Modern Hardware Technology in Inverters and Servo Systems

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1. Introduction

With the popularization of variable speed drive systems for electric motors, including general-purpose inverters, have come great advances such as smaller size, lighter weight, lower price, higher performance with diversified functions, and improved quality. As a result, the volume of a 750W general-purpose inverter, for example, has decreased to 1/10 or less of the volume of the initial product. Behind the scenes of these developments have been remarkable advances in hardware technology due to application of high performance microprocessors, development of power semiconductor devices and cooling technology, etc.

Recently, the higher frequency switching for downsizing and lighter weight of the inverter have generated noise that may trigger a malfunction of the peripheral equipment, and this has caused a new problem. Desired hardware technology has also become diversified since communication functions are demanded along with networking capability.

This paper introduces the hardware technology of modern general-purpose inverters and servo systems.

2. Recent Main Circuit Technology

2.1 Power devices

In a general-purpose inverter and servo system, power devices generate most of the heat, and the loss thus generated accounts for 50 to 70% of the overall system loss.

The performance of IGBT (insulated gate bipolar transistor) elements, chiefly used as power devices, also has advanced greatly over the past ten years. The fourth generation IGBT has now been developed (Fig. 1) using technologies of the trench gate IGBT and the planer-type micro-machined NPT (non-punch through) -IGBT. The saturation voltage between collector and emitter $V_{CE(sat)}$ has been decreased to about 1.6V in the 600V class, and about 2.3V in the 1,200V class.

Moreover, because this IGBT is used at higher-frequency switching of about 10 to 15kHz, the loss due switching is so large that it accounts for 50 to 70% of the generated loss of the IGBT. Therefore, to decrease the switching loss, the on/off switching of voltage and current has been as abruptly as possible. This is the main cause of noise generation from the inverter and the servo system. When actually used in the field, this generated noise has caused peripheral equipment to malfunction.

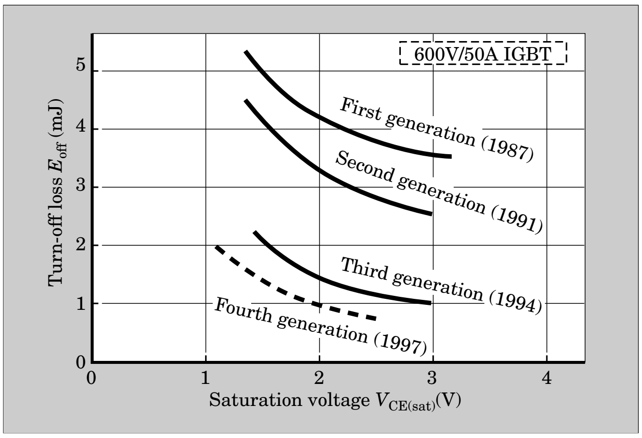
By limiting the voltage change rate *dV/dt* of this switching to about 5kV/µs on average in the FRENIC5000G11/P11 series of general-purpose inverters and the FALDIC-α series of servo systems that Fuji Electric has developed, the generated noises are suppressed to a lower value.

2.2 Intelligent power module (IPM)

Because the treated energy is large, the rectifier diodes and IGBT elements that compose the main circuit exert a significant influence on any damage due to usage or power-supply circumstances where a general-purpose inverter or servo amplifier have been setup. Therefore, it is strongly required to enhance reliability and protective functions of the main circuit unit.

In general, the system was designed so that the inverter apparatus side, where the IGBT modules compose the main circuit, may actuate protection by detecting the output current of the inverter apparatus or the current of the DC circuit. This protection circuit

Fig.1 Evolution of IGBT trade-off



was installed outside the IGBT modules.

In addition, if the system is to provide overcurrent detection for each IGBT element to protect the IGBTs and improve reliability, IPMs with built-in protection circuits must be used.

In the FRENIC5000G11/P11 series of general-purpose inverters that has been developed by Fuji Electric, IPMs are utilized for all systems of 22kW or less, in order to enhance the protection and reliability of the main circuit.

Especially for capacities of 5.5kW or more, the system adopts a protection method using the junction temperature detected by a measuring element directly buried in each IGBT element. This method achieves secure temperature protection compared with the previous indirect protection method that estimated the junction temperature from that of the cooling fin.

Table 1 compares the protective functions of the conventional model using standard IGBT modules with those of the new model using IPMs.

Table 1 Comparison of protective functions

Protective functions	FRENIC5000G9 (standard IGBT)	FRENIC5000G11 (IPM)
Overload	○ ◦ Overcurrent protection by output current detection ◦ Indirect junction temperature protection by detecting cooling fin temperature	◎ ◦ Overcurrent protection by output current detection ◦ Direct junction temperature protection by detecting IGBT element temperature
Output short-circuit and ground fault	○	○
Arm short-circuit (malfunction by noises)	×	○ Overcurrent protection for each IGBT element
Influence of damage on external circuits such as control power supply, drive circuit, etc.	Extended damage of IGBT due to damage of peripheral circuits	Minimized damage compared with that of standard IGBT

2.3 Dedicated power modules for inverters

In the pursuit of downsizing and cost reduction of the inverter apparatus, a technical limit is encountered especially for small capacity models when using only rectifier diodes or IGBT general-purpose modules. Therefore, it is necessary to utilize dedicated power modules containing as many essential functions as possible.

Fuji Electric has developed the FRENIC5000G11/P11 series of general-purpose inverters and the FALDIC-α series of servo systems, which exclusively use amplifiers with dedicated power modules based on IPM technology.

Figure 2 shows the internal circuit diagram of the dedicated power module.

As a structural feature, the power module has integrated the main circuit terminal block connected with the external power supply and the electric motor.

The copper wiring bars that had been used up to now for each connection were almost eliminated, and the apparatus was greatly simplified.

Current detection was an important factor in the integration with the terminal block.

Although Hall CTs that use Hall elements are generally used to detect the current, they must be inserted between the IGBT output and terminal block, and, in this case, integration becomes difficult from the viewpoint of sizing.

Fig.2 Internal circuit diagram of dedicated IPM (50A, 600V)

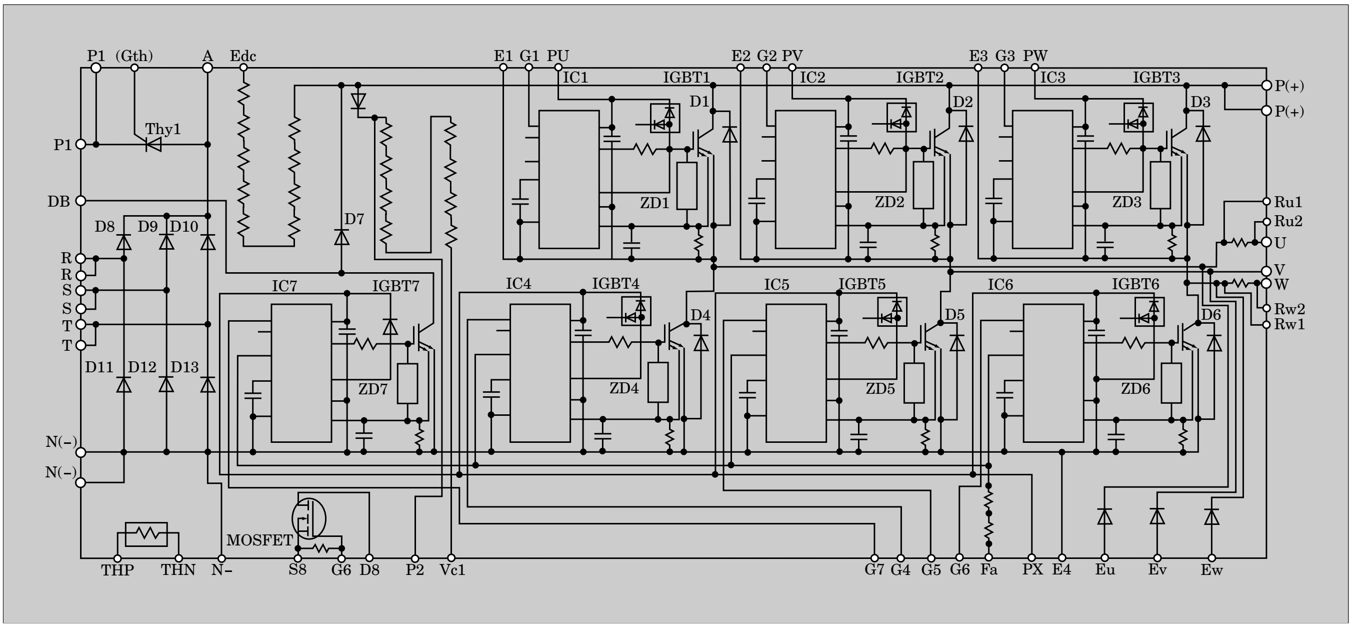


Fig.3 Integrated power modules and terminal blocks

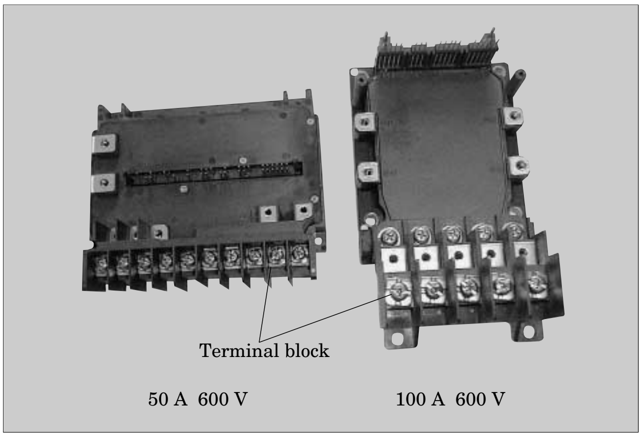
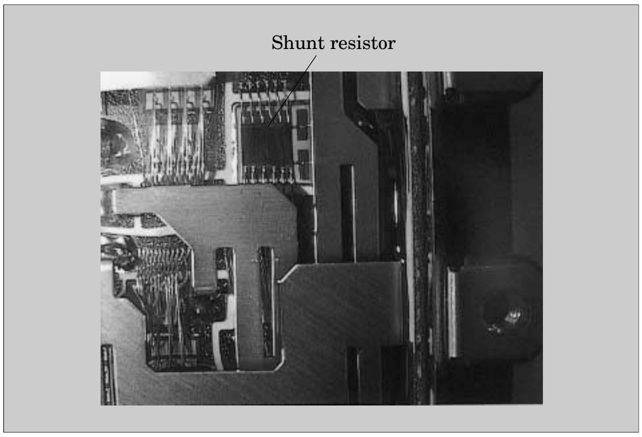


Fig.4 Shunt resistor with high thermal conduction



Fuji Electric has utilized a 10mm square shunt resistor in its dedicated IPMs to achieve an integrated structure of the power module and terminal block for models up to 200A/600V (Fig. 3 and Fig. 4).

2.4 Cooling technology

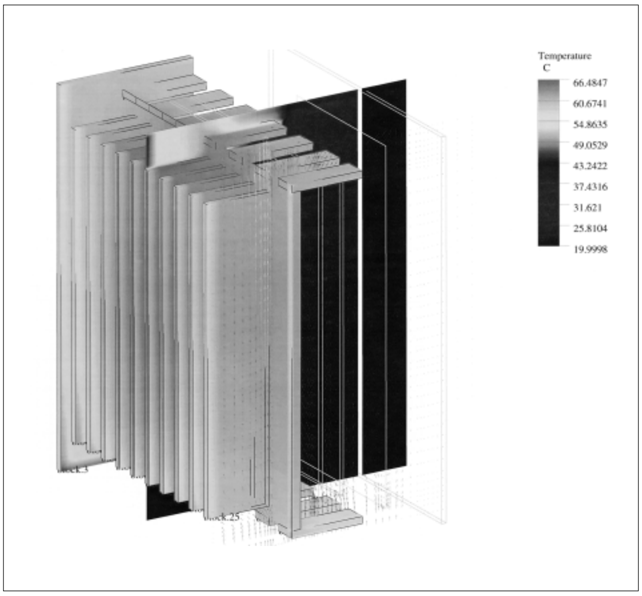
The conversion efficiency of the inverter apparatus is approximately 95%, and the remaining approximate 5% is loss. For instance, a loss of approximately 1kW will be generated in an inverter apparatus of 22kW output. The cooling technology basically determines the downsizing.

The natural air method of cooling is applied to the smallest capacities of 750W or less, and forced air cooling is generally used for capacities of more than 750W. With forced air cooling, the amount of wind from the cooling fans is the key factor when enhancing the cooling capability by increasing the rotation speed of fans. Direct current drive fans of 5,000r/min or greater are being used at present.

Increasing the surface area of the cooling fins as much as possible, fins with a narrower rib pitch are especially effective for forced air cooling. Cooling fins with a pitch of 4mm or less are currently applied by using caulking and brazing technology.

Repeated temperature testing consumes a great deal of time when designing apparatus, and the arrangement of components has been optimized while tests are repeated many times.

Fig.5 Example of thermal simulation results



However, Fuji Electric has recently introduced simulation technology. Simulation is used for verification before implementation, such as to examine the shape of the cooling fins or simulate the mutual interference of heat in order to setup the inverter apparatus.

Figure 5 shows an example of actual analyzed results of the servo amplifier using thermal simulation. It is anticipated that thermal simulation technology will further develop in the future.

3. Recent Control Circuit Technology

General-purpose inverters and servo amplifiers are used as actuators in the field of industrial machinery. Therefore, their required performance and functions are often demanded directly from the machinery itself. For instance, shortening the time required to start and stop the electric motor can reduce the operating hours of each machine. Moreover, processing accuracy of the machinery improves by decreasing rotational fluctuation of the electric motor and enhancing its positioning accuracy. Consequently, neither ultra low-speed processing nor correction process is needed. The performance of the control circuit plays a significant role in improving the performance of the apparatus. Some of the control circuit technology is introduced here.

3.1 Speed-up of operation

The installed microprocessor is responsible for internal processing in recent general-purpose inverters and servo systems. Software is necessary of course. Although there is some difference in the inverter and the servo amplifier, high-speed operation processing of the feedback system and sequential processing of the functional parts are necessary for the position adjustment, speed and current systems.

So far, most of such processing was executed with one microprocessor to satisfy product requirements for downsizing and cost reduction.

However, to implement basic performance improvements strongly demanded by the marketplace such as high-speed rotation, high-speed response, and high accuracy, there is the need for operations such as observers that are compatible with estimated control and turbulence, in addition to making the operation cycle and operation speed of the feedback adjustment system much higher.

In order to deal with such an increase in operation load, Fuji Electric utilized a RISC (reduced instruction set computer) type microprocessor with processing speed of approximately 30MIPS (million instructions per second). Fuji Electric has also responded to the problem by shifting those tasks which demand more high-speed operation to hardware by using ASICs (application specific ICs).

3.2 Shift to hardware processing

Along with higher integration of ASICs, it has become possible for operation processing to shift from software to hardware. That is, it has become possible to speed up operation processing with ASIC hardware, avoiding a significant cost increase and greatly improving the product performance.

Here, three examples where processing was shifted to the hardware for performance improvement are described.

(1) Voltage control by pulse width compensation

A key technology for the general-purpose inverter is to obtain an ideal output voltage even for low speed and to achieve smooth electric motor drive. Conventionally, although the voltage distortion caused by the nonlinear performance of switching devices such as IGBTs has been compensated by the software, the processing speed has not always been sufficient.

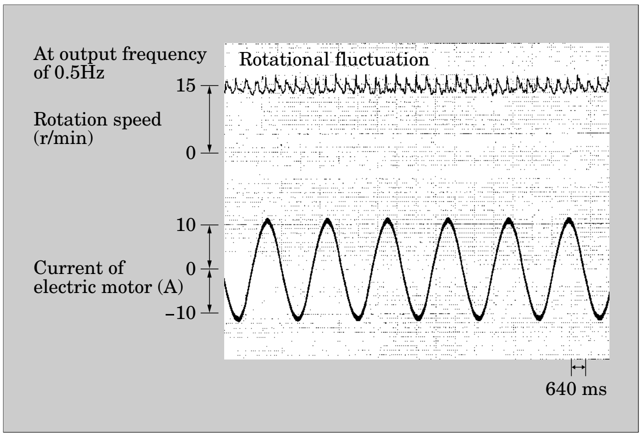
This technology detects shifting in the IGBT switching timing and compensates the switching pulse width. An ASIC is used for timing processes of 1μs or less. Application of this technology makes the low-speed current waveform more closely resemble an ideal sinusoidal wave. Figure 6 shows the rotational fluctuation and output current waveform of an inverter at 0.5Hz. This waveform is an almost ideal sinusoidal.

(2) Digital voltage control

This is an example of a feedback control that detects the output voltage for the purpose of controlling the output voltage of the general-purpose inverter as described above.

Containing an operation circuit that performs three-phase adjustment such that the detected output voltage agrees with the instructed voltage, the system performs all processing with ASICs, from the adjusting

Fig.6 Rotational fluctuation and current waveform



operation to PWM (pulse width modulation) processing. By using ASICs, it is possible to perform operation processing in a cycle of several tens of μs.

Ideal voltage control is made possible through high-speed operation processing and the detection of the output voltage.

(3) Digital current control

The servo amplifier controls positioning, speed, and current.

The current control requires the highest speed operation, and its performance determines the response of positioning and speed control. So far, however, this control has been implemented in software, because it requires a complex adjuster operation.

By implementing all these current control operations with an ASIC, the operation cycle has speeded up by approximately a factor of ten. This system has achieved a frequency response of 500Hz or more for the speed control loop.

Product performance has been improved through an appropriate paradigm shift to ASIC control.

3.3 High-resolution of pulse encoder

The feedback control in the servo amplifier needs a signal from the pulse encoder attached to the electric motor axle or the mechanical system to know the rotation of the electric motor.

The pulse encoder outputs a predetermined number of pulses to the electric motor per rotation. Currently, the output of several thousand pulses per rotation is common in the general industrial machinery field, excluding some super-precision machining equipment.

However, the pulse output within a fixed time (100 to several hundred μs) decreases as the rotation of the servomotor approaches low-speed. Therefore, the rotation of the servomotor cannot accurately be detected on the servo amplifier side, and problems such as low-speed axle vibration occur.

The performance of machinery has continued to be enhanced, and tens of thousands of pulses per rotation or more is being required in general industrial machinery.

On the other hand, because the output pulse frequency for high-resolution response enters the MHz region due to high-speed rotation, transmission of the pulse train signals becomes difficult. A recent measure implemented between the pulse encoder and servo amplifier is to exchange positioning information detected from the electric motor, while synchronizing at the operation cycle of the servo amplifier, using serially transmit numerical values.

Fuji Electric has implemented its original serial transmission format for Manchester code on an ASIC, resulting in high frequency transmission.

3.4 Field networking

To issue operational instructions to multiple general-purpose inverters and servo systems installed in machinery, and to collectively manage operational situations and internally set data, the networking of high-ranking control equipment with inverters and servo systems is becoming increasingly common.

Such networking only requires one serial communication cable to wire each piece of equipment. In conventional I/O wiring, each signal (each function) required its own separate wire. Networking can dramatically decrease the necessary wiring, leading to downsizing of the control board.

However, the currently existing methods of networking are many and diverse, and are adopted by certain countries, regions, industrial equipment manufacturers or fields of application.

Because of this situation, there are various movements by local regions throughout the world to standardize their own method. On the other hand, because of advantages and disadvantages of each method, it is difficult for the user to choose only one system as the standard networking method for their own equipment.

Table 2 lists some typical types of networks.

Moreover, the servo amplifier is responsible for increasing the speed and accuracy of the machinery. In addition, a multi-axle servomotor installed in a machine must not be allowed to operate with a time delay in response to a high-ranking instruction. In particular, complete synchronization of each axle is demanded for track control implemented processing applications.

Table 2 List of various networks

RS-485 (HL)
Modbus RTU
Modbus Plus
Profibus DP
Interbus S
JPCN1
Device Net
T-link (original link of Fuji Electric)
SX-bus (original link of Fuji Electric)

Because some time difference is inevitable when transmitting instructions by serial communication between each piece of networked equipment, positioning shifts are likely to result among the machine axles. To suppress such shifts to an allowable level, it is necessary to exchange the information of positioning instructions at an extremely fast cycle. A dedicated network with transmission speeds of about 10MHz or more is necessary.

Thus, the performance of the servo amplifier is influenced by the networking method, and many servo system makers are currently striving to develop and find applications for their original networking methods.

4. Conclusion

This paper described the modern hardware technology of inverters and servo systems. Since these products are indispensable in the industrial machinery field, high functions and high performance are always required, and, especially in recent years, the manufacture of environment-friendly products has also been demanded.

In the future, the authors will continue efforts to establish a product design technology that considers not only performance and functions, but also adapts to the environment and is concerned with simplified waste disposal and product recycling.