

Core Technology of Power Electronics Equipment

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1. Introduction

Power electronics equipment is used in a wide range of fields, ranging from consumer electronics device to industrial and public infrastructure applications, and contributes to the realization of greater energy savings, improved productivity, and the more efficient utilization of electric power energy.

Fuji Electric has a history of providing many families of products to the industrial, public infrastructure, transportation, energy and environmental fields, and has advanced the development of power electronics which is fundamental to these fields.

This paper describes Fuji Electric's efforts involving the core technology of power electronics equipment.

2. Efforts in Core Technology Development

The social environment is changing due to factors such as global environmental issues (global warming, environmental pollution, etc.), depletion of fossil fuels, decreasing birth rates and aging populations, shrinking labor forces, globalization, and the pursuit of security and safety. In the marketplace, there are strong demands for reduced CO₂ emissions, energy savings, utilization of natural energy, productivity enhance-

ments, and better safety and reliability.

Accordingly, power electronics equipment is requested to facilitate the realization of further miniaturization and higher efficiency through the use of miniaturized and lower loss power semiconductor devices, the use of high frequency circuits and improved packaging technology, a greater sophistication of control functions, higher reliability for continuing stable operation at a production site, and reduced power source harmonics and lower electromagnetic noise for improved environmental harmony.

As shown in Fig. 1, Fuji Electric has provided distinctive power electronics products to the market for a wide range of applications, capacities and frequencies, including a DC/DC converter (50 watt class) for use in information-processing equipment, an uninterruptible power supply (UPS) (500 kVA), an inverter for rolling mills (5 MVA and greater), an aluminum electrolytic rectifier (800 MW class) and an induction heater (1 MHz, 1 MW class).

The basic types of power electronics technology can be broadly classified as: (1) power conversion circuit technology involving power semiconductor devices and their application technology, (2) control theory and control technology for the specific control for various power electronics devices and for network, and (3)

Fig.1 Power electronics products by Fuji Electric

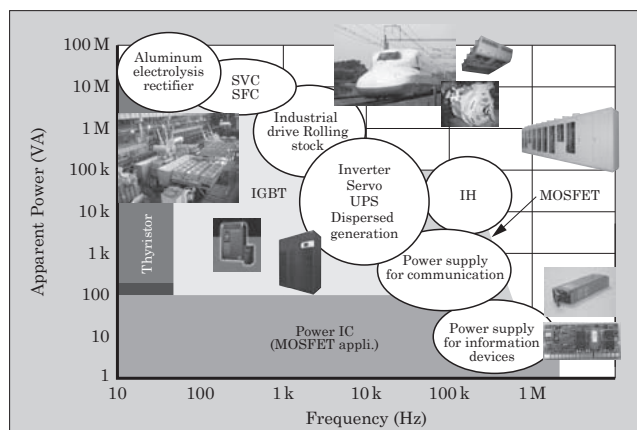
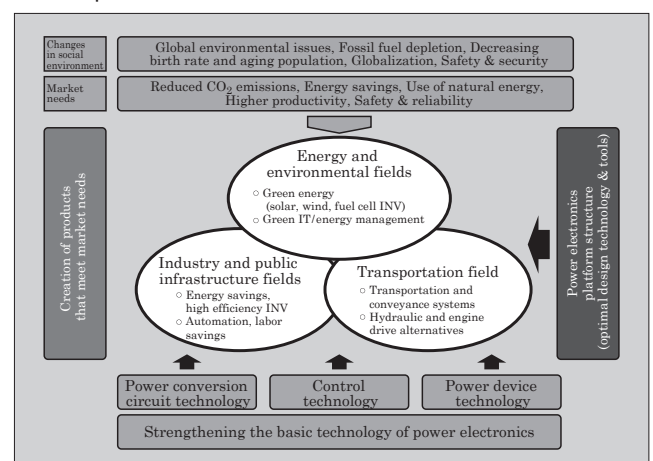


Fig.2 Market needs and power electronics equipment development efforts



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transformers, reactors, rotating machines and other hardware-related power equipment technology. In order to provide the abovementioned distinctive product families and to provide desirable next-generation products that satisfy market needs in such fields as industrial and public infrastructure, transportation, energy, and environmental regulatory compliance, Fuji Electric is advancing the development of core technologies to strengthen its basic power electronics technology and to establish a power electronics platform (to develop optimal design technology that can be shared among various devices). (See Fig. 2.)

This paper describes the relevant issues and Fuji Electric's recent efforts involving capacity-expanding technology for increasing the stand-alone capacity of equipment and high-power density technology for realizing miniaturization as power converter technology, drive control technology for realizing more sophisticated drive devices, motor design technology as power device technology, and power electronics platform technology.

3. Power Converter Technology

3.1 Capacity-expanding technology

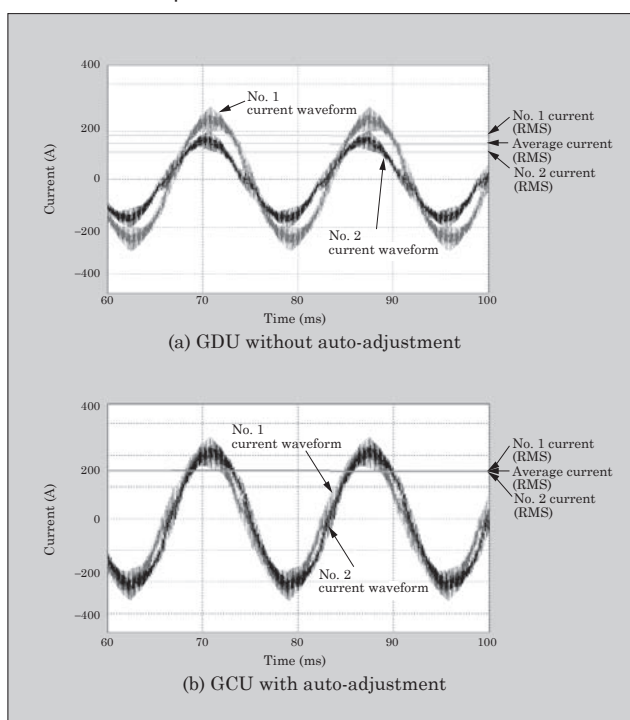
To expand the range of applications of products that use power electronics technology, Fuji Electric is working to develop capacity-expanding technologies for realizing serial-parallel connections of power semiconductors, parallel connections of power units, multi-converters and multi-level power converters. Serial-parallel connection technology and power unit parallel connection technology are described below.

As serial-parallel connection technology for power semiconductors, we developed a circuit method which has an extremely simple circuit configuration and is capable of balancing the voltage of a serially-connected IGBT even during transient operation. Features of this method are the capability to realize serial connections with almost no change in the device switching characteristics, and the ability to prevent an increase in switching losses. Fuji Electric realizes high-performance, high voltage and large capacity converters by using, instead of a high voltage IGBT, a 1 kV-class general-purpose IGBT, having good switching characteristics at high frequencies, applied to a multi-serial connection of this method to achieve higher blocking voltage.

Moreover, as an application of power unit parallel connection technology, Fuji Electric's new large capacity UPS 7700F Series uses shared power units (100 kVA) and parallel connections to realize a wider lineup of models with expanded capacity from 100 kVA to 600 kVA (max.).

When connecting power units in a parallel configuration, limiting the current imbalance among outputs of the various units presents a challenge. Differences in the values of the filter inductor L_f , also used for

Fig.3 Simulated waveforms of two inverter power units connected in parallel



parallel connections, and differences in the IGBT gate drive unit (GDU) delay times are the main factors responsible for the current imbalance among units operating in response to the same control signals within a device. Figure 3(a) shows simulated waveforms of two inverter power units connected in parallel in the case where differences exist in the L_f values and in the GDU delay times. According to the results of the simulation, when using standard-specification L_f and GDU values, current imbalances of approximately 20% and 40% occur when 2 units and 6 units, respectively, are connected in parallel configurations. Therefore, we added to the power unit's GDU a function for detecting the amount of current difference of the unit and for automatically adjusting the IGBT drive signal. Specifically, an adjustment function was added to increase the amount of dead time between a pair of IGBT arms only when the unit's output current difference is positive. This simulated waveform is shown in Fig. 3(b). As a result of the above-described method, even when there are differences among the L_f values and GDU delay times, the unit's current imbalance could be suppressed and a parallel connection of 6 power units (max.) was realized with a simple method.

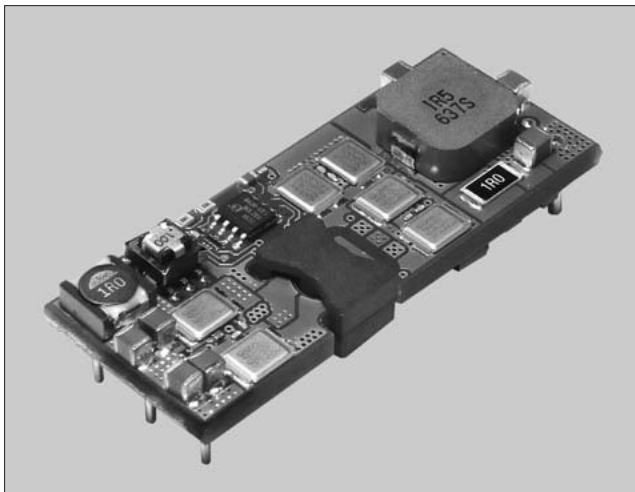
3.2 High power density technology

Miniaturization is continuously sought in power supplies, and especially in the information and communications sectors in recent years, there are increasing requests for higher power density, i.e., a reduction in size while maintaining the same capacity or increased capacity while maintaining the same size.

A bus converter is an insulated DC/DC converter for converting the output voltage of a front-end power supply (AC input/DC output) in a communication device or the like to an intermediate bus voltage (such as 12 V), and the industry standard size is known as a “brick”. In the 100 W class, the 1/4 brick size had been the mainstream size but the 1/8 brick size is gaining popularity. Fuji Electric has successfully downsized to the 1/8 brick size while boosting the output of that size from 100 W to 200 W. Figure 4 shows the external appearance of this 200 W bus converter. The external dimensions are 22.8 (W) × 57.8 (D) × 9.5 (H) (mm), and the rated input voltage is 48 V and the output voltage is 12 V. The following technologies were utilized to realize higher power density.

- (a) The windings of the isolation transformer were constructed using the wiring pattern of a high-count multi-layer PCB to realize a thinner design. Additionally, the shape and arrangement of the wiring pattern were designed so as to minimize leakage inductance and winding resistance, and to reduce the amount of loss generated.
- (b) A wiring pattern is used to disperse the heat emitted from heat-producing components such as semiconductor switching elements and the like. For this reason, the wiring pattern is provided with a shape and structure such that the heat transfer characteristic is extremely large in the horizontal (in-plane) and vertical (layer) directions.
- (c) The bus converter is configured with a switching unit and a control unit for the main circuit current located in extremely close proximity to each other, and therefore the wiring pattern is shielded, or a through-hole connecting layers of the circuit board is grounded, in order to prevent mis-operation due to main circuit noise.
- (d) The use of a new-type snubber circuit (voltage suppressor) in the rectifier circuit on the second-

Fig.4 200 W bus converter



ary-side of a transformer enables the use of low-loss, low-voltage semiconductor components.

Presently, Fuji Electric is working to deploy the abovementioned technology in other types of devices.

4. Control Technology

Fuji Electric is working to develop application techniques, such as vector control and observer theory, to improve the performance of drive systems with motors. Sensor-less magnetic position control technology for a permanent magnet synchronous motor to improve motor driving performance and anti-sway crane control technology to improve the drive system performance are introduced below.

4.1 Motor drive performance-enhancing technology

In applications for electrical rolling stock, fans, pumps and the like, the use of permanent magnet motors (PM motors) is increasing due to their smaller size and higher efficiency compared to induction motors. In response to needs for sensor-less and high-accuracy torque control similar to that of an induction motor, Fuji Electric is working to develop vector control technology that does not use a magnetic position sensor. Performance in the low-speed region, which has been a problem, is described below.

As a technique for improving stability in the low-speed region, inductance can be used as a function of the magnetic position. This method detects inductance fluctuations from the voltage and current values when a high-frequency component is applied, and then estimates the magnetic position. This method has the advantage of being capable of accurate estimation of the magnetic position even during low-speed operation, but also has the disadvantages of acoustic noise from the applied high-frequency component and of not being applicable to low saliency motors.

Fuji Electric is researching and developing a flux observer method capable of accurate estimation of the magnetic position even during low-speed operation,

Fig.5 Magnetic position and sensor-less vector control configuration

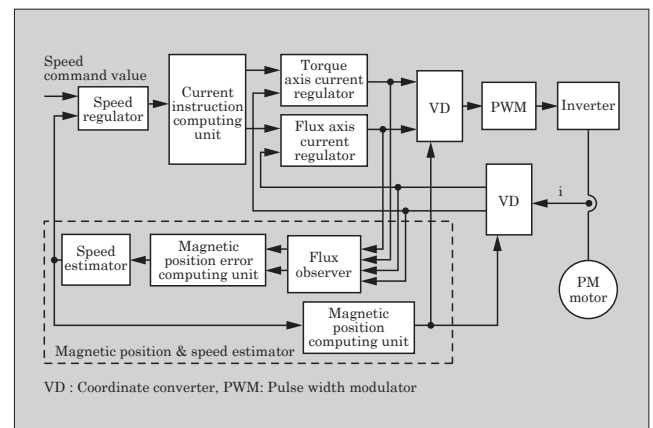
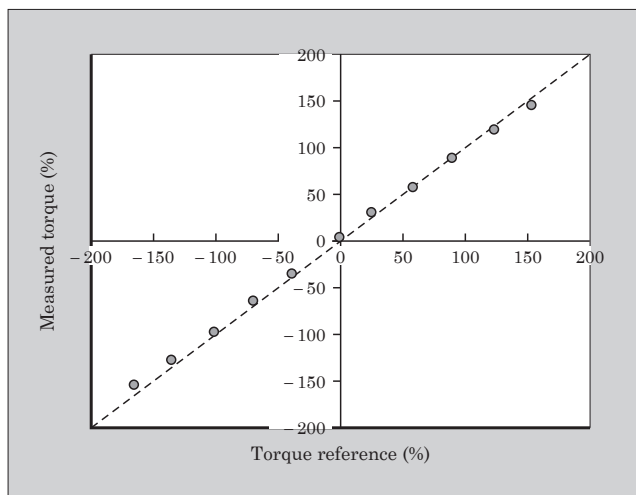


Fig.6 Torque performance (2% speed)



and that is not limited by noise or applicable types of motors. The flux observer method estimates the magnetic position and rotor speed from a value of magnetic flux that is computed based on a state equation of the motor. With the magnetic position and speed estimator configured as shown in Fig. 5, an adjusting operation is performed such that the magnetic position error becomes zero and the estimated magnetic position value matches the correct value. Figure 6 shows the torque performance at low speed (2% speed). Good performance can be ensured within the torque range from -150% to $+150\%$.

4.2 Drive device performance-enhancing technology

In drive systems where the load is a conveyance machine, machine tool or other mechanical system, vibration suppression of the mechanical system is critical from the perspectives of both work efficiency and safety. The anti-sway control for a crane is described below.

Anti-sway control for a crane system is typically implemented by detecting the sway angle with a camera. Because image processing is implemented, however, the sway angle cannot be detected at the same rate of frequency as with which motor control computations are performed and detection delays also occur which inhibit performance improvement.

Fuji Electric is engaged in the research and development of sway angle estimation technology that uses a dual-rate observer and has high accuracy and minimal detection delays. The sway angle observer, as shown in the control system configuration of Fig. 7, is configured from a high-rate sampling observer that performs an estimate for each motor control computation, and a low-rate sampling observer that performs computational processing for each camera image processing interval. The low-rate sampling observer computes an amount of observer model compensation from the difference between the detected value of sway angle, which includes the computed time delay due to

Fig.7 Crane anti-sway system configuration

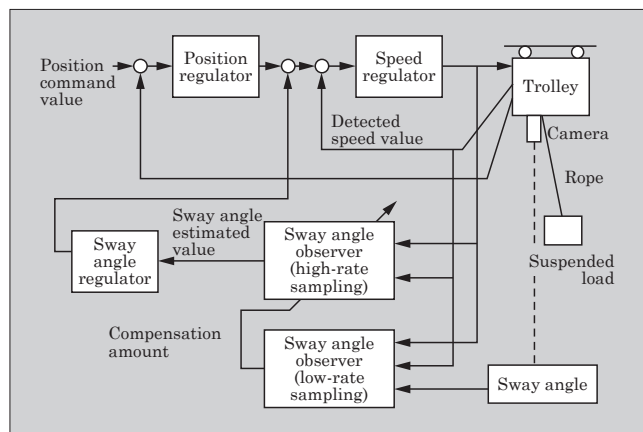
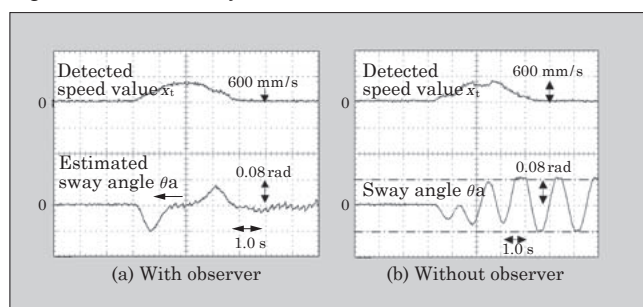


Fig.8 Crane anti-sway test results



the image processing, and an estimated value of the sway angle computed from an equation of up-motion for the crane. The high-rate sampling observer corrects the observer model, based on this compensation amount, to a suitable value and thereby increases the accuracy of the estimated sway angle used in the sway angle control. Figure 8 shows the results of the evaluation of sway angle control in an experimental setup in which the rope length was shortened by 15% and the equation of up-motion for the crane, i.e., the observer model, contains a certain amount of error. Even in this case, as long as the correction to the observer model by the low-rate sampling observer is effective, good results for the sway control could be verified.

5. Platform Technology for Power Electronics Design

Aiming to organize and restructure basic technologies common among power electronics, Fuji Electric is pushing to strengthen the design platform technology for electric circuits, control devices, software, cooling, construction, electromagnetic compatibility (EMC), and so on. Power electronics design technology has previously been applied to uninterruptible power systems (UPS), inverters, switching power supplies and driving units for train, achieving smaller size and lighter weight and helping to shorten the development time.

This chapter introduces a design tool for magnetic

components which are indispensable in power electronics devices, a design tool for unit-type power supplies, such as switching power supplies, and capable of instantaneously supporting designs for customization, and a design tool for cooling which is a key technology for higher density equipment.

5.1 Magnetic component design tool

As a result of advances in semiconductor elements and with the continuing trend toward higher density power electronics devices, the percentage by volume and the generated loss of main magnetic components, such as transformers and inductors, has increased on a relative basis. On the other hand, with the sudden rise in materials prices in recent years, in order to meet the requested component performance with fewer materials, it has become more important than ever to pursue optimal design and limit design.

Fuji Electric has developed a magnetic component design tool, and is advancing the development of high-quality and highly cost-effective power electronics devices.

Figure 9 shows the configuration of Fuji Electric's magnetic component design tool. The tool consists of an input sheet for selecting the required electric specifications, the iron core material to be used, and the like from a data sheet, and a characteristic computation sheet that automatically computes the various characteristics. The design tool supports the design of DC/AC (single-phase and three-phase) inductors and single-phase/three-phase transformers used in inverters, and automatically computes such characteristics as the inductance, gap length and loss (core loss and

copper loss). The design tool is additionally provided with a function for computing, according to the shapes of the core and coil and the amount of generated loss, the temperature rise of each component under actual usage conditions, thereby enabling a reduction in the amount of time required for determining the optimal design conditions for realizing the desired performance and reliability of the magnetic components with the minimum materials.

As a result, not only could the performance expected in the design stage be realized with fewer prototypes and less verification testing, and the time required for product development be shortened, but the materials were also minimized and the components miniaturized.

5.2 Automatic design tool for unit-type switching power supplies

Unit-type switching power supplies are often custom products based on various specifications, and design, manufacturing and evaluation processes are implemented in each case according to the customer specifications. Fuji Electric has developed an automatic design tool for unit-type switching power supplies, and this tool is being used to provide products speedily in response to customer requests.

This tool is configured as shown in Fig. 10, and upon inputting the desired specifications, the tool is able to compute circuit parameters automatically. In the design of magnetic components, the number of turns, the core, wires and the like are computed and selected based on the circuit parameters obtained so as to minimize loss and size. The design algorithm incorporates Fuji Electric's proprietary know-how and leverages the ability of a computer to perform repetitive operations to realize an optimal design. The design results are reflected in Bode diagrams and circuit simulations, enabling immediate verification of the stability and circuit operation. Moreover, the loss and temperature for each component are computed automatically, and reflected in the thermal design. Lastly, a series of results for design, analysis and the like are saved as a single file, and traceability is ensured.

At present, circuits are becoming more diversified, and the automatic design tool can be used with various switching power supply products. Use of this tool not only shortens the design time, but also makes it possible to realize designs that contain few mistakes, reduces the amount of time required for design changes and reevaluation of prototypes, and strengthens the ability to handle customized designs. For example, use of this tool enables development times to be shortened by 20% on average compared to the case when conventional design techniques are used.

5.3 Tool for cooling design

In the conventional cooling design of power electronics equipment, the path from a heat emitting part

Fig.9 Configuration of magnetic component design tool

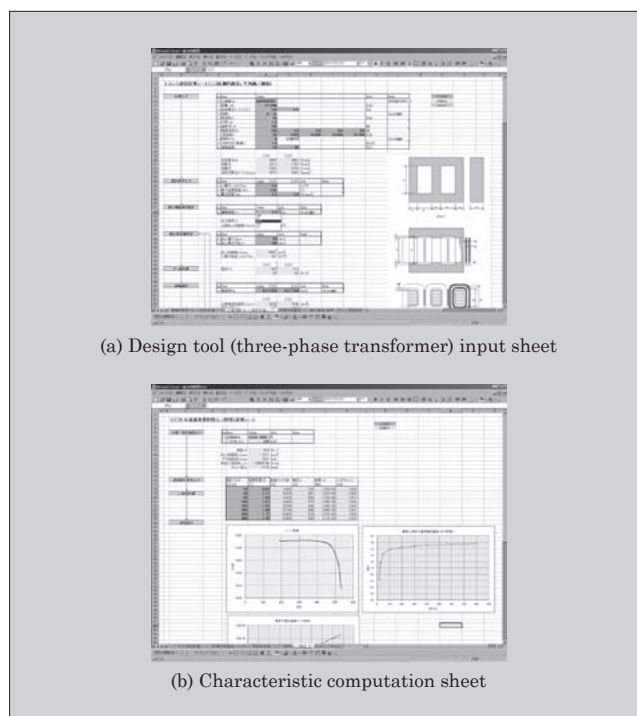
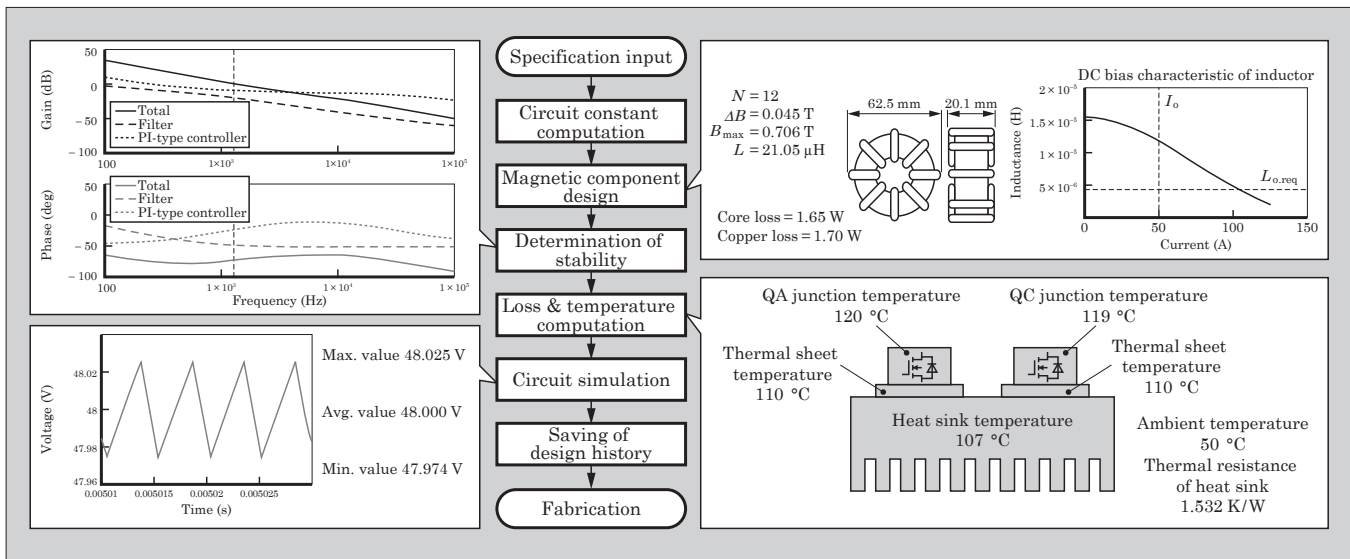


Fig.10 Overview of design tool for unit-type switching power supplies



to a cooling part was expressed as a thermal circuit, and the steady temperature rise and transient temperature rise were computed. With high-density large-scale products, however, the component layout and structures are complex and therefore significant differences between the design values and the actual device evaluation results may occur according to the level of modeling and the accuracy of such boundary condition settings as the heat transfer coefficient and so on. Additionally, since measurement of the temperature distribution of a semiconductor module junction and the wind speed distribution at small voids inside a cooling fin are difficult, three-dimensional computational thermo-fluid simulations must also be used.

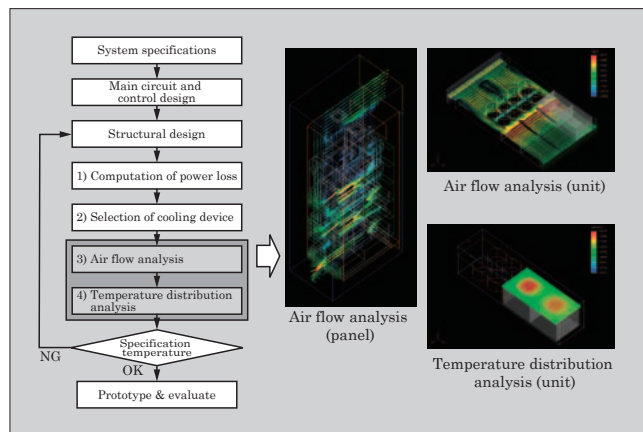
Thus, Fuji Electric developed techniques for analyzing airflow and temperature distributions in conjunction with three-dimensional CAD, and consolidated these techniques as a cooling design tool capable of quickly performing highly accurate computations of the airflow distribution within a large cubicle structure and of the temperature distribution corresponding to the chip-level heat generated by a semiconductor module.

Figure 11 shows an overview of the cooling design process flow for power electronics equipment; highly accurate power loss computations and steady and non-steady thermo-fluid analyses are performed. Thus, since the temperature distribution can be assessed accurately during the design stage, the number of prototype and evaluation iterations can be reduced and the development time shortened.

Moreover, the pursuit of smaller size, lighter weight and lower cost makes it possible to realize an optimized design with high reliability.

Using these design techniques, Fuji Electric intends to enrich the functionality of and to deploy this tool to implement cooling designs within a short time and with high reliability.

Fig.11 Overview of cooling design process flow



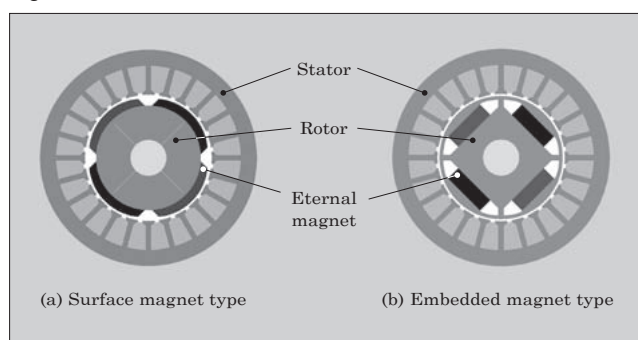
6. Motor Technology

6.1 Surrounding circumstances and technical issues

With the global needs for energy savings and reduced CO₂ emissions, there is an increased opportunity for improving the efficiency of all sorts of electrical products. Of the approximate 400 billion kWh of annual total electric power consumption by Japan's industrial sector, preliminary calculations show that the electric power consumption by motors accounts for approximately 70% of that figure, and increased efficiency will have a large effect. Also, for factories and other individual utility customers, improved motor efficiency will lead to a reduction in CO₂ emissions, lower electric power fees and lower capacity requirements at electric power utilities, and as a result, will contribute to reductions in cost.

In consideration of the abovementioned types of trends, motors, especially PM motors and their drive systems are positioned as strategically important items for Fuji Electric's drive business, and Fuji

Fig.12 PM motor structure



Electric is advancing their technical development. As shown in Fig. 12, PM motors are equipped with a permanent magnet inside the rotor part. Compared to induction motors which are widely used in industrial applications, the significant reduction in loss within a rotor enables PM motors to achieve higher efficiency, smaller size, and to be suitable for machine-embedded applications requiring a high degree of design freedom.

On the other hand, optimal design technology is needed to overcome the major technical challenges facing PM motors, i.e., achieving higher efficiency and the use of fewer materials. Particularly since customized design is often necessary to provide the required degree of freedom, the capability to implement a design and to estimate performance within a short time interval is critical. Moreover, neodymium magnets, often used as high-performance magnets, have low resistivity and as a result, changes in their flux density causes large eddy currents, and the resultant heating and temperature rise may lead to increased susceptibility to demagnetization. Accordingly, durability against demagnetization is a critical design item for a permanent magnet.

In response to these issues and in support of business expansion that promotes PM motors, Fuji Electric has developed the following design platform and is working to advance the application of this platform to design tasks.

6.2 PM motor design platform

In order to shorten the time required for PM motor design, Fuji Electric has constructed a design platform that incorporates simulations. Figure 13 shows examples of the operating screen. The main features are as follows.

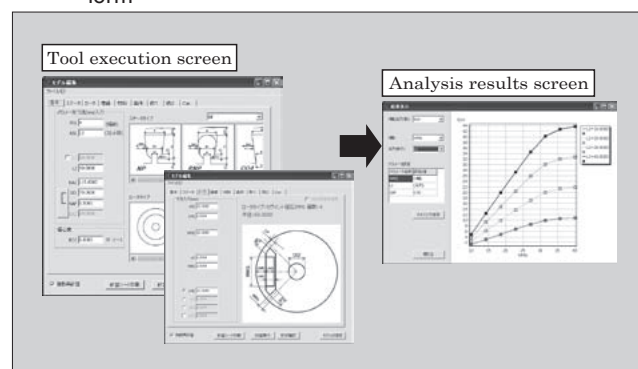
(1) Design conditions input

The various motor parts and parameters can be set with this dialog-style input screen.

(2) Design computation

Fuji Electric's accumulated design guidelines and know-how are compiled into a database and referenced, and characteristics can be computed using the

Fig.13 Example of operating screen of PM motor design platform



latest magnetic circuit analysis solver and numerical analysis solver technology. Parameter searches and highly accurate designs can be implemented efficiently.

(3) Design results output

Graphical displays of parameter search results and the seamless transition of design information to manufacturing documents are possible.

(4) Add-on function

The durability against demagnetization of a permanent magnet is evaluated, and assuming the most severe conditions, the extent to which the operating point of the permanent magnet approaches the demagnetization limit can be estimated by numerical analysis.

The accuracy of design computations is verified through multiple prototype tests.

Use of this platform enables the design time to be reduced to approximately one third of its prior value, and because the design can be optimized, estimates regarding the required specifications can be received in shorter times, and products that meet user needs can be provided.

7. Postscript

Fuji Electric's efforts in strengthening the core technology of power electronics equipment have been described.

The 21st century is being called the century of energy and the environment. As a basic technology for solving energy and environmental issues, expectations toward power electronics, which is indispensable for the effective utilization of clean and easily controllable electric energy, will increase further in conjunction with the progress of technical development of next-generation energy-saving power devices.

Fuji Electric will continue to develop power electronics technology so as to be able to provide products that are desirable and meet the needs of the market.



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