

IGBT Module for Advanced NPC Topology

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ABSTRACT

A new IGBT module has been developed to realize advanced NPC (A-NPC: advanced neutral-point-clamped) inverters. The IGBT (insulated gate bipolar transistor) module used for A-NPC minimized power loss by using a 6th generation IGBT and FWD (free wheeling diode), as well as a 2nd generation RB-IGBT (reverse blocking IGBT). The internal inductance between each of the main terminals is less than 40 nH, and the terminal layout was optimized to reduce the A-NPC inverter size. This product can be applied to reduce the number of devices inside equipment, and can also contribute to the development of various types of power conversion equipment having lower power loss and higher power conversion efficiency.

1. Introduction

In recent years, the reduction of CO₂ emissions has become one of the most important challenges facing for humanity. Accordingly, various efforts to reduce such emissions are being advanced on a global scale.

To contribute to a solution, in power electronics, energy savings has been promoted and inverter/converter systems, which are an effective means for achieving energy savings, have been developed and their use promoted. These systems are used not only in consumption-type applications such as motors, traction and FA (factory automation) systems, but have spread to power generation, transmission and power supply applications such as UPSs, wind power generators, solar power generators and fuel cell generators.

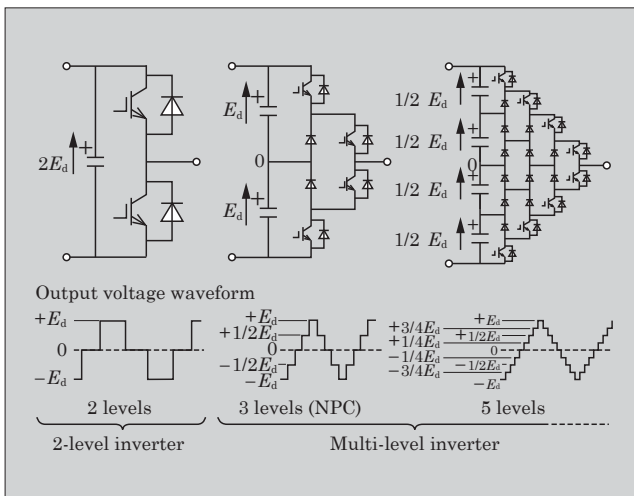


Fig.1 Circuit system and output voltage waveform for each inverter

In these applications, improved power conversion efficiency of the power conversion system is sought, and numbers of studies are being carried out. Several NPC (neutral-point-clamped) inverters have been proposed for the multilevel inverter, which one of the most effective ways to increase power conversion efficiency⁽¹⁾. In recent years, NPC inverters, having neutral-point clamps implemented with diodes, have begun to be used in inverters for AC driving, UPSs and the like. Fig. 1 shows circuit diagrams of a conventional 2-level inverter and a multi-level inverter*¹. As can be seen from the output voltage waveforms of Fig. 1, the output voltage waveform of the multi-level inverter is closer to an ideal sine wave. Thus, the NPC inverter can be used effectively to reduce switching loss and to miniaturize filters⁽²⁾.

The NPC inverter, however, uses many semiconductor devices and has a complicated configuration. In terms of conduction loss and cost, application to system of less than several hundred kVA is particularly challenging.

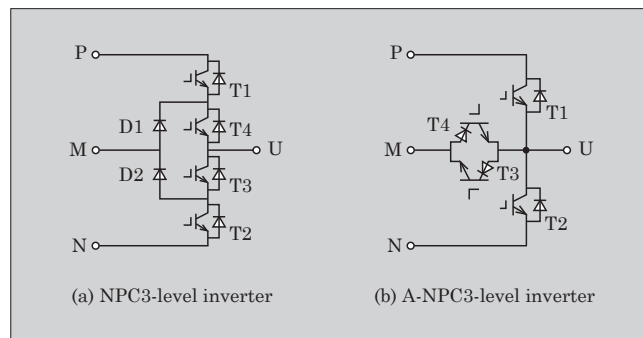


Fig.2 Equivalent circuits

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*1: 3-level inverter technology: See explanation on page 108 for further details

To solve this problem, Fuji Electric uses one of its proprietary power semiconductors, an RB-IGBT (reverse-blocking IGBT⁽³⁾), for the neutral point clamp and has developed an IGBT insulated gate bipolar transistor) module for an advanced NPC (A-NPC) used as bidirectional switch⁽⁴⁾. An equivalent circuit is shown in Fig. 2.

Fuji Electric has developed a UPS that fully utilizes the characteristics of this A-NPC, and through releasing this UPS on the market, has contributed positively to the “energy” and “environment” fields.

An overview and a description of the technical development of the IGBT module for A-NPC topology are presented herein.

2. Characteristics of IGBT Module for A-NPC Topology

2.1 Ratings and external appearance

Table 1 lists the ratings, package and the like, and Fig. 3 shows the external appearance of the IGBT module for A-NPC topology.

The IGBT module for A-NPC topology is housed in a 4-in-1 package, and is configured from 1,200 V/300 A IGBT devices T1 and T2, which are the main switches, and 600 V/300 A RB-IGBT devices T3 and T4, which are bidirectional switches, (see Fig. 2(b)).

T1 and T2 have the same circuit configuration as standard 2-in-1 modules. The bidirectional switches T3 and T4 are configured from RB-IGBTs in an anti-parallel connection.



Fig.3 External appearance of IGBT module for A-NPC topology

2.2 Device electrical characteristics

(1) Main switches

A 1,200 V-rated 6th generation “V Series” IGBT and a FWD (free wheeling diode) are used in the main switches of T1 and T2.

For the 6th generation V Series, the surface structure was optimized and the wafer was made thinner to achieve lower resistance of the drift layer and to reduce the on-state voltage $V_{CE(sat)}$ and switching loss. In addition, controllability of the turn-on di/dt was improved so as to realize lower radiation noise than with a conventional device.

(2) Bidirectional switches

A 600 V-rated 2nd generation RB-IGBT was used in the bidirectional switches of T3 and T4.

An RB-IGBT is a semiconductor device having reverse blocking capability of which a conventional IGBT is incapable. Previously, bidirectional switches had to be configured with an IGBT and a diode. But, by using an RB-IGBT, there is no need for a diode to maintain the reverse blocking capability, and on-state voltage can be reduced.

Fig. 4 compares the on-state voltage of a conventional NPC inverter and an A-NPC inverter.

In a conventional NPC inverter, the on-state voltage was large for all current routes (modes 1 to 4), because either two IGBTs or diodes are connected in series, or an IGBT and a diode are connected in series in the circuit. On the other hand, in an A-NPC inverter, because devices having twice the rated voltage of the NPC inverter are used and because RB-IGBTs

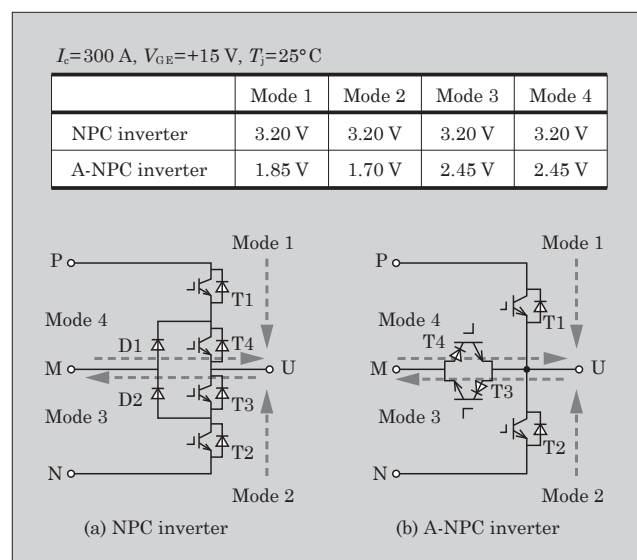


Fig.4 Comparison of on-state voltages for NPC inverter and A-NPC inverter

Table 1 Summary of IGBT module for A-NPC topology

Model name	Package dimensions	Rated voltage	Rated current
4 MBI300VG-120R-50	L110×W80×H30 (mm)	1,200 V (main switch part)	300 A (main switch part)
		600 V (bidirectional switch part)	300 A (bidirectional switch part)

are used in T3 and T4, the number of devices through which current flows is halved for all modes 1 to 4.

As a result, compared to a module for a conventional NPC 3-level inverter, the module for an A-NPC 3-level inverter realizes approximately 30% less conduction loss, keeping equivalent switching loss and noise.

An RB-IGBT has the same fundamental structure as a conventional IGBT. Therefore, the tradeoff between switching loss and on-state voltage in a RB-IGBT does not differ from that of a conventional IGBT. When reverse biased, the recovery characteristics are the same as for a conventional FWD. Fig. 5 shows the curve of the tradeoff between on-state voltage and turn-off loss in an RB-IGBT. The curve has the same slope as an IGBT+FWD combination, but the $V_{CE(sat)}$ is smaller because of the fewer conducting devices.

2.3 Package for A-NPC inverters

For this product, optimization design with an emphasis on the following items was carried out to realize an optimal package for configuring an A-NPC inverter.

- (a) Main pins P, U, N, and M shall be arranged to facilitate the placement of a snubber capacitor for reducing surge voltage
- (b) The U output pin shall be placed as far as possible from the control pin, and the output current shall not affect the control signals
- (c) The package size shall be selected based on the external shape and dimensions of conventional products, and shall be made as small as possible

As a result, the pin layout conditions were satisfied and a package size of 110×80 (mm), equivalent to that of the M247, was achieved.

2.4 Low inductance package

The circuit inductance directly affects the surge voltage generated at turn-off of the semiconductor device. If a conventional 2-in-1 module and a 1-in-1 module were used to realize the same circuit configura-

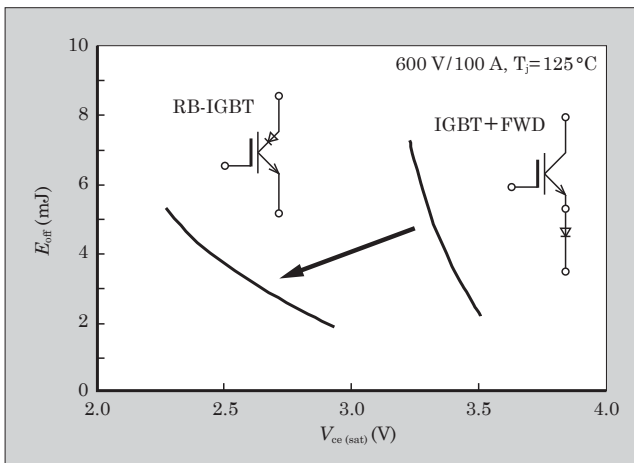


Fig.5 Curve of RB-IGBT tradeoff between on-state voltage and turn-off loss

tion as this product, the total inductance of the bus bar for connecting the modules and the internal inductance of the package would be a large value of more than 100 nH, and the A-NPC inverter would be difficult to realize. Therefore, this product houses the 2-in-1 topology and the 1-in-1 topology inside a single package so as to reduce the bus bar inductance significantly. In each current route, the internal inductance has become the equivalent package internal inductance of a conventional 2-in-1 module (internal inductance of 40 nH or less in each P-N, P-M and M-N current route) to a level at which the surge voltage at turn-off can be suppressed.

2.5 High reliability package

In this product, the DCB (direct copper bonding) substrate for mounting the semiconductor devices is subdivided into four substrates, and as a result, compared to a conventional product of the same size (M236 single substrate), less amount of stress is generated on the substrate and the solder underneath the substrate at the time of thermal contraction.

Fig. 6 shows a comparison, based on FEM (finite element method) analysis, of the strain on the solder underneath the DCB substrate that is generated during thermal cycle tests. At high temperatures, if the ratio of solder strain generated with a single substrate is 1.0, the ratio of strain with 4 substrates is 0.45, which is a 55% reduction in the strain.

Accordingly, compared to a conventional product, improved tolerance to thermal cycle testing and reliability against thermal expansion and thermal contraction can be expected.

Furthermore, as an environmental measure, the package is lead-free and is in compliance with the European RoHS Directive*2.

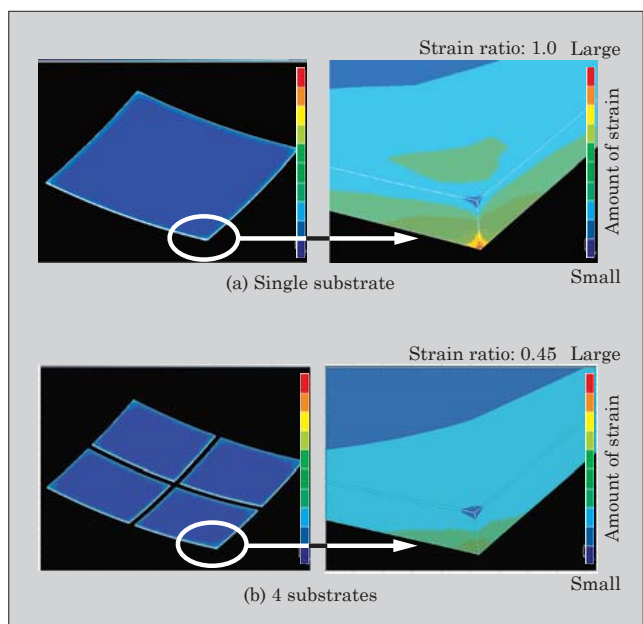


Fig.6 FEM analysis results (at high temperature)

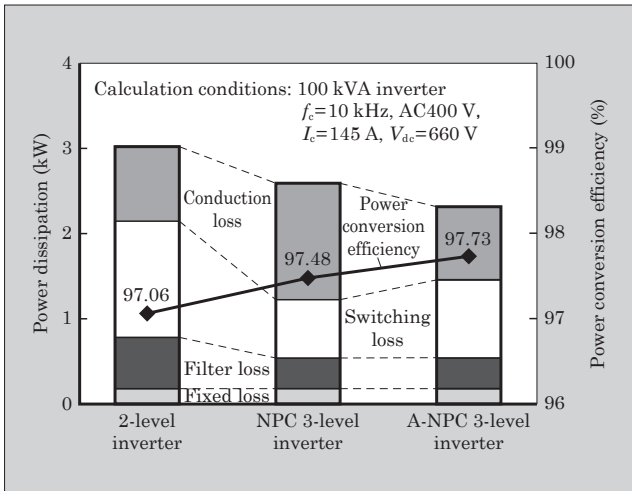


Fig.7 Comparison of power dissipation and power conversion efficiency for each inverter

3. Power Dissipation/Power Conversion Efficiency

Fig. 7 compares the power dissipation and power conversion efficiency of the conventional 2-level inverter, the NPC 3-level inverter and the A-NPC 3-level inverter when operated under the same conditions.

For the conventional 2-level inverter, the characteristics of a 1,200 V 6th generation V Series device were used, and for the NPC inverter, the characteristics of a 600 V 6th generation V Series device were used. The internal inductance of the module for NPC inverter was assumed to be the same as that of the module for A-NPC inverters.

The inverter operating conditions were $f_c = 10$ kHz, DC voltage=660 V and output current=145 A. As a result, the A-NPC inverter exhibited the smallest power dissipation and was 23% lower than the conventional 2-level inverter and 9% lower than the NPC inverter. Additionally, A-NPC has the highest power conversion efficiency of 97.73%, which was an improvement of 0.25 percentage points over the NPC inverter and 0.67 percentage points over the conventional 2-level inverter.

The reasons for these results are as follows.

- Reduced filter loss: Less higher harmonics in output voltage waveform due to use of 3 levels
- Reduced switching loss due to use of 3 levels
- Reduced conduction loss: Combination of devices having different voltage ratings and use of RB-IGBT

In addition, Fig. 8 compares the carrier frequency dependency of power dissipation. Basically, power dissipation is lower with a 3-level inverter than with

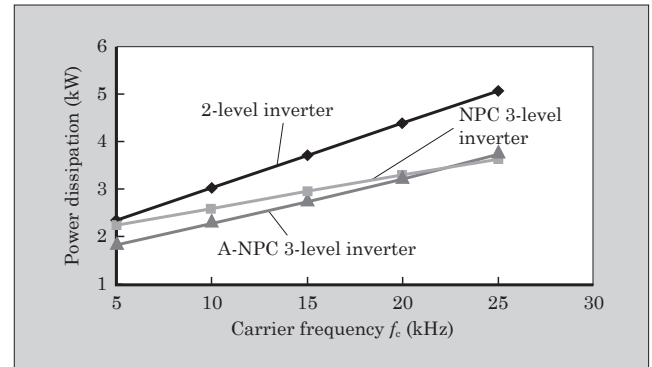


Fig.8 Carrier frequency dependency of power dissipation

a 2-level inverter. However, in comparing the NPC inverter and A-NPC inverter, a cross-point can be seen at $f_c = 21.5$ kHz. This suggests that with the A-NPC inverter, switching loss accounts for a larger percentage of the power dissipation. Additionally, this shows that the A-NPC inverter is effective for applications where f_c is 21.5 kHz or less.

4. Postscript

An overview and description of the characteristics of a new IGBT module for use in A-NPC inverter circuits have been presented. With this product, lower noise by 3-level control, reduced switching loss by using a 6th generation IGBT and FWD, reduced conduction loss by using a 2nd generation RB-IGBT, optimization of the pin layout, lower surge voltage by reducing the package internal inductance and so on, have been realized. As a result, our customers are able to design A-NPC inverters with greater ease. In addition, the reduced number of devices used, and the miniaturization and common usage of constituent components, enable our customers to realize lower cost equipment.

For applications involving a relatively low carrier frequency, in terms of the power dissipation and power conversion efficiency, higher performance can be achieved with the A-NPC inverter than with either a 2-level inverter or an NPC inverter.

Fuji Electric, in addition to improving device performance, is also advancing a package design capable of offering further miniaturization and higher reliability, and intends to continue to develop modules in response to market demands.

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*2: RoHS directive: EU (European Union) directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment





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