Line-Up of Compact 7th-Generation IGBT-IPMs with RC-IGBTs

KUROSAWA, Eiji* JOZUKA, Naohiko* KARAMOTO, Yuki*

ABSTRACT

In order to meet the demand for further miniaturization and higher reliability in power conversion systems, Fuji Electric has developed a line-up of the 7th-generation IGBT-IPMs that is equipped with RC-IGBT chips and uses the new compact "P639" package, the footprint of which is 27% smaller than that of "P629" package used for 6th-generation IGBT-IPMs. By applying the 7th-generation chip technology and new control technology for driving the IGBT, the new compact P639 has reduced the power dissipation during continuous operation by 7%. Moreover, it applies the 7th-generation packaging technology to achieve high-temperature operation at 150°C.

1. Introduction

With the widespread adoption of factory automation and communication devices including mobile phones in recent years, the demand for servo systems used for industrial robots, machine tools and other applications has been increasing. These kinds of equipment are strongly required to save space. Since the power semiconductors used in them also need to be miniaturized, high temperature operation and low power dissipation of semiconductors are quite important to achieve this requirement. In addition, they are expected to be highly reliable in order to prevent sudden failures.

IGBT-IPMs have gate driving and protection circuits. IGBT IPMs are used in a wide variety of applications, including NC machine tools, robots and elevators that require particularly high reliability.

For 7th-generation IGBT-IPM(1)-(4), which is the latest generation of IGBT-IPM, Fuji electric has applied 7th-generation chip technology, in which the finer IGBT trench gate structure and the thinner drift layer stemmed from a thin wafer processing technology are adopted to achieve low power dissipation. In addition to that, Fuji electric has adopted a new control technology to drive the IGBT optimally. Furthermore, the IGBT-IPM has realized higher temperature operation by applying the 7th-generation packaging technologies such as high heat resistant gel and highly reliable solder. In order to meet the demand for further size reduction and high reliability, Fuji Electric has added a new product to the existing 7th-generation IGBT-IPM line-up, which is equipped with the new compact package "P639" with reverse conducting IGBT (RC-IGBT) chips(5). This product has high heat dissipation characteristics and high-precision protection function that directly detects the characteristics of IGBT chips. As a result, it has achieved the industry-leading size reduction. It will contribute to the miniaturization of the systems.

2. Features

2.1 Overview of product

Figure 1 shows the external appearance of the new compact P639 package. The external dimensions of the P639 package are D36.0 × W70.0 × H12.0 (mm), and it features a 6-in-1 circuit configuration, which integrates a three-phase inverter circuit into one module. The P639 achieves its compactness by incorporating an RC-IGBT chip.

Table 1 shows the line-up of the 7th-generation IGBT-IPM and the previous 6th-generation IGBT-IPM at ratings of below 650 V/50 A and 1,200 V/25 A. The 6th-generation IGBT-IPM line-up only includes the "P629" package, which is equipped with the pre-

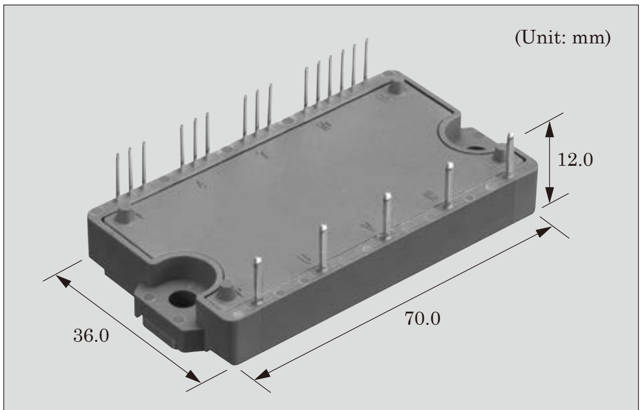

Fig.1 Appearance of the new compact package "P639"

* Semiconductors Business Group, Fuji Electric Co., Ltd.

Table 1 Product line-up

Rating		6th-generation IGBT-IPM	7th-generation IGBT-IPM
650 V	1,200 V		
20 A	10 A	P629	P639
30 A	–		
50 A	25 A		P629

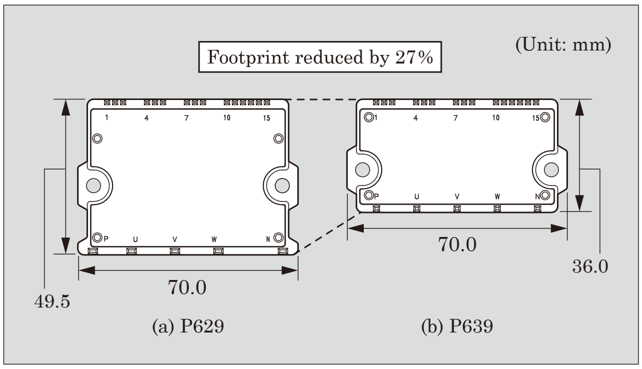

Fig.2 Comparison of external dimensions between the “P629” and “P639”

vious IGBT chip. On the other hand, 7th-generation IGBT-IPM line-up, which includes the more compact P639 package models, contributes to size reductions in equipment.

Figure 2 shows a comparison of the external dimensions between the P629 and P639. The P639 has a 27% smaller footprint compared to the P629. Furthermore, it is easy to replace the P629 with the P639 due to the same arrangement of the main and control terminals.

The new compact P639 has reduced the power dissipation by 7% compared to the previous 6th-generation IPM by applying the 7th-generation chip technology and the new control technology. Furthermore, the 7th-generation packaging technology enables higher temperature operation. Moreover, by using RC-IGBT chips, which can reduce chip temperature swing during low-frequency operation, the ΔT_{vj} power cycling lifetime has been improved in comparison with the product mounted with the 6th-generation IGBT and free wheeling diode (FWD) chips.

2.2 Product features

(1) Package size reduction

Since the chip mounting area occupied approximately 30% of the total area in the conventional P629, it is important to reduce the chip size in order to achieve the miniaturization of the product. However, the chip characteristic, such as thermal resistance will get worse as the chip size shrinks. In addition, it may lead to the decrease in the reliability when the number of aluminum wires is reduced. In order to solve these issues, the new compact P639 has applied RC-IGBT chips.

Figure 3 shows the schematic diagram and the equivalent circuit diagram of the RC-IGBT chip. As mentioned above, an IGBT and a FWD are integrated on the same RC-IGBT chip, and the area of the RC-IGBT chip is smaller than the combined area (total area) of the 6th-generation IGBT and FWD chips.

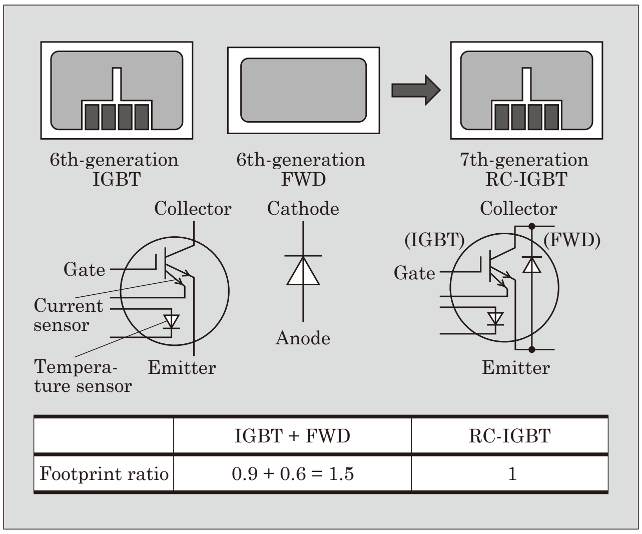

Fig.3 Schematic diagrams and equivalent circuit diagrams of the RC-IGBT chip

Table 2 Comparison between 6th- and 7th-generation chips at 650V/20A

Item	6th-generation IGBT + FWD	7th-generation RC-IGBT
Total chip area ratio	IGBT + FWD 0.9 + 0.6 = 1.5	1.0 (–33%)*
Number of aluminum wires	4	4
FWD thermal resistance (°C/W)	1.96	1.21 (–38%)*

*Rate of reduction from the 6th generation

Table 2 shows a comparison between the 6th-generation and the 7th-generation chips with a rating of 650 V/20 A. The 7th-generation IGBT-IPM’s total chip area is reduced by 33% compared to the 6th-generation IGBT-IPM. Since the chip area of the 7th-generation RC-IGBT is larger than that of each individual 6th-generation IGBT and FWD, the same number of aluminum wires can be bonded. Furthermore, the thermal resistance is reduced by 38% due to the increased chip size, and for this reason, it is expected to have better heat dissipation performance. As a result of these features, the new compact P639 has achieved size reduction without sacrificing the product characteristics and reliability.

(2) ΔT_{vj} power cycling lifetime improvement

The ΔT_{vj} power cycling lifetime is a important lifetime characteristic of the power modules described in this paper. This is defined by the number of repeated temperature swing ΔT_{vj} permissible for the chip. The product will break down if ΔT_{vj} is repeated for more than the capability. This is because thermal stress caused by ΔT_{vj} causes the degradation in the chip-aluminum wire and chip-solder bonding areas. In addition, the ΔT_{vj} power cycling lifetime depends on the magnitude of ΔT_{vj} and therefore decreases when ΔT_{vj} is higher.

NC machine tools and other devices have some modes in which low frequencies are used for low-speed or high-torque operation. At low-frequency operation, the chip temperature is prone to rise because current flows through the IGBT or FWD in the same phase for a long time. On the other hand, since the time during which no current flows is also long, causing the chip temperature decreases during this period. Therefore, the ΔT_{vj} of the chip is higher and the thermal stress produced is also higher, resulting in shorter ΔT_{vj} power cycling lifetime.

Figure 4 shows the calculation results of chip temperature swing at low-frequency operation. The 6th-generation IGBT-IPM equipped with conventional IGBT and FWD chips has a higher ΔT_{vj} depending on the presence of the heat generation period because the IGBT chip and the FWD chip generate heat alternately during inverter operation. As a result, ΔT_{vj} of the IGBT is 24°C and that of FWD is 28°C. On the other hand, the 7th-generation IGBT-IPM equipped with RC-IGBT chips features reduced changes in chip temperature because the RC-IGBT generates heat in the IGBT region and the FWD region alternately within one chip. In addition, the increase of chip temperature is suppressed due to the improved thermal resistance. As a result of this feature, the ΔT_{vj} of the 7th-generation IGBT-IPM's RC-IGBT chip is 7°C lower than that of the FWD chip, in which the temperature swing is larger when used in combination with the IGBT chip in the 6th-generation IGBT-IPM combination. Figure 5 shows the ΔT_{vj} power cycling lifetime curve. In this example, the ΔT_{vj} power cycling lifetime of the 7th-generation IGBT-IPM estimated to be

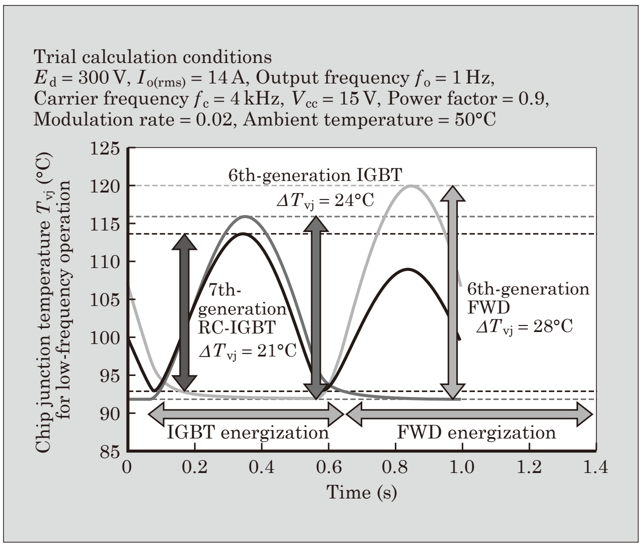

Fig.4 Trial calculation results of changes in chip temperature at low-frequency operation

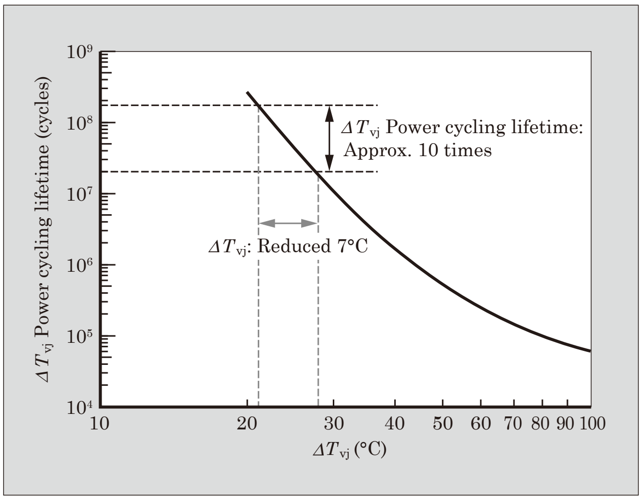

Fig.5 ΔT_{vj} Power cycling lifetime curve

approximately 10 times higher than that of the 6th-generation IGBT-IPM.

(3) Reduction of power dissipation

(a) IGBT saturation voltage and turn-off energy

The 7th-generation IGBT features improved trade-off characteristics between collector-emitter saturation voltage $V_{CE(sat)}$ and turn-off energy E_{off} due to the finer pattern of the surface trench gate structure and the thinner drift layer achieved through the use of thin wafer processing technology.[1],[6] For this reason, the newly developed RC-IGBT chip mounted on the P639 has reduced $V_{CE(sat)}$ by 0.05 V and E_{off} by 0.14 mJ compared to those of the conventional 6th-generation IGBT chip, as shown in Fig. 6.

(b) Turn-on energy

Figure 7 shows the current dependency of turn-on energy E_{on} for the 650-V/20-A 7th-generation IGBT-IPM. In order to reduce E_{on}, the P639 has adopted a new control technology for the IGBT drive control. In general, the dv/dt of IGBT chips at turn-on decreases as the chip junction tempera-

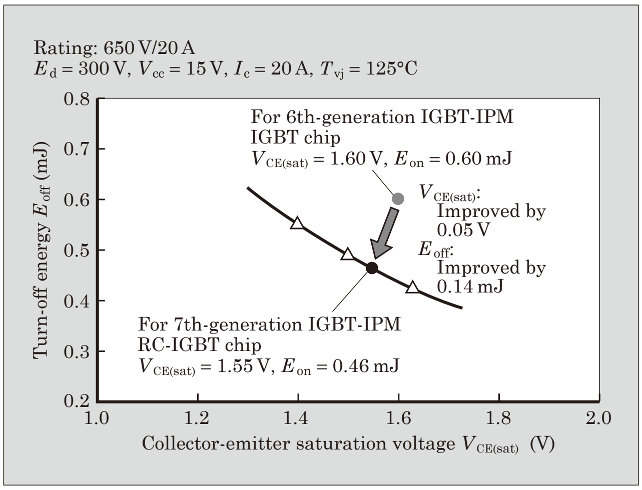

Fig.6 Trade-off relation between collector-emitter saturation voltage and turn-off energy

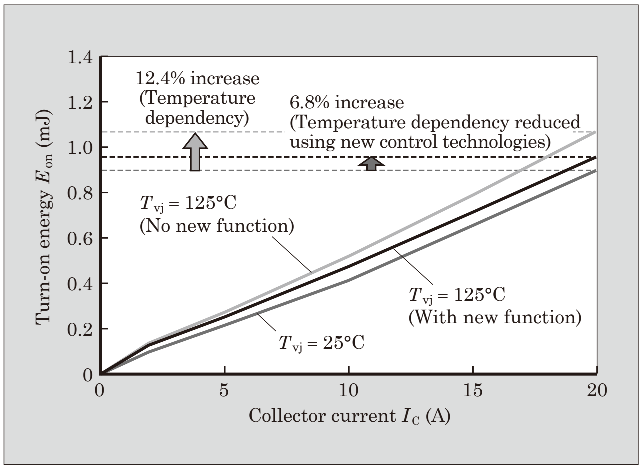

Fig.7 Collector current dependency of the turn-on energy

ture increases. Therefore, E_{on} increases as the chip temperature rises. As a result, in the case of 650 V/20 A with the conventional control technique applied, E_{on} at the rated current condition increases by 12.4% at a high temperature (125°C) compared to a room temperature (25°C). On the other hand, thanks to the new control technique, the 7th-generation IGBT-IPM optimizes the dv/dt by increasing turn-on gate drive current when the IGBT chip temperature rises. By feeding back the temperature measured by the temperature sensor formed on the IGBT chip to the gate drive circuit, the gate drive current is adjusted to optimally control dv/dt. With this new function, the increase of E_{on} at 125°C can be reduced by 6.8% compared to E_{on} at 25°C.

(c) Power dissipation during inverter operation

Figure 8 shows the simulation results of power dissipations per arm* for the 7th-generation IGBT-IPM and the 6th-generation IGBT-IPM in a three-phase inverter system. The rating of both IPMs is 1200 V/200 A. The 7th-generation P639 has reduced the power dissipation by 7% compared to the 6th-generation IGBT-IPM, due to the improved trade-off characteristics between $V_{CE(sat)}$ and E_{off} and the reduction of E_{on}.

(d) Heat dissipation performance

As shown in Fig. 9, the footprint of the copper base, which has the role to facilitate the heat dissipation, has been reduced by 32% for the P639 compared to the P629 in order to make the package more compact, and as a consequence, the heat dissipation performance has become worse. Figure 10 shows the results of temperature distribution analysis of the copper base using the finite element method (FEM), in which heatsink dissipation performance and power dissipation were analyzed under the same conditions. Compared to that of the P629, the temperature change ΔT_c in the P639 increased by 6% due to the reduction in the surface area of the copper base.

However, the new compact P639 has reduced the power dissipation by 7% compared to the 6th-generation IGBT-IPM as mentioned before. There-

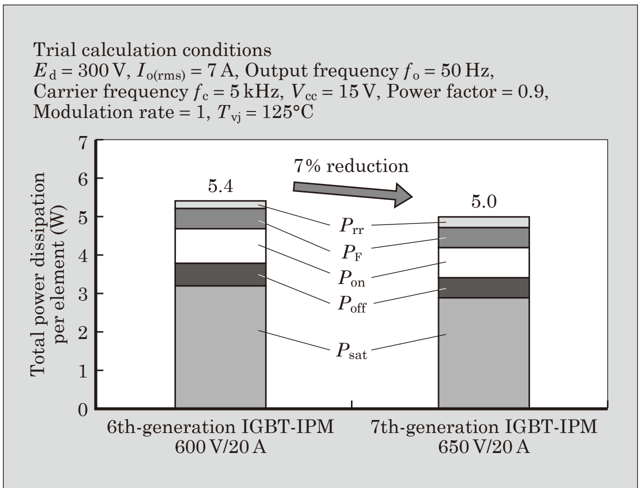

Fig.8 Comparison of total power dissipation

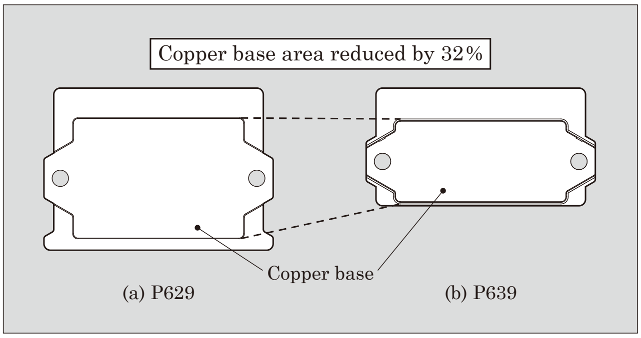

Fig.9 Comparison of copper base size

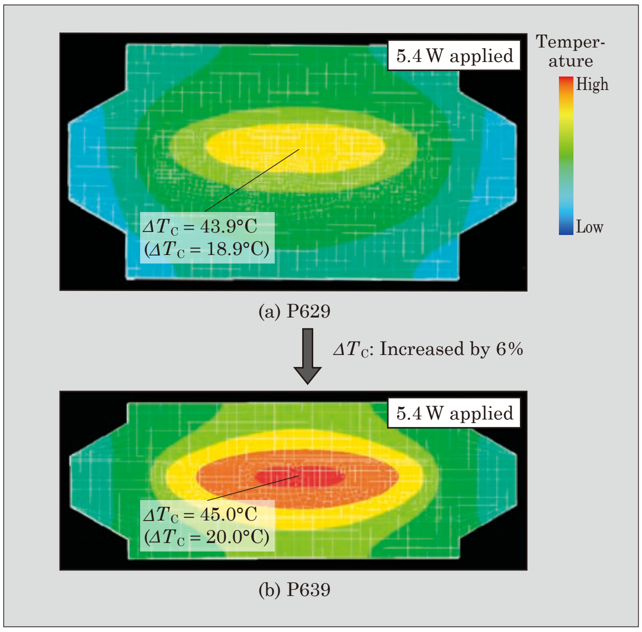

Fig.10 FEM analysis results of copper base temperature distribution

* Arm: Refer to page 209, "Explanation 1."

Table 3 Comparison of permissible operating temperatures

Item	6th-generation IGBT-IPM	7th-generation IGBT-IPM
Maximum case temperature T_{cmax}	110°C	125°C
Maximum junction temperature during continuous operation T_{vjop}	125°C	150°C
Maximum junction temperature T_{vjmax}	150°C	175°C

fore, in spite of the increase in ΔT_c caused by the reduction of the copper base size, it is possible to surpress the chip temperature to the same level as the 6th-generation IGBT-IPM. For this reason, the 7th-generation IGBT-IPM can easily replace conventional products.

(4) High temperature operation

Table 3 shows the permissible operating temperatures between the 7th-generation and 6th-generation IGBT-IPMs. The 7th-generation IGBT-IPM has expanded the maximum junction temperature T_{vjop} during continuous operation to 150°C from 125°C for the 6th-generation IGBT-IPM. This is due to the adoption of technologies that enable high temperature operation, such as high heat-resistant gel and highly reliable solder, which are 7th-generation packaging technologies. In addition, the maximum junction temperature T_{vjmax} has been expanded from 150°C to 175°C. This enables the size reduction of cooling parts in the equipment.

4. Contribution to the Size Reduction of Applied Equipment

This section describes a size reduction case study where a 60-mm width servo amplifier equipped with the P629 6th-generation IGBT-IPM can be made more compact using the P639 7th-generation IGBT-IPM. As shown in Fig. 11, there is a back-fin type servo amplifier, which has the cooling part attached in the rear of the casing. In this type of servo amplifier, the width of the servo amplifier casing can be reduced due to the reduced width of the short-side direction of the IGBT-IPM. That is, the replacement from the P629 to the P639 can reduce the amplifier width by 13.5 mm (approx. 20%). This means that the control panel containing the servo amplifier is made more compact, and as a result, it is expected to reduce the space of the entire servo systems.

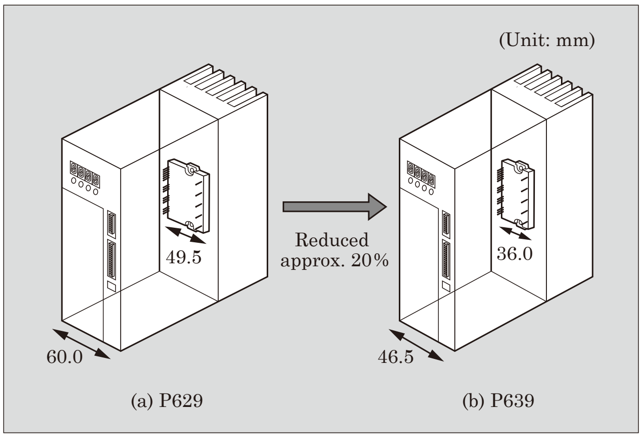

Fig.11 Schematic diagram of a back-fin type servo amplifier

5. Postscript

This paper described the features of the P639, which is the new compact series of 7th-generation IGBT-IPMs equipped with RC-IGBT chips.

Fuji Electric is confident that the expansion of this line-up of compact products will contribute to further reductions in the size of power conversion equipment.

In the future, we intend to continue advancing technological innovations and develop products to meet market demand. Furthermore, through the development of IGBT modules, Fuji Electric is committed to advancing measures against global warming to realize a safe and sustainable society.

References

(1) Minagawa, K. et al. 7th-Generation “X Series” IGBT-IPMs. FUJI ELECTRIC REVIEW. 2019, vol.65, no.4, p.210-214.

(2) Terashima, K. et al. 7th-Generation “X Series” IGBT-IPM with “P644” Compact Package. FUJI ELECTRIC REVIEW. 2020, vol.66, no.4, p.221-226.

(3) Minagawa, K. et al. “P631” Package 7th-Generation “X Series” High Power IGBT-IPM. FUJI ELECTRIC REVIEW. 2021, vol.65, no.4, p.247-251.

(4) Satou, K. et al. “The 7th Generation Intelligent Power Module for Industrial Applications”. Proceeding of PCIM Asia 2021.

(5) Ebukuro, Y. et al. 7th-Generation “X Series” RC-IGBT “Dual XT” Modules for Industrial Applications. FUJI ELECTRIC REVIEW. 2021, vol.67, no.4, p.242-246.

(6) Kawabata, J. et al. “The New High Power Density 7th Generation IGBT Module for Compact Power Conversion Systems”. Proceeding of PCIM Europe 2015.

Fuji Electric

Innovating Energy Technology