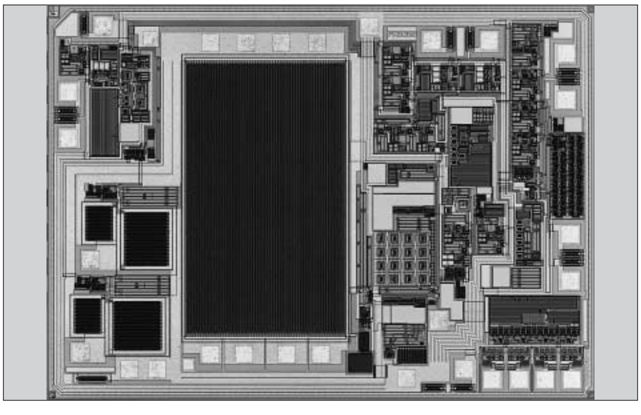


Fig.4 Method of standby power reduction

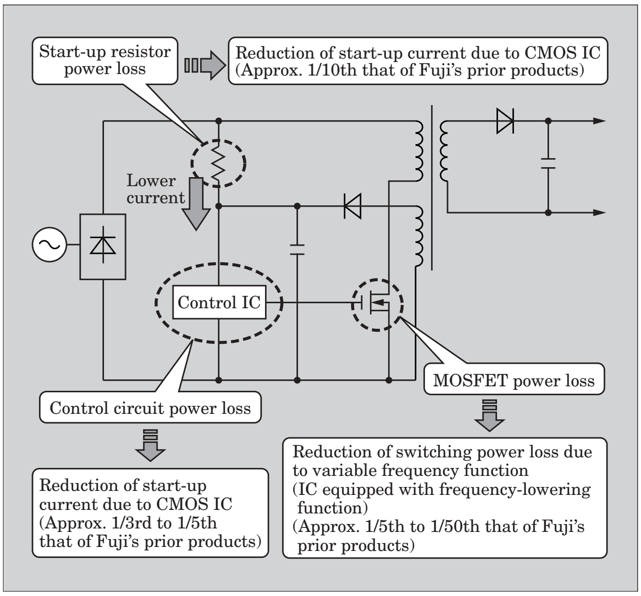
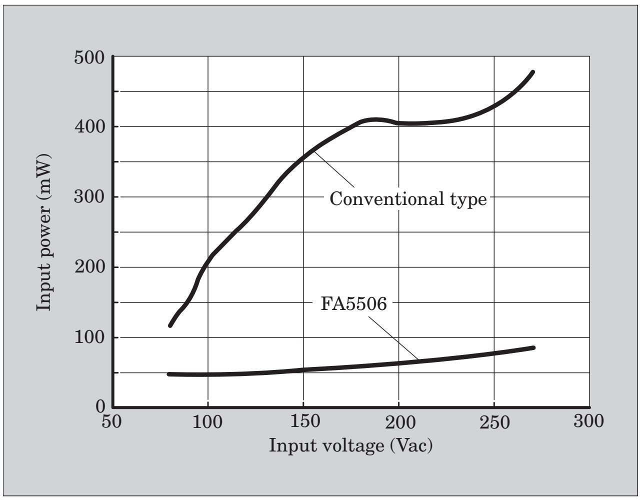


Fig.5 FA5506 input power characteristics at no load



Fuji Electric's newest IC, the FA5506, under unloaded conditions in an evaluation power supply circuit. Even at 240 V AC, the standby power was 0.1 W or less.

3.1.2 700 V monolithic power IC

In order to miniaturize low-output power supplies in the several-tens-of-watts class, it is desirable for the power element to be integrated with the control circuit. Fuji Electric has also commercialized a power supply IC that integrates a 700 V power MOSFET and PWM (pulse width modulation) control circuit into a monolithic chip, which is directly connectable to worldwide commercial power supply inputs. High voltage devices are generally susceptible to fluctuations in their characteristics due to ions in the mold resin, moisture that infiltrates from the exterior and the like, but Fuji Electric's proprietary double metal ion shield structure achieves high reliability. Figure 6 shows an example die photo of this product.

Fig.6 Die photo of 700 V monolithic power IC (FA5701P)

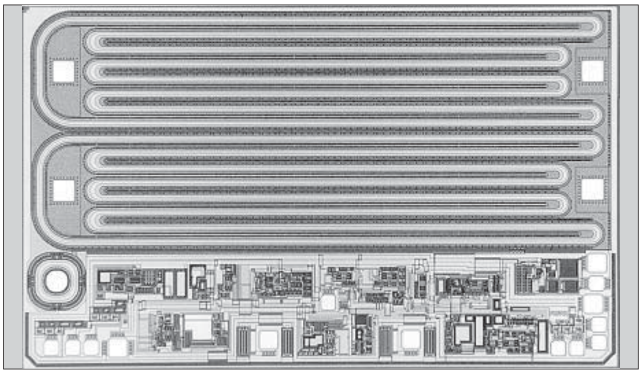
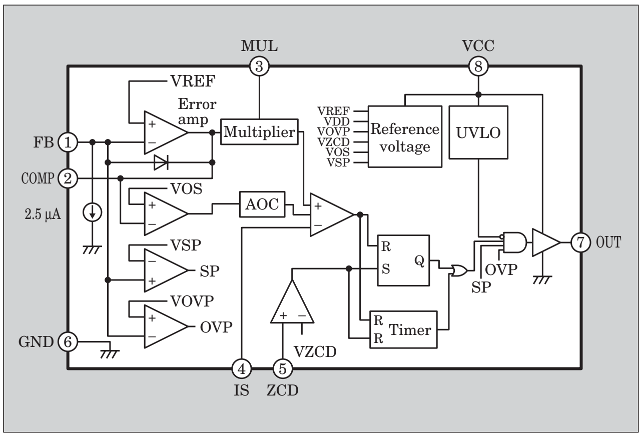


Fig.7 Block diagram of CMOS control IC for power factor correction (FA5500)



3.1.3 CMOS control ICs for power factor correction

In the past, because most power supply circuits used a capacitor input-type rectifier circuit, the AC input current was distorted and a large harmonic input current was generated. Because the presence of harmonic components brought about a decrease in the power factor and they also had a negative impact on the power distribution equipment, regulations concerning the power supply harmonic content were enacted worldwide. Various solutions have been proposed and implemented, but the active filter circuit is widely used because it can easily achieve a power factor of 99 % or higher. Fuji Electric was early to commercialize bipolar technology-based control ICs and has promoted the adoption of CMOS technology in this field as well, commercializing CMOS control ICs that utilize either the peak current control method or the average current control method. Figure 7 shows a block diagram of the peak current control IC.

3.2 Power supply ICs for DC-DC converters

Fuji Electric is applying CMOS technology to commercialize power supply ICs for DC-DC converters used in battery driven devices and the secondary side of AC-DC power supplies. AC-DC power supply ICs are general-purpose products, but power supply ICs for DC-DC converters are a product family that is specially designed per chip set.

3.2.1 Power supply ICs for portable devices

In order to extend the duration of battery operation for portable devices such as video cameras, digital still cameras and PDAs (personal digital assistants), it is necessary to supply an optimal voltage and to perform precise ON/OFF control for each internal circuit block. Multi-output power supplies are being promoted for this reason. Figure 8 shows a die photo of a 5-channel PWM control IC commercialized for use in a digital still camera. CMOS technology has been applied to integrate the multi-channel PWM control circuit and the driver circuits into a compact size. Moreover, Fuji's proprietary level shift circuit enables the driver unit to achieve both higher speed and lower current consumption. At present, 3 to 10-channel ICs are commercially available, and synchronous rectifier circuits are used in many cases to increase efficiency. Also, as a recent trend, in order to provide flexibility to support the individual power supply specifications for each chip set, settings for the output voltage, maximum duty cycle, ON/OFF control and the like are increasingly being made via serial control data from the CPU (central processing unit).

3.2.2 Power supply ICs for LCD panels

LCD panels require several different driving voltages. Figure 9 is a block diagram of a power supply IC containing a built-in 3-channel PWM control circuit for use with a large-screen LCD monitor. This IC contains a built-in driver circuit capable of providing a peak current of 800 mA in order to drive the externally attached power MOSFET having a large gate capacitance at high speed, and the power supply circuitry necessary for the LCD panel can be configured easily. In addition to this IC, Fuji Electric also provides a line of products with input voltages ranging from 3 to 5 V and that are capable of supporting boost, buck and inverting circuits for LCD panels in notebook computers.

3.2.3 Step-down converter ICs for inkjet printers

Figure 10 shows an IC application circuit for a DC-DC converter that produces an output of 3 to 5 V from a high input voltage (10 to 45 V). A high voltage p-channel power MOSFET is built-in and a step-down converter circuit can easily be configured. The CMOS process reduces IC current consumption down to 1/10th that of a bipolar IC in the same class, and the power consumption of the IC during a high voltage input has been reduced greatly (from 1.1 W to 0.06 W). The result is dramatic since power consumption of the device is decreased and heat sinks are unnecessary.

4. Future Outlook

Continuing to regard high voltage CMOS analog technology as a core technology, Fuji Electric intends

Fig.8 Die photo of 5-channel PWM controller (FA7716R)

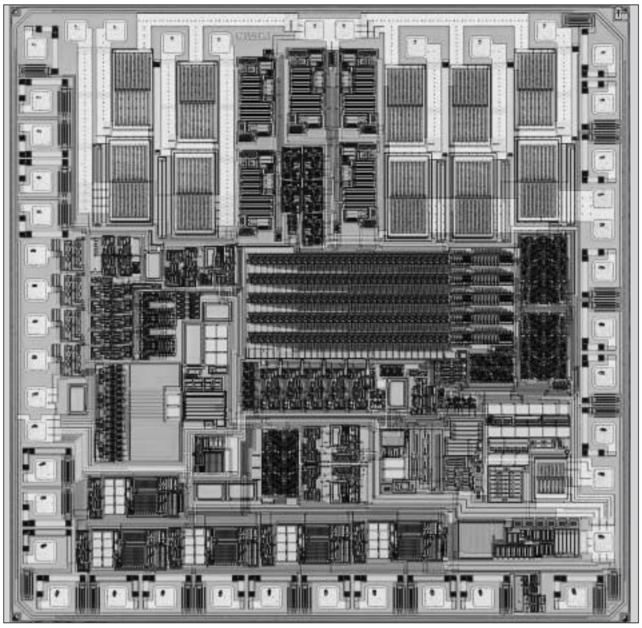


Fig.9 Block diagram of power supply IC (FA7711V) for LCD panel

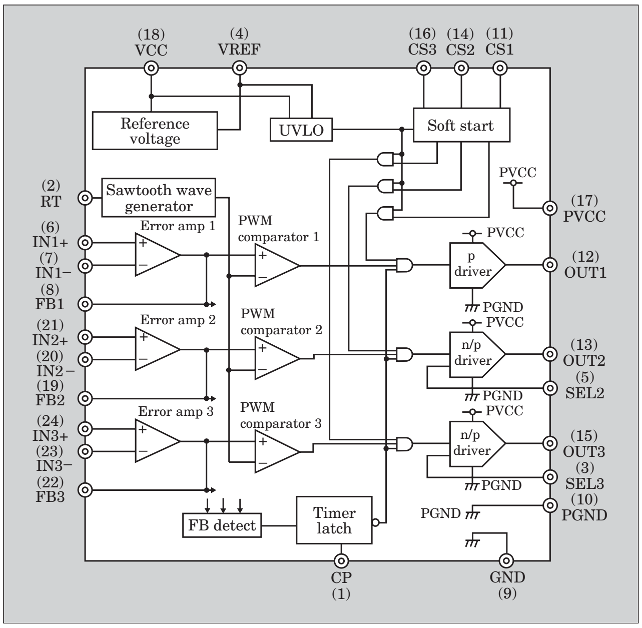
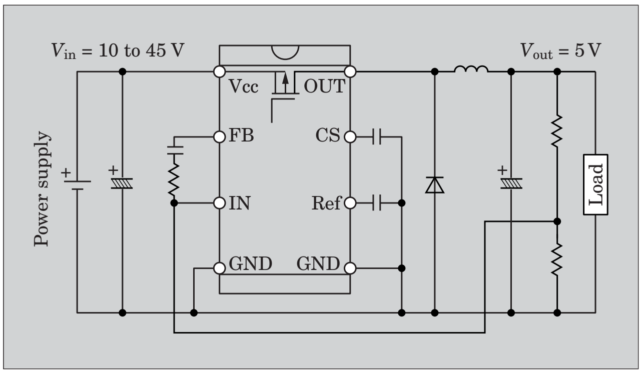


Fig.10 Application circuit of high input voltage step-down converter IC (FA3635P)



to advance technical development in the field of power supply ICs in order to contribute to making electronic devices smaller, lighter and consume less power.

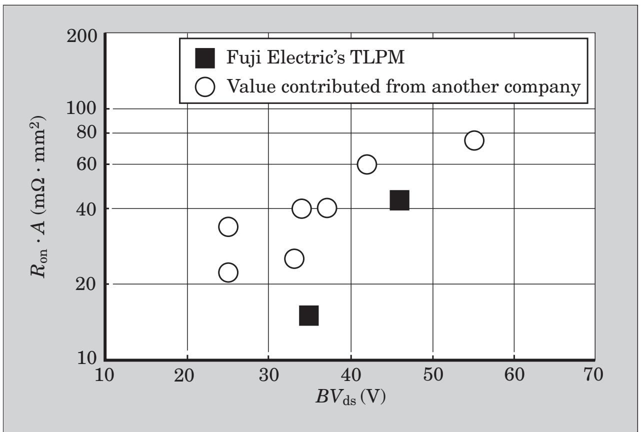
4.1 Low ON-resistance device and process technology

To make the power supply unit smaller and occupy less space, there is a growing trend for integrating the switching power device with the power supply IC. Moreover, due to progress in the miniaturization of the LSI (large scale IC) that is the load and in the lowering of voltage and increasing of current, the development of a lower Ron·A power device that can be integrated onto the IC presents a big challenge for realizing a highly cost effective power supply IC. Rather than the conventional plane structure lateral device, a device having a novel structure based on trench process technology that can easily be integrated with the control IC is presently under development at Fuji Electric. As shown in Fig. 11, this device has already achieved the industry's top class of low ON-resistance. In the future, Fuji Electric plans to promote miniaturization of the power supply by establishing technology for integration of the control unit and by embedding the power device in the IC.

4.2 Circuit technology

The higher the switching frequency, the smaller the magnetic components and capacitors used in the switching power supply can be made. Fuji Electric plans to further advance the development of devices and processes that use CMOS technology, which is advantageous for higher speeds, and to increase the switching frequency up to the 10 MHz level. Switching noise is expected to increase at higher frequencies, but we intend to handle this by incorporating spread spectrum technology and the like. Fuji Electric also plans to promote the development of high performance mixed signal IC technology in preparation for the integration of battery management circuit with the power supply IC.

Fig.11 Breakdown voltage vs. $R_{on} \cdot A$ of TLPM (trench lateral power MOSFET)



4.3 Micro DC-DC converter technology

Cellular phones, PDAs and the like have, until now, generally used a series regulator. To increase the performance of these electronic devices, the LSIs that are installed therein are miniaturized and the power supply voltages supplied to the LSIs have been decreasing year-by-year. At present, a power supply voltage of 1.5 V or less is the mainstream, but 1 V or less is predicted to become the mainstream in the future. Meanwhile, because the lithium-ion batteries typically in use at present have a rated voltage of 3.6 V and the use of a series regulator causes a large power loss to be generated, there is increased awareness of the need to improve conversion efficiency of the power supply circuit. Consequently, a changeover to the switching-type DC-DC converter having excellent conversion efficiency is being considered. However, because the conventional DC-DC converter requires a power inductor and has larger external dimensions than the series regulator, smaller size and lighter weight are strongly demanded. Each company is studying ways to achieve smaller size and lighter weight, and from the perspective of an IC manufactur-

Fig.12 External view of micro DC-DC converter module

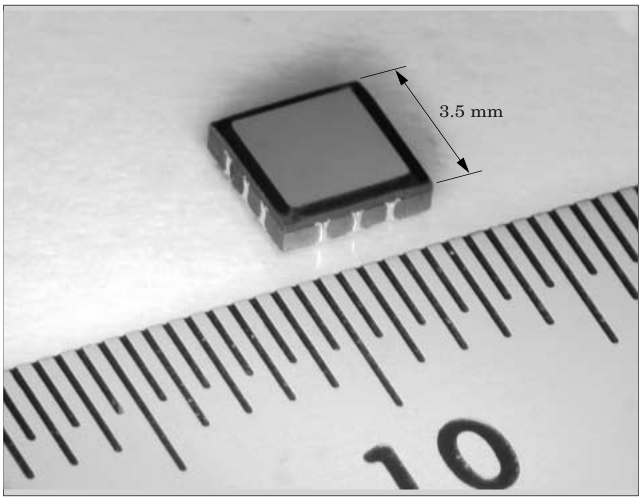
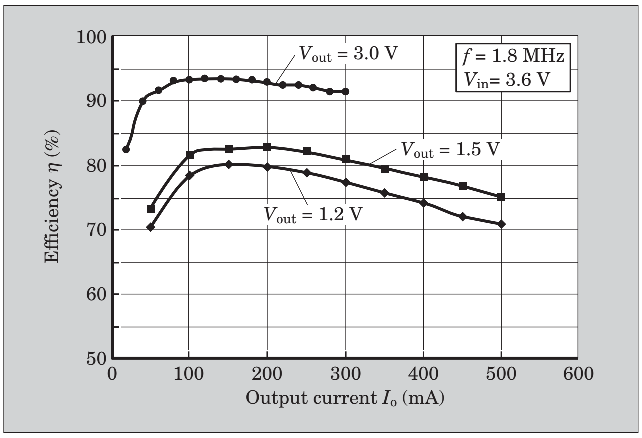


Fig.13 Efficiency of micro DC-DC converter module



er, Fuji Electric had the idea to fabricate an inductor in a ferrate substrate and then use that as the support substrate of the IC chip in a novel structure. Fuji Electric is the first in the industry to realize this structure as a module having external dimensions of 3.5 by 3.5 by 1 (mm). In order to realize a module of this size, Fuji newly developed a proprietary inductor structure, a 2.5 MHz high frequency switching power supply IC with built-in power device, as well as assembly technology to combine the ferrate substrate and IC chip. Figure 12 shows an external view of the module and Fig. 13 shows its efficiency characteristics. Fuji Electric intends to use this technology to promote commercialization of portable electronic devices in the future and to contribute to the realization of chip sets that are smaller in size and consume less power.

5. Conclusion

Fuji Electric's efforts to date concerning the adoption of CMOS technology for power supply ICs and the future outlook for that technology have been discussed above. Power supply circuits and their key component, the power supply IC, are becoming increasingly important for the future progress of electronic devices. Fuji Electric is committed to continue to develop power supply IC technology and products through decreasing their size and power consumption and increasing their level of integration so that in the near future Fuji Electric's name will become synonymous with power supply ICs.

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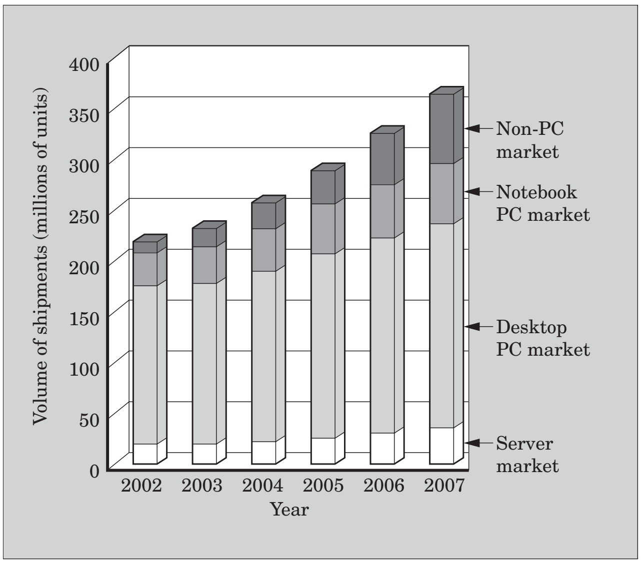
Development of Granular-type Perpendicular Magnetic Recording Media

Akihiro Otsuki

1. Introduction

Hard disk drives (HDDs) were developed in 1956 and initially were applied mainly as external memories for mainframe computers. Subsequent advances in HDD technologies leading to higher areal density, smaller size and lower cost have brought HDDs into widespread use for their convenience. HDDs are now the mainstream external memories used for personal computers and mainframe computers. Recently, the technology of longitudinal recording, which has been in use for a long time, is approaching its technical limit. Perpendicular magnetic recording technology, however, which realizes higher areal density, has been edging closer to practical use in recent years. In the year 2005 and thereafter, large capacity and small size HDDs that utilize perpendicular magnet recording technology are expected to acquire a large share of the market. In the ubiquitous society of the 21st century, we predict that the HDD market will continue to expand as HDDs come to be used in vehicle equipment, home information appliances and cellular phones (Fig. 1). The main component that is mounted in these HDDs and that stores more than 100 Gbytes (800×10^9 bits) of data is the magnetic recording media which we have developed.

Fig.1 HDD market trends



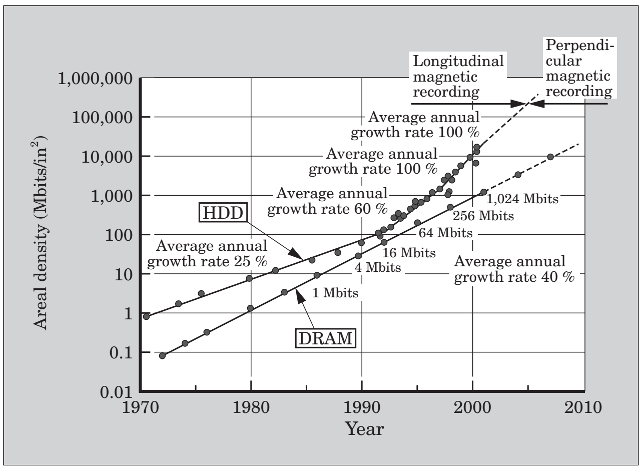
In 1985, Fuji Electric succeeded in developing a sputtered Co-alloy magnetic recording media to replace the coated γ-Fe_2O_3 media that had been in use previously. Since then, Fuji Electric has been a major manufacturer of media and a worldwide supplier of longitudinal magnetic recording media. Recently, Fuji Electric succeeded in developing the world's highest areal density perpendicular magnetic recording media. Below, we shall describe the development status of our perpendicular magnetic recording media.

2. Changes in Magnetic Recording Technology and Fuji Electric's R&D Activities

The average annual growth rate of areal density of HDDs has exceeded that of DRAM (dynamic random access memory) since 1992 (Fig. 2). Consequently, in 2005 or later, HDDs may reach the critical areal density (up to 200 Gbits/in^2) at which longitudinal recording media causes a thermal decay problem.

The difference between longitudinal magnetic recording and perpendicular magnetic recording is illustrated in Fig. 3. The longitudinal magnetic method aligns recording bits in the plane of a magnetic layer. Longitudinal recording has a problem, however, in that

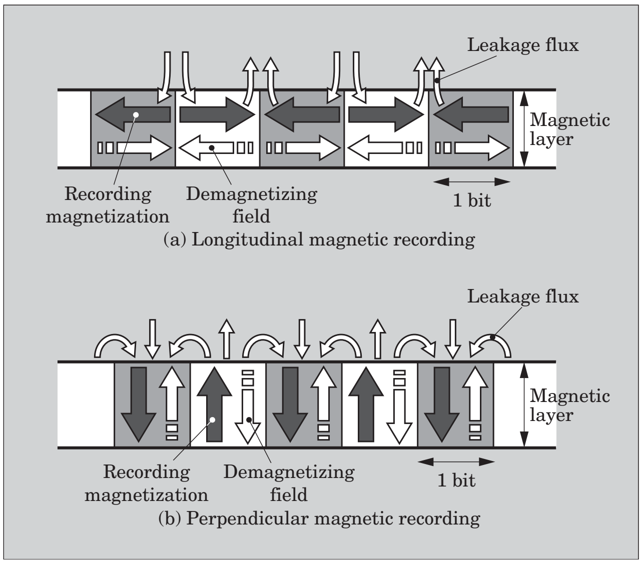
Fig.2 HDD areal density trends



recording bits become thermally unstable at high areal densities due to a demagnetization field oriented in a direction opposite to the recording bits and that acts to erase the magnetization of the recorded bits. At high areal densities, if the size of a recording bit becomes small, the magnetic energy maintaining the recording bit also becomes small causing the recording bit to be erased thermally at room temperature (the so-called thermal decay problem). In contrast, perpendicular magnetic recording is thought to be able to realize several times the areal density (up to 1 Tbits/in^2) of longitudinal recording. In the future, perpendicular magnetic recording will be able to realize areal densities of 40 to 50 Tbits/in^2 when used in combination with thermal assist recording and patterned media (Fig. 4).

Leading HDD makers worldwide are racing to develop perpendicular magnetic recording HDDs because they know that perpendicular magnetic recording technology will drastically change the HDD business (creation of new markets) and HDD technology.

Fig.3 Schematic diagram of longitudinal recording and perpendicular recording



Fuji Electric started to develop perpendicular magnetic recording in 1999 in order to position itself as the leading company in the worldwide memory market. Specifically, we started to develop both granular-type longitudinal magnetic recording media and amorphous Co alloy perpendicular magnetic recording media in order to correct the thermal decay problem. We integrated these two media into granular-type perpendicular magnetic recording media in 2000, began shipping samples to several laboratories in 2001, and demonstrated an areal density of 150 Gbits/in^2, which was the highest in the world at the end of 2002. In March 2003, we began to envision the prospects for practical application of 200 Gbits/in^2 perpendicular magnetic recording media.

3. Configuration of Perpendicular Magnetic Recording Media and Development Challenges

The configuration of perpendicular magnetic recording media is shown in Fig. 5 and the manufacturing process flow is shown in Fig. 6. Perpendicular

Fig.5 Configuration of perpendicular magnetic recording media

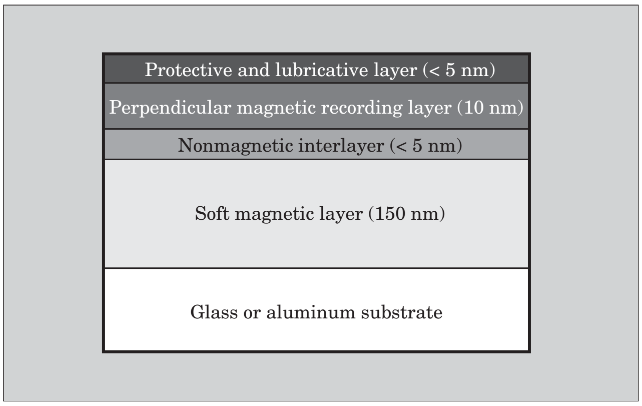
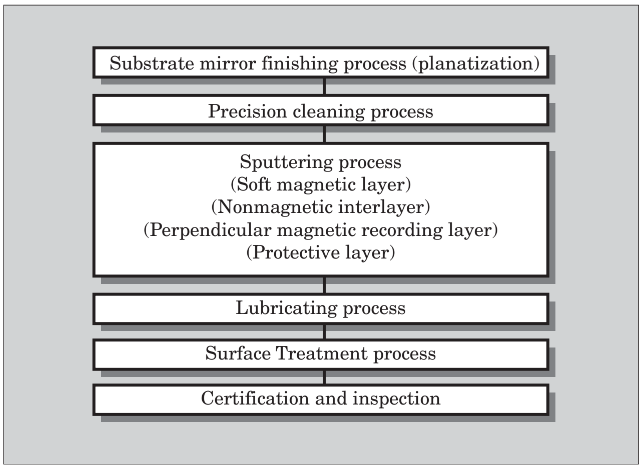


Fig.4 Roadmap of magnetic recording technologies

Year		2002	2003	2004	2005	2006	2007	···	2010
Areal density (bits/in^2)		120G	200G	400G	550G	750G	1T		5T
Coercive force (A/m)		4 to 5×10^5		6 to 7×10^5					
K_u (J/m^3)		3 to 4×10^5		5 to 6×10^5		>1×10^6			
D_{grain}/D_{act} (nm)		6/9		5/5					
Media design	Recording method	Longitudinal recording							
		Perpendicular recording (conventional)							
		(Thermal assist recording)							
		(Patterned media)							
	Magnetic material	Granular-type Co alloy							
		Multilayer (CoX/Pt)							
		Ordered alloy							

Remarks: D_{grain} = Physical grain size, D_{act} = Grain size calculated from activation volume

Fig.6 Manufacturing process flow of perpendicular magnetic recording media



magnetic recording media consists of aluminum and glass substrates on which soft magnetic layers are formed, and above which are fabricated perpendicular magnetic layers and then protective and lubricative layers. Although the manufacturing process shown in Fig. 6 is simple, each layer is a multilayer and is produced with advanced precision equipment. The following technologies are used in the fabrication of perpendicular magnetic recording media.

(1) Substrate manufacturing and cleaning technologies (Super-polished substrate technology which produces a surface roughness of 0.1 nm for assuring a minimum flying height of 3.7 nm and cleaning technology to eliminate small particles)
(2) Soft magnetic layer technologies (Soft magnetic layer technology that supports the perpendicular magnetic recording head appropriately and is unaffected by electromagnetic noise)
(3) Granular-type magnetic layer technology (Low-noise magnetic layer that supports 200 Gbits/in^2)
(4) Protective and lubricative layer technologies (Protective and lubricative layers that ensure the continuous seek operation of magnetic recording heads at a low flying height of 6 to 7 nm in HDDs)
(5) Durability technologies (Technologies that ensure high durability in computer, vehicular and consumer electronics environments)

4. Development Status

4.1 Substrate technology

Substrates used for perpendicular recording media had to satisfy the required characteristics for surface smoothness and surface cleanliness so as not to inflict mechanical or electrical damage to heads which fly at a low flying height of 6 to 7 nm.

In order to achieve our goal of 200 Gbits/in^2, it was necessary to design the magnetic recording head glide assurance height to be 3.7 nm. This required that the surface be polished to a roughness of 0.1 nm, but there were no available aluminum or glass substrates that could achieve such a smooth surface. Fortunately, Fuji Electric had become the world-leading producer of aluminum substrates for magnetic recording media and had acquired much expertise in substrate production and polishing. Consequently, Fuji Electric was able to develop substrate manufacturing technologies and succeeded in achieving the necessary surface roughness for aluminum and glass substrates. The image obtained by an atomic force microscope (AFM) of a polished aluminum substrate is shown in Fig. 7. The AFM image of a polished glass substrate is shown in Fig. 8. In both cases, it can be seen that the substrate surfaces have been made highly uniformly. Perpendicular magnetic recording media have a good signal-to-noise ratio (SNR) characteristic when the surface roughness is small as shown in Fig. 9. The good SNR characteristic of Fuji Electric's perpendicular magnetic recording media is achieved by using such substrates.

Fig.7 AFM image of aluminum substrate surface

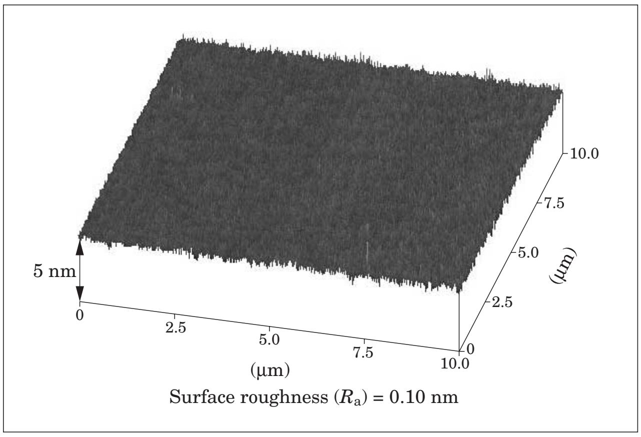
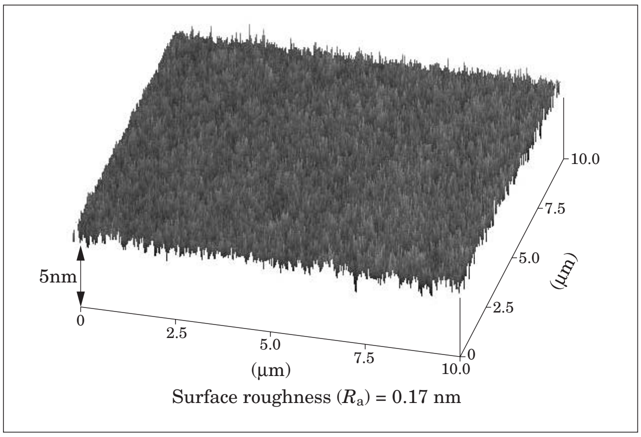


Fig.8 AFM image of glass substrate surface



The substrates used for perpendicular magnetic recording media require a surface cleanliness of 0.01 nm in order to assure the signal quality of very small recording bits. Also, the cleanliness of the substrate surface dominates the bit error rate characteristic which has a strong influence on HDD performance. Therefore, we introduced a new dry cleaning

Fig.9 Relationship between surface roughness and signal-to-noise ratio

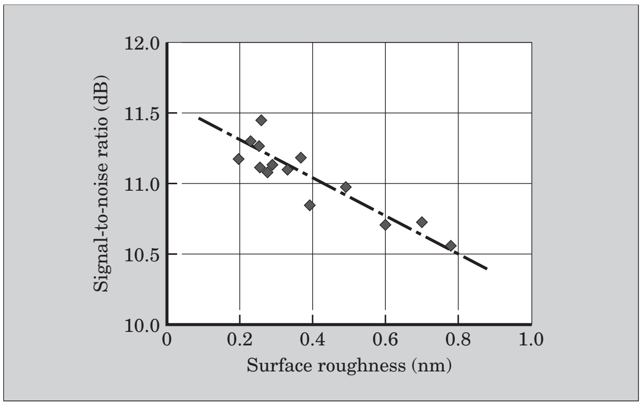
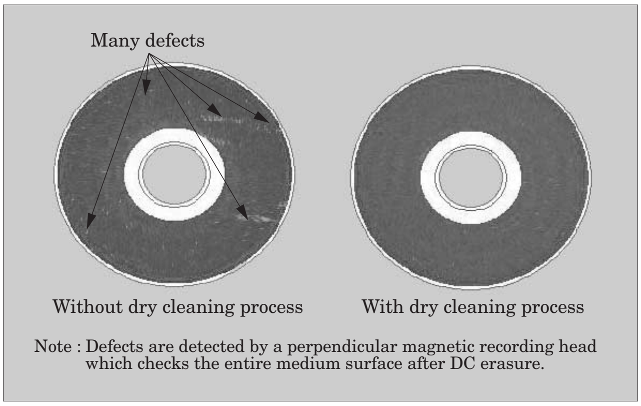


Fig.10 Improvement of substrate cleanliness by dry cleaning



process after the precision cleaning process used in longitudinal recording media, and have succeeded in achieving a high level of substrate surface cleanliness. As shown in Fig. 10, the new dry cleaning process has resulted in a dramatic decrease in media noise due to very small media defects.

4.2 Soft magnetic layer technology

The soft magnetic layer is an additional layer unique to perpendicular magnetic recording media and it forms the underlayer that attracts leakage magnetic flux generated from the perpendicular magnetic recording head when the head records bit data. Therefore, the soft magnetic layer is desired to have a high saturation flux density, uniform ability to attract flux by magnetic domain control, and low noise due to control of microcrystalline and amorphous microstructures.

We chose a soft magnetic layer made from the amorphous CoZrNb to strike a balance between high saturation flux density and low noise. We also designed the composition of an amorphous alloy having high heat resistance capability for the post-process heat treatment and having no problem in passing field reliability tests under severe conditions.

On the other hand, the width of the soft magnetic layer, the thickest among all layers of the perpendicular magnetic recording media, was a factor that limited the sputtering process throughput speed and the production cost. We tried to increase the thickness of the sputtering target used for a soft magnetic layer in order to lengthen the sputtering target life and to reduce production cost. However, such a target would not discharge in a vacuum process because the soft magnetic material has high permeability and traps the magnetic flux used for magnetron sputtering. Consequently, we examined two methods for increasing the thickness of the sputtering target. One method was to change the alignment of magnets in the sputtering cathode, and this succeeded in extending the target life by 30 to 50 percent. The other method was to reduce the thickness of the soft magnetic layer from 400 nm to 150 nm by optimizing the sputtering conditions. The combination of these two methods greatly increased the productivity of perpendicular magnetic recording media.

We are trying to improve the productivity of perpendicular magnetic recording media even further, and these efforts are summarized as follows:

(1) Development of soft magnetic material having higher saturation flux density (2.2 T, twice that of the present material)
(2) Development of soft magnetic material capable of super high-speed film deposition (10 times the present deposition rate)

Additionally, we are developing two technologies for the magnetic domain control of a soft magnetic layer and aim to commercialize two products based on these results.

(1) Development of the pinning layer, which is deposited between the substrate and soft magnetic layer, and acts to control the magnetic domain of the soft magnetic layer (Because the soft magnetic layer of this product has a high permeability, this product will be suitable for high-end HDDs that require a high transfer rate)
(2) Development of a soft magnetic layer for which magnetic domain control is unnecessary (This product will be suitable for low-end HDDs in which low cost is the first priority)

4.3 Granular magnetic layer technology

The ideal microstructure for either a longitudinal or perpendicular recording magnetic layer will have the following characteristics.

(1) Epitaxial growth in the desired crystal plane only (Epitaxial growth in the plane of the c-axis in the case of longitudinal recording media, or epitaxial growth perpendicular to the c-axis in the case of perpendicular recording media)
(2) A segregated structure that achieves magnetic separation between grains (Reduction of media noise due to magnetic interference)
(3) A grain size that is sufficiently small but not to the extent that causes thermal decay; low varia-

tion in the grain size

Conventionally, a metallic magnetic layer was deposited after heating of the substrate and thermally nonmagnetic materials of Cr and B were thermally diffused to grain boundaries to realize a segregated structure. However, the inducing of a segregated structure by a heating process caused the crystals to grow too. After all we could not have it both ways (Fig. 11).

On the other hand, a granular-type magnetic layer, which is characterized by low temperature deposition, realized a segregated structure by diffusing nonmagnetic material (e.g. SiO_2) at room temperature. That is to say, as it was unnecessary to heat the substrate of the granular-type magnetic layer, the crystal growth was more regular and there was less variation in grain size than with a metallic magnetic layer (Fig. 12).

A granular-type magnetic layer, however, presents some major technical challenges. The main challenge concerned initial crystal growth. In contrast to a metallic magnetic layer, thermal energy does not induce crystal growth and a segregated structure in a granular-type magnetic layer. So it was very difficult for a granular-type magnetic layer to achieve good crystallinity and good segregated structures from its initial deposition layer. Fuji Electric has successfully resolved these problems by improving deposition process technologies for soft magnetic layers and magnetic layers and by redesigning the composition of these magnetic layers.

Fig.11 Transmission electron microscope image of longitudinal magnetic recording media

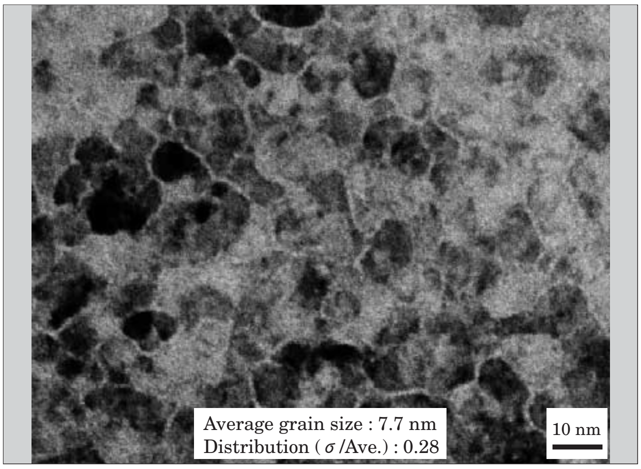
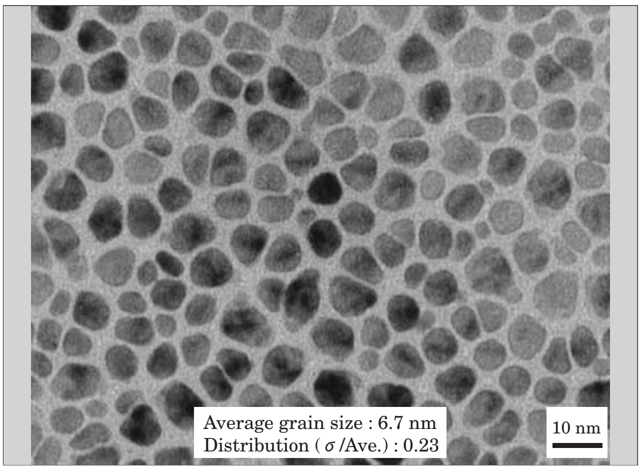


Fig.12 Transmission electron microscope image of granular-type perpendicular magnetic recording media



Several problems were encountered in achieving an areal density of more than 200 Gbits/in[2]. One was the development of a technology to prevent the growth of face centered cubic (fcc) structures that reduce the magnetic anisotropic energy of the magnetic layer. A granular-type magnetic layer formed from Co alloy material needs to form a hexagonal close-packed (hcp) structure, but Co alloy material has the problem of tending to grow fcc structures when the doping concentration of Pt increased to realize a high coercive force. Since the microstructure of nm-order thin film was very difficult to analyze with regular analytical equipment, in 1999, Fuji Electric started to develop analysis technology for microstructures of magnetic layers used by Japan's SPring-8 Synchrotron Radiation Research Institute, which is the world's largest third-generation synchrotron radiation facility, and we have verified the existence of fcc structures in a granular-type magnetic layer (Fig. 13). Based on such analytical results, we hope to be able to develop high performance perpendicular magnetic recording media that is almost completely free of fcc structures, because we will be able to control precisely the deposition process of the thin film.

4.4 Protective and lubricative layers technology

Establishment of the following technologies is critical for developing protective and lubricative layers for perpendicular magnetic recording media.

(1) Highly reliable technology for assuring trouble-free seeking operation of a perpendicular magnetic recording head even at a low flying height, and in severe conditions of the temperature, vibration and impact occurred in a vehicle or mobile device.

Fig.13 Analysis of granular-type magnetic layer

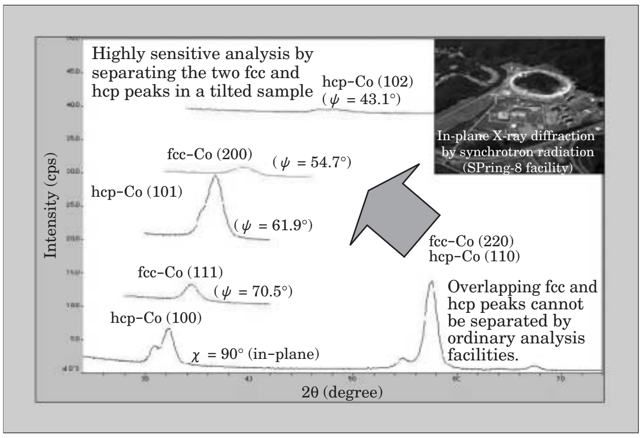


Fig.14 Schematic diagram of protective and lubricative layers

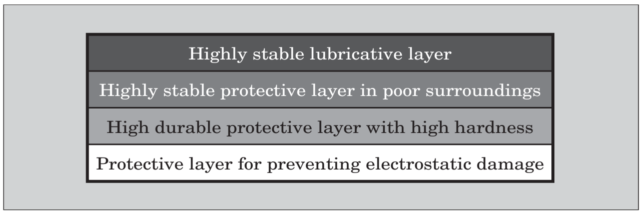


Table 1 Demonstration of areal density

Time	Areal density ($Gbits/in^2$)	Linear density ($kbits/in^2$)
Nov. 2001	61	616
May 2002	105	727
Sep. 2002	134	793
Nov. 2002	146	813
July 2003	—	867

(2) Technology for preventing electrostatic damage, because the resistivity of a granular-type magnetic layer is higher than that of a metallic magnetic layer

Fuji Electric has developed new protective and lubricative layers that have a functionally separated structure. Figure 14 shows a schematic diagram of this structure. Perpendicular magnetic recording media based on these technologies have been experimentally verified to achieve performance and corrosion resistance equal to that of the present longitudinal recording media.

4.5 Read-write characteristics

The read-write characteristics of our perpendicular magnetic recording media produced by these technologies has been verified by several laboratories throughout the world. Table 1 shows some of the data. Each data value in the table indicates that our perpendicular magnetic recording media achieved the highest areal density level in the world at that time.

5. Conclusion

It has been more than 25 years since Emeritus Professor Iwasaki of Tohoku University published his pioneering work of perpendicular magnetic recording media. Thereafter, longitudinal recording has been predicted to be about to reach its limit of areal density again and again, but each time, that limit has been surpassed by technical innovation of the magnetic recording head, circuitry and HDD mechanism. However, longitudinal recording is reaching its practical limit at last, because it is impossible to increase the areal density to more than 160 to 200 $Gbits/in^2$ due to the thermal decay problem of magnetic recording media. Fortunately, Fuji Electric's perpendicular magnet recording media will be able to surpass this limit.

We at Fuji Electric have not developed perpendicular magnetic recording media by ourselves, however. Compared to other companies, we were late to begin developing perpendicular magnetic recording media. Fortunately we have been able to compensate for this late start in development by receiving assistance from many people in various laboratories, including Emeritus Professor Nakamura of Tohoku University, Emeritus Professor Muraoka of Tohoku University and Assistant Professor Shimazu of the Research Center for 21st Century. We would like to express our appreciation to all these individuals.

Fuji Electric expects that the year of 2005 will be a turning point for its media business and is planning to start mass-producing perpendicular magnetic recording media in that year. Moreover, in addition to the perpendicular magnetic recording media business, we are also thinking about the possibilities for our substrate business. In our medium-term business plan, the perpendicular magnetic recording media business is a very important part of Fuji Electric. We have already started to develop future perpendicular magnetic recording media of 400 $Gbits/in^2$, and we aim to become a leading media manufacturer in the external memory market and to contribute to the safe and convenient ubiquitous computing society of the 21st century.

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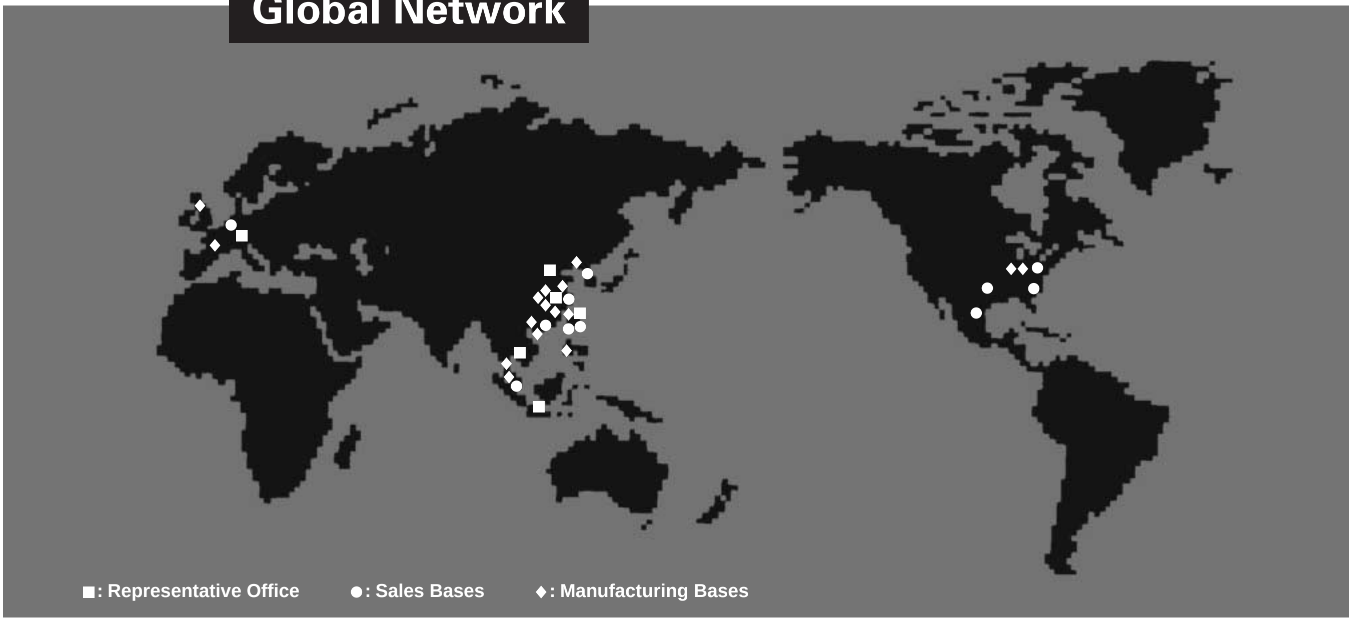

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