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ADVANCE

Power Electronics: Supporting People and Society

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Changes for the Better

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Mitsubishi Electric ADVANCE

Power Electronics: Supporting People and Society

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CONTENTS

Technical Reports

Precis

We have been working to satisfy various needs for power electronics devices and systems. Technology elements such as switching devices and modules, converters, integration, circuits, EMC, and control have been advancing in an interrelated manner. This issue highlights such elements of our power electronics technologies and products that support diverse applications in houses, offices, factories, and society.

Overview

Author: *Takahiro Urakabe**

Power electronics technology controls electricity by the on-off action of power semiconductor devices to realize rotation operation of motors and electric power transmission. The technology is used in personal goods such as automobiles and home appliances, systems that support social infrastructure such as railways and power transmission and distribution systems, and electrical equipment at many factories and offices. The technology makes it possible to supply electricity in a highly efficient and stable way, thus making life more comfortable.

Mitsubishi Electric Corporation has been manufacturing and selling power electronics products and developing technologies for them. Regarding power semiconductor devices, silicon carbide and other wide band gap semiconductor devices started spreading and were first applied to air conditioners for which energy saving was needed. Regarding power converters for power transmission and distribution, modular multilevel converters suitable for high voltage were applied to STATCOM for electric power. Regarding control technologies of power electronics, there has been remarkable progress in the position sensorless control of permanent magnet synchronous motors. Technologies for extending the service life of storage batteries and for monitoring their statuses are under development for differentiation in energy management. In addition, many researchers have been working on integration technologies that optimize the layout of each H/W for downsizing. This paper introduces the latest trend of technologies that support power electronics products and the latest power electronics systems.

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Prospective Technology of Power Electronics

Authors: *Akihiko Iwata** and *Takeshi Ohi**

1. Introduction

Mitsubishi Electric Corporation is involved in the business of power devices from small-capacity dual-in-line package intelligent power modules (DIPIPMs) to large-capacity thyristors, as well as power electronics systems using such power devices and related equipment. Small-capacity devices are used in houses and offices; intermediate-capacity devices in factories; and high-power devices for social infrastructure.

2. Performance Barometers and Technologies for Power Electronics Systems

Figure 1 illustrates the increase in performance of typical power electronics systems. The power density and injection efficiency (output/loss) have approximately trebled in 20 years. This improvement is thanks to the switching of elements from insulated gate bipolar transistors (IGBTs) to SiC-metal-oxide-semiconductor field-effect transistors (SiC-MOSFETs) and the establishment of a board level packaging technology that drives and protects high-speed elements and reduces surges. In addition, the speed frequency response has improved approximately ten-fold, thanks to more sophisticated arithmetic devices and the use of modern control theory.

In the past, development mainly targeted and power devices, converters, and control in particular. Currently, there is a need to develop elements and integration technologies for thermal and structural systems, with a good balance of technologies for key parts.

3. Advancement of Power Devices and Wide Band Gap Semiconductors

Power electronics systems dramatically spread after variable voltage variable frequency (VVVF) inverters entered practical use thanks to the development of self-turn-off power devices such as bipolar transistors and gate turn-off (GTO) thyristors. Today, IGBTs are used as main devices in diverse sectors from home appliances to electric power. Meanwhile, the development of wide band gap semiconductors such as SiC and GaN was started with the aim of enhancing their performance for practical

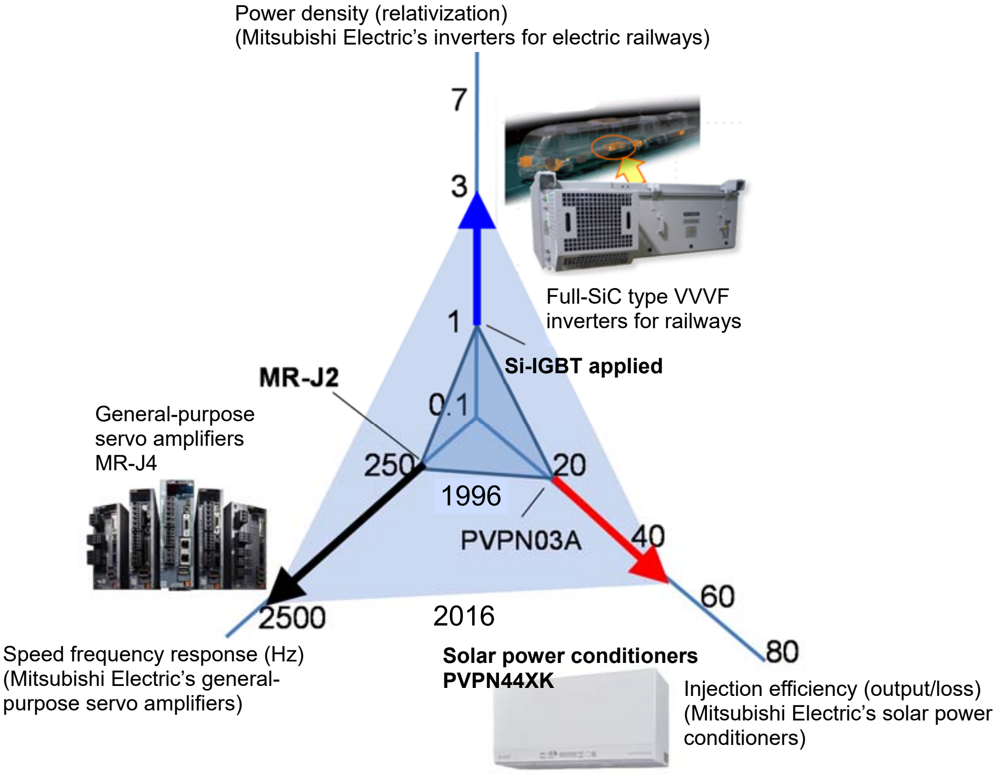

Fig. 1 Evolution of performance barometer of power electronics products

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application. Regarding SiC, Schottky barrier diodes (SBDs) and MOSFETs have been commercialized. Although bipolar devices are the mainstream for Si, unipolar devices are the mainstream for wide band gap semiconductors. Figure 2 is a map of products that include Mitsubishi Electric's SiC devices. The history of SiC began with the application of SBDs. The first type of products to use SiC were room air conditioners. Then, SiC started to be used for inverters for railways and FA equipment. Mitsubishi Electric commercialized propulsion control systems for railway vehicles using SiC-MOSFETs for the first time in the world. Furthermore, Mitsubishi Electric has applied SiC to solar power conditioners and air conditioners.

SiC devices started to be used for applications where it was considered that energy-saving and downsizing were important. To spread them further, the functions need to be improved and the costs reduced. Many researchers have been working to develop packaging technologies and trench gate MOSFETs that can operate at high temperatures and high speed, which are the strong points of SiC devices. In addition, regarding application to high-voltage power electronics systems, 6.5-kV-MOSFET modules and over 10-kV devices are under development. SiC devices are strongly expected to help reduce power consumption. Mitsubishi Electric will continue sophisticated development to help spread SiC devices further.

4. Converters and Integration Technologies

In addition to standard two-level converters, three-level converters and gradationally controlled voltage inverters have been adopted depending on the application. Recently, modular multilevel converters (MMCs) with more levels have been under development. The conventional two-level method has a problem with voltage dividing of elements. In MMC converters, cell modules are connected in series and the cell voltage is controlled to be stable. The phases output from the cells are shifted, so as to achieve waveforms with little harmonics for the entire arms. It is easy to increase the voltage of MMC converters and they are used for self-excited VAR systems.

In more and more cases, step-up choppers are installed in the DC sections to optimize the input voltage of inverters, but this lowers the efficiency. For a cooperatively controlled converter as shown in Fig. 3, when the voltage of the PV cells is higher than the system voltage, only the inverter switches; and when it is lower, only the chopper switches. These behaviors form sine waves as a whole. There is no period during which both chopper and inverter switch, which reduces losses and increases the efficiency.

Recently, 3-kW two-way noncontact power transmission systems for charging onboard batteries have been gaining attention as an application of wireless power supply converters. For such a system, the DC/DC

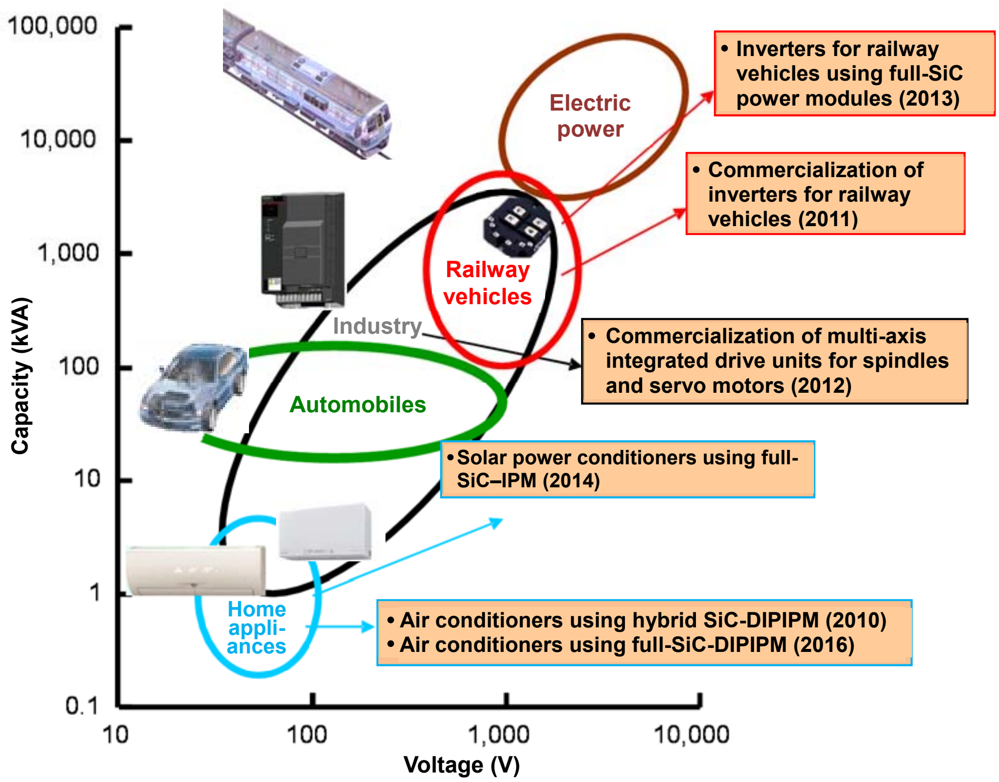


Fig. 2 Product map of SiC applications

converter on the sending side controls electric power, the inverter on the sending side controls output phases, and the DC/DC converter on the receiving side makes adjustments to raise the efficiency; the efficiency is 84% or higher even when the position of the power-sending coil deviates from the receiving coil by 15 cm.

Noise is a problem with high-speed, high-frequency switching, and much work is being done to develop measures to suppress noise after equipment has been completed. One developed technology can estimate complicated frequency characteristics of the attenuation of noise filters by electromagnetic field analysis and automatically calculate an equivalent circuit constant for noise. This technology allows noise countermeasures to be taken in advance, thus reducing the total development period.

To downsize equipment, integration technologies that consider the arrangement of elements, filters, and coolers are required. Figure 4 is a configuration example in which a control board, elements, wires, and base and fin for cooling have been integrated. Molded resin is used to house the electronic components, which enhances the reliability. A single cooling route using a heat-conducting sheet can reduce the entire thermal resistance. The size was reduced to two thirds compared to the conventional type.

5. Control Technologies

For position sensorless adaptive magnetic flux observer control used for permanent magnet synchronous motors, control in low speed ranges where the induced voltage was low was difficult. A new method has been developed to identify inductance and estimate the position by superimposing high-frequency waves to output waveforms in low-speed ranges using the dependence of motor inductance on position.

For driving large-capacity AC motors, multiple inverters are connected using large and expensive reactors in some cases. Figure 5 shows the configuration of a driving system for a double-winding permanent magnet synchronous motor for which a single motor can be driven by multiple inverters without any reactors. When electric currents are controlled by the inverters separately, the control becomes unstable due to the union between the winding wires. To counter this problem, a stable, high-response control system which incorporates the influence of the union between winding wires into a control model has been developed.

6. Technology of Key Parts

As the frequency of converters has been increasing, it has become important for magnetic parts to reduce the loss at high frequency. Figure 6 shows a planar transformer for which the arrangement of the winding wires and core was optimized using a printed board. The primary and secondary winding wires are formed as patterns on a multilayer board and the core with the circuit board inserted forms a magnetic circuit. The coupling coefficient is high and the skin effect is minimal, so eddy-current loss can be significantly reduced. In addition, the length of the magnetic circuit of the core is shorter, thus reducing the volume and core loss.

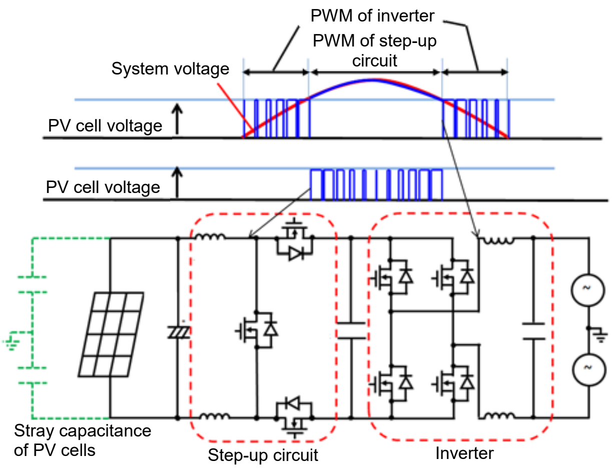


Fig. 3 Cooperatively controlled PV inverter

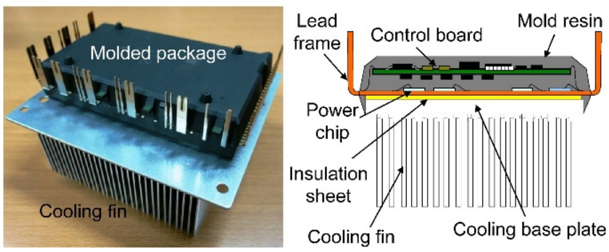


Fig. 4 High integration inverter

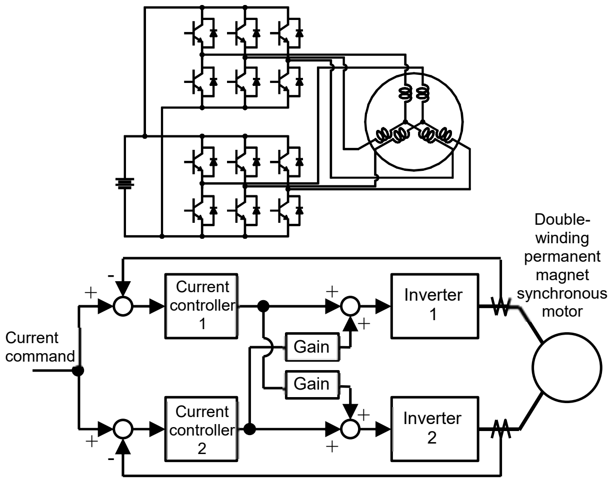


Fig. 5 Driving control of double-winding permanent magnet synchronous motor

7. Power Electronics System Products that Support Humans and Society

Power conditioners for electric vehicles (EVs) control three types of electric power simultaneously—EVs, PV power generation (PV), and

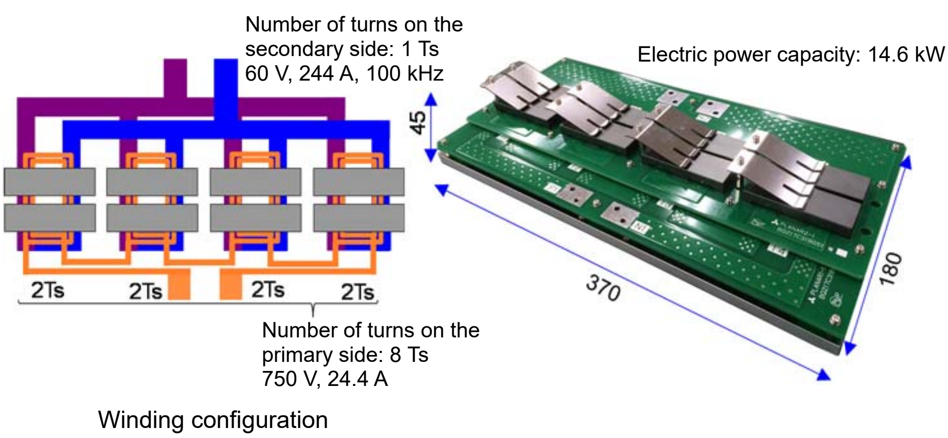


Fig. 6 Planar transformer

commercial power supply systems—and they use EVs to store electric power. A power conditioner for EVs has a built-in two-way converter that charges and discharges an EV and a built-in inverter that supplies electric power from the EV to the electric power system and house. When an electric power system fails, PV can supply power to the home and can charge an EV, and the EV can supply power to the house.

Station energy-saving inverters use regenerated energy from railway vehicles effectively at stations. Surplus power regenerated through a 1,500-V wire is converted to high-frequency electric power with a resonant-type high-frequency inverter. The electric power is converted to direct current with a rectifier via a transformer. The DC is converted to commercial alternating current with an SiC inverter, which is used in the station building.

More and more servo motors have been applied to enhance the performance of systems and shorten the cycle time. Servo motors that rapidly output large torque require large instantaneous power. Servo motor drive systems with circuits for energy assistance are available. Condenser units and step-up/step-down choppers work to compensate for changes in electric power on DC bus bars which varies due to increases and decreases in the output from the servo motors. As a result, the maximum electric power supplied from the power source side to the converters is decreased, which reduces the burden on power facilities.

8. Conclusion

To spread more energy-saving systems using power electronics technologies, the loss of the systems themselves needs to be reduced, system costs and size need to be reduced, and the value of systems needs to be enhanced.

6.5 kV Full-SiC Power Semiconductor Module

Author: *Hiroshi Kobayashi**

1. Introduction

Mitsubishi Electric Corporation has developed 6.5 kV full-SiC power semiconductor modules with the world's highest power density (calculated from rated voltage and current). These modules have made it possible to increase the power density and operating frequency and reduce switching loss significantly, contributing to smaller and more energy-efficient high-voltage power electronics systems.

Characteristics of these modules include: (1) the use of Mitsubishi Electric's original Schottky-barrier-diode (SBD) embedded SiC-MOSFETs has significantly reduced the chip footprint; and (2) a new type of small package for high heat dissipation and high heat tolerance has been realized thanks to ceramic substrates having both excellent thermal conductivity and thermal resistance and a highly reliable bonding technology.

2. SBD-embedded SiC-MOSFETs

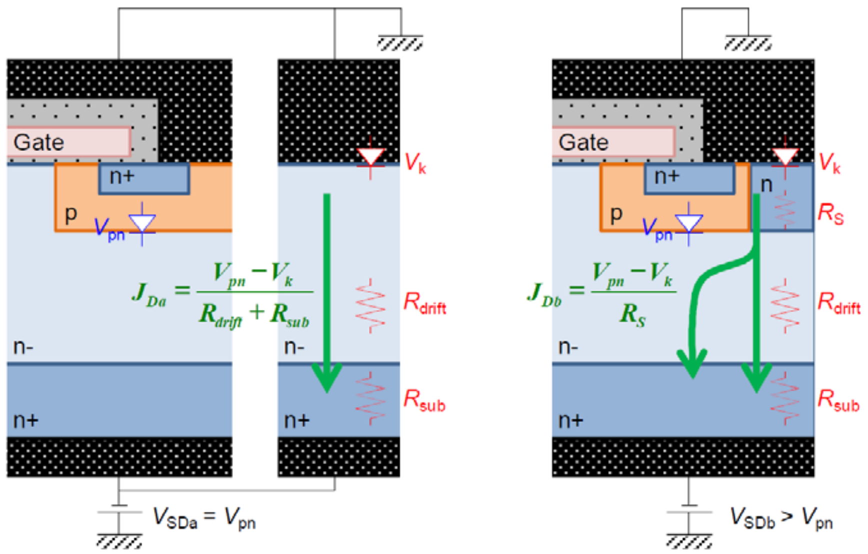
It is known that current conduction of the body diodes of SiC-MOSFETs causes bipolar degradation following the expansion of stacking faults. For higher-voltage SiC modules, larger external SBD chips are required as free-wheel diodes to suppress this current conduction.

In this development, a new type of switching device that is free from bipolar degradation without an external SBD has been realized by embedding an SBD into each unit cell of a 6.5 kV SiC-MOSFET. Figure 1(a) is the cross section of a conventional MOSFET with an external SBD and Fig. 1(b) is that of an SBD-embedded unit cell. The figures show that the embedded SBD section can pass a larger current than the external diode (See the reference (1) for details). As a result, Mitsubishi Electric has succeeded in reducing the chip footprint significantly compared to the conventional type.

3. Newly Developed Packages for High Heat Dissipation and High Heat Tolerance

3.1 Power semiconductor module structure

As the power density of a device increases, the loss per unit area increases, so measures against generated heat become more important. Mitsubishi Electric has developed elemental technologies for heat dissipation



Conventional MOSFET external SBD
(a)

SBD-embedded MOSFET
(b)

V_{pn}: built-in potential of pn junction
V_k: Schottky voltage
J_{Da}: current density in (a)
J_{Db}: current density in (b)

Fig. 1 Schematic cross sections of (a) a conventional MOSFET with an external SBD and (b) an SBD-embedded MOSFET

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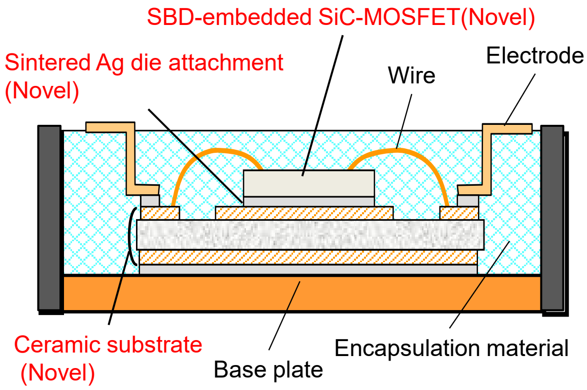

Fig. 2 Schematic cross section of the novel power module

and heat tolerance and designed highly reliable 6.5 kV full-SiC power semiconductor modules using such elemental technologies. Figure 2 illustrates the schematic cross section of such power module.

3.2 Ceramic substrates

Mitsubishi Electric focused on ceramic substrates, which were bottleneck of heat dissipation on power modules, and has been working to increase their heat dissipation. In addition, temperature cycling reliability also needs to be secured in this project. Two types of ceramic were used as shown in Fig. 3: aluminum nitride (AlN) and silicon nitride (SiN).

The thermal conductivity of AlN is high at approximately 180 W/(m·K), but its mechanical strength is low, so when the operating temperature is high, it breaks due to thermal stress. This problem was solved by inserting an Al electrode between the Cu electrode and AlN as a stress relaxation layer to reduce the thermal stress acting between the Cu and AlN. On the other hand, SiN has high mechanical strength and so is suitable for higher temperature, but its thermal conductivity is low at approximately 70 to 90 W/(m·K). To address this problem, the National Institute of Advanced Industrial Science and Technology has a technology to improve the thermal conductivity significantly by reducing impurities in particles and the amount of grain boundary phases that hinder heat conduction. This technology was used to obtain SiN with improved thermal conductivity.

These AlN and SiN substrates were mounted in modules and a thermal cycling test and thermal conductivity evaluation were carried out. It was showed that both AlN and SiN substrates are reliable during thermal cycling between −55 and 175°C, and that the thermal resistance R_{th} of the power modules was reduced by approximately 15%.

3.3 Sintered Ag bonding

As the operating temperature of a chip approaches the melting point of solder, which is the conventional

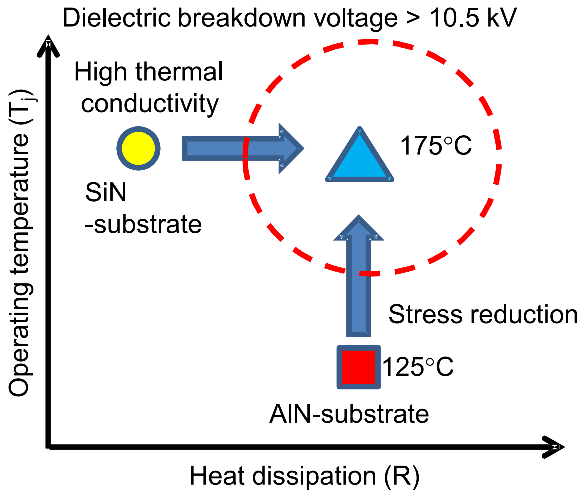

Fig. 3 Direction of ceramic substrate development

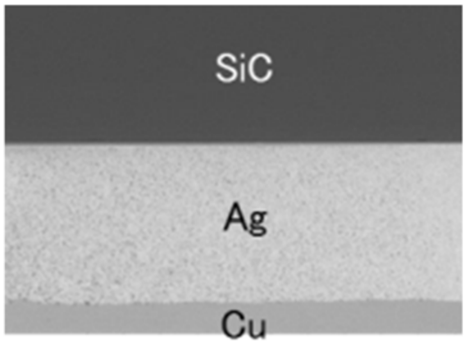

Fig. 4 SEM cross section image of die attachment using low-pressure-sintered Ag

bonding material, the temperature cycling reliability at the junction immediately below the chip becomes a problem. Sintered Ag bonding is a technology to bond a chip and substrate electrode using Ag, which has a high melting point at the process temperature the same as that of solder, by using Ag nanoparticles covered with organic protective film. The melting point of Ag is high at 962°C, so the thermal cycling reliability is high. However, for the conventional Ag bonding material, a high pressure of several tens of MPa is required for pressurization to form the connection. It is necessary to reduce this pressure to simplify the bonding process.

It has been succeeded that forming sintered Ag bonding between the SiC power device and the copper electrode on a ceramic substrate at a low welding pressure of 5 MPa using a newly developed Ag bonding material (Fig. 4). In addition, it has demonstrated that the thermal cycling reliability of this junction can be secured between −55 and 175°C.

4. 6.5 kV Full-SiC Power Semiconductor Module

Figure 5 shows the appearance of the developed power module. This shape is compatible with the package which we aim to be used as the industry

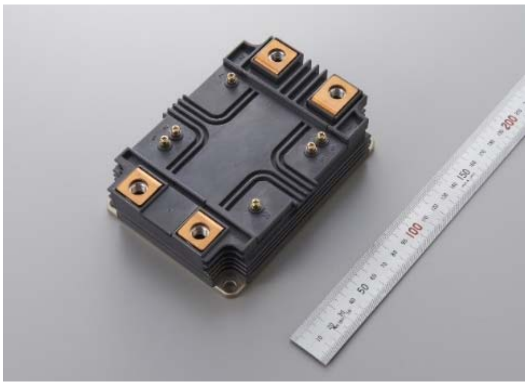

Fig. 5 6.5 kV full-SiC power module

Table1 Full-SiC power semiconductor module vs. conventional silicon IGBT module

	Power density	Power loss	Assumed operating frequency
Full-SiC module	1.8*	1/3	4
Conventional silicon IGBT module	1**	1	1

Note: Values normalized to corresponding values of Mitsubishi Electric's conventional silicon IGBT module
* Corresponds to 9.3 kVA/cm^3
**Corresponds to 5.1 kVA/cm^3

standard (Mitsubishi Electric HV100). Table 1 shows a comparison with a conventional Si-IGBT module. The rated power density is 1.8 times (9.3 kVA/cm^3) that of the conventional type. In addition, it has been confirmed that the electrical stability during switching operation is excellent.(2)

5. Conclusion

The 6.5 kV full-SiC power module has achieved the world's highest power density (9.3 kVA/cm^3) as a power semiconductor module thanks to the SBD-embedded SiC-MOSFET and newly developed package for high heat dissipation and high heat tolerance. Mitsubishi Electric expects the module to lead to smaller and more energy-efficient power equipment for high-voltage railcars and electric power systems.

Acknowledgement

Mitsubishi Electric's development of a 6.5 kV full-SiC power module has been supported by a project that is subsidized by the New Energy and Industrial Technology Development Organization (NEDO). Participants in the project, in addition to the four material manufacturers (DOWA Electronics Materials Co. Ltd., Mitsubishi Materials Corp., Denka Co. Ltd., and Japan Fine Ceramics Co. Ltd.), also include three universities (Tokyo Institute of Technology, Shibaura Institute of Technology, and Kyushu Institute of Technology) and one public research institute (National Institute of Advanced Industrial Science and Technology).

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Conversion Circuit Technology for High Efficiency and Downsizing

Authors: *Takaaki Takahara** and *Hiroyasu Iwabuki***

1. Introduction

Smaller converters with higher efficiency are demanded for industrial equipment, consumer appliances, and automotive devices because more energy needs to be saved and space is limited. To develop smaller converters with higher efficiency, conversion circuit and control technologies must make maximum use of the characteristics of advanced parts and material technologies (next-generation devices, magnetic components, and cooling parts). This paper describes conversion circuit technologies for high efficiency that help reduce the size and increase the efficiency, as well as a multiport circuit technology that optimizes the electric power flow from multiple power sources from the aspect of systems.

2. Circuit Technologies for High Efficiency

2.1 Circuit technology for AC-DC converters with higher efficiency

We have proposed AC-DC converters with gradationally controlled voltage inverters (GCVI) as shown in Reference (1) and has demonstrated that their charging operation is highly efficient by applying them to electric vehicle battery chargers. These inverters reduce the switching voltage and frequency and use high-performance low-voltage elements to improve efficiency. This section describes development examples of GCVI.

2.1.1 Gradationally controlled voltage inverters with voltage doubler rectification

Recently, devices to be connected to power supply systems need to be made compatible with AC input voltages (85 to 260 V) found worldwide. In the conventional gradationally controlled voltage inverters where only sub-converters (single-phase inverters) and short-circuiting switches were used for boost operation, how to improve the efficiency at an AC input voltage of 100 V, which was the condition of high boosting ratio operation, was a problem. Therefore, we have proposed AC-DC converters with gradationally controlled voltage inverters to which voltage doubler rectification shown in Fig. 1 was applied. Voltage doubler switches were added to the conventional circuit and voltage doubler rectification is carried out at an AC input voltage of 100 V. This voltage doubler rectification operation can reduce the DC voltage of the sub-converters and the voltage applied to the PFC inductor by 50% and can reduce the conduction interval of the short-circuiting switches. Although a new loss of 14 W is produced by the added voltage doubler switches compared to the conventional method, the conduction loss on the short-circuiting switches is reduced by 9 W, the switching loss on the sub-converters is reduced by 4 W, and the core loss on the current control inductor is reduced by 5 W. The total loss (the new loss minus the three loss reductions) is 4 W lower. Figure 2 shows the measured actual efficiency. The efficiency at 100 V (1.5 kW) was improved by 0.4 points thanks to the voltage doubler rectification and the efficiency was improved in the range of AC input voltage of 85 to 120 V to which the voltage doubler rectification was applied.

2.1.2 Simple gradationally controlled voltage inverters

We have proposed AC-DC converters with simple gradationally controlled voltage inverters to further simplify and downsize circuits while maintaining their

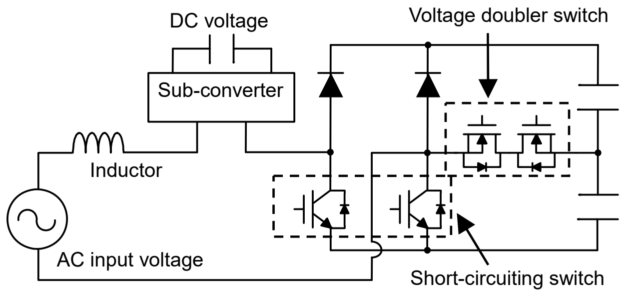

Fig. 1 AC-DC converter with gradationally controlled voltage inverter (GCVI) using voltage doubler topology

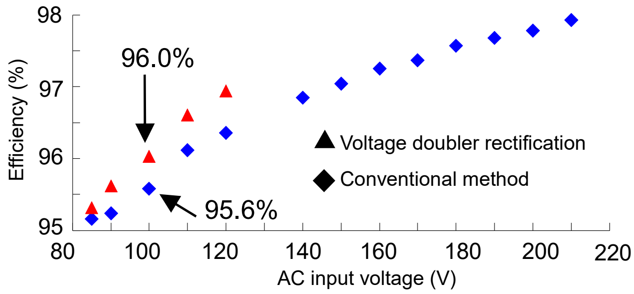

Fig. 2 Improvement of conversion efficiency with voltage doubler type GCVI

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high efficiency characteristic. Figure 3 shows the circuit diagram. In the conventional configuration, the sub-converters, short-circuiting switches, and AC input terminal are connected in series as shown in Fig. 1. As a characteristic of the simple configuration, the sub-converters, short-circuiting switches, and output capacitor are connected in parallel. This configuration reduced the amount of active semiconductors by 55% compared to the conventional method. In addition, the maximum efficiency in a demonstration using an actual system (AC input voltage of 200 V and electric power of 3.0 kW) was as high as 96.5%.

2.2 Circuit technology for DC-DC converter with higher efficiency

As more and more DC applications are used, DC-DC converters are becoming more important. Smaller DC-DC converters with higher efficiency are demanded to save the energy consumed by the entire system and to make it easier to mount. Figure 4 illustrates a boost DC/DC converter with SiC devices that boosts the DC voltage of a storage battery for driving vehicles to the DC bus voltage of an inverter for driving motors. In this circuit, an SiC-metal-oxide-semiconductor field-effect transistor (SiC-MOSFET) module was used and the device was driven at 50 kHz, which was three times that of the conventional method using an Si device (insulated gate bipolar transistor (IGBT)). In addition, the 2-phase interleaved converter reduced the required capacities of inductors and input and output capacitors that have a high occupied volume ratio, achieving the power density of 22.1 kW/L (under continuous rated power of 54 kW when the volume was 2.44 L and the water temperature was 60°C). Figure 5 shows details of the loss. The values have been standardized relative to the loss with the conventional Si device as 100. The use of an SiC-MOSFET reduced the switching loss by 51%, the conduction loss by 58%, and the diode conduction loss by 94%. The loss of the magnetic component was reduced by 38% thanks to the reduced core loss due to the reduced capacity and size. As a result, the total loss was effectively reduced by 53.6%.

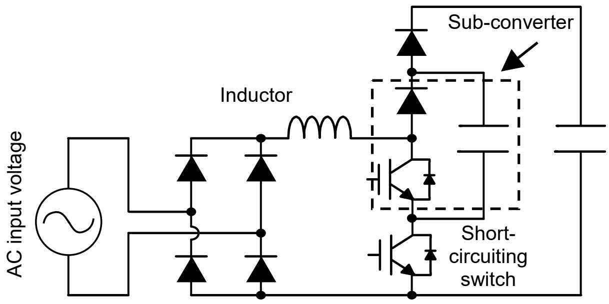

Fig. 3 AC-DC converter with simple GCVI

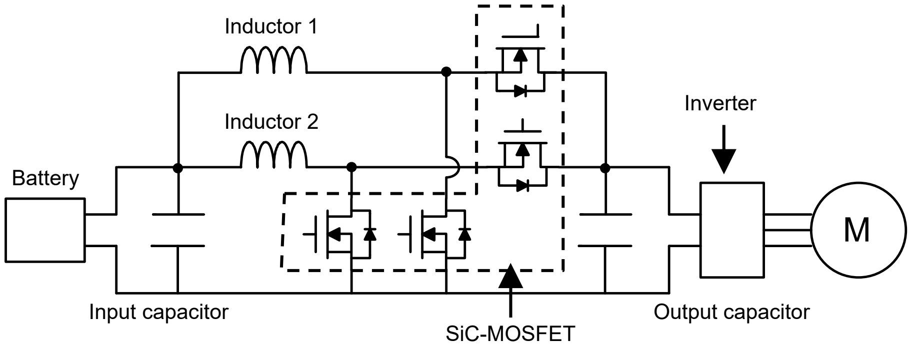

Fig. 4 Boost DC-DC converter using SiC-MOSFET

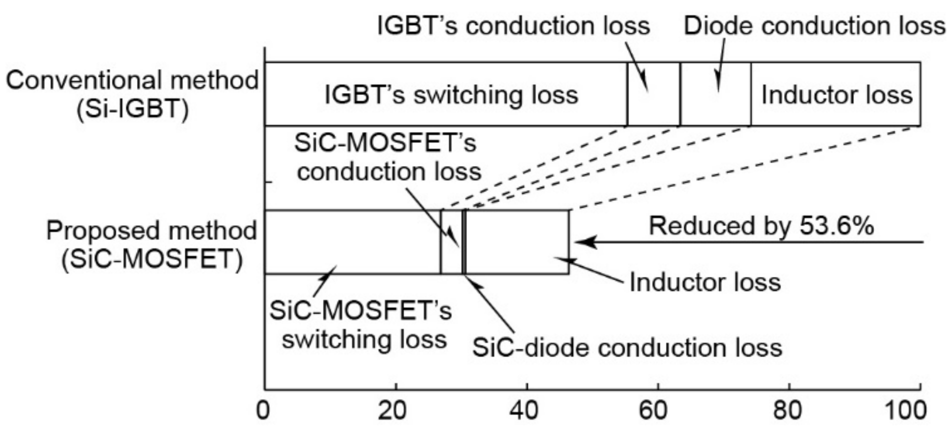

Fig. 5 Loss reduction effect

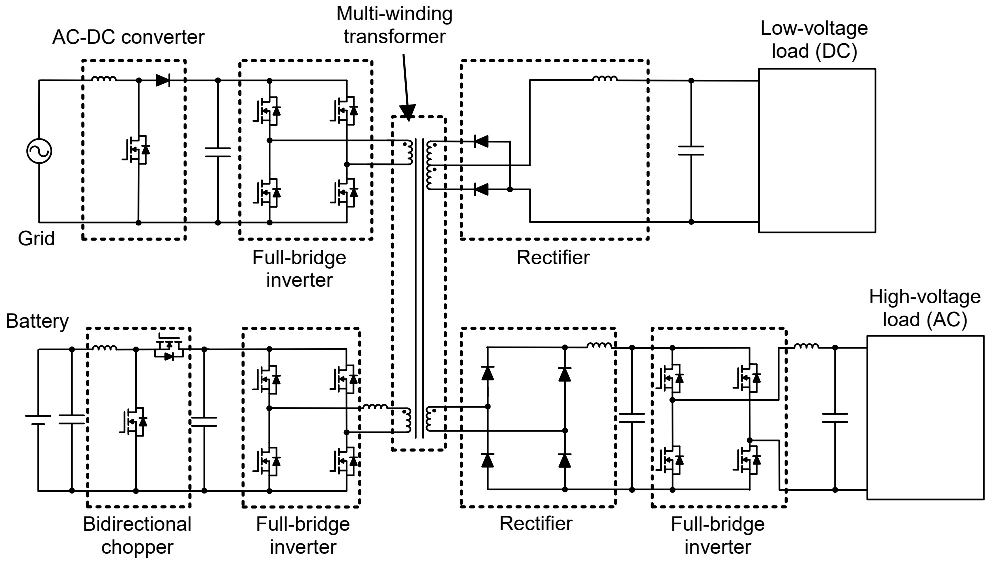

Fig. 6 Circuit configuration of a multi-port converter

3. Multiport Circuit Technology

We have succeeded in downsizing converters themselves and improving their efficiency as mentioned above. We have also developed a multiport circuit technology that optimizes the electric power flow in a system consisting of multiple power sources.

Figure 6 is the circuit configuration of the developed multiport converter. A multiport converter has a multi-winding transformer consisting of five winding wires and one core. Each winding wire is connected to each of the converters connected to grid, battery, low-voltage load, and high-voltage load. By using a single isolation transformer of the multiport converter for insulation between the ports, the number of converters and isolation transformers included in a system can be reduced compared to the conventional multiple-power source system that has an insulated converter between each of the battery, grid, low-voltage load, and high-voltage load. As a result, the efficiency of the electric power flow of the multiple-power source systems is improved. By controlling the voltage output phases and duty ratios of the full-bridge inverters connected to the grid side and the battery side of the multi-winding transformer, we have achieved electric power flow to supply power to the low-voltage load and high-voltage load from the grid and battery at the same time, as with the conventional system.

4. Conclusion

This paper described technologies for downsizing converters and improving their efficiency along with the multiport circuit technology to optimize the electric power flow from multiple power sources in a system. Conversion circuit technologies for downsizing and high efficiency are at the heart of energy conservation that supports the recycling-oriented society of the 21st century. We will continue to contribute to the development and sophistication of parts and material technologies as well as applications.

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Low-Cost Electronics Packaging Technology for Power Electronics Equipment Utilizing a Printed Circuit Board

Authors: *Yuji Shirakata** and *Kenta Fujii**

1. Introduction

Mitsubishi Electric Corporation has developed a thermal conductive power circuit assembled board (TC-PAB) technology that enables the creation of high-current printed circuit boards (PCBs) from general-purpose PCBs and the integration of magnetic components in PCBs by effectively cooling PCBs through conductive cooling. This technology, which combines various cooling element technologies, is a low-cost packaging technology that maximizes the PCB's functions, such as fixing, wiring, connection, and insulation of components.

2. PAB Technology

2.1 Background

Mitsubishi Electric has been developing a packaging technology for the main circuits of power electronics equipment using general-purpose PCBs as a base. PCBs were introduced more than half a century ago into the packaging of electronic equipment and the integration of the four key functions of fixing, wiring, connection, and insulation of components, thus significantly reducing equipment size and cost. However, the main circuits of power electronics equipment with a current of more than 50 A have remained unchanged and many components are often individually packaged. If PCBs could be applied to the main circuits of power electronics equipment, their product structure could be simplified.

2.2 Advantages of PCBs

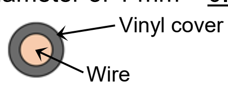
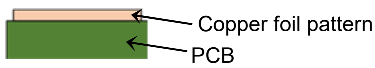
Among conventional wire connection methods, screws were widely used to fasten the wire harnesses and bus bars of mainly vinyl-covered wires. However, the development of mold-type power devices having larger capacities (50 to 75 A) has necessitated the main circuits of power electronics equipment to be constructed in PCBs.

As PCBs serve both to mutually connect and fix components, processing costs can be significantly reduced.

Table 1 compares a vinyl-covered wire and a PCB copper foil pattern. The value of the current that can flow in a conductor is restricted mainly by the temperature of the insulator. A widely-used vinyl-covered wire has a round cross-sectional surface and the ratio of surface area per unit cross-sectional area is small. In addition, such wires do not dissipate heat well due to the insulating coating and so are not suitable for high currents.

A copper foil pattern has a large surface area per unit cross-sectional area and offers excellent heat dissipation. However, it has challenges in terms of support and fixing, as well as insulation. PCBs with

Table 1 Comparison between a vinyl-covered wire and a PCB copper foil pattern

	Vinyl-covered wire	PCB copper foil pattern
Cross-sectional area	Diameter of 1 mm ≈ 0.79 mm^2 	Thickness of 35 μm × width of 22.5 mm ≈ 0.79 mm^2 
Surface area	100%	1,400%
Current	100%	370%
Characteristics	• Poor heat dissipation • Needs to be fixed • Connected by screwing • Wiring space required	• Good heat dissipation • Wire and component are fixed • Collectively assembled by soldering • Wiring space not required

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excellent heat dissipation can simultaneously solve these two challenges and so are inherently suitable for conductive components that carry high current.

2.3 Heat dissipation structure through auxiliary components

IPC-2221 and other standards provide design guidelines for copper foil patterns. However, when these standards are used for high-current copper foil patterns, wide patterns are required, which results in larger PCBs.

To solve this problem, we measured temperature data of relatively low-cost PCBs with copper foil patterns with a thickness of 70 to 105 μm using the current and pattern width as variables and defined the maximum allowable current. Furthermore, we mounted a conduction and heat dissipation auxiliary component to reduce electric resistance and suppressed the rise of temperature by increasing the heat dissipation area, thereby achieving a high current more than five times higher than that of 35-μm copper foil patterns. Subsequently, we made the design guideline into a manual. The circuit board technology having these cooling functions is called power circuit assembled board (PAB) technology.

As described above, PAB technology using conduction and heat dissipation auxiliary components enables general-purpose PCBs to be used for the main circuits of power electronics equipment with up to 100 A.

Mitsubishi Electric has been applying the PAB technology to package air conditioners, elevator control panels, induction heating (IH) cookers, and other products one after another and has been continuing to reduce their size and cost.

3. TC-PAB Technology

The PAB technology suppresses the rise in temperature by increasing the area of heat dissipation from the PCBs to the ambient air, enabling currents of up to 100 A to flow. Furthermore, Mitsubishi Electric has made copper foil patterns able to withstand even higher currents by applying conduction cooling used for chassis to PCBs.

The use of conduction cooling has enabled the integration of magnetic components, such as transformers and reactors, and semiconductor devices, such as metal-oxide-semiconductor field-effect transistors (MOSFETs), insulated-gate bipolar transistors (IGBTs), and diodes, on PCBs. These element technologies are collectively called thermal conductive PAB (TC-PAB) technology (Fig. 1).

By dissipating heat to the metal chassis, which doubles as a cooler, the temperature rise of the PCB can be reduced by 87% compared to dissipating heat only to the ambient air.

3.1 Element technologies

Figure 2 shows the packaging structure of power electronics equipment using the TC-PAB technology. The main element technologies used for this structure are described below.

3.1.1 Layer construction of PCBs

Figure 3 shows the relationship between the layer structure of PCBs and temperature rise. The temperature rise can be reduced by approximately 90% by reducing the electric resistance and thermal resistance by optimizing the layer structure. Using these technologies, a current of 150 A can be flowed in a four-

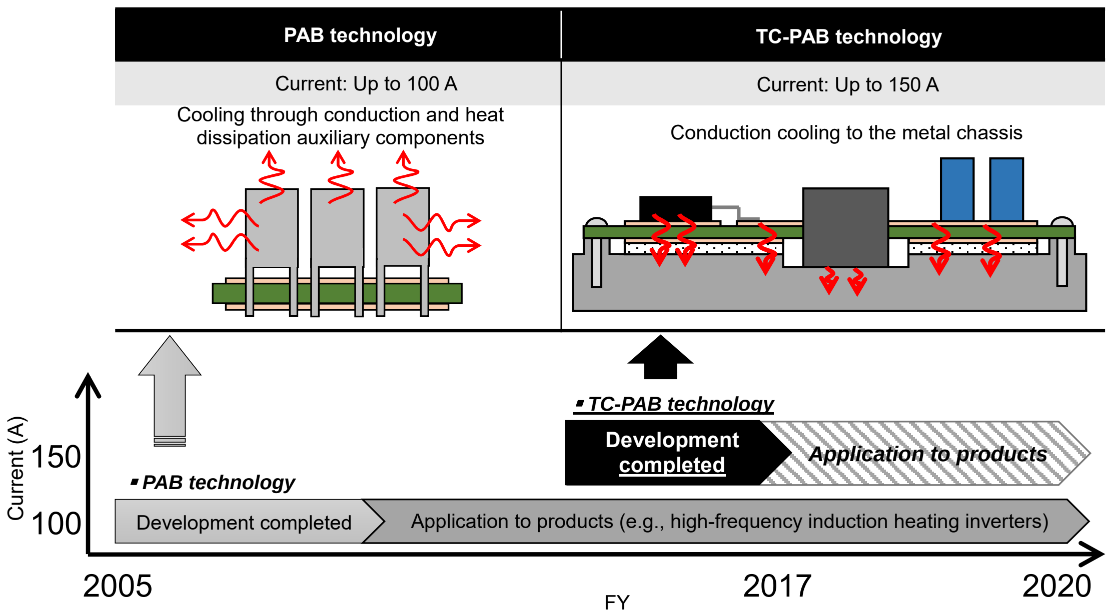

Fig. 1 Development of PAB technology and TC-PAB technology

layer PCB with a copper foil thickness of 105 μm. The design index has now been turned into a manual.

3.1.2 Method for selecting heat dissipation material

A heat conduction sheet or curable resin is used as a thermal interface material (TIM) to thermally connect the PCB and metal chassis with low heat resistance.

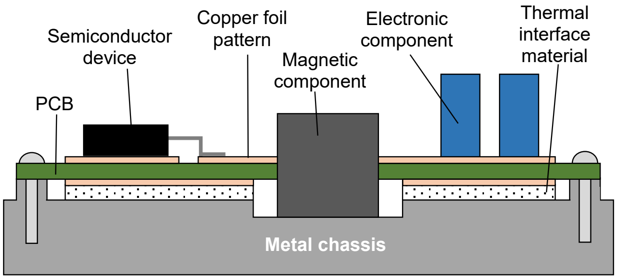

Fig. 2 Packaging structure using the TC-PAB technology

When a heat conduction sheet is used, it is necessary to judge superiority or inferiority by taking into consideration the contact heat resistance that is generated at the contact interface; hence, we developed a method that allows stable evaluation of contact thermal resistance and obtained accurate data for a variety of thermal conduction sheets as design information.

3.1.3 Cooling of semiconductor devices

To improve the heat dissipation property of surface-mounted-type semiconductor devices, we mounted a heat spreader plate (HSP), which is a high heat conduction plate material, on the back surface of a PCB at the location where the device is mounted.

Figure 4 shows the packaging structure using an HSP and its effect. In the path that transmits heat from the surface-mounted-type semiconductor device to the

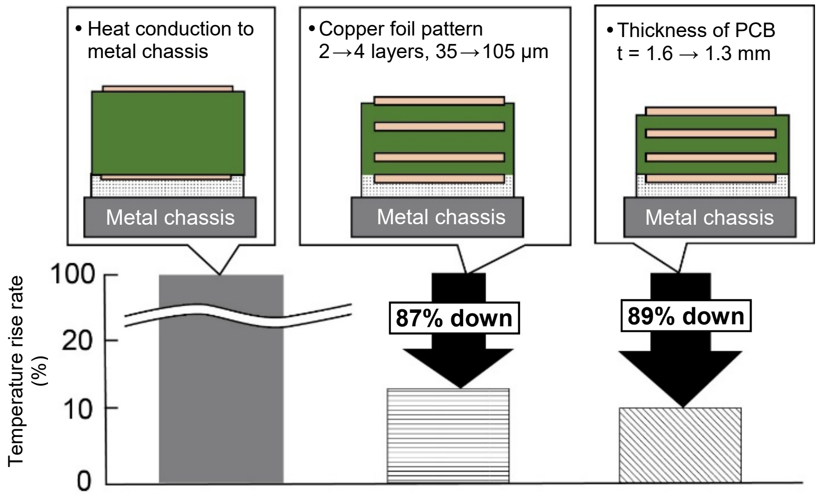

Fig. 3 Relationship between the layer structure of PCB and temperature rise

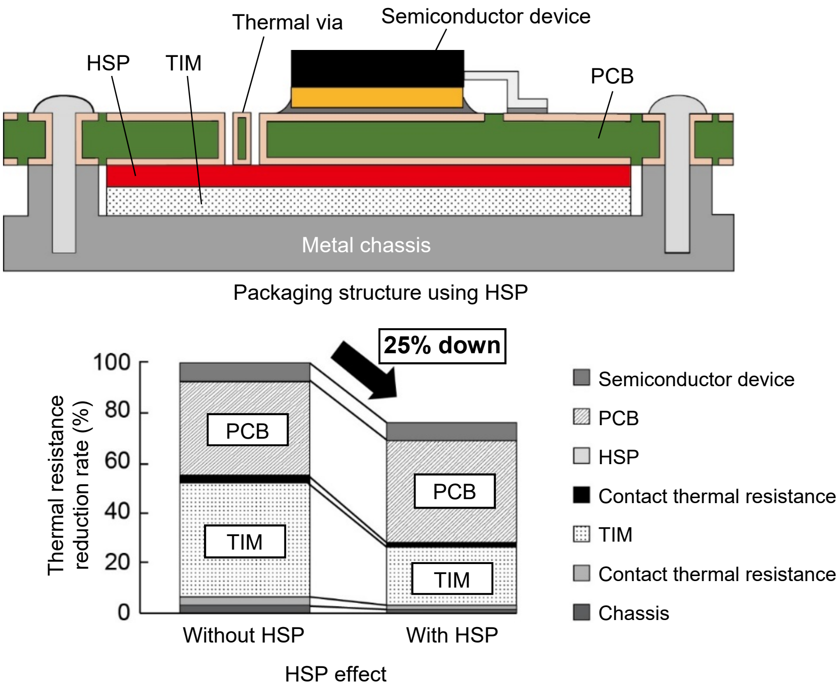

Fig. 4 Packaging structure using HSP and its effect

chassis, heat spreads in the planar direction in the HSP that has excellent heat conduction property. As a result, the cross-sectional area where heat passes the TIM expands, which reduces the thermal resistance. Thus, the HSP reduces the thermal resistance without using expensive components (e.g., copper inlay substrates).

3.1.4 Planar transformers

By constructing magnetic components such as transformers using a pattern coil formed on a PCB and a core that is mounted on the PCB, a miniaturized planar transformer is formed on the main circuit PCB. With the pattern at the core penetrating part, which is difficult to cool through conduction, the core is formed into an elongated shape and is divided to minimize it, thereby expanding the ratio of the pattern-exposed part and enhancing the effect of conduction cooling. In addition, an HSP is mounted on the pattern at the core penetrating part to conduct heat in the planar direction in order to effectively transport heat to the pattern-exposed part.

Furthermore, for the winding of the transformer, two circuits of the secondary winding with the minimum number of 0.5 turns are used to form a magnetic circuit (Fig. 5) to reduce the number of turns of the pattern coil, thereby reducing copper loss by approximately 40%.

3.2 Example of application to insulated step-down DC/DC converters

Figure 6 shows an example of an insulated step-down DC/DC converter, which was designed and prototyped by applying the TC-PAB technology.

The main circuit uses the insulated zero voltage switching (ZVS) method with oscillation frequency of 100 kHz and a general-purpose semiconductor device. By concentrating the main circuit components, including transformers and reactors, on the PCB, the whole main circuit is constructed on a single PCB, thereby achieving a volume of 0.5 liter (125.0 × 152.0 × 27.5 (mm)), excluding the cooler, output of 2.1 kW (14 V, 150 A), and output power density of 4.0 kW/L.

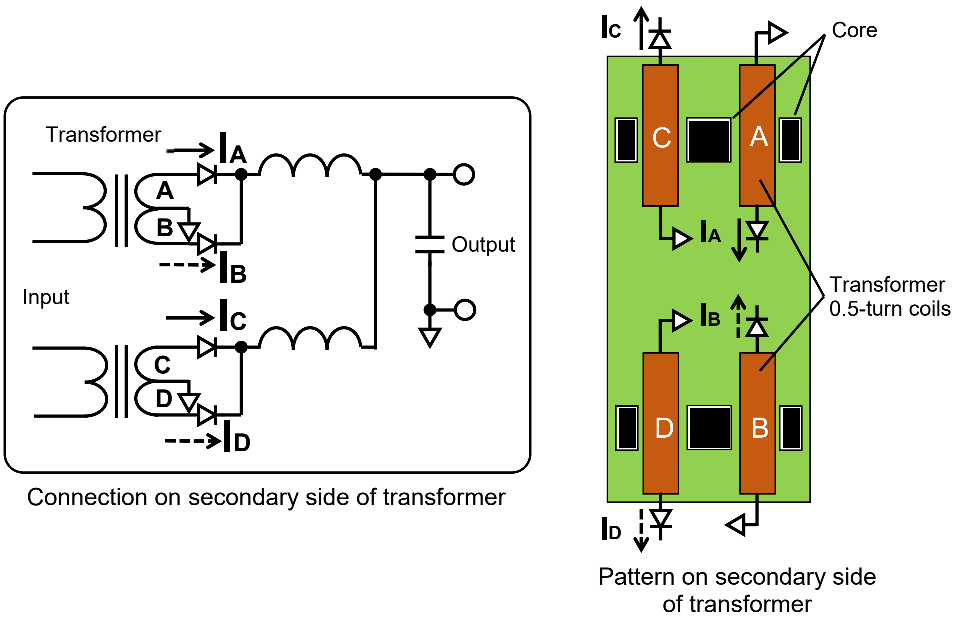

Fig. 5 Transformer coil using 0.5-turn coil

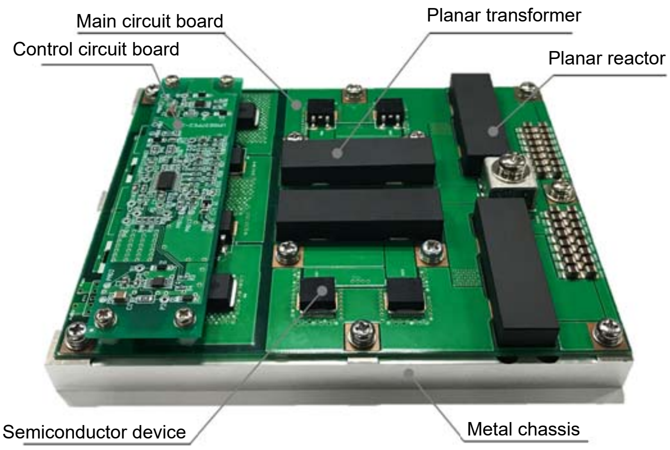

Fig. 6 Insulated step-down DC/DC converter using the TC-PAB technology

4. Conclusion

The packaging technology for electronic equipment has been improved by concentrating element functions, such as fixing, wiring, connection, insulation, and cooling of components. The PAB technology developed by Mitsubishi Electric enables a current flow of 100 A using general-purpose PCBs. Furthermore, the TC-PAB technology has integrated these element functions through conduction cooling, enabling currents of 150 A and higher to flow. We will continue to apply the technology to products.

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Progress and Future Prospects of Motor Drive Technology in Society

Authors: *Akira Satake** and *Hisanori Yamasaki**

1. Introduction

Two key needs for drive systems today are lower costs and high energy efficiency, for which control technologies can contribute greatly. This paper introduces a sensor-less servo technology and a multi-windings motor drive technology as control technologies that can reduce costs.

The paper also introduces the application of SiC to products for driving rolling stock, and technologies for driving and controlling permanent magnet synchronous motors.

2. Various Motor Drive Technologies

2.1 Sensor-less control technologies

2.1.1 Sensor-less drive technology in all speed ranges

Sensor-less servo products detect and control the positions of magnetic poles based on sensor-less vector control of permanent magnet (PM) motors, without using magnetic position sensors. Such a product has a motor model in its drive unit and estimates and controls the speed and position with an adaptive flux observer that calculates the magnetic flux from the voltage and current. However, such estimation becomes impossible in the low-speed range where the voltage is low. Therefore, a different method is required in the low-speed range: a high-frequency voltage is applied to the motor and motor inductance is detected based on the generated current to estimate the position using the inductance's dependency on position (saliency).

These two position estimation methods need to be switched depending on the speed. However, in a simple method (e.g., weighted average), when the method is switched at the time of sudden acceleration and deceleration, the discontinuity of the speed and position signals may cause a shock, so a more sophisticated switching method is required. Figure 1 illustrates the configuration of such a control system where an observer and saliency-based position estimator are combined. The observer estimates speed and position and the saliency-based position estimator adds assistance signals regarding the estimated magnetic pole position in the low-speed range. Thanks to this, even in the low-speed range where the voltage is low, the magnetic pole position estimated by the observer can accurately follow the actual magnetic pole position. By varying the magnitude of assistance signals based on the rotation speed, it is possible to estimate the position mainly based on the saliency in the low-speed range and mainly based on the voltage data in the high-speed range.

In 2014, Mitsubishi Electric Corporation's sensor-less servo products developed using these technologies won an R&D100 Award (by R&D Magazine in the U.S.) which is given to innovative technologies.

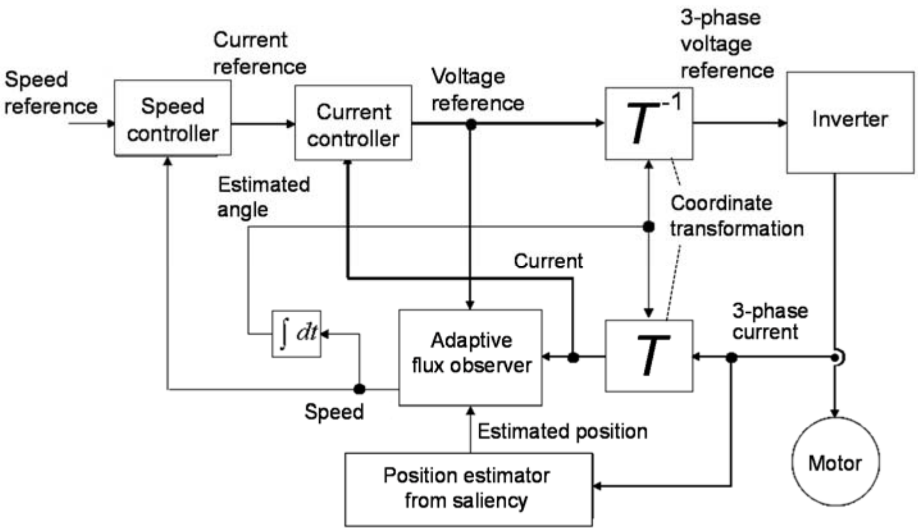


Fig. 1 Configuration of sensor-less servo control system

*Advanced Technology R&D Center

2.1.2 Automatic tuning technology

To enable heavy load operation in sensor-less vector control, it is necessary to grasp changes in inductance due to flux saturation. Inductance can be detected from changes in the current when a pulse voltage is applied, but applying excessive voltage may result in overcurrent. Therefore, Mitsubishi Electric has developed a function for automatically controlling pulse width, making it possible to detect inductance without generating overcurrent even on other companies' motors whose parameters are unknown, enabling stable operation up to 150% of the rated torque. In addition, to control the speed and position control system of a sensor-less servo product stably at high speed, data on the load inertia connected to the motor shaft is required. Figure 2 shows the effect of the online automatic tuning technology installed onto the sensor-less servo E700EX series. This technology estimates the load inertia connected to the motor shaft during driving and adjusts the speed and position control system automatically based on this estimated inertia.

As the series has no rotation angle sensor, the estimated motor speed and torque values at the time of a change in acceleration of the equipment during driving are used to estimate the inertia. This technology eliminates the need for prior adjustment of the control system based on equipment and ensures a stable response even when the load inertia changes during driving.

2.2 Multi-windings motor drive technology

Motors and inverters require larger capacity to satisfy market needs. One existing technology to drive a large-capacity motor by multiple inverters is the multiple inverter method (Fig. 3(a)) using reactors, but the cost and size of reactors were problems. On the other hand, the method in which a multi-windings motor is driven by multiple inverters (Fig. 3(b)) does not have such problems. However, the magnetic connection between the windings in the motor causes coupling behavior, which makes it impossible to control the output torque responsively. To solve this problem, Mitsubishi Electric has developed a control system that suppresses the influence of coupling components by adding components that cancel such coupling components to the output voltage in advance. Figure 4 shows its effect. The comparison shows that in a situation where the current control becomes vibratory due to windings coupling and thereby highly-responsive setting is impossible, the afore-mentioned suppression control reduces the influence of the coupling components and thereby improves the response.

This technology has been applied to large-capacity drives and various other systems since FY2016.

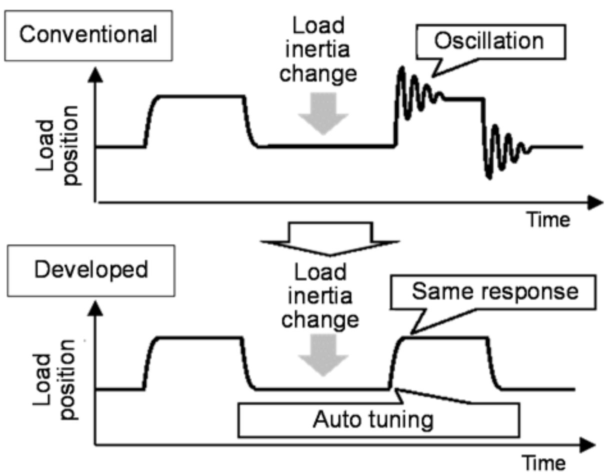


Fig. 2 Effect of online auto tuning

2.3 Drive control technologies for SiC-applied power inverters

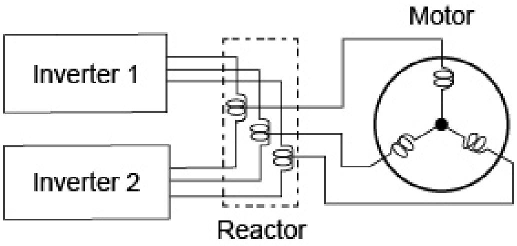
Conventionally, silicon (Si) has been used for power devices for conventional inverters for the propulsion system of rolling stock. Recently, the application of silicon carbide (SiC) has been increasing. Mitsubishi Electric introduced a 1.7-kV hybrid-SiC to commercial rolling stock in 2012 and 3.3-kV full-SiC in 2015. Generally, losses can be reduced with SiC compared to Si, which enables the semiconductor packages themselves and accompanying cooling systems to be made smaller. This downsizing has allowed the external shape and weight of power inverters to be reduced by 40–80% compared with the conventional type with Si. Some proposals have been made using this low-loss characteristic of SiC for motor control technologies. The examples of (1) diversification of pulse width modulation (PWM) modes and (2) improved regenerative ratio thanks to large-current motor design are described below.

2.3.1 Diversification of PWM modes

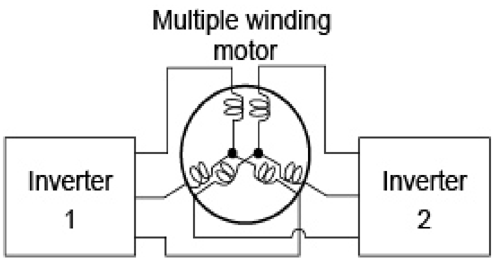
In the design of inverters for railways, the upper limit of the switching frequency is determined based on the downsizing of cooling systems and reduction of loss in inverters. Formerly, various synchronous PWM modes were switched based on the acceleration and deceleration to reduce the switching loss and synchronous 1-pulse operation was used in the high-speed range. Low-loss SiC overcomes this restriction, and so this advantage has been applied to all-range asynchronous PWM. In this example, the switching frequency was improved to approximately double that of the conventional type and asynchronous PWM was achieved in all the ranges. As a result, the distortion of motor currents and magnetostrictive noise were reduced and the harmonic loss was reduced by up to 40%.

2.3.2 Improved regenerative ratio thanks to large-current motor design

Meanwhile, for designing the performance of motors

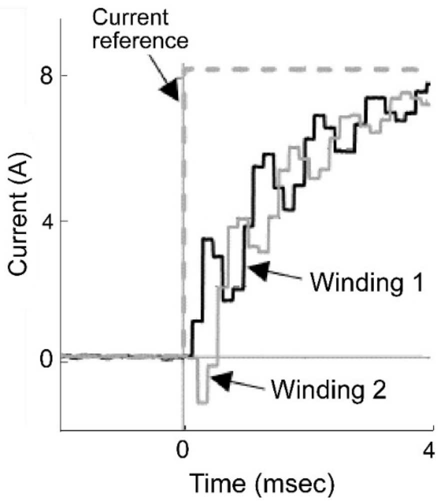


(a) Multiple inverter method

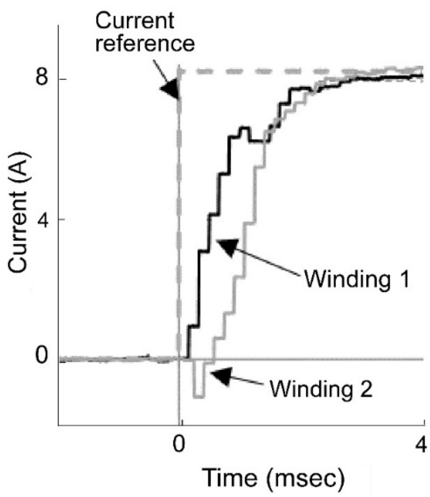


(b) Multiple winding motor method

Fig. 3 Motor drive system controlled by multiple inverters



(a) Without suppression control



(b) With suppression control

Fig. 4 Suppression control of windings coupling

to be combined with inverters, in addition to the matters noted in 2.3.1, the torque output performance needs to be secured in consideration of the upper limit of the current in terms of the loss in inverters.

Applying SiC can increase the output (current) of inverter systems, so motors can be designed to reduce the rating flux and to increase the current per torque. This is equivalent to designing to reduce the impedance of motors. It means that the torque output limit (stall torque characteristic) existing in the high-speed range can be moved to the higher speed range and the regeneration torque output range can be expanded (Fig. 5). For the propulsion system of rolling stock drawing on this advantage, the operation range in which friction braking is used conventionally, can be covered by the regenerative braking of motors. It has been demonstrated that energy consumption can be reduced by up to 40% for the run-curves of subways and conventional lines where frequent stops are involved.

2.4 Permanent magnet synchronous motors for rolling stock

Although induction motors that can drive multiple motors in parallel by a single inverter are standard for rolling stock, recently, some railway companies have started using PM motors to save energy. Mitsubishi Electric promoted development and has commercialized inverters for PM motors for rolling stock. In the magnetic pole position sensor-less vector control in PM motors, when high-frequency voltage is applied to detect the

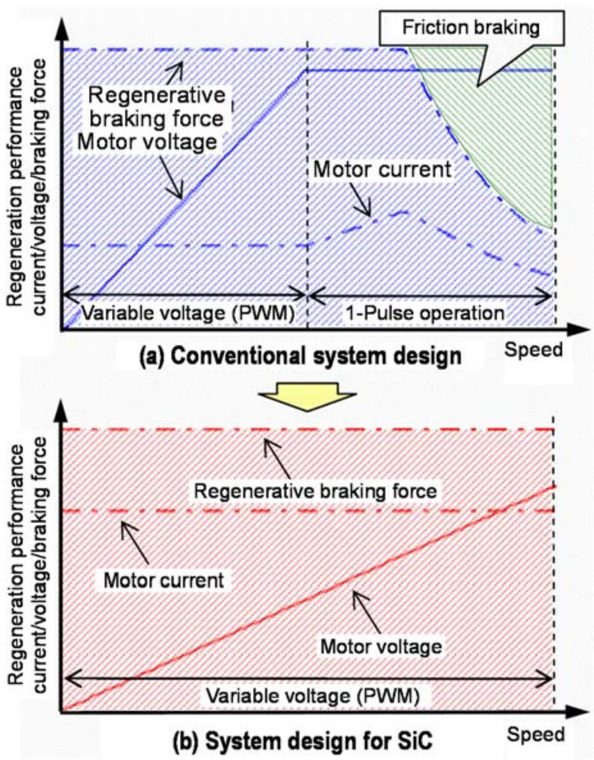


Fig. 5 Comparison of regenerative braking performance setting

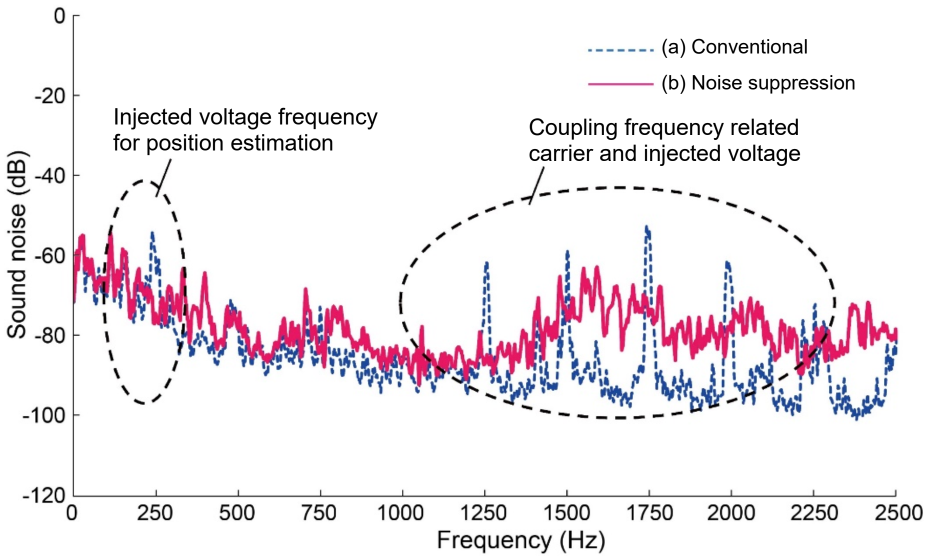


Fig. 6 Noise suppression of high-frequency injection in sensor-less control of low-speed range

magnetic pole position in the very-low-speed range, unique magnetostrictive noise is generated. Generating a PWM voltage waveform in a random manner in the range where the magnetic pole position estimation function can be secured improves the sound noise feeling (Fig. 6).

3. Conclusion

This paper outlined example control technologies in recent drive systems to satisfy the needs of society. Mitsubishi Electric will continue working to secure and improve the functions of products by control technologies to flexibly meet increasingly diverse and sophisticated needs.

MITSUBISHI ELECTRIC CORPORATION