High-Power IGBT Modules for 3-Level Power Converters

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ABSTRACT

Recently, renewable energy has been attracting attention and, photovoltaic and wind power generation markets are growing rapidly in particular. In these fields, low- and medium-power IGBT modules are often connected in parallel to realize high power converters; but this will cause high surge voltage due to wiring inductance. Fuji Electric is developing one package for high-power IGBT modules for 3-level power converters. Improvement for power conversion efficiency and miniaturization of equipment can be expected. It has also realized a laminated structure for the main terminal bus bar to reduced internal inductance.

1. Introduction

Renewable energy has come to be valued more than ever in recent years for its role in the prevention of global warming and effective use of energy resources. For this reason, there is a fast-growing market for photovoltaic and wind-power generation systems as they provide power while lowering greenhouse gas (CO_2) emissions. Power electronics technology facilitates efficient use of electrical power, allowing for low CO_2 emissions in power generation, leading to wider use of renewable energy.

Fuji Electric is developing high-power insulated gate bipolar transistor (IGBT) modules for three-level power converters designed for high-power converters for photovoltaic and wind power generators. This paper describes their characteristic and features.

2. 3-Level Power Conversion

Two-level power conversion is common in electrical power conversion, but 3-level power conversion*1 is also available to enhance conversion efficiency. Having a neutral point, this method facilitates switching at half the voltage of 2-level power converters and gives advantages such as suppressing harmonics, reducing generated losses and enabling equipment miniaturization. There are two types of 3-level power conversion: a neutral-point-clamped type (NPC)[1], which has switching elements arranged in series, and an advanced T-type (AT)-NPC[2], which uses intermediate bi-directional switching.

*1: 3-level power conversion: see "Supplemental expla-nation 1" on p.255.

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Fuji Electric is focusing on developing 3-level modules to be applied for photovoltaic power generation and uninterruptible power supplies (UPSs). So far Fuji Electric expanded a line-up of low- to mid-power AT-NPC IGBT modules[2]-[4] which are contributing to efficiency improvement of equipment[5].

A multiple number of low/mid-power IGBT modules are commonly used in parallel to develop high-power photovoltaic power generators (mega solar) and UPSs. However, there are issues to overcome in using IGBT modules in parallel such as a high surge voltage, which occurs due to wiring inductance between modules or between the modules and the main circuit. There is also a tendency for the cooling fin to have a larger area when IGBT modules are used in parallel. For these reasons, high-power IGBT modules have been eagerly anticipated by the market.

3. Features and Electrical Characteristics of High-Power IGBT Modules for 3-Level Power Converters

3.1 Features

The high-power IGBT module for a 3-level power converter is a one-package IGBT module with AT-NPC/NPC conversion circuit and a thermistor. Figure 1 shows the external appearance of the IGBT module and Fig. 2 illustrates the equivalent circuit.

The maximum ratings of the module are 1,200 V/900 A for AT-NPC and 1,200 V/600 A for NPC. "V-Series" chips and reverse blocking (RB)-IGBT chips are used for the module. These modules leverage electromagnetic induction to keep the internal inductance within the IGBT module at a low level.

These modules have the following advantages against low/mid-power IGBT modules in parallel:

(a) Reduced internal inductance by one package

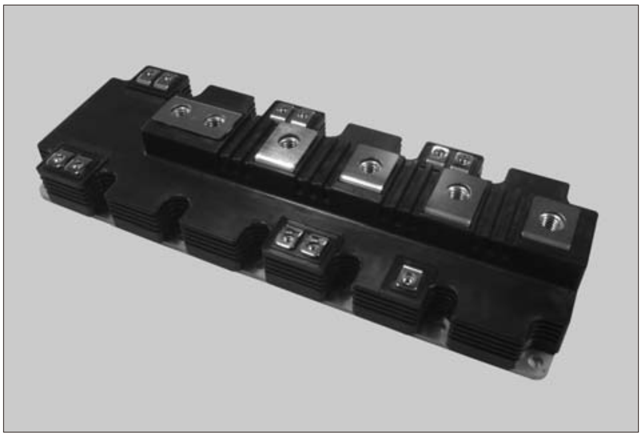

Fig.1 High-power IGBT modules for 3-level power converters

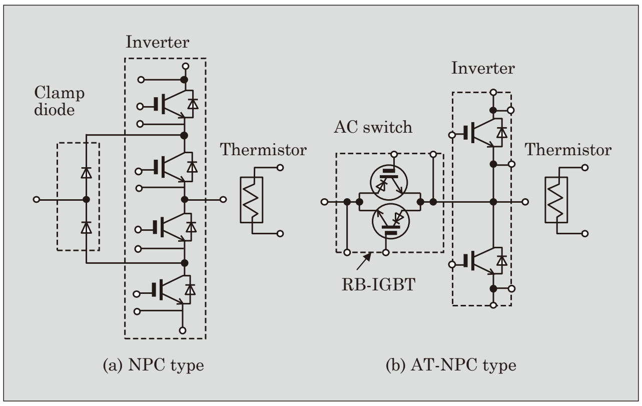

Fig.2 IGBT equivalent circuit

(b) Because of small mounting footprint and a smaller area for a cooling fin, miniaturization of equipment can be achieved

The external appearance of AT-NPC and NPC IGBT modules are the same. AT-NPC IGBT modules can reduce conduction losses because the inverter blocking voltage is identical to 2-level inverter, and the current passes through fewer devices than in the case of the NPC IGBT module. On the other hand, switching devices of NPC IGBT modules are in a serial connection. Therefore, the device blocking voltage is halved from a 2-level power converter, and the module is suited for high-voltage operations. The characteristics of the two IGBT modules are as follows:

(a) Switching voltage is half of that for a 2-level power conversion circuit, so that the switching losses of the converter can be reduced.
(b) Switching waveforms are stepwise, so that it can suppresses harmonics more than a 2-level power conversion. It makes it possible to fit smaller filters and therefore miniaturize the device.

3.2 Electrical characteristics of the IGBT modules

Table 1 shows types and device ratings of high-power IGBT modules for 3-level power converters. We have three different rated current products of AT-NPC IGBT modules for 1,000 V DC-bus application. We are also developing a NPC IGBT module for 1,500 V DC-bus application.

Table 1 Descriptions of IGBT modules

Type	Model	Package dimensions	Rated voltage	Rated current
AT-NPC	4MBI450VB-120R1-50	L250×W89×H38 (mm)	Inverter: 1,200 V AC switch: 900 V	450 A
	4MBI650VB-120R1-50	L250×W89×H38 (mm)	Inverter: 1,200 V AC switch: 900 V	650 A
	4MBI900VB-120R1-50	L250×W89×H38 (mm)	Inverter: 1,200 V AC switch: 900 V	900 A
NPC	4MBI600VC-120-50	L250×W89×H38 (mm)	1,200 V	600 A

The characteristics of the chips used are as follows:

(1) Inverter of AT-NPC IGBT module and NPC IGBT module

The latest "V-Series" IGBT chips and free-wheeling diode (FWD) chips are used.

(a) A field stop structure and trench-gate structure are optimized for the reduction of on-voltage $V_{CE(sat)}$ and switching losses.
(b) The turn-on di/dt controllability by gate resistance R_g was improved.

(2) AC switch of AT-NPC IGBT modules

Fuji Electric's RB-IGBT[6] having a junction isolation region and reverse blocking voltage is deployed to enable bi-directional switching.

(a) According to reverse blocking voltage of RB-IGBT, it is possible to switch in either direction by connecting the RB-IGBTs in antiparallel.
(b) Reverse recovery can be performed as FWD when forward bias voltage above the threshold is applied to the gate.

Figure 3 illustrates cross-sectional structures of IGBT and RB-IGBT chips. The RB-IGBT chip has a thick p+ junction isolation region covering the dicing side, which prevents the depletion layer from reaching the diced surface to secure the reverse blocking voltage.

Figure 4 shows the structure of a bi-directional switch. Bi-directional switches can be configured with the form of RB-IGBT or IGBT+FWD. IGBTs need to connect with diodes in serial because it is impossible to secure blocking voltage when reverse bias is applied to IGBT. This happens due to the facts that the PN junction, which supports the voltage, is in direct contact with the dicing surface, and that a large amount of carrier is generated because of the faults in high-density crystals created in the dicing process. Therefore, there is a problem that the on-voltage will be increased in case of IGBT+FWD. On the other hand, RB-IGBTs have lower on-voltage than the IGBT+FWD combination type owing to the structure with reverse blocking voltage. Lower on-voltage means less conduction losses.

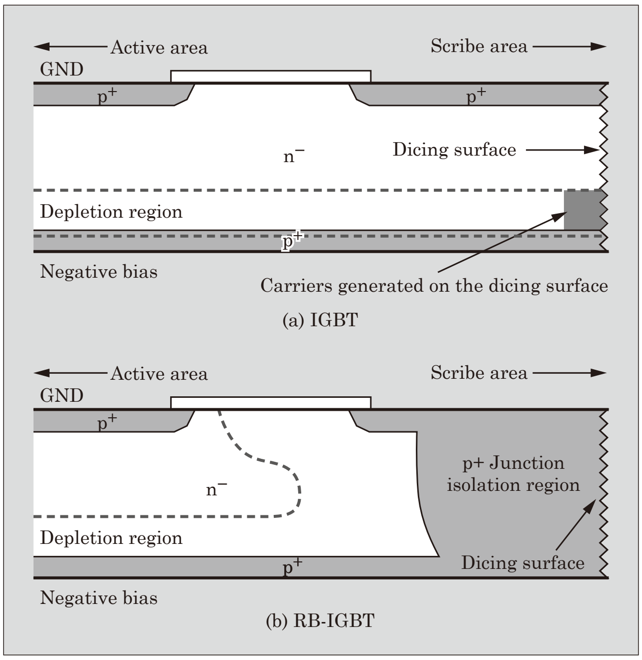

Fig.3 Cross-sectional structures of IGBT and RB-IGBT chips

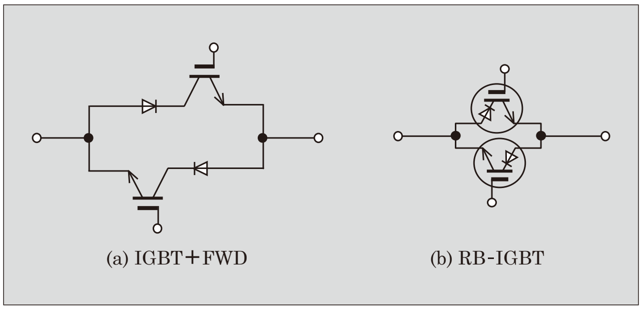

Fig.4 Structure of bi-directional switch

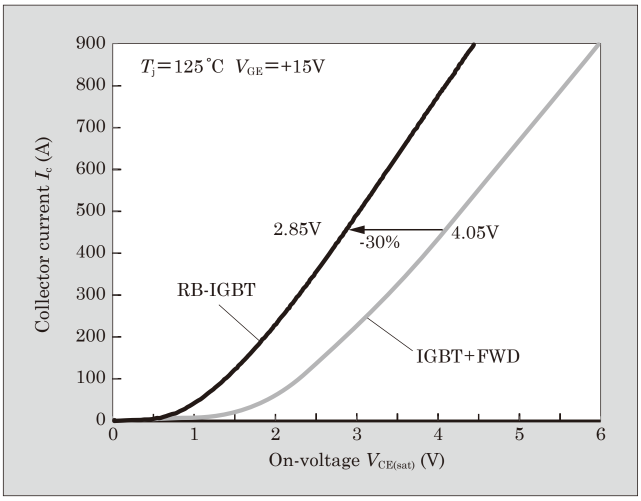

Fig. 5 Output characteristics of 900 V RB-IGBT chip and 1,200 V IGBT+FWD chip

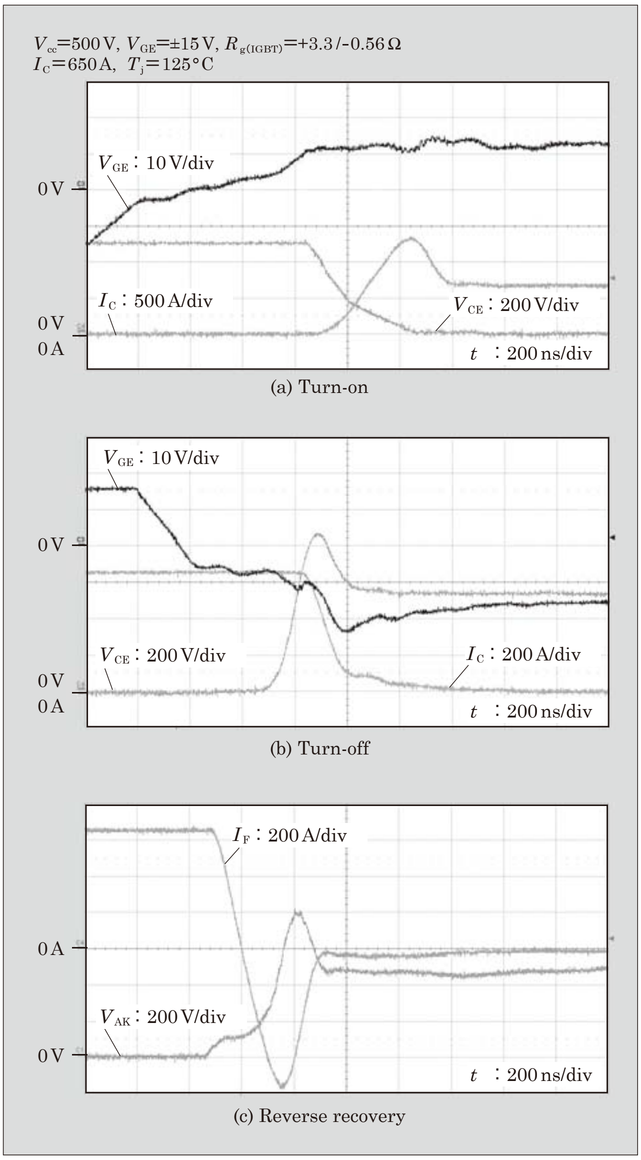

Fig.6 Switching waveforms of prototype IGBT module in switching mode A

In the photovoltaic power system, 1,000 V DC bus is becoming a mainstream feature. With 3-level inverters at 1,000 V DC-bus application, the bi-directional switch is switched at 500 V. Therefore, intermediate devices in AT-NPC with a blocking voltage of 600 V may not withstand the voltage. On the other hand, raising the blocking voltage of devices to 1,200 V will result in reducing the rated current of the IGBT modules and increasing the conduction losses.

To address this issue, Fuji Electric is developing 900 V RB-IGBT to be adopted in a 1,000 V DC-bus application for the photovoltaic power system market. Figure 5 illustrates output characteristics of 900 V RB-IGBT and 1,200 V IGBT+FWD in the IGBT module with a rated current of 450 A. On-voltage of 900 V RB-IGBT is 30% lower than that of 1,200 V IGBT+FWD.

3.3 Switching waveforms

Fuji Electric AT-NPC IGBT modules provide two switching modes. Mode A runs on the basis of IGBT switching and RB-IGBT reverse recovery, and mode B lets the RB-IGBT do the switching and FWD performs the reverse recovery.

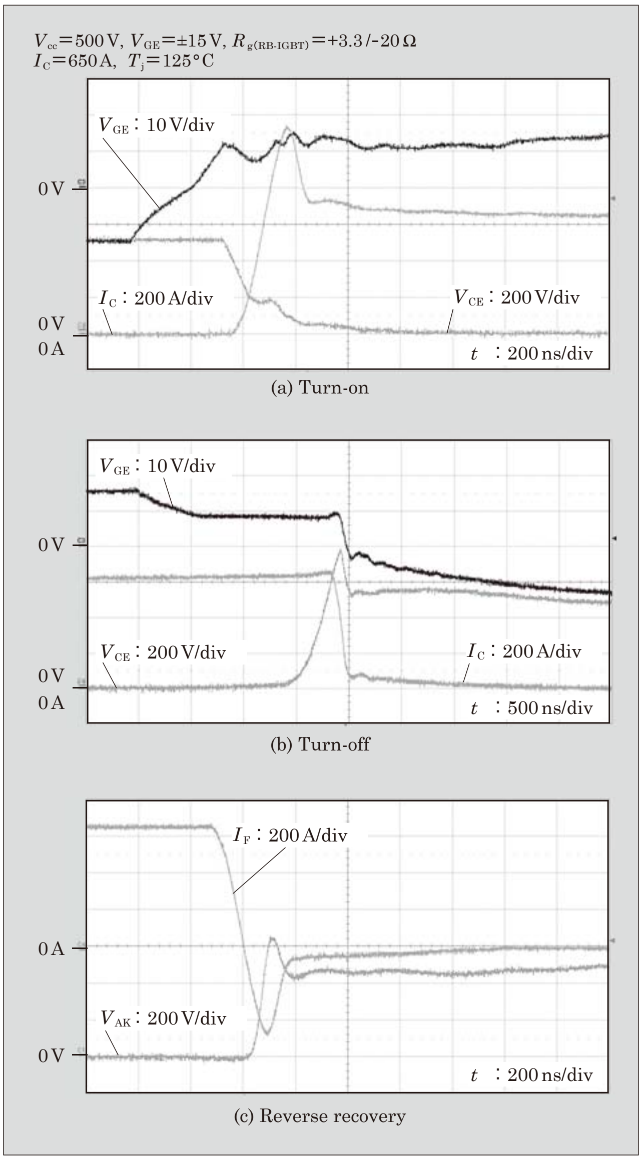

Fig.7 Switching waveforms of prototype IGBT module in switching mode B

Figures 6 and 7 show the switching waveforms of a prototype module (4MBI650VB-120R1-50). Figure 6 shows the waveforms in the mode A (V_{cc} 500 V, I_c 650 A, $R_{g(IGBT)}$ +3.3/−0.56 Ω, T_j 125 °C). The switching losses are 21.7 mJ at turn-on, 85.4 mJ at turn-off, and 76.4 mJ at reverse recovery. All waveforms are in good forms.

Figure 7 shows the waveforms in mode B (V_{cc} 500 V, I_c 650 A, $R_{g(RG+IGBT)}$ +3.3/−20 Ω, T_j 125 °C). The switching losses are 31.6 mJ at turn-on, 136.8 mJ at turn-off, and 35.3 mJ at reverse recovery. All waveforms are in good forms.

3.4 Package structures

The package structures are described below:

(1) Main terminals with P-M-N layout

The terminals are arranged for easy installation of a snubber capacitor to reduce surge voltage (between P and M, and M and N terminals).

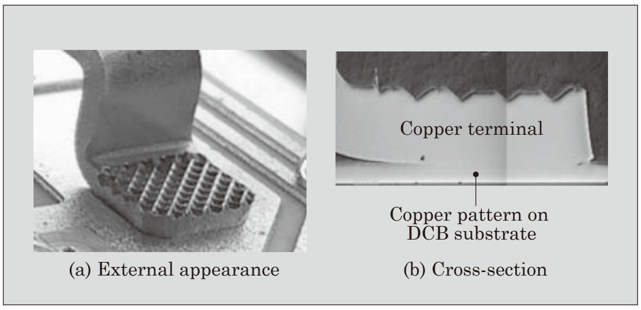

Fig.8 Ultrasonic bonding between DCB substrate and copper terminal

(2) Environmental compliance

Lead-free solder is used to comply with the RoHS Directive*2.

(3) High blocking voltage package

The package structure supports 690 V AC input, and an insulation blocking voltage (V_{iso}) of AC 4 kV/min can be guaranteed.

(4) Ultrasonic bonding

Ultrasonic bonding is applied to this IGBT module with directly connecting copper terminals and copper patterns on direct copper bonding (DCB) substrate. High reliability is achieved due to the fact that the bonded surfaces have no difference in their thermal expansion coefficient. Tensile strength of conventional solder bonding will be reduced by approximately 50% after 300 cycles in a thermal cycle test (between −40 and +150 °C). The ultrasonic bonding hardly causes weakening of the tensile strength. Figure 8 shows the external appearance and cross-section of DCB substrate and the ultrasonic bonding.

(5) Low inductance

The parallel arrangement for P-M and M-N terminals realize low inductance by electromagnetic mutual induction. Compared with the M403 package, its volume increases approximately 2.36 times, but internal inductance is a maximum of 30nH and minimum of 18nH. The internal inductance is lower than M403 (33nH).

4. Postscript

This paper described the high-power IGBT modules for 3-level power converters, which Fuji Electric is developing. The IGBT modules feature high power, low inductance, high reliability, low power dissipation, and they are anticipated to apply to the renewable energy field.

We will continue enhancing the technologies for semiconductors and assembly to meet the needs, and

*2: RoHS Directive: The Restriction of Hazardous Substances Directive adopted by the European Union, specifying hazardous substances in electrical and electronic equipment and restricting their use.

develop products that contribute to the efficiency improvement of photovoltaic power system and UPSs.

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