Power Semiconductor Devices for Inverters

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1. Introduction

In recent years, power electronics, which is mainly power conversion and control technology, has shown remarkable progress, and its application is expanding to a wide range of fields, including industry, transportation, information, and household appliances. In particular, inverter circuits for power conversion have been applied to general-purpose inverters, uninterrupted power systems, numerically controlled machine tools, and industrial robots, and are regarded as one of the most rapidly developing fields.

Development of the inverter circuit has resulted from progress in such areas as performance, size, mass, cost, and reliability. New semiconductor devices, key components of the configuration of the inverter circuit, are continually developed such as the thyristor, GTO (Gate Turn-Off Thyristor), BJT (Bipolar Junction Transistor), power MOSFET, and IGBT (Insulated Gate Bipolar Transistor), and their performance, function, capacity, and cost have been improved. As a result, they have contributed to the development of the inverter circuit.

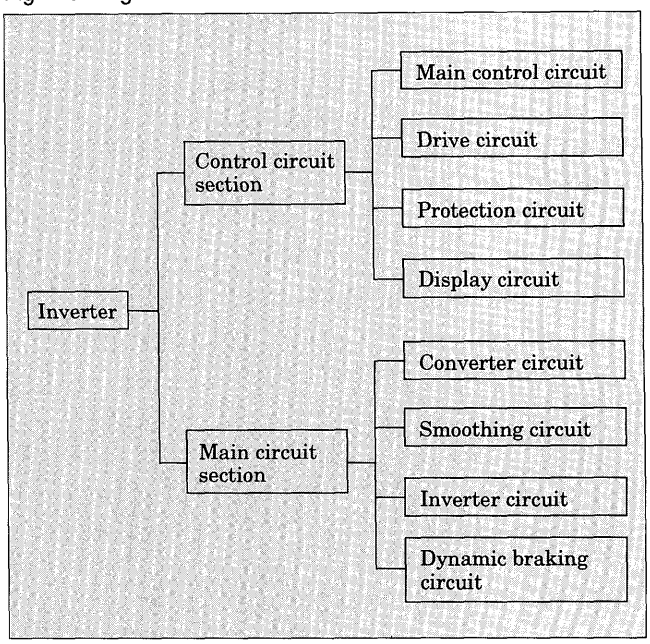
Among these types of power semiconductors, the IGBT has been given attention because of such features as low loss, simplicity of the drive circuit design and development of high-voltage, large-capacity devices. In addition, it plays an important role in promoting higher performance, higher functionality, smaller size, and lighter weight in the inverter.

In this environment, Fuji Electric developed the first generation of IGBT modules in 1988, the second generation as a low loss series in 1990, and the third generation, which has low loss characteristics nearing the minimum possible for the IGBT configuration, in 1992, to respond to market needs.

This time, we have developed and introduced of the new third generation IGBT modules (N series) in which simplicity of use, which facilitates drive and circumferential circuit design, and high reliability were pursued in addition to the low loss characteristic of the IGBTs currently in use.

In this paper, we will describe the present state of Fuji Electric semiconductor devices for the inverter and give an outline of our newest N series IGBT modules.

Fig.1 Configuration of the inverter circuit



2. Inverter Circuit Configuration

The configuration of the inverter circuit is roughly divided into a control circuit section and a main circuit section, as shown in Fig. 1.

The control circuit section consists of a main control circuit for controlling inverter output such as voltage and frequency; a drive circuit for controlling of power devices; a protection circuit for preventing the inverter from being damaged by an overcurrent or overvoltage; and a display circuit for displaying the operation status and the content of faults. The main circuit section includes a converter circuit for rectifying the AC power supply and converting it to DC power; a smoothing circuit for suppressing ripple voltage in the DC power converted by the converter circuit (a capacitor of large capacitances is usually used); an inverter circuit for inversion of DC power to output AC power; and a dynamic braking circuit for preventing a voltage across the terminals of the smoothing capacitor caused by the current from regenerative operation of the motor from rising.

Figure 2 shows an inverter circuit diagram of a PWM (Pulse Width Modulation) control system, a typical inverter circuit.

3. Semiconductor Device for the Inverter

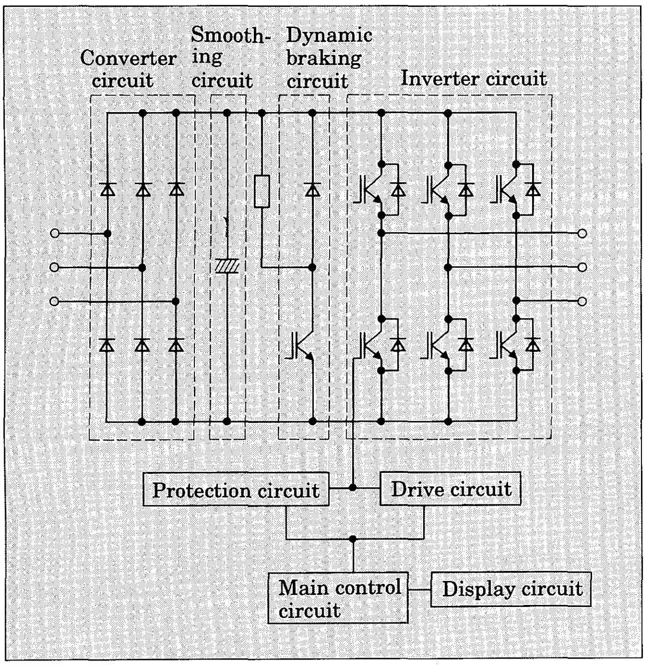
Typical semiconductor devices by Fuji Electric for configuring the above-mentioned inverter circuits are described below.

3.1 Diode module

A diode module is a device for the converter circuit. They are shown in Fig. 3, and the ratings for a typical product series are listed in Table 1. The main features of the diode modules are:

(1) Simplified circuit wiring, as two or more diodes are built into a single package
(2) High reliability, achieved through glass passivation technology
(3) Easy attachment to a heat sink, as electrodes and substrates (cases are insulated)
(4) A large product line of 30 to 250A for the 600V and 800V classes, and 30 to 100A for the 1,200V and 1,600V classes

Fig. 2 PWM inverter circuit diagram



3.2 Transistor module

A transistor module consists of one or more transistors into a single package, and applied to the inverter circuit and dynamic braking circuit. Furthermore, the transistor modules have recently been used as a device for suppressing harmonic noise for a PWM converter.

The devices used in the transistor modules include the BJT, power MOSFET, and IGBT. The ratings of elements and the series differ greatly for each device. As typical example, The newly developed N series IGBT modules will be described in detail in Chapter 4.

3.3 Power integrated module

A power integrated module consists of the power devices of the converter circuit, dynamic braking circuit, and inverter circuit all built into a single package, and is sometimes referred to as "PIM."

Since this module is one of the N series IGBT modules, its features and characteristics will be described in Chapter 4.

3.4 Hybrid IC for the drive circuit

A hybrid IC for the drive circuit includes built-in drive circuits for controlling the transistor module and

Fig. 3 Exterior view of diode modules

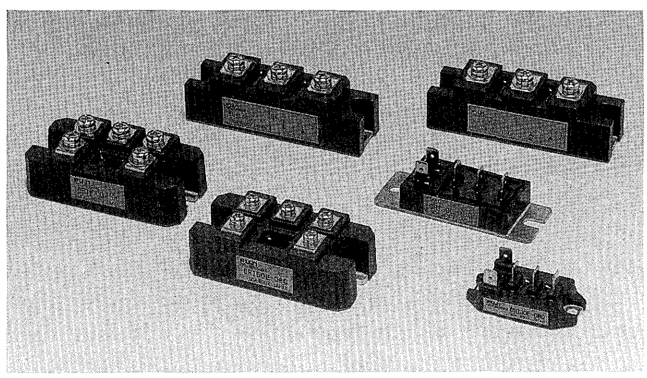


Table 1 Diode module product line

Class		E series				G series			
Repetitive peak voltage		600V		800V		1,200V		1,600V	
Configuration		2 devices/pack	3-phase bridge	2 devices/pack	3-phase bridge	2 devices/pack	3-phase bridge	2 devices/pack	3-phase bridge
Average output current	30A	–	6RI30E-060	–	6RI30E-080	–	6RI30G-120	–	6RI30G-160
	50A	–	6RI50E-060	–	6RI50E-080	–	–	–	–
	60A	2RI70E-060	–	2RI60E-080	–	2RI60G-120	–	2RI60G-160	–
	75A	–	6RI75E-060	–	6RI75E-080	–	6RI75G-120	–	6RI75G-160
	100A	2RI100G-060	6RI100E-060	2RI100E-080	6RI100E-080	2RI100G-120	6RI100G-120	2RI100G-160	6RI100G-160
	150A	2RI150E-060	6RI150E-060	2RI150E-080	6RI150E-080	–			
	250A	2RI250E-060	–	2RI250E-080	–				

overcurrent detection and protection circuits.

It is developed and designed according to the device and frequency to be used, which makes designing the circumferential circuits of the device easier. The hybrid IC series for IGBT drives are listed in Table 2.

3.5 IPM (Intelligent Power Module)

The IPM is a device consisting of an inverter circuit section, drive circuit section, and protection circuit built into a single package.

A dynamic braking circuit may be included as well. The main power device applied to the IPM is the IGBT, and the 15 to 200A for the 600V class, and the 50 to 100A in the 1,200V class have each been mode into a series. The features of these IPMs are[1] :

(1) Difficult to damage

Because the optimally designed drive circuit and protection circuit are built-in, it is difficult to damage the device.

(2) Low loss and high-speed switching

Because IGBTs are applied to the devices in the inverter section, there is low loss, and high-speed switching is possible.

(3) High integration and compact size

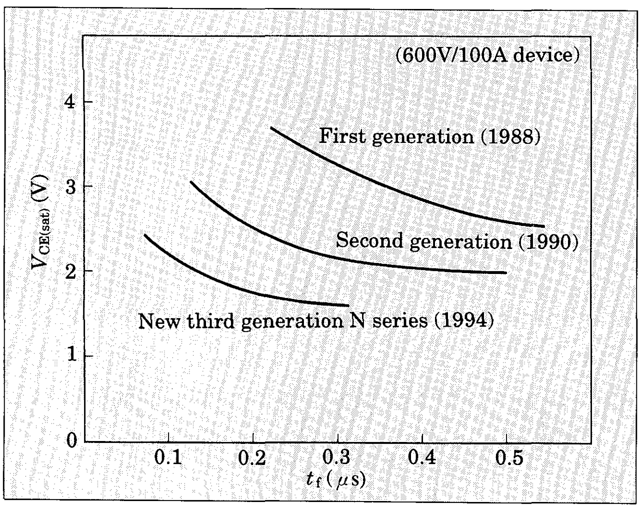
High integration and compact size have been made possible through specialized ICs and packages.

Table 2 Hybrid IC series for IGBT drive

IGBT / Applicable hybrid IC	600V class, up to 150A 1,200V class, up to 75A	600V class, 200 to 400A 1,200V class, 100 to 300A
Medium speed	EXB850	EXB851
High speed	EXB840	EXB841
High dv/dt withstand capability	EXB844*	

* : Optimum for the new third generation IGBT, currently under development
Medium speed : Signal transmission delay in drive circuit Max. 4 μs
High speed : Signal transmission delay in drive circuit Max. 1.5 μs

Fig. 4 Trade-off between $V_{CE(sat)}$ and t_f



4. The New Third Generation IGBT Modules

The new third generation IGBT modules (N series) which have been developed are described below.

4.1 Development concept of the N series IGBT modules

The requirements of a power device applied to an inverter circuit for power inversion are:

(1) Reduction of loss, in oder to make the device highly efficient, compact, and lightweight

(2) Ease of use to simplify drive circuit and circumferential circuit design

(3) High reliability

In order to fulfill these requirements, we kept the high-speed switching and low loss characteristics of our previous modules while trying to make an easy-to-use product with high reliability, with the goal of developing a device outstanding in total balance.

4.2 Features of the N series IGBT modules

4.2.1 Low loss and soft switching

Figure 4 shows the trade-off between collector-emitter saturation voltage $V_{CE(sat)}$ and fall time t_f, Fig. 5 shows the calculated power loss when the IGBT module is applied to a PWM inverter. Figure 6 shows the waveform when the IGBT module is turned off.

From this information, it is apparent that the N series IGBT module is a device that has soft switching, which suppresses surge voltage during switching, along with the characteristics of high-speed and low loss.

The characteristic of reverse recovery of a FWD (Free Wheeling Diode) is shown in Fig. 7. The peak current and surge voltage at reverse recovery have been reduced.

These improvements are the result of the optimization of the structure and process of the IGBT and FWD chips. Attaining the soft switching characteristic is considered useful for simplifying the design of circumfer-

Fig. 5 Power loss at application of PWM inverter (calculated)

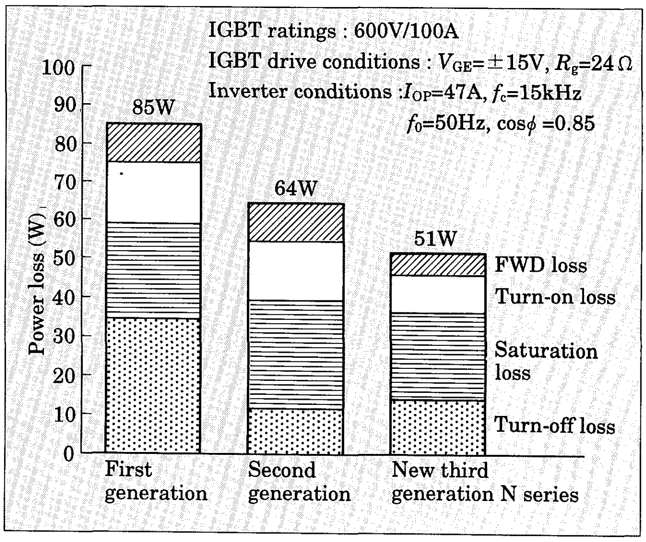


Fig. 6 Waveform at turn-off of the IGBT modules

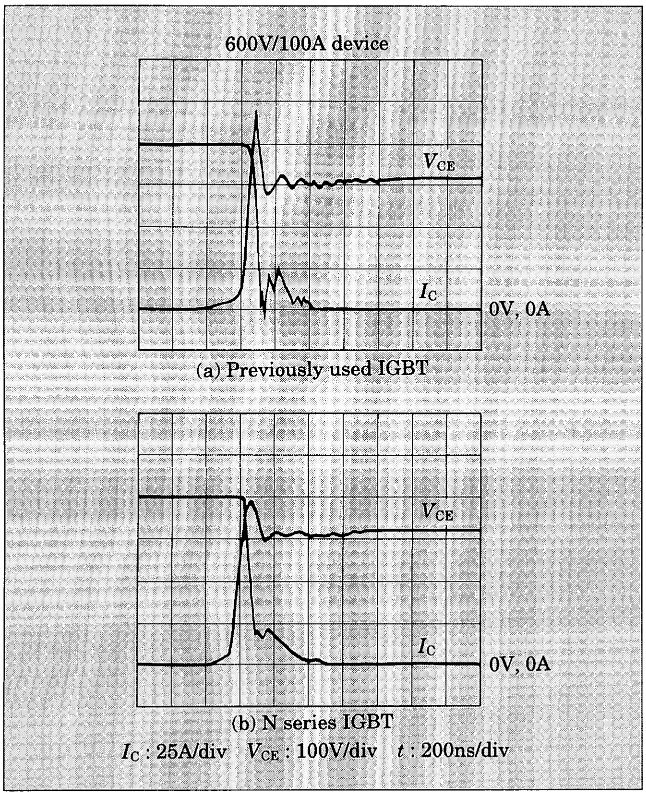
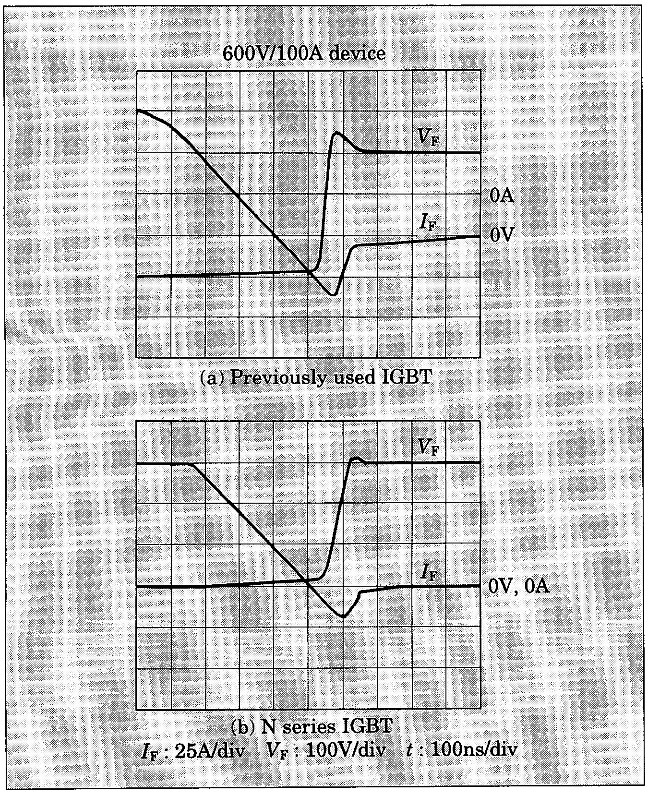


Fig. 7 Reverse recovery characteristics of the FWD



ential circuits such as the drive circuit, snabber circuit, and noise protection circuit.

Fig. 8 Equivalant circuit of an NLU circuit

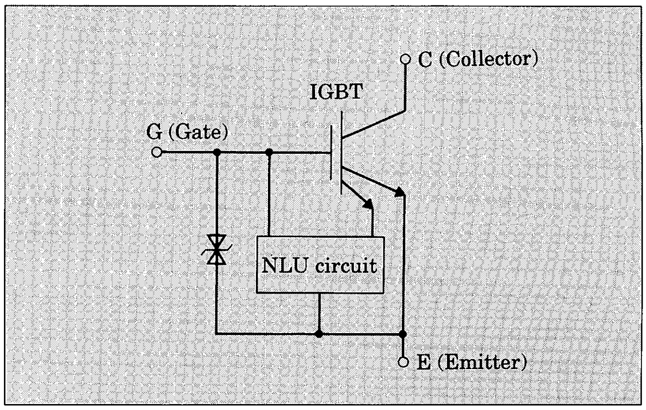


Fig. 9 Waveform of a short-circuit test of the N series IGBT

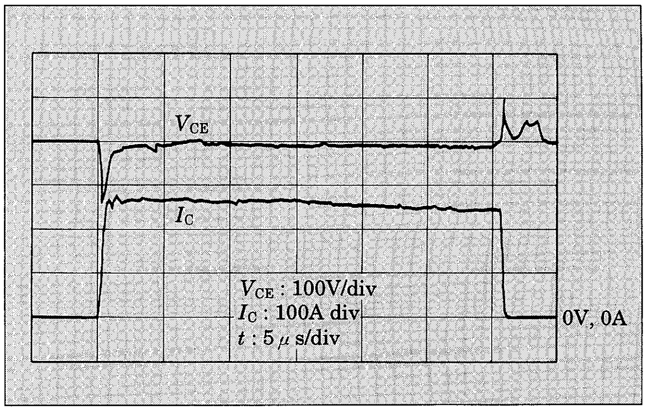
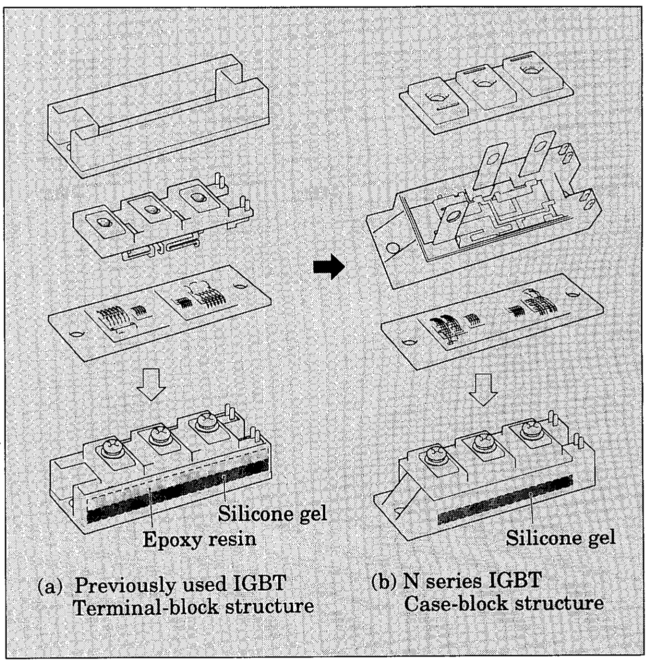


Fig. 10 Structural comparison of IGBT modules



4.2.2 High short-circuit withstand capability by the NLU circuit

A short-circuit current is suppressed to about 3 times the rated current of a device by the NLU (Non

Latch-Up) circuit, creating a high short-circuit withstand capability (excluding one group of models). Figure 8 shows an equivalent circuit of the NLU circuit, and Fig. 9 shows the waveform when a short-circuit current is suppressed by an NLU circuit.

4.2.3 New package structure

(1) Use of a new direct bonding copper substrate

The strength of the substrate and its low thermal resistance have been enhanced by the use of a new alumina plate which uses new substrate materials.

The improved substrate strength has made enlargement of the substrate possible, simplifying the wiring inside the module and reducing the number of parts.

(2) Use of a case-block structure

The new N series IGBT module uses a new case-block structure instead of the terminal-block structure used in the past. This has made simplification of the wiring inside the module, a significant reduction in the

Table 3 N series IGBT modules

Class / I_c	600V				1,200V			
	PIM*1	7-in-1*2	2-in-1	1-in-1	PIM*1	7-in-1*2	2-in-1	1-in-1
10A	–	–	–	–	7MBR10NF120 (PIM C)	–	–	–
15A	–	–	–	–	7MBR15NF120 (PIM C)	–	–	–
25A	–	–	–	–	7MBR25NF120 (PIM C)	–	–	–
30A	7MBR30NF060 (PIM C)	–	–	–	–	–	–	–
40A	–	–	–	–		7MBI40N-120 (P607)	–	–
50A	7MBR50NF060 (PIM C)	–	2MBI50N-060 (M232)	–	–	7MBI50N-120 (P607)	2MBI50N-120 (M232)	–
75A	–	7MBI75N-060 (P607)	2MBI75N-060 (M232)	–	–	–	2MBI75N-120 (M232)	–
100A	–	7MBI100N-060 (P607)	2MBI100N-060 (M232)	–	–	–	2MBI100N-120 (M234) 2MBI100NB-120 (M235) 2MBI100NC-120 (M233)	–
150A	–	–	2MBI150N-060 (M233) 2MBI150NC-060 (M232)	–	–	–	2MBI150N-120 (M234) 2MBI150NB-120 (M235) 2MBI150NC-120 (M233)	–
200A	–	–	2MBI200N-060 (M233)	–	–	–	2MBI200N-120 (M234) 2MBI200NB-120 (M235)	1MBI200N-120 (M127)
300A	–	–	2MBI300N-060 (M233) 2MBI300NB-060 (M235)	–	–	–	2MBI300N-120 (M236)	1MBI300N-120 (M127) 1MBI300NP-120 (M128) 1MBI300NN-120 (M129)
400A	–	–	2MBI400N-060 (M235)	–	–	–	–	1MBI400N-120 (M127) 1MBI400NP-120 (M128) 1MBI400NN-120 (M129)
600A	–	–	–	1MBI600NP-060 (M128) 1MBI600NN-060 (M129)	–	–	–	–

*1 : With built-in rectfiers for the power supply and IGBT for dynamic braking
*2 : With a built-in IGBT for dynamic braking
The upper part of the squares in the table is the model number, and inside the parentthesis lower part is the package number.

Table 4 Main characteristics of power integrated modules and 7-in-1 modules

Model No.	Inverter (IGBT)				Brake (IGBT-FWD)				Converter (FWD)				Outline
	V_{CES} (V)	I_C (A)	P_C (W)	$V_{CE\,(sat)}$ Typical value (V)	V_{CES} (V)	I_C (A)	V_{RRM} (V)	$I_{F\,(AV)}$ (A)	V_{RRM} (V)	I_O (A)	V_{FM} Max. value (V)	I_{FSM} (A)	
7MBR30NF060	600	30	120	2.2	600	30	600	1	800	50	1.55	350	PIM C
7MBR50NF060		50	200			50							
7MBR10NF120	1,200	10	60	2.7	1,200	5	1,200	1	1,600	25	1.4	320	
7MBR15NF120		15	120			10							
7MBR25NF120		25	200			15							
7MBI75N-060	600	75	320	2.2	600	50	600	1	–	–	–	–	P607
7MBI100N-060		100	400			50							
7MBI40N-120	1,200	40	320	2.7	1,200	15	1,200	1	–	–	–	–	
7MBI50N-120		50	400			25							

⟨Note⟩ In "Outline" PIM C stands for power integrated module and P607 stand for 7-in-1 module.

Fig. 11 Equivalent circuits of the power integrated module and 7-in-1 module

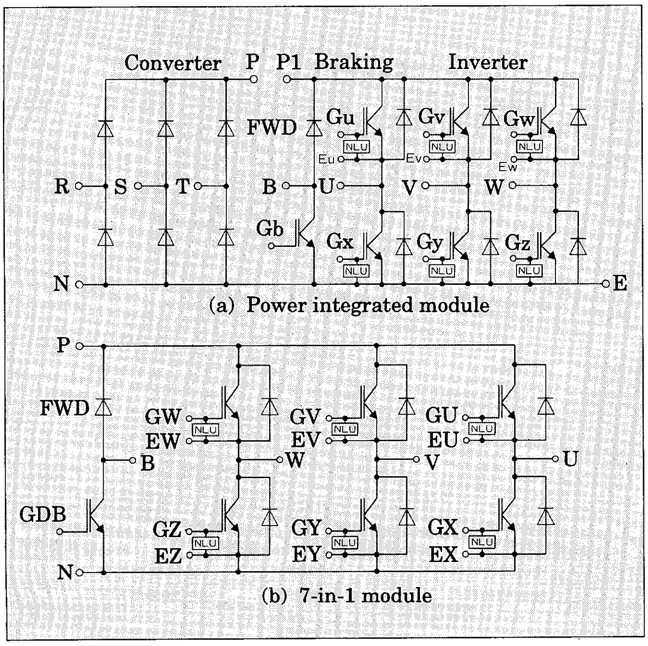
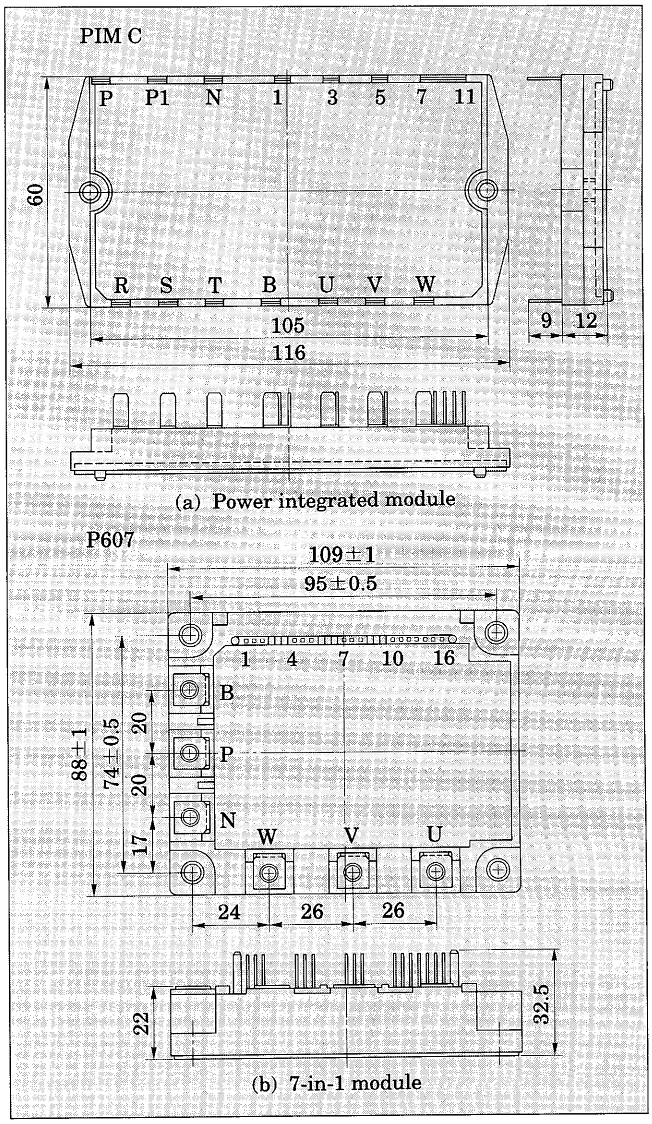


Fig. 12 Mechanical drawings of the power integrated module and 7-in-1 module



number of parts, and reduction of the number of inductive components inside the device possible. In particular, reduction of the number of inductive components inside the device, together with the soft-switching characteristic of the IGBT chip, has been effective in suppressing the surge voltage during switching of the device.

Figure 10 shows a comparison of the previously used terminal-block structure and the case-block structure of the N series.

4.2.4 Large product line

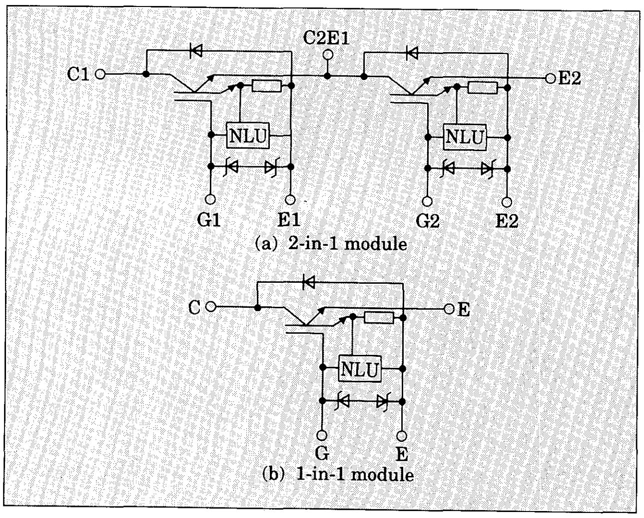
In order to meet the demand to replace the old device with a new one and reduce the size, a power integrated module series was introduced for the low capacity region. For the medium capacity region, a 7-in-1 (one set of 7 devices in one package) module (with built-in dynamic braking) and 2-in-1 (one set of 2 devices in one package) module were introduced. And

Table 5 Main characteristics of 2-in-1 modules and 1-in-1 modules

Model No.	V_{CES} (V)	V_{GES} (V)	I_C (A)	P_C (W)	$V_{CE(sat)}$ Typical value (V)	Switching time (max.)			Outline
						t_{on} (μs)	t_{off} (μs)	t_f (μs)	
2MBI50N-060	600	±20	50	250	2.2	1.2	1.0	0.35	M232
2MBI75N-060	600	±20	75	320	2.2	1.2	1.0	0.35	M232
2MBI100N-060	600	±20	100	400	2.2	1.2	1.0	0.35	M232
2MBI150NC-060	600	±20	150	600	2.2	1.2	1.0	0.35	M232
2MBI150N-060	600	±20	150	600	2.2	1.2	1.0	0.35	M233
2MBI200N-060	600	±20	200	780	2.2	1.2	1.0	0.35	M233
2MBI300N-060	600	±20	300	1,100	2.2	1.2	1.0	0.35	M233
2MBI300NB-060	600	±20	300	1,100	2.2	1.2	1.0	0.35	M235
2MBI400N-060	600	±20	400	1,500	2.2	1.2	1.0	0.35	M235
1MBI600NP-060	600	±20	600	2,000	2.2	1.2	1.0	0.35	M128
1MBI600NN-060	600	±20	600	2,000	2.2	1.2	1.0	0.35	M129
2MBI50N-120	1,200	±20	50	400	2.7	1.2	1.5	0.5	M232
2MBI75N-120	1,200	±20	75	600	2.7	1.2	1.5	0.5	M232
2MBI100N-120	1,200	±20	100	780	2.7	1.2	1.5	0.5	M234
2MBI100NB-120	1,200	±20	100	780	2.7	1.2	1.5	0.5	M235
2MBI100NC-120	1,200	±20	100	780	2.7	1.2	1.5	0.5	M233
2MBI150N-120	1,200	±20	150	1,100	2.7	1.2	1.5	0.5	M234
2MBI150NB-120	1,200	±20	150	1,100	2.7	1.2	1.5	0.5	M235
2MBI150NC-120	1,200	±20	150	1,100	2.7	1.2	1.5	0.5	M233
2MBI200N-120	1,200	±20	200	1,500	2.7	1.2	1.5	0.5	M234
2MBI200NB-120	1,200	±20	200	1,500	2.7	1.2	1.5	0.5	M235
1MBI200N-120	1,200	±20	200	1,500	2.7	1.2	1.5	0.5	M127
2MBI300N-120	1,200	±20	300	2,100	2.7	1.2	1.5	0.5	M236
1MBI300N-120	1,200	±20	300	2,100	2.7	1.2	1.5	0.5	M127
1MBI300NP-120	1,200	±20	300	2,100	2.7	1.2	1.5	0.5	M128
1MBI300NN-120	1,200	±20	300	2,100	2.7	1.2	1.5	0.5	M129
1MBI400N-120	1,200	±20	400	3,100	2.7	1.2	1.5	0.5	M127
1MBI400NP-120	1,200	±20	400	3,100	2.7	1.2	1.5	0.5	M128
1MBI400NN-120	1,200	±20	400	3,100	2.7	1.2	1.5	0.5	M129

〈Note〉 In "Model No." 2MBI ··· stands for 2-in-1 moduels and 1MBI ··· stands for 1-in-1 moduels.

Fig. 13 Equivalent circuits of the 2-in-1 and 1-in-1 IGBT modules



for the large capacity region, a 2-in-1 module and 1-in-1 (one device in one package) module were introduced. Furthermore, in the 1-in-1 module, the upper arm and lower arm package has been made standard in the product line. This package is compatible with the power printed substrate installation, configures all terminals on the same plane, and allows minimization of the length of the wiring connections between modules. Therefore, a large product line consisting of 10 packages and 38 models is available.

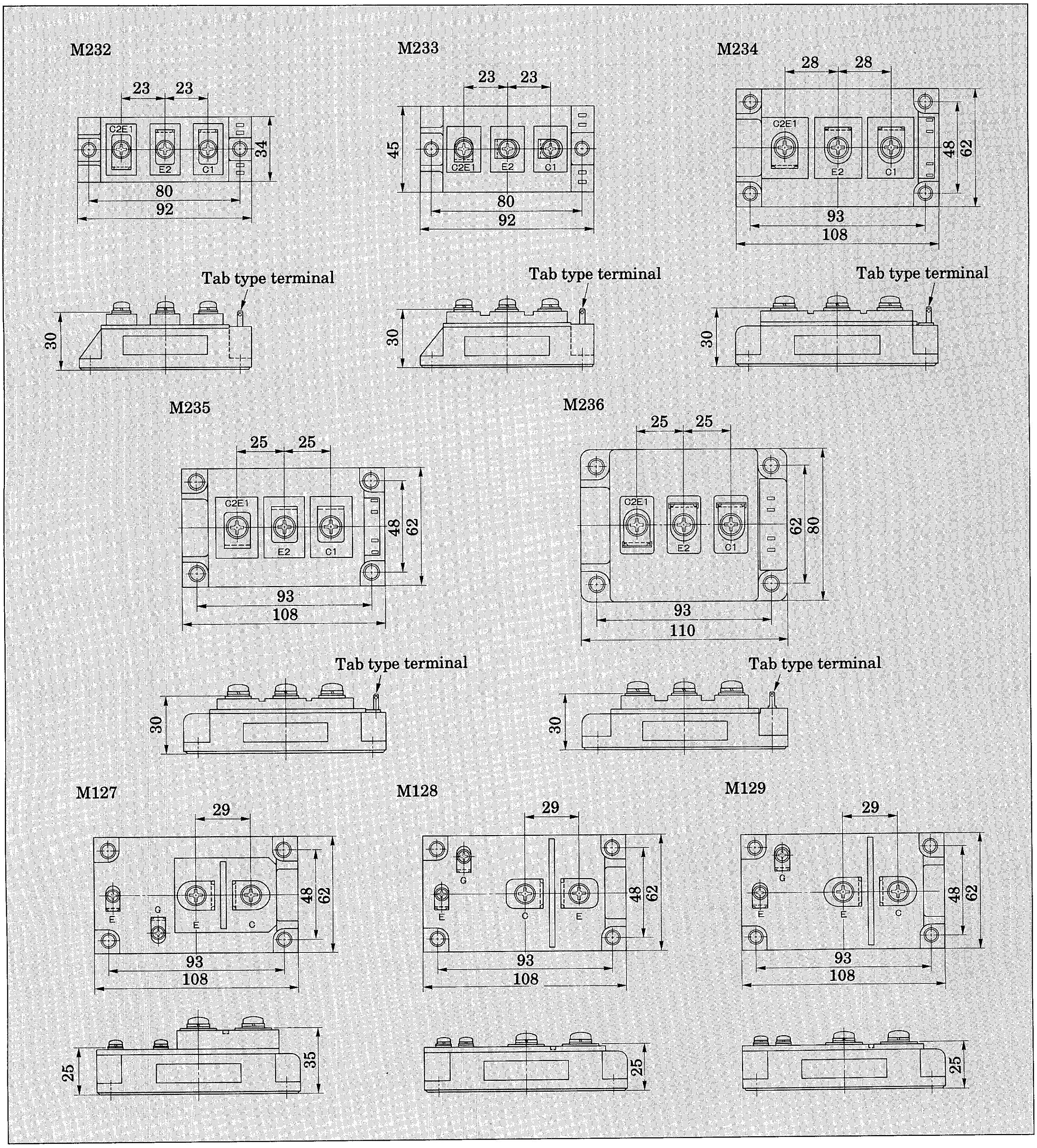
Table 3 lists the N series IGBT modules.

(1) Power integrated module and 7-in-1 module

The main characteristics of the power integrated module which uses N series IGBTs, the 7-in-1 module with built-in dynamic braking are shown in Table 4. The equivalent circuits are shown in Fig. 11, and the mechanical drawings are shown in Fig. 12.

(2) 2-in-1 module and 1-in-1 module

Fig. 14 Mechanical drawings of the 2-in-1 and 1-in-1 IGBT modules



In Table 5, the main characteristics of the N series IGBT modules of the 2-in-1 and 1-in-1 are shown, and the equivalent circuits and the mechanical drawings of each package are shown in Fig. 13 and 14 respectively.

5. Conclusion

The work of Fuji Electric in semiconductor devices for inverters have been presented, concentrating on the newly developed N series IGBT modules.

We are convinced that the N series IGBT modules can respond to broad market needs with their excellent performance and the large product line available. Fuji Electric will further endeavor to develop power devices of higher performance, functionality, and reliability to respond to the ever-changing needs and expectations of the market, and to contribute to the development of power electronics.