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

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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.

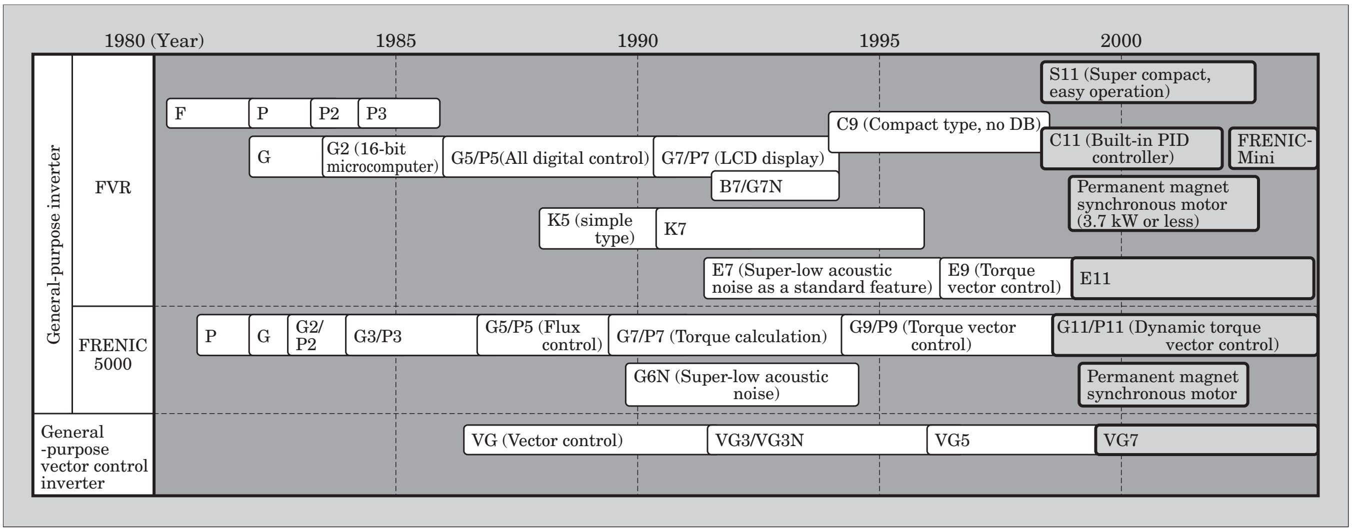
This paper looks back on the progress of Fuji Electric's general-purpose inverters, describes future technologies to provide the functionality and performance required for future general-purpose inverters, and also discusses future goals of Fuji Electric's general-purpose inverters.

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

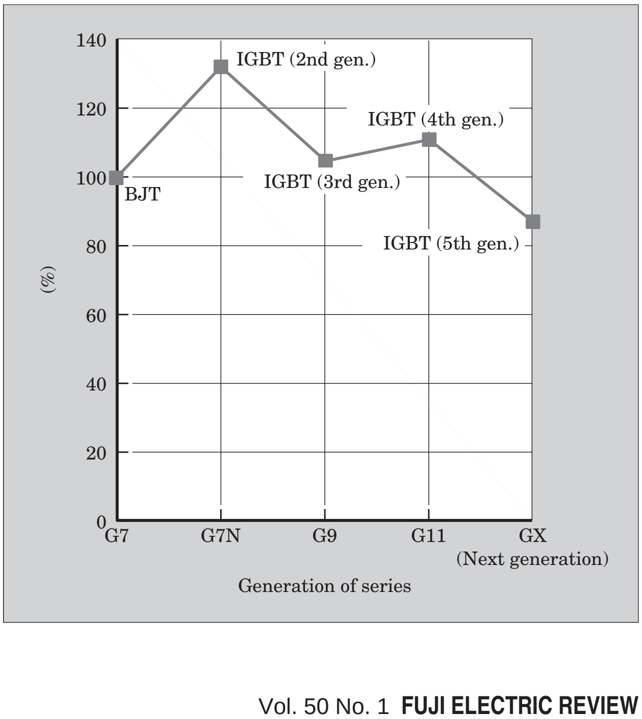
Main circuit technology has progressed along with advances in power devices. By applying PWM control to a full bridge-type inverter that uses a BJT, a compact and low-cost general-purpose inverter was realized. When a BJT was utilized, however, the carrier frequency, which was the switching frequency 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.

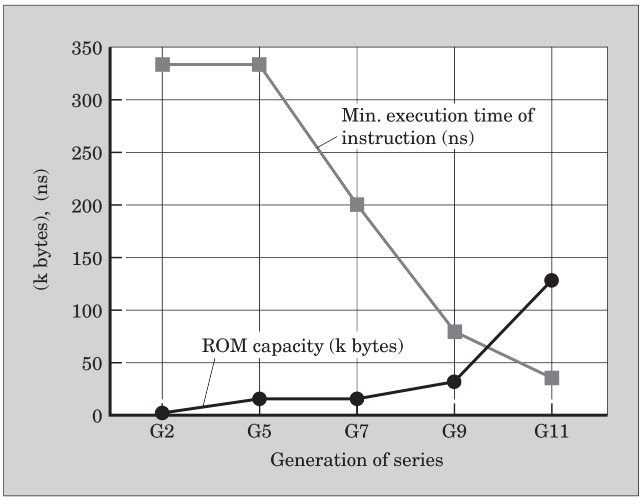
Figure 3 shows the history of improvement in the performance of CPUs used in general-purpose inverters. Performance improvements have resulted in approximately 10 times the computational processing speed and 30 times the program capacity, thereby making it possible to realize inverters having higher 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

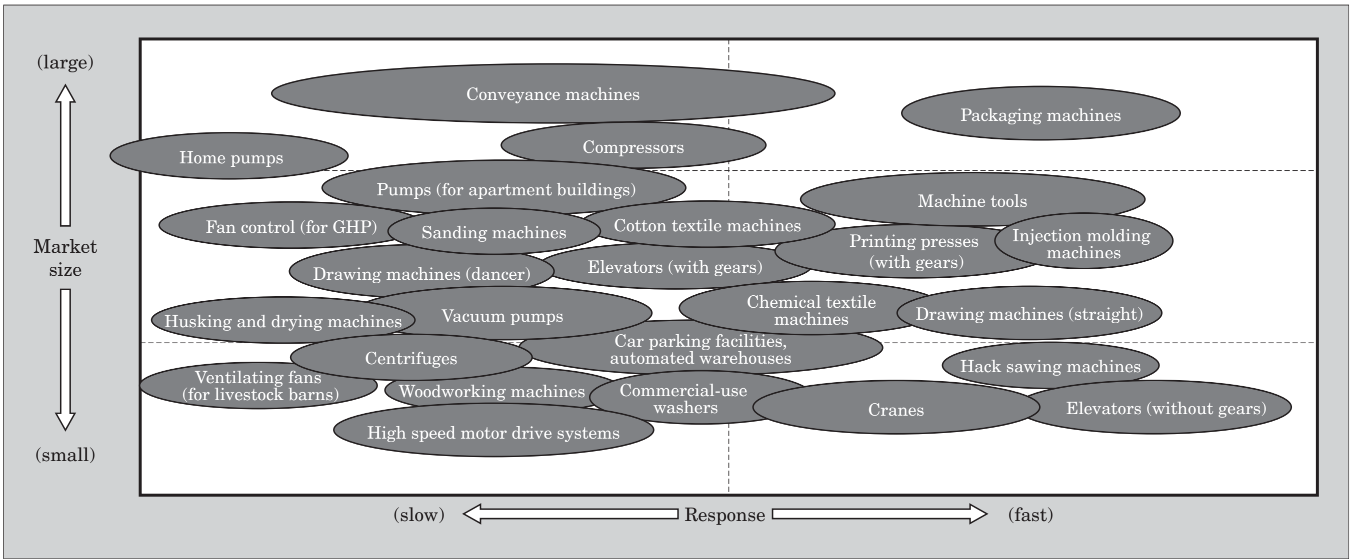
In looking back at the progress of inverters, progress has been made in response to requirements for smaller size, higher performance and multi-functionality. The expected future requirements of general-purpose inverters are listed below.

(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



"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

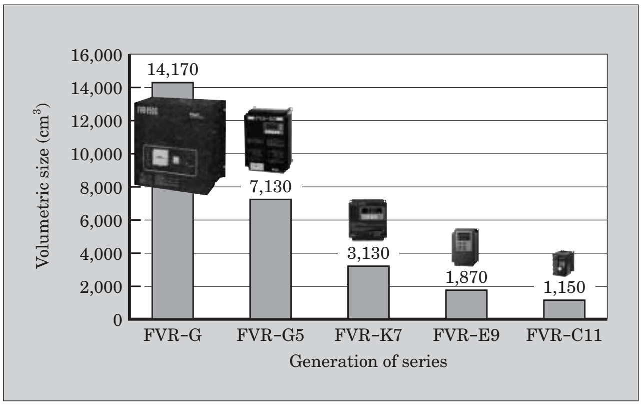
The use of highly integrated LSI chips containing a CPU core is expected to increase in response to demands for miniaturization and for the application of high-speed CPUs in order to achieve higher performance and increased multi-functionality. Requests for connection to an open field bus have also resulted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

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



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.

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