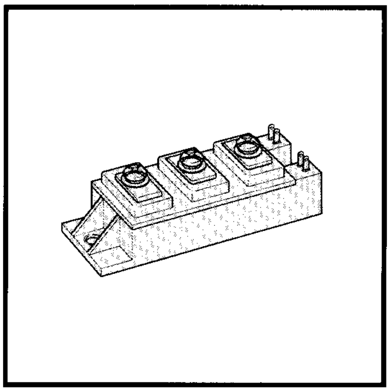
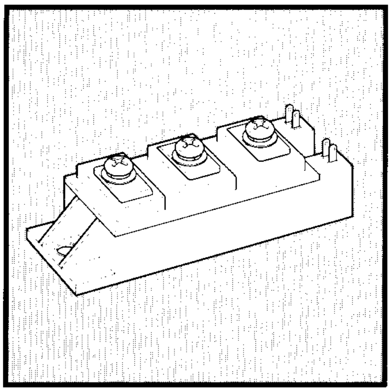
FUJI ELECTRIC

NEW 3rd-Generation

FUJI IGBT MODULES

N series





APPLICATION MANUAL

N-Series IGBT-Modules / Application Manual

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ALPHABETICAL INDEX

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N-Series IGBT-Modules / Application Manual

PREFACE

Power converters, such as variable-speed motor drives and uninterruptable power supplies for computers, were revolutionized with the introduction of bipolar power transistor modules and power MOSFETs. The demand for compact, lightweight, and efficient power converters has consequently also promoted the rapid development of these switching devices.
Bipolar transistor modules and MOSFETs however, can not fully satisfy the demands of these power converters. For example, while bipolar power transistor modules can withstand high voltages and control large currents, their switching speed is rather slow. Conversely, power MOSFETs switch fast, but have a low withstand voltage and current capacity.
Therefore, to satisfy these requirements, the insulated gate bipolar transistor (IGBT) was developed. The IGBT is a switching device designed to have the high-speed switching performance and gate voltage control of a power MOSFET as well as the high-voltage/large-current handling capacity of a bipolar transistor.

Chapter 1

Structure and Features

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1.1: Device Structure and Characterisitcs

1 Device structure and characteristics

Figure 1 compares the basic structure of an IGBT and a power MOSFET. The IGBT is characterized by a P^+-layer added to the drain side of the power MOSFET structure. It is this P^+-layer that enables the various IGBT features explained in this manual.

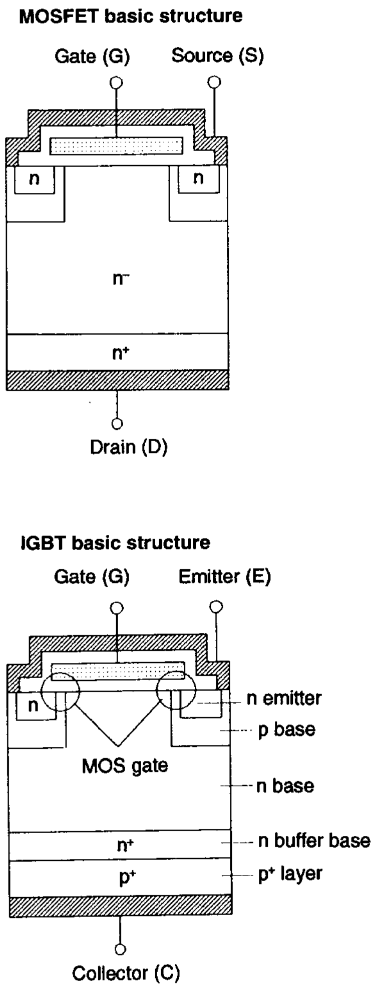

Fig. 1 Basic structure of MOSFET and IGBT

1.1 Voltage-controlled device

As shown in Fig. 2, the ideal IGBT equivalent circuit is a monolithic Bi-MOS transistor in which a pnp bipolar transistor and a power MOSFET are darlington connected.
Applying a positive voltage between the gate and the emitter, switches on the MOSFET and produces a low resistance effect between the base and the collector of the pnp transistor, thereby switching it on.
When the applied voltage between the gate and the emitter is set to "0", the MOSFET will switch off, causing the supply of base current to the pnp transistor to stop and thereby switching that off as well.
This means that an IGBT can be switched on and off using voltage signals in the same way as a power MOSFET.

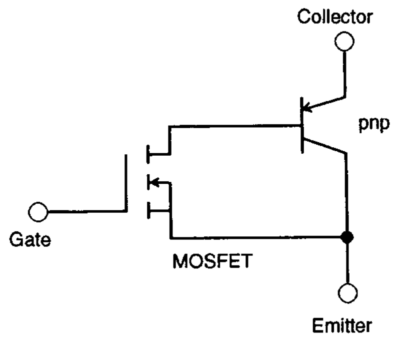

Fig. 2 Ideal equivalent circuit

1.2 Higher voltage and higher current switching capability than power MOSFETs

Like the power MOSFET, a positive voltage between the gate and the emitter produces a current flow through the IGBT, switching it on. When the IGBT is on, positive carriers are injected from the p^+-layer on the drain side into the n-type base layer, thereby precipitating conductivity modulation. This enables an IGBT to achieve a much lower on-resistance than a power MOSFET.

1.2: Faster than Bipolar Transistor

Explanation

The IGBT has a very low on resistance for the following reasons:
A power MOSFET becomes a single-layer semiconductor (n-type in the diagram) when it is in the on-state, and has resistor characteristics between the drain and the source. The higher the breakdown voltage of the device, the thicker the n^--layer has to be, but this results in an increased drain-to-source resistance. Thus, as the breakdown voltage increases so does the on-resistance, making it difficult to develop large capacity power MOSFETs.
Unlike the power MOSFET, the n-base layer resistance of the IGBT becomes negligible due to the effect of the pn diode formed by the junction of the added p^+-layer and n-type base layer when viewed from the drain side.
As the ideal equivalent circuit in Fig. 2 shows, the IGBT is a monolithic cascade-type Bi-MOS transistor that consists of a pnp bipolar transistor and a power MOSFET connected in Darlington form.
This device can be compared to a hybrid cascade-type Bi-MOS transistor that consists of a bipolar transistor chip and a power MOSFET chip. The major difference is the on-resistance of the power MOSFET. The on-resistance is extremely small in the IGBT. Considering the need for inter-chip wiring, the IGBT is superior to the hybrid cascade-type Bi-MOS transistor.

2 Faster than bipolar transistors

As explained in the previous section, the performance of the pnp transistor controls the switching speed of the IGBT collector current.
The turn-on speed of an IGBT is equivalent to that of a single bipolar transistor driven with a high base current. (The IGBT turn-on speed is even faster than Darlington-connected ordinary bipolar transistors.)
The IGBT is turned off by simply blocking the base current of the pnp transistor (a reverse bias current is not needed). Generally speaking, without a reverse bias current, it takes longer to turn off a bipolar transistor.
IGBTs use the following to achieve high speed switching:

1) Optimization of the thickness of the n^+-buffer layer and the impurity concentration, allows for the suppression of excessive carrier injection from the p^+ substrata.
2) Introduction of lifetime killers to reduce the recombination time of stored carriers.

IGBTs must trade off between on-voltage and switching time (fall time: tf). In 1st and 2nd generation IGBTs, Fuji Electric attempted to improve this trade off by using finer patterning, minimizing cell size and optimizing the carrier lifetime control. Finally, with the New 3rd-generation IGBT N series, Fuji Electric has almost reached the theoretical limits of this trade-off relationship. The N series combines a very low on-voltage with a high switching speed.

1.3: Gate Cotrolled Overcurrent Protection
1.4: Overcurrent Limitig Feature

3 Gate controlled overcurrent protection

The most difficult challenge in producing an IGBT was making gate controlled overcurrent protection possible. Differing from the ideal equivalent circuit shown in Fig. 2, the actual IGBT is a combination of thyristor and MOSFET as shown in Fig. 3.
The circuit design in Fig. 3 has one problem however, if the thyristor is triggered, then the IGBT cannot be turned off. This phenomenon, known as "latch-up", may allow an overcurrent to destroy the device.
To prevent this "latch-up phenomenon, the following techniques are used:

1) Reducing the base-emitter resistance makes the device less susceptible to latch-up.
2) Optimizing the thickness of the n^+-buffer layer and the impurity concentration, allows the h_{FE} of the pnp transistor to be controlled.
3) Implementing a lifetime killer, allows the h_{FE} of the pnp transistor to be controlled.

Using the above techniques, high speed, high voltage and high current IGBTs that don't latch-up can be produced.

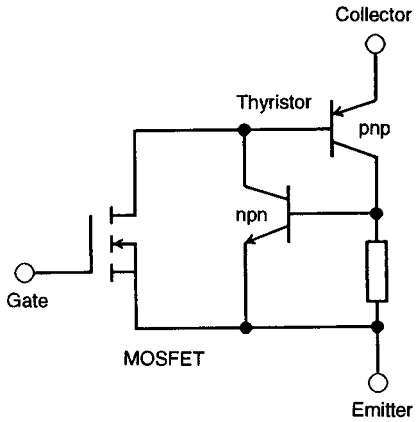

Fig. 3 Practical equivalent circuit

4 Overcurrent limiting feature

During operation, a load short-circuit or similar problem may cause an overcurrent in the IGBT. If the overcurrent is allowed to continue, the device may quickly overheat and be destroyed. The time span from the beginning of an overcurrent to the destruction of the device, is generally called the short-circuit withstand capability time.
Each N series IGBT module contains an overcurrent limiting circuit (Fig. 4). In the event of a short circuit, the overcurrent is limited, giving the device a high short-circuit withstand capability.

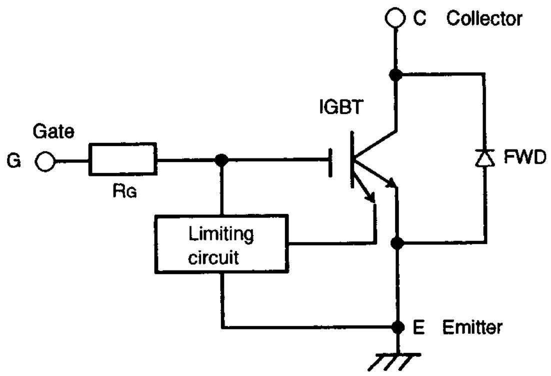

Fig. 4 Overcurrent limiting circuit

1.5: Module Structure
1.6. Selectrion of IGBT Module Ratings

5 Module structure

Figure 5 shows the structure of an N series IGBT module. The new package design has the connection terminals molded together with the casing, thereby reducing not only the number of parts needed for assembly but also the internal wiring inductance. A new DBC substrate has also been developed in order to reduce thermal resistance and increase tensile strength. These structural changes have greatly improved the modules reliability.

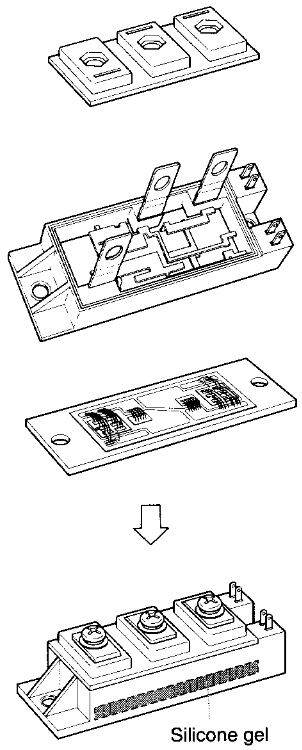

Fig. 5 Structure of N series IGBT module

6 Selection of IGBT module ratings

6.1 Voltage rating

The voltage rating of an IGBT module must be selected by considering the input voltage to the IGBT. Table 1 lists IGBT rated voltages and applicable input voltages. Use this table to select an optimum device for a particular application.

IGBT rated voltages and applicable input voltages
Table 1

		IGBT rated voltage		
		600V	**1200V**	**1400V**
Applicable input voltage	**U.S.A.**	208V 230V 240V 246V	460V 480V	575V
	Europe	200V 220V 230V 240V	346V 350V 380V 400V 415V 440V	
	Japan	200V 220V	400V 440V	

6.2 Current rating

An increase in the IGBT module's collector current will cause a rise in the V_{CE} (sat) and the static power dissipation loss. At the same time the switching loss will grow, and as a result the module's temperature will rise. Despite the heat generated by the static loss and switching loss, the elements switching temperature should be maintained below 150°C (125°C for safety). In general it is advisable to keep the collector current below the maximum rated DC current, since this also reduces operation costs.

6.3 An application example in PWM inverters

Table 2, as a example, shows the proper selection of an IGBT module to be installed in a PWM inverter.

Application example Table 2

Input voltage 220V AC		
Motor rating (kW)	Inverter rating (kVA)	IGBT type
1.5	3.0	7MBR30NF060
2.2	4.0	7MBR30NF060
3.7	6.0	7MBR50NF060
		2MBI50N-060 × 3
5.5	9.0	7MBI75N-060
		2MBI75N-060 × 3
7.5	13.0	7MBI100N-060
		2MBI100N-060 × 3
11.0 15.0	17.0 22.0	2MBI150N-060 × 3
18.5	28.0	2MBI200N-060 × 3
22.0	33.0	2MBI300N-060 × 3
30.0	44.0	2MBI400N-060 × 3
37.0 45.0	55.0 67.0	1MBI600NN-060 × 3 1MBI600NP-060 × 3

Input voltage 440V AC		
Motor rating (kW)	Inverter rating (kVA)	IGBT type
0.75	2.0	7MBR10NF120
1.5 2.2	3.0 4.0	7MBR15NF120
3.7	6.0	7MBR25NF120
5.5	9.0	7MBI40N-120
7.5	13.0	7MBI50N-120
		2MBI50N-120 × 3
11.0	17.0	2MBI75N-120 × 3
15.0	22.0	2MBI100N-120 × 3
18.5 22.0	28.0 33.0	2MBI150N-120 × 3
30.0	44.0	2MBI200N-120 × 3
37.0 45.0	55.0 67.0	2MBI300N-120 × 3
		1MBI300N-120 × 6
		1MBI300NN-120 × 3 1MBI300NP-120 × 3
55.0	84.0	1MBI400N-120 × 6
		1MBI400NN-120 × 3 1MBI400NP-120 × 3

Chapter 2

Technical Terms and Characteristics

CONTENTS Page

2.1: IGBT-Terms

This section explains relevant technical terms and characteristics of IGBT modules.

1 IGBT terms

Term	Symbol	**Definition and explanation** (See specifications for test conditions)
Collector-emitter voltage	VCES	Maximum collector-emitter voltage with gate-emitter shorted
Gate-emitter voltage	VGES	Maximum gate-emitter voltage with collector-emitter shorted
Collector current	IC	Maximum DC collector current
	IC pulse	Maximum pulse collector current
	−IC	Maximum forward DC current of internal diode
	−C pulse	Maximum forward pulse current of internal diode
Maximum power dissipation	PC	Maximum power dissipation per element
Junction temperature	Tj	Chip temperature during continuous operation
Storage temperature	Tstg	Temperature range for storage or transportation, when there is no electrical load on the terminals
Isolation voltage	Vis	Maximum effective value of the sine-wave voltage between the terminals and the heat sink, when all terminals are shorted simultaneously
Screw torque	Mounting	Maximum and recommended torques when mounting an IGBT on a heat sink with the specified screws
	Terminal	Maximum and recommended torques when connecting external wires to the terminals with the specified screws
Collector-emitter cut-off current	ICES	Collector current when a specified voltage is applied between the collector and emitter with the gate and emitter shorted
Gate-emitter leakage current	IGES	Gate current when a specified voltage is applied between the gate and emitter with the collector and emitter shorted
Gate-emitter threshold voltage	VGE(th)	Gate-emitter voltage at a specified collector current and collector-emitter voltage
Collector-emitter saturation voltage	VCE(sat)	Collector-emitter voltage at a specified collector current and gate-emitter voltage
Input capacitance	Cies	Gate-emitter capacitance, when a specified voltage is applied between the gate and emitter as well as between the collector and emitter, with the collector and emitter shorted in AC
Output capacitance	Coes	Collector-emitter capacitance, when a specified voltage is applied between the gate and emitter as well as between the collector and emitter, with the gate and emitter shorted in AC
Reverse transfer capacitance	Cres	Collector-gate capacitance, when a specified voltage is applied between the gate and emitter, while the emitter is grounded

Term	Symbol	**Definition and explanation** (See specifications for test conditions)
Turn-on time	t_{on}	The time between when the gate-emitter voltage rises from 0V at IGBT turn-on and when the collector-emitter voltage drops to 10% of the maximum value
Rise time	t_r	The time between when the collector current rises to 10% of the maximum value at IGBT turn-on and when collector-emitter voltage drops to 10% of the maximum value
Turn-off time	t_{off}	The time between when the gate-emitter voltage drops to 90% of the maximum value at IGBT turn-off and when the collector current drops to 10% of the maximum value
Fall time	t_f	Time required for collector current to drop from 90% to 10% of maximum value
Diode forward voltage	V_F	Forward voltage when the specified forward current is applied to the internal diode
Reverse recovery time	t_{rr}	Time required for reverse recovery current in the internal diode to decay
Reverse recovery current	I_{rr}	Peak reverse current during reverse recovery
Thermal resistance	$R_{th(j-c)}$	Thermal resistance between the IGBT case and the chip or internal diode
	$R_{th(c-f)}$	Thermal resistance between the case and the heat sink, when the IGBT is mounted on a heat sink using the specified torque and thermal compound
Gate resistance	R_G	Gate series resistance (See switching time test conditions for recommended values)
Gate charge capacity	Q_g	Gate charge to turn on IGBT
Reverse bias safe operating area	RBSOA	Current and voltage area where IGBT can be turned off under specified conditions
Case temperature	T_C	IGBT case temperature

Caution: The absolute maximum ratings must not be exceeded under any circumstances.

2 IGBT characteristics

This section illustrates the characteristics of new 3rd-generation IGBT modules, using the N series 2MBI100N-120 (1200V, 100A) as an example.

2.1 Static characteristics

While the IGBT is on, the collector-emitter voltage (V_{CE}) changes in accordance with the collector current (IC), gate voltage (V_{GE}), and temperature (Tj). The V_{CE} represents a collector-emitter voltage drop in the ON state, and is used to calculate the power dissipation loss of the IGBT. The smaller the V_{CE} value, the lower the power dissipation loss. Therefore, it is necessary to design the IGBT to have the smallest V_{CE} value possible.
The dependence of V_{CE}-Ic on V_{GE} is shown on the graph in Fig.1 (Tj=25°C), and Fig. 2 (Tj=125°C).
The dependence of V_{CE}-V_{GE} on Ic is shown on the graph in Fig.3 (Tj=25°C), and Fig. 4 (Tj=125°C). V_{CE} increases in direct proportion to the collector current and in inverse proportion to the V_{GE} value. Note that when the Ic value is small, as Tj increases V_{CE} decreases, and when the Ic value is large, as Tj increases V_{CE} increases. Keep this in mind when determining operating conditions.
It is generally recommended to keep V_{GE} at 15V, and the collector current at the rated Ic current or lower.

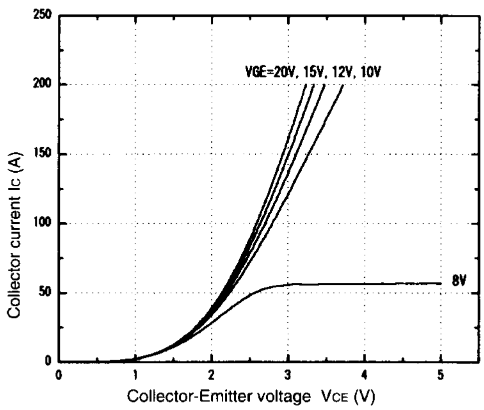

Fig. 1 V_{CE}—Ic (Tj=25°C)

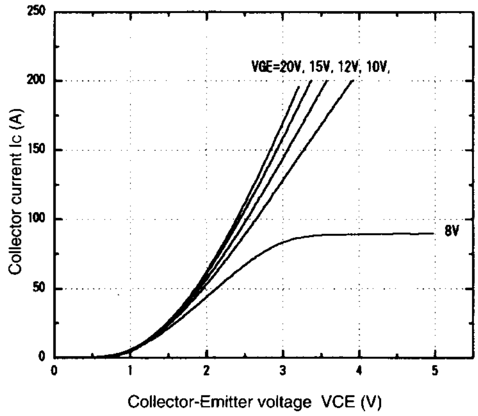

Fig. 2 V_{CE}—Ic (Tj=125°C)

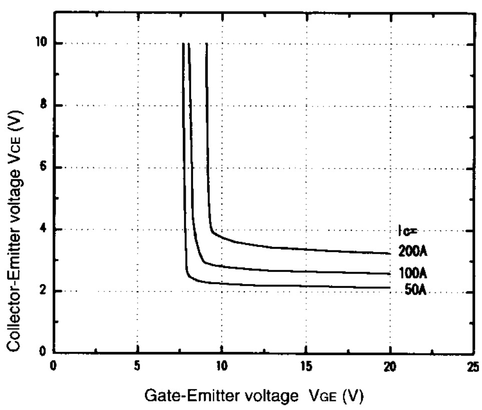

Fig. 3 V_{CE}—V_{GE} (Tj=25°C)

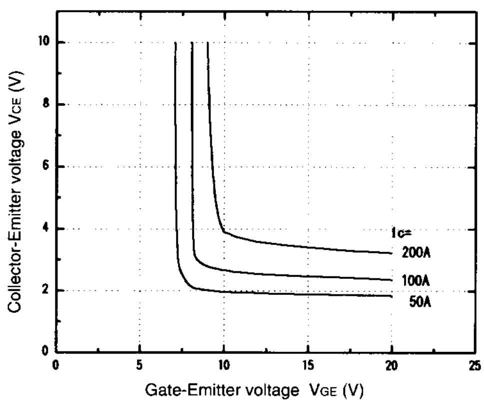

Fig. 4 V_{CE}—V_{GE} (Tj=125°C)

2.2 Switching characteristics

As the IGBT is generally used for switching, it is important to fully understand the turn-on and turn-off switching characteristics in order to determine "switching loss" (power dissipation loss at switching). It is also important to remember that these characteristics are effected by various parameters when determining operating conditions.
The circuit shown in Fig. 5 is used to measure the four parameters of switching time, tr, ton, tf and toff as shown in Fig. 6. The relationship between switching time and collector current is shown in Fig. 7 (Tj=25°C) and Fig. 8 (Tj=125°C). The greater the collector current or the higher the Tj, the longer the switching time. The effect of gate resistance (Rg) on switching time can be seen in Fig. 9. When the IGBT is installed in an inverter or some other equipment, if the switching time (especially t_{off}) is too long, it may exceed the dead time of the upper and lower transistors, thereby causing a short-circuit. It is also important to be aware that if the switching time (t_f) is too short, the transient current change rate (di/dt) will increase and then the circuit inductance may cause a high turn-off spike voltage (L di/dt).
Switching loss (Eon, Eoff) occurs every time an IGBT is turned on or off, and therefore it is important to minimize this loss as much as possible. As can be seen in Fig. 10, the greater the collector current or the higher the Tj, the greater the switching loss will be.

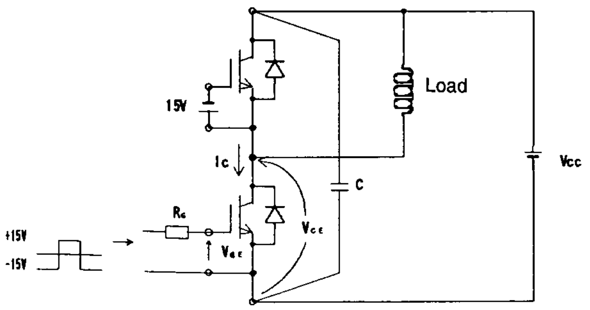

Fig. 5 Switching time measuring circuit

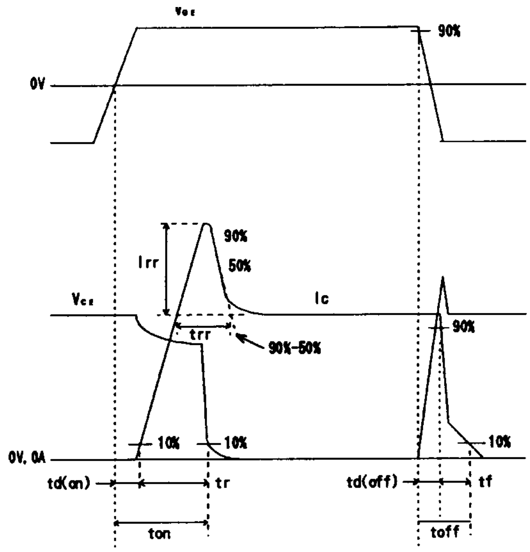

Fig. 6 Switching time parameters

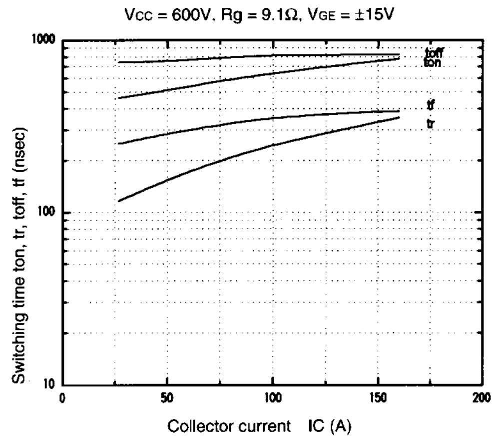

Fig. 7 Switching time—Ic (Tj = 25°C)

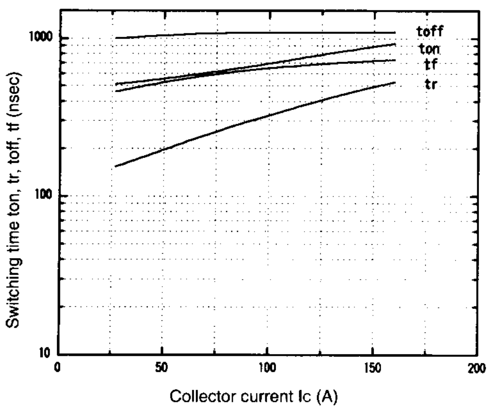

Fig. 8 Switching time—Ic (Tj = 125°C)

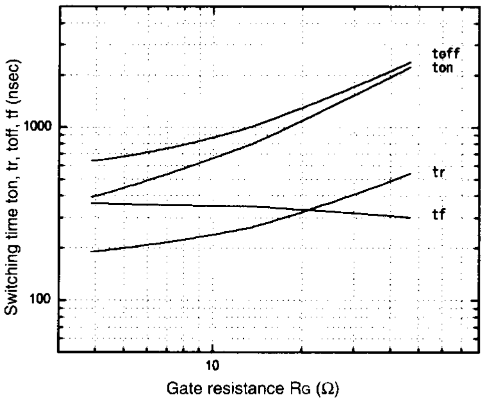

Fig. 9 Switching time—RG

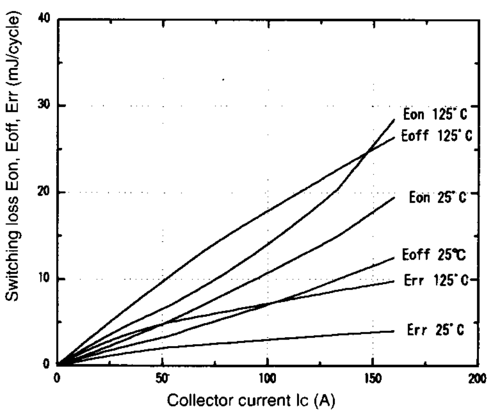

Fig. 10 Switching loss–Ic

2.3 Capacitance characteristics

The gate charge capacity (Qg) characteristics, with the main circuit supply voltage (VCC) as a parameter, are shown in Fig. 11. Here can be seen how the collector-emitter voltage (VCE) and gate-emitter voltage (VGE) fluctuate when the gate charge is changed. Since the gate charge capacity indicates the size of the charge required to drive an IGBT, it can be used to determine the power-supply capacity of the drive circuit.

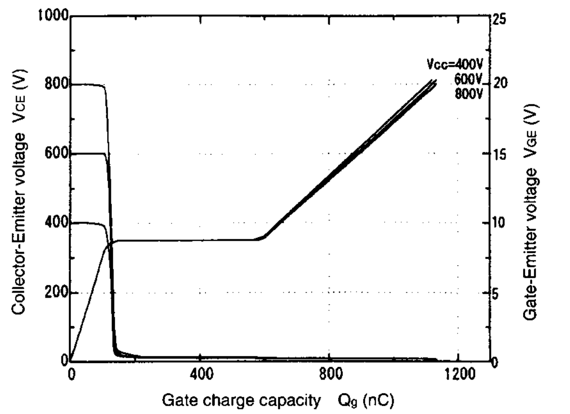

Fig. 11 VCE and VGE—Qg

Figure 12 shows the capacitance of each of the IGBT's junctions: gate-emitter input capacitance (Cies), collector-emitter output capacitance (Coes) and collector-gate reverse transfer capacitance (Cres). Use these characteristics along with Qg to design your drive circuits.

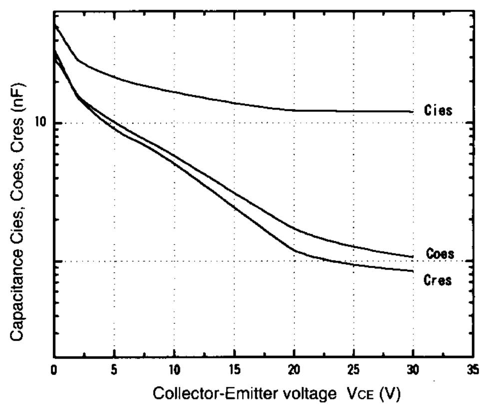

Fig. 12 Cies, Coes, Cres—VCE

2.4 Safe operating areas (RBSOA and SCSOA)

When turned off, the IGBT has a safe operating area defined by V_{CE} and I_C called the "reverse bias safe operating area" or RBSOA. This area is shown by the solid line in Fig. 13.
It is important to design a snubber circuit that will keep V_{CC} and I_C within the limits of the RBSOA when the IGBT is turned off.
Even in the case of a short-circuit (non-repetitive), an IGBT still has a safe operating area defined by V_{CE} and I_C called the "short circuit safe operating area" or SCSOA. As shown by the dotted line in Fig. 13, the SCSOA voltage tends to get smaller as the collector current increases.
In the event of a short circuit, all the new 3rd-generation N series IGBT modules have a built-in circuit to limit collector current to approximately three times the rated current of the I_C. This feature makes the design of application circuits extremely easy.

$+V_{GE} = 15V$, $-V_{GE} \leqq 15V$, $T_j \leqq 125°C$, $R_G \geqq 9.1\Omega$)

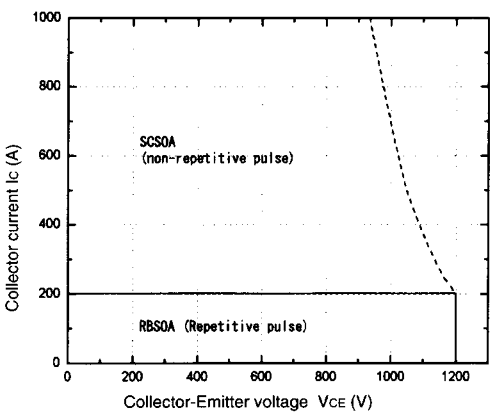

Fig. 13 Reverse bias safe operating area

2.5 Internal diode (FWD) characteristics

The IGBT module has a high-speed diode (Free Wheel Diode/FWD) connected in anti-parallel with the IGBT for operating with reverse polarity. This FWD has the V_F-I_F characteristic shown in Fig. 14, the reverse recovery characteristic (trr, Irr) shown in Fig. 15, and the switching power loss characteristic (Err) at reverse recovery shown in Fig. 10.
Use these characteristics to calculate the power loss in the FWD as well as the IGBT, but remember that the FWD characteristics vary in accordance with the collector current and temperature.

$V_{GE} = 0V$

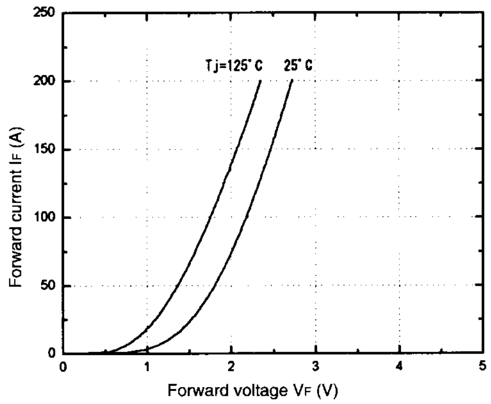

Fig. 14 V_F—I_F

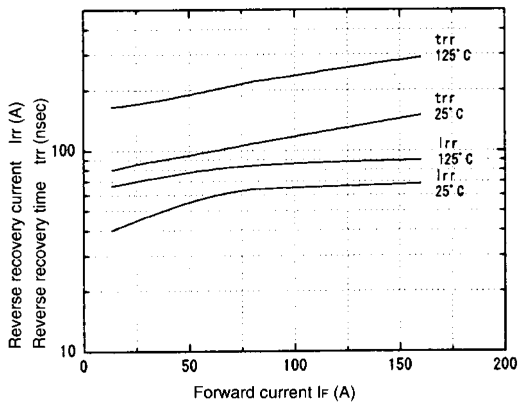

Fig. 15 Reverse recovery characteristics (trr, Irr—I_F)

2.6 Transient thermal resistance characteristics

The transient thermal resistance characteristics, used to calculate the temperature rise of a module and to design a heat sink, are shown in Fig. 16.
The characteristics in the figure vary according to each individual IGBT and FWD. Since the thermal resistance of an N series IGBT module saturates at Pw = 500ms (a constant thermal resistance unique to that particular IGBT), if the Pw exceeds 500ms, use the constant thermal resistance value.

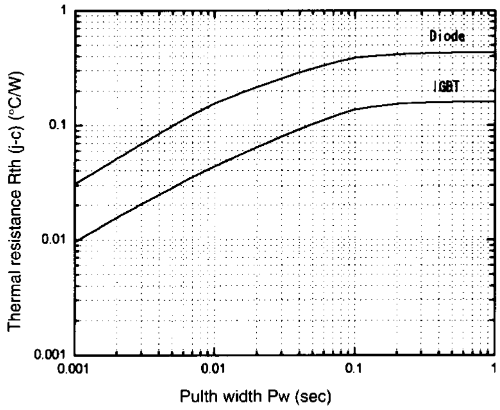

Fig. 16 Transient thermal resistance

Chapter 3

IGBT Module Selection and Application

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FUJI ELECTRIC

N-Series IGBT-Modules Application Manual

3.1: Selection of IGBT Module Ratings
3.2: Static Electricity Countermeasures

1 Selection of IGBT module ratings

When using IGBT modules, it is important to select models which have the voltage and current ratings most suited for the intended application.

1.1 Voltage rating

An IGBT must have a voltage rating that is suitable for dealing with the input voltage of the unit in which it will be installed. Table 1 lists IGBT voltage ratings and applicable input voltages. Use this table as a reference when selecting modules for a particular application.

IGBT rated voltages and applicable input voltages
Table 1

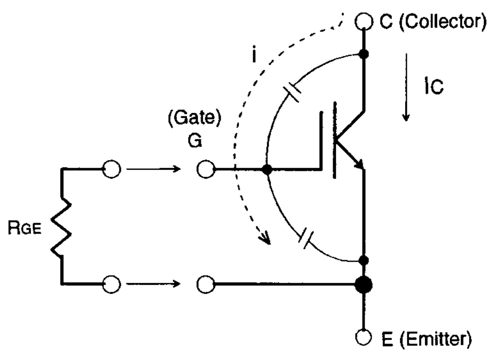
	IGBT rated voltage (V_{CES})		
	600V	**1200V**	**1400V**
U.S.A.	208V, 230V 240V, 246V	460V 480V	575V
Europe	200V, 220V 230V, 240V	346V, 350V 380V, 400V 415V, 440V	
Japan	200V 220V	400V 440V	

1.2 Current rating

When the IGBT module's collector current increases, consequently so will the V_{CE}(sat) and then also the power dissipation loss. Also, simultaneously, there will be in increase in switching loss, resulting in an increase in the module's temperature.
It is necessary to control the collector current in order to keep the junction temperature well below 150°C (below 125°C is recommended for safety reasons), despite the heat generated by static loss and switching loss. When designing a circuit, be careful of the fact that as the switching frequency increases, so will the switching loss and the amount of heat generated.
We recommend keeping the collector current at or below the maximum rating for the reasons stated above and that it is more economical.

2 Static electricity countermeasures

The V_{GE} of an IGBT is rated at ±20V. If an IGBT is subjected to a V_{GES} that exceeds this rated value, then there is a danger that the module may be destroyed. Therefore, ensure that the voltage between the gate and emitter is never greater than the maximum allowable value.
When a voltage is applied between the collector and emitter while the gate emitter connection is open as shown in the diagram below, depending on changes in the electric potential of the collector, the current (i) will flow, the gate's voltage will rise and collector current will flow.
Under these circumstance, since the voltage between the collector and emitter is high, the IGBT may overheat and be destroyed.
Also, when the IGBT has been installed, if the gate circuit is faulty or completely inoperative (while the gate is open), the IGBT may be destroyed when a voltage is applied to the main circuit. In order to prevent this destruction, it is recommended that a 10KΩ resistor (R_{GE}) be connected between the gate and emitter.



Furthermore, since IGBT modules have a MOS structure that is easily destroyed by static electricity, observe the following points of caution.

1) When handling IGBTs, hold them by the case and do not touch the terminals.
2) If the terminals are connected by some conductive material, do not remove the material until immediately before wiring.
3) It is recommended that any handling of IGBTs is done while standing on a grounded mat.
4) Before touching a modules terminals, discharge any static electricity from your body or clothes by grounding out through a high capacity resistor (1MΩ).
5) When soldering, in order to protect the module from static electricity, ground the soldering iron through a low capacity resistor.

3.3: Dependance of Current Limiting on V_{GE} and R_G
3.4: Designing ProtectionCircuits
3.5: Designing Heat Sinks
3.6: Designing Drive Circuits
3.7: Parallel Connection

3 Dependence of current limiting on VGE and RG

N series IGBTs, due to a built in current limiting circuit, will limit the collector current during a short circuit, and thereby increase the modules ruggedness. The "current limit" is set by the values of VGE and RG and therefore the smaller the VGE or the greater the RG, the lower the limit will be. It is also important that the overcurrent trip level of the equipment in which the module is installed be set below this current limit point.
The sole capability of the current limiting circuit is to limit current and not to protect the module. Therefore, in order to prevent a short circuit from destroying the IGBT, an external circuit is required to detect short circuits and to immediately cut off input signals.
Further details regarding the dependence of current limiting on VGE and RG, are explained under "Drive circuit design" in Chapter 7 of this manual.

4 Designing protection circuits

Since IGBT modules may be destroyed by overcurrent, overvoltage, or other abnormality, it is necessary to design protection circuits.
It is important when designing these circuits that a module's characteristics are fully taken into consideration, since an inappropriate circuit will allow the module to be destroyed. (For example, the overcurrent cut-off time may be too long or the capacitance of the snubber circuit's capacitor may be too small.)
For more details on overcurrent and overvoltage protection methods, refer to Chapter 5 of this manual.

5 Designing heat sinks

As the maximum allowable junction temperature (Tj) of an IGBT module is fixed, an appropriate heat sink must be designed to keep it at or below this value.
When designing appropriate cooling, first calculate the loss of a single IGBT module, then based on that loss, select a heat sink that will keep the Tj within the required limits.
If the IGBT module is not sufficiently cooled, the junction temperature may exceed Tj (max.) during operation and destroy the module.
For more information on IGBT power loss calculations and heat sink selection methods, refer to Chapter 6 of this manual.

6 Designing drive circuits

It cannot be emphasized enough, that it is the design of the drive circuit that ultimately determines the performance of the IGBT. It is important that drive circuit design is also closely linked to protection circuit design.
Drive circuits consist of a forward bias voltage section to turn the IGBT on and a reverse bias voltage section to accelerate and maintain turn-off. Remember that the characteristics of the IGBT change in accordance with the conditions of the circuit. Also, if the circuit is wired improperly, it may cause the module to malfunction.
For more information on how to design the best drive circuits, refer to Chapter 7 of this manual.

7 Parallel connection

In high capacity inverters and other equipment that needs to control large currents, it may be necessary to connect IGBT modules in parallel.
When connected in parallel, it is important that the circuit design allows for an even flow of current to each of the modules. If the current is not balanced among the IGBTs, a high current may build up in just one device and destroy it.
The electrical characteristics of the module as well as the wiring design change the balance of the current between parallel connected IGBTs. In order to maintain the balance it may be necessary, for example, to match the VCE(sat) values of all the devices.
For more detailed information on parallel connections, refer to Chapter 8 of this manual.

3.8: Mounting Notes
3.9: Storage and Transportation Notes
3.10: Additional Points

8 Mounting notes

When mounting IGBT modules in designated equipment, note the following points:

1) When mounting an IGBT module on a heat sink, first apply a thermal compound to the module's base and then secure it properly to the heat sink by tightening the specified screws using the recommended torque.
   Use a heat sink with a mounting surface finished to a roughness of 10μm or less and a flatness of 100μm or less between screw mounting pitches.
   For more details, refer to Chapter 6 of this manual.
2) Avoid wiring designs that place too much stress on the module's electrical terminals.

9 Storage and transportation notes

9.1 Storage

1) The IGBT modules should be stored at a standard temperature of 5 to 35°C and humidity of 45 to 75%.
   If the storage area is very dry, a humidifier may be required. In such a case, use only deionized water or boiled water, since the chlorine in tap water may corrode the module terminals.
2) Avoid exposure to corrosive gases and dust.
3) Rapid temperature changes may cause condensation on the module surface. Therefore, store modules in a place with few temperature changes.
4) While in storage, it is important that nothing be loaded on top of the modules, since this may cause excessive external force on the case.
5) Store modules with unprocessed terminals. Rust may cause presoldered connections to go bad during later processing.
6) Use only antistatic containers for storing IGBT modules.

9.2 Transportation

1) Do not drop or otherwise shock the modules.
2) When transporting several modules in the same box or container, insert soft spacers between IGBTs in order to protect the terminals and to keep the modules from shifting.

10 Additional points

1) When only using an FWD (in a chopper circuit for example), apply a –5V or more (max.–20V) reverse bias voltage between the gate and emitter of the unused IGBT.
2) To confirm whether or not the prescribed voltage is being applied, measure the IGBT's drive voltage at the module's terminals. (If the voltage drop in the drive circuit gets very big, it may mean that the prescribed V_{GE} is not being applied to the IGBT.)
3) Only the IGBT's terminals are necessary to measure the turn-on and turn-off surge voltage.

Chapter 4

Troubleshooting

CONTENTS

4.1: Failure Analysis

1 Failure analysis

As an example, incorrect wiring or mounting of an IGBT in an inverter circuit may cause the module to be destroyed. Once some sort of trouble like the above example has appeared, it is important to first determine the cause of the problem, and then to take the necessary corrective action. Table 1 below, illustrates how to determine a module's failure modes as well as the original causes of the trouble by observing irregularities outside of the device.

Diagram "IGBT module failure analysis" (page 4-4 to 4-6), on the other hand, shows how to analyze module failures. If a module fails, this diagram will illustrate the cause of the problem from a different perspective. Therefore, in the event of any trouble, refer to Table 1 and diagram "IGBT module failure analysis" in order to determine the causes and the appropriate countermeasures.

Causes of device failure modes Table 1

External abnormalities		Cause		Device failure mode	Further checkpoints
Short circuit	Arm short circuit	Short circuit destruction of one element		Outside SCSOA	Confirm locus and device ruggedness match during an arm short circuit
	Series arm short circuit	Gate or logic Circuit malfunction	Noise, etc.	Outside SCSOA	Check for circuit malfunction Apply the above
		dv/dt	Insufficient gate reverse bias Gate wiring too long	Overheating	Check for accidental turn-on caused by dv/dt
		Dead time too short	Insufficient gate reverse bias Dead time setting error	Overheating	Check that elements t_{off} and deadtime match
	Output short circuit	Miswiring, abnormal wire contact, or load short circuit		Outside SCSOA	Check conditions at time of failure Check that device ruggedness and protection circuit match Check wiring condition
	Ground short	Miswiring, abnormal wire contact		Outside SCSOA	
Overload		Logic circuit malfunction Overcurrent protection circuit setting error		Overheating	Check that overload current and gate voltage match If necessary, adjust overcurrent protection level
Over-voltage	Excessive	Excessive input voltage Insufficient overvoltage protection		Avalanche Overvoltage	If necessary, adjust overvoltage protection level
	Excessive spike voltage	High di/dt resulting from switching turn-off		Outside RBSOA	Check that turn-off operation loci and RBSOA match If necessary, adjust snubber circuit
		High di/dt resulting from FWD commutation		Avalanche Overvoltage	Check that spike voltage and device ruggedness match If necessary, adjust snubber circuit
Drive supply voltage drop		DC-DC converter malfunction		Overheating	Check circuit
		Drive voltage rise is too slow			
		Disconnected wire			
Gate overvoltage		Static electricity Spike voltage due to excessive length of gate wiring		Avalanche Overvoltage	Check operating conditions (anti-static protection) Check gate voltage
Over-heating	Overheating	Loose terminal screw or cooling fan shut down		Overheating	Check cooling conditions Check logic circuit
	Thermal runaway	Logic circuit malfunction			Logic circuit malfunction

4.2: IGBT Test Procedures

2 IGBT test procedures

The following conditions of an IGBT can be measured with a transistor curve tracer:

① Leakage current between gate and emitter, and threshold voltage between gate and emitter
② Short circuit, breakdown voltage, open circuit between collector and emitter (Short gate and emitter.)
③ Output characteristic (V_{CE}-I_C with V_{GE}, V_F-I_F)

If a curve tracer is not available, the above items are easy to check with a V-ohm multimeter.

① Resistance measurement between gate and emitter

Short collector and emitter and measure the gate ⇒ emitter and emitter ⇒ gate resistances. (The battery voltage of the multimeter must be 20V or less.) If the resistance is ∞, the IGBT is normal.

② Resistance measurement between collector and emitter

Short gate and emitter and measure the resistance between collector and emitter (when current flows from the collector to the emitter). If the resistance is only several ohms, there is a short circuit between collector and emitter, and the IGBT is faulty.

Do not measure the withstand voltage between the collector and gate. Such a measurement may destroy the insulation of the oxide film which creates the Miller Capacitance between the collector and gate.

IGBT module failure analysis

- IGBT module destruction
  - IGBT chip destruction
    - Outside RBSOA → **A**
    - Gate overvoltage → **B**
    - Junction overheating → **C**
  - FWD chip destruction → **D**

A Outside RBSOA

(Presumed origin of failure given after →)

- **Excessive cut-off current** — Excessive turn-off current
  - Overcurrent protection failure → Faulty control PCB
  - Series arm short circuit
    - Gate drive circuit malfunction → Faulty control PCB; Faulty gate drive circuit
    - Insufficient dead-time → Faulty control PCB
  - Output short circuit → Faulty load
  - Ground fault → Faulty load
- **Overvoltage**
  - Excessive supply voltage → Faulty input voltage
  - Motor regeneration → Faulty regeneration circuit
  - Overvoltage protection circuit failure → Faulty control PCB
  - Insufficient snubber discharge
    - Faulty snubber circuit → Disconnected snubber resistor
    - Fall time too short → Faulty gate drive circuit; Faulty control PCB
  - Excessive surge voltage at FWD reverse recovery → **D**

B Gate overvoltage

(Presumed origin of failure given after →)

- **Static electricity** — Still no antistatic protection → Manufacturing fault
- **Spike voltage**
  - Oscillation → Gate wiring too long
  - L · di/dt voltage → Gate wiring too long

C Junction overheating

(Presumed origin of failure shown after →)

- **Static power loss increase**
  - Saturation voltage $V_{CE}(sat)$ increase
    - Insufficient forward bias gate voltage → Faulty gate drive circuit; Faulty power supply control circuit
  - Collector current increase
    - Overcurrent
      - Overcurrent protection circuit failure → Faulty control PCB
      - Series arm short circuit
        - Gate drive circuit malfunction → Faulty control PCB; Faulty gate drive circuit
        - Insufficient dead time → Faulty control PCB
      - Output short circuit → Abnormal load
      - Ground fault → Abnormal load
    - Overload → Faulty control PCB; Abnormal load
- **Switching loss increase**
  - Switching increase
    - Increase in carrier frequency → Faulty control PCB
    - dv/dt malfunction → Faulty snubber circuit; Faulty gate drive circuit
    - Gate drive signal malfunction → Faulty control PCB; Faulty gate drive circuit
  - Increase in turn-on loss
    - Turn-on time increase
      - Insufficient forward bias gate voltage → Faulty gate drive circuit
      - Gate resistance increase → Faulty gate drive circuit
    - Excessive turn-on current
      - Excessive snubber discharge current → Faulty snubber circuit
      - Series arm short circuit — Insufficient dead time → Faulty control PCB
  - Increase in turn-off loss
    - Turn-off time increase
      - Reverse bias gate voltage decrease → Faulty gate drive circuit
      - Gate resistance increase → Faulty gate drive circuit
    - Series arm short circuit
      - Insufficient dead time → Faulty control PCB; Faulty gate drive circuit
- Contact thermal resistance increase
  - Device mounting force insufficient → Insufficient mounting torque
  - Excessive heat sink warping → Bad heat sink warping
  - Unsuitable thermal compound volume → Insufficient adjustment of thermal compound volume
- Rise in case temperature
  - Cooling capability drop
    - Heat sink obstruction → Insufficient dust prevention
    - Cooling fan operation slow or stopped → Faulty cooling fan
  - Abnormal rise in ambient temperature
    - Partial overheating of stack → Faulty cooling system
  - Temperature maintenance equipment failure → Faulty temperature maintenance equipment

D FWD destruction

Presumed origin of failure (last item of each branch)

- **Excessive junction temperature rise**
  - Static loss increase — Overload
    - Power factor drop
    - Abnormal load
    - Faulty PCB
  - Switching loss increase — Switching increase
    - dv/dt malfunction
      - Faulty snubber circuit
      - Gate drive circuit malfunction
    - Gate drive signal malfunction
      - Faulty PCB
      - Gate drive circuit malfunction
    - Increase in carrier frequency — Faulty PCB
  - Contact thermal resistance increase
    - Device mounting force insufficient — Insufficient mounting torque
    - Excessive heat sink warping — Bad heat sink warping
    - Unsuitable thermal compound volume — Insufficient adjustment of thermal compound volume
  - Rise in case temperature
    - Cooling capability drop
      - Heat sink obstruction — Insufficient dust prevention
      - Cooling fan operation slow or stopped — Faulty cooling fan
    - Abnormal rise in ambient temperature — Partial overheating of stack — Faulty cooling system
    - Temperature maintenance equipment failure — Faulty temperature maintenance equipment
- **Overvoltage**
  - Excessive reverse recovery surge voltage — Faulty snubber circuit
    - di/dt increase at turn-on
      - Forward bias gate voltage increase — Gate drive circuit malfunction
      - Gate resistance drop — Gate drive circuit malfunction
  - Excessive surge voltage at IGBT turn-off — A

Chapter 5

Protection Circuit Design

CONTENTS

Page

5.1: Short Circuit (Overcurrent) Protection

1 Short circuit (overcurrent) protection

1.1 Short circuit withstand capability

In the event of a short circuit, first the IGBT's collector current will rise and then, once it has reached a certain level, the C-E voltage will shoot up. Depending on the device's characteristics, during a short-circuit, the collector current can be kept at or below a certain level. However the IGBT will still continue to be subjected to a heavy load of high voltage and high current, and therefore this burden must be removed as soon as possible. The amount of time allowed between the start of a short circuit until the current is cut off, is limited by the IGBT's short circuit withstand capability.

The short-circuit withstand capability, as illustrated in Fig.1, is determined by the amount of time it takes from the outbreak of a short-circuit current until the module is destroyed. The withstand capability of N series IGBTs is as follows:

Short-circuit withstand capability ≧ 15μs minimum

< Conditions >

- V_{CC} 600V series: Ed(V_{CC})=400V
  1200V series: Ed(V_{CC})=800V
- V_{GE} = 15V
- R_G: Recommended R_G value
- Tj = 125°C

The above specifications do not apply to 7MBR10NF120 PIMs.

In general, the higher the supply voltage (Ed) or temperature (Tj) rises, the lower the short-circuit withstand capability.

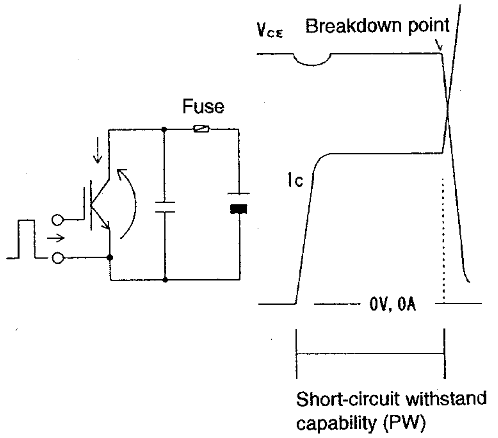


Fig. 1 Measuring circuit and waveform

Normally, in the event of a short-circuit, the collector current will rise as high as the IGBT's output characteristics will allow. However, due to the built in overcurrent limiting feature, during short-circuits, N series IGBTs can hold the collector current to typically, around three times the normal rating.

The overcurrent limit and short-circuit withstand capability are dependent on the gate resistance. When using a gate resistance other than the one recommended by Fuji Electric, it is important to be careful when setting the overcurrent detection value and short-circuit protection cut-off time. The dependence of the overcurrent limit and short circuit withstand capability on the gate resistance is displayed in Fig. 2.

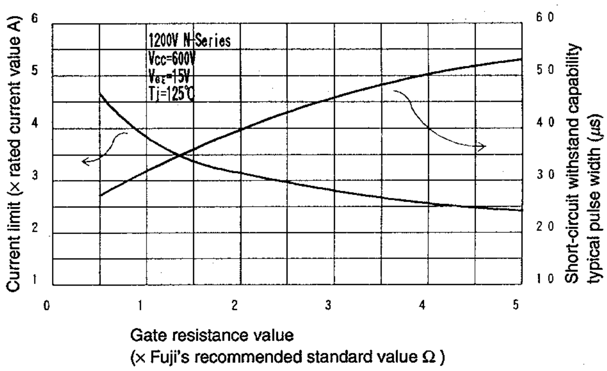
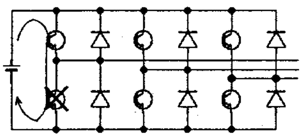
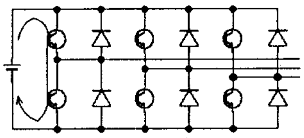
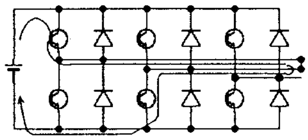
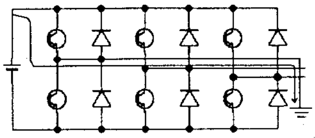


Fig. 2 Dependence of current limit and short-circuit withstand capability on gate resistance

1.2 Short-circuit modes and causes

Table 1 lists the short-circuit modes and causes that occur in inverters.

Short-circuit modes and causes Table 1

Short-circuit mode	Cause
Arm short-circuit 	Transistor or diode destruction
Series arm short-circuit 	Faulty control/drive circuit or noise induced malfunction
Short in output circuit 	Miswiring or dielectric breakdown of load
Ground fault 	Miswiring or dielectric breakdown of load

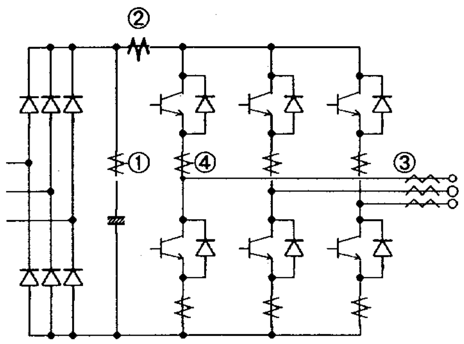
1.3 Short-circuit (overcurrent) detection

1) Detection in the circuit

As stated previously, in the event of a short-circuit, the IGBT must be disabled as soon as possible. Therefore, the delay from overcurrent detection to complete turn-off in each circuit must be made as short as possible.

Since an IGBT turns off very quickly, if the overcurrent is shut off using an ordinary drive signal, then the collector-emitter voltage will rise due to the inductive kick, and the IGBT may be destroyed by overvoltage (RBSOA destruction). Therefore, it is recommended that when cutting off the overcurrent that the IGBT be turned off gently (Soft turn-off).

Figure 3 shows the insertion methods for overcurrent detectors, and Table 2 lists the features of the various methods along with their detection possibilities. After determining what kind of protection is necessary, select the most appropriate form.



Note : /\/\ Overcurrent detectors

Fig. 3 Overcurrent detector insertion methods

Overcurrent detector insertion positions and function Table 2

Detector insertion position	Features	Detection function	
Insertion in line with smoothing capacitor Fig.3/①	• AC current transformer available • Low detection precision	• Arm short-circuit • Short in output circuit	• Series arm short-circuit • Ground fault
Insertion at inverter input Fig.3/②	• Necessary to use DC current transformer • Low detection precision	• Arm short-circuit • Short in output circuit	• Series arm short-circuit • Ground fault
Insertion at inverter output Fig.3/③	• AC current transformer available for high frequency output equipment • High detection precision	• Short in output circuit	• Ground fault
Insertion in line with switches Fig.3/④	• Necessary to use DC current transformer • High detection precision	• Arm short-circuit • Short in output circuit	• Series arm short-circuit • Ground fault

2) Detection using VCE (sat)

This method can protect against all of the short-circuit types listed in Table 1. Since all operations from overcurrent detection to protection are done on the drive circuit side, this offers the fastest protection possible.
A short-circuit protection circuit schematic, based on VCE(sat) detection, is shown in Fig. 4.

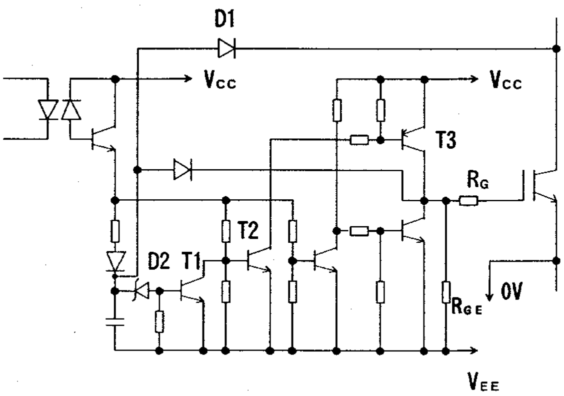
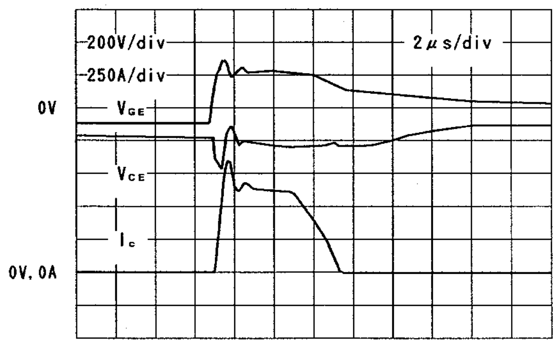


Fig. 4. Short-circuit protection circuit schematic based on VCE(sat) detection

This circuit uses D1 to constantly monitor the collector-emitter voltage, so if during operation the IGBT's collector-emitter voltage rises above the limit at D2, then a short-circuit condition will be detected and T1 will be switched on while T2 and T3 are switched off. At this time, the accumulated charge at the gate is slowly released through the RGE, so a large voltage spike is prevented when the IGBT is turned off.
Fuji Electric's gate driver hybrid ICs (model EXB840, 841) have the same kind of protective circuit built in, thereby simplifying the drive circuit design. For more details, refer to Chapter 7 "Drive circuit design" of this manual. The waveforms showing an IGBT being protected from a short circuit can be seen in Fig. 5.



Ed(VCC) = 800V
VGE = +15V, –5V(EXB841)
RG = 9.1Ω
Tj = 25°C

VCE: 200V/div
IC: 250A/div
VGE: 10V/div

Fig. 5 Waveforms during short-circuit protection

2 Overvoltage protection

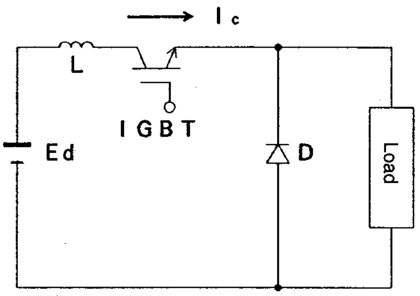
2.1 Overvoltage causes and their suppression

1) Overvoltage causes

Due to the high switching speed of IGBTs, at IGBT turn-off or during FWD reverse recovery, the current change rate (di/dt) is very high. Therefore the inductance of the wiring surrounding the module can cause a turn-off surge voltage (V=L(di/dt))

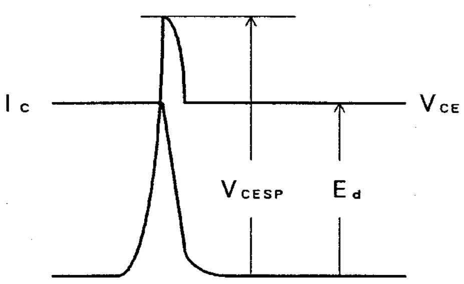
At this point, using the IGBT's wave form at turn off as an example, we will introduce the causes and methods of their suppression, as well as illustrate a concrete example of a circuit (Using an IGBT and FWD together).

To demonstrate the turn off surge voltage, a simplified chopper circuit is shown in Fig. 6, and the IGBT turn-off voltage and current wave forms are shown in Fig. 7.



Ed(V_{CC}): DC supply voltage
L: Main circuit wiring inductance
D: Free wheel diode
Load: L, R

Fig. 6 Chopper circuit



V_{CE}: IGBT collector-emitter voltage
V_{CESP}: Turn-off surge voltage peak value
I_C: IGBT collector current

Fig. 7 Turn-off current and voltage wave forms

The turn-off surge voltage peak can be calculated as follows:

$V_{CESP} = Ed + (-L * dI_C/dt)$ .... ①

dI_C/dt : Maximum collector current change rate at turn-off

If V_{CESP} exceeds the IGBT's C-E (V_{CES}) rating, then the module will be destroyed.

2) Overvoltage suppression methods

Several methods for suppressing turn-off surge voltage, the cause of overvoltage, are listed below.

a. Control the surge voltage by adding a protection circuit (= snubber circuit) to the IGBT. Use a film capacitor in the snubber circuit, and then set it near the IGBT in order to bypass high frequency surge currents.
b. Adjust the IGBT drive circuit's $-V_{GE}$ or R_G in order to reduce the di/dt value. (Refer to Chapter 7, "Drive Circuit Design", of this manual.)
c. Set the electrolytic capacitor as close as possible to the IGBT in order to reduce the effective inductance of the wiring. Using a low impedance capacitor is the most effective.
d. To reduce the inductance of the main as well as snubber circuit's wiring, use thicker and shorter wires. It is also very effective to use laminated copper bars in the wiring.

2.2 Types of snubber circuits and their features

Snubber circuits can be classified into two types: individual and lump. Individual snubber circuits are connected to each IGBT, while lump snubber circuits are connected between the DC power-supply bus and the ground for centralized protection.

1) Individual snubber circuits

Examples of typical individual snubber circuits are listed below.

a. RC snubber circuit
b. Charge and discharge RCD snubber circuit
c. Discharge-suppressing RCD snubber circuit

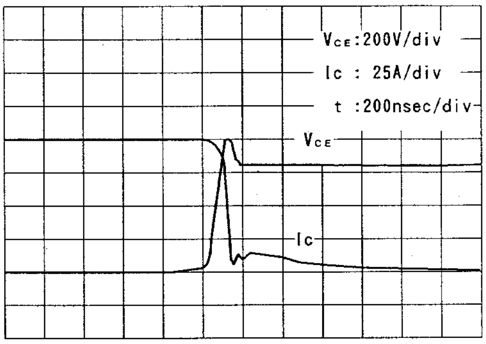
Table 3 shows the schematic of each type of individual snubber circuit, its features, and an outline of its main uses.

2) Lump snubber circuits

Examples of typical lump snubber circuits are listed below.

a. C snubber circuits
b. RCD snubber circuits

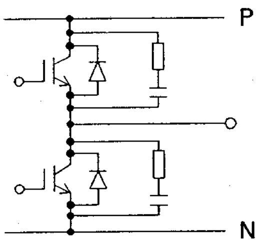
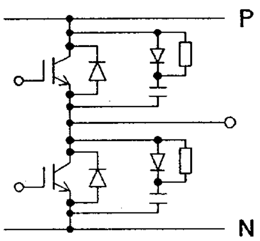
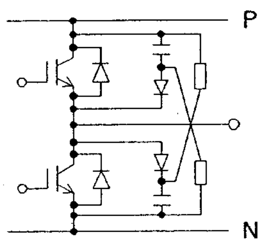
Recently, in an effort at snubber circuit simplification, lump snubber circuits are becoming increasingly popular. Table 4 shows the schematic of each type of lump snubber circuit, its features, and an outline of its main applications. Table 5 shows how to determine the capacity of a C type snubber circuit and Fig. 8 shows the current and voltage wave forms at turn-off of an IGBT connected to a lump snubber circuit.



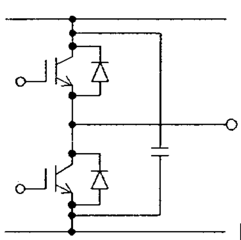
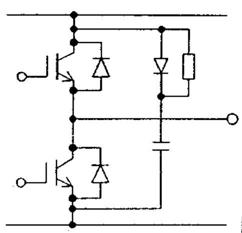
Ed(Vcc) = 600V
V_{GE} = +15V, −15V
RG = 9.1Ω
Tj = 25°C   Cs=0.47μF

Fig. 8 Current and voltage waveforms of IGBT in lump snubber circuit at turn-off

Individual snubber circuits Table 3

Snubber circuit schematic	Features (Points of caution)	Main application
RC snubber circuit  	• The effect on turn-off surge voltage suppression is great. • Perfect for chopper circuits • When applied to large capacity IGBTs, the snubber's resistance must be low. Consequently however, the above makes the load conditions at turn-on more severe.	Arc welder Switching power supply
Charge and discharge RCD snubber circuit  	• The effect on turn-off surge voltage is moderate. • As opposed to the RC snubber circuit, here, a snubber diode has been added. This allows the snubber's resistance to increase and consequently avoids the IGBT load conditions at turn-on problem. • Since the power dissipation loss of this circuit (primarily caused by the snubber's resistance) is much greater than that of a discharge suppressing snubber circuit, it is not considered suitable for high frequency switching applications. • The power dissipation loss caused by the resistance of this circuit can be calculated as follows: $P = \frac{L*Io^2*f}{2} + \frac{Cs*Ed^2*f}{2}$ L: Wiring inductance of main circuit Io: Collector current at IGBT turn-off Cs: Capacitance of snubber capacitor Ed: DC supply voltage f: Switching frequency	
Discharge suppressing RCD snubber circuit  	• The effect on turn-off surge voltage is small. • Suitable for high frequency switching. • Power dissipation loss caused by snubber circuit is small. • The power dissipation loss caused by the resistance of this circuit can be calculated as follows: $P = \frac{L*Io^2*f}{2}$ L: Wiring inductance of main circuit Io: Collector current at IGBT turn-off f: Switching frequency	Inverter

Lump snubber circuits Table 4

Snubber circuit schematic	Features (Points of caution)	Main application
C snubber circuit 	• This is the simplest circuit • The LC resonance circuit, which consists of a main circuit inductance coil and snubber capacitor, may cause the C-E voltage to oscillate.	Inverter
RCD snubber circuit 	• If the wrong snubber diode is used, a high spike voltage will be generated and the output voltage will oscillate at the diodes reverse recovery.	Inverter

Guidelines for determining lump C snubber circuit capacity Table 5

Module ratings \ Item		Drive conditions –VGE (V)	Drive conditions RG (Ω)	Main circuit wiring inductance (μH)	Capacitance of snubber capacitor Cs (μF)
600V	50A	≦15	≧51	—	0.47
	75A		≧33		
	100A		≧24		
	150A		≧16	≦0.2	1.5
	200A		≧9.1	≦0.16	2.2
	300A		≧6.8	≦0.1	3.3
	400A		≧4.7	≦0.08	4.7
1200V	50A	≦15	≧24	—	0.47
	75A		≧16		
	100A		≧9.1		
	150A		≧5.6	≦0.2	1.5
	200A		≧4.7	≦0.16	2.2
	300A		≧2.7	≦0.1	3.3

2.3 Discharge-suppressing RCD snubber circuit design

The discharge suppressing RCD can be considered the most suitable snubber circuit for IGBTs. Basic design methods for this type of circuit are explained in the following.

1) Study of applicability

Figure 9 is a diagram of the operating locus of an IGBT in a discharge-suppressing RCD snubber circuit at turn-off. Fig.10 shows the current and voltage waveforms at IGBT turn-off.

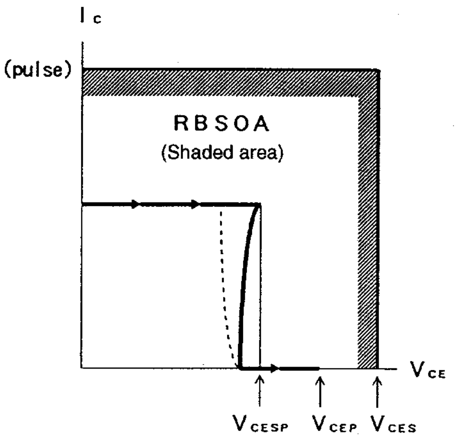


Fig. 9 Operating locus at IGBT turn-off

The discharge-suppressing RCD snubber circuit is activated when the IGBT C-E voltage starts to exceed the DC supply voltage. The dotted line in the above diagram (Fig. 9) shows the ideal operating locus of an IGBT.
In an actual application, the wiring inductance of the snubber circuit or a transient forward voltage drop in the snubber diode can cause a spike voltage at IGBT turn-off. This spike voltage causes the sharp-cornered locus indicated by the solid line in Fig. 9.

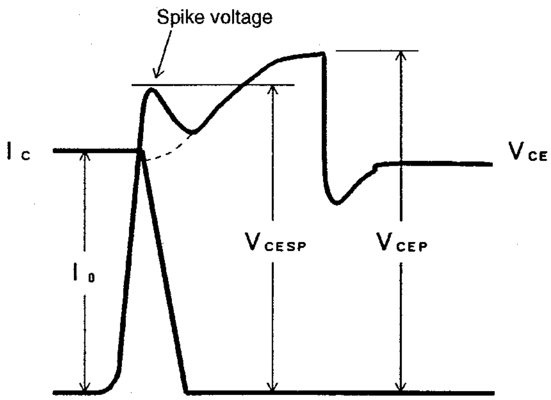


Fig. 10 Voltage and current waveforms at turn-off

The discharge-suppressing RCD snubber circuits applicability is decided by whether or not the IGBT's operating locus is within the RBSOA at turn-off.

The spike voltage at IGBT turn-off is calculated as follows:

$V_{CESP}=Ed+V_{FM}+(-L_S*dIc/dt)$ .... ②

Ed: Dc supply voltage
V_{FM}: Transient forward voltage drop in snubber diode*
L_S: Snubber circuit wiring inductance
dIc/dt: Maximum collector current change rate at IGBT turn-off

* The reference values for the transient forward voltage drop in snubber diodes is as follows:
600V class: 20 to 30V
1200V class: 40 to 60V

2) Calculating the capacitance of the snubber capacitor (Cs)

The necessary capacitance of a snubber capacitor is calculated as follows:

$$C_S = \frac{L * I_O^2}{(V_{CEP} - Ed)^2} \quad \text{......} ③$$

L: Main circuit wiring inductance
Io: Collector current at IGBT turn-off
VCEP: Snubber capacitor peak voltage
Ed: DC supply voltage

V_{CEP} must be limited to less than or equal to the IGBT C-E withstand voltage.

3) Calculating snubber resistance (Rs)

The function required of snubber resistance is to discharge the electric charge accumulated in the snubber capacitor before the next IGBT turn-off.
To discharge 90% of the accumulated energy by the next IGBT turn-off, the snubber resistance must be as follows:

$$R_S \leqq \frac{1}{2.3 * C_S * f} \quad \text{......} ④$$

f : Switching frequency

If the snubber resistance is set too low, the snubber circuit current will oscillate and the peak collector current at IGBT turn-off will increase. Therefore, set the snubber resistance in a range below the value calculated in equation ④.
Irrespective of the resistance, the power dissipation loss P (Rs) is calculated as follows:

$$P(R_S) = \frac{L * I_O^2 * f}{2} \quad \text{......} ⑤$$

4) Snubber diode selection

A transient forward voltage drop in the snubber diode is one of the factors that can cause a spike voltage at IGBT turn-off.
If the reverse recovery time of the snubber diode is too long, then the power dissipation loss is also much greater during high frequency switching. If the snubber diode's reverse recovery is too hard, then the IGBT C-E voltage will drastically oscillate.

Select a snubber diode that has a low transient forward voltage, short reverse recovery time and a soft recovery.

5) Snubber circuit wiring precautions

The snubber circuit's wiring inductance is one of the main causes of spike voltages, therefore it is important to design the circuit with the lowest inductance possible.

Chapter 6

Cooling Design

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6.1: Power Dissipation LossCalculation

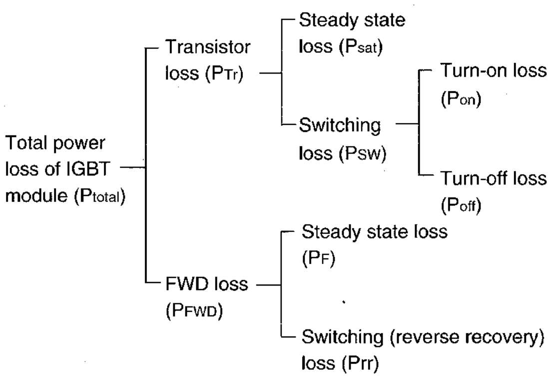
For safe IGBT operation, the junction temperature (Tj) must never exceed Tj(max). Therefore, it is necessary to have a cooling design capable of keeping the junction temperature below Tj(max), even during overload conditions.

1 Power dissipation loss calculation

1.1 Types of power loss

An IGBT module consists of IGBT chips and FWD chips. The sum of the power losses from these sections equals the total power loss for the module. Power loss can be classified as either steady state loss or switching loss. A diagram of the power loss factors is shown as follows.

Power loss factors



The steady state power loss from the IGBT and FWD sections can be calculated using the output characteristics, while switching loss can be calculated from switching loss vs. collector current characteristics. Use these power loss calculations in order to design cooling sufficient to keep the junction temperature Tj below the maximum rated value. The on-voltage and switching loss values to be used here, are based on the standard junction temperature Tj (125°C is recommended).
For characteristics data, refer to the module specification sheets.

1.2 DC chopper circuit power loss calculations

For easy approximate calculations, consider the current flowing to the IGBT or FWD as a train of square waves. Figure 2 is a diagram showing the approximate waveforms of a DC chopper circuit. At collector current I_C, the saturation voltage is represented by $V_{CE}(sat)$ and switching energy is represented by Eon, and Eoff. At FWD forward current I_F, V_F represents the on-voltage and Err represents the energy loss during reverse recovery. Using the above parameters, IGBT power loss can be calculated as follows:

IGBT power dissipation loss (w)
= Steady state loss + Turn-on loss + Turn-off loss
= [t1/t2 * V_{CE}(sat) * Ic] + [fc * (Eon + Eoff)]

FWD power dissipation loss (w)
= Steady state loss + Reverse recovery loss
= [(1−(t1/t2)) * I_F * V_F] + [fc * Err]

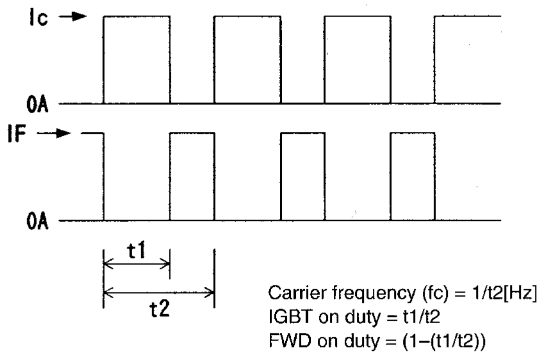


Fig. 1 DC chopper circuit current waveforms

The DC supply voltage, gate resistance, and other circuit parameters, may deviate from the standard values listed in the module specification sheets. In this event, approximate values can be calculated according to the following rules.

- DC supply voltage Ed(V_{CC}) deviation
  On voltage: Not depencent on Ed(V_{CC})
  Switching loss: Proportional to Ed(V_{CC})

- Gate resistance deviation
  On voltage: Not dependent on gate resistance
  Switching loss: Proportional to switching time and dependent on gate resistance

1.3 Sine-wave VVVF inverter application power dissipation loss calculation

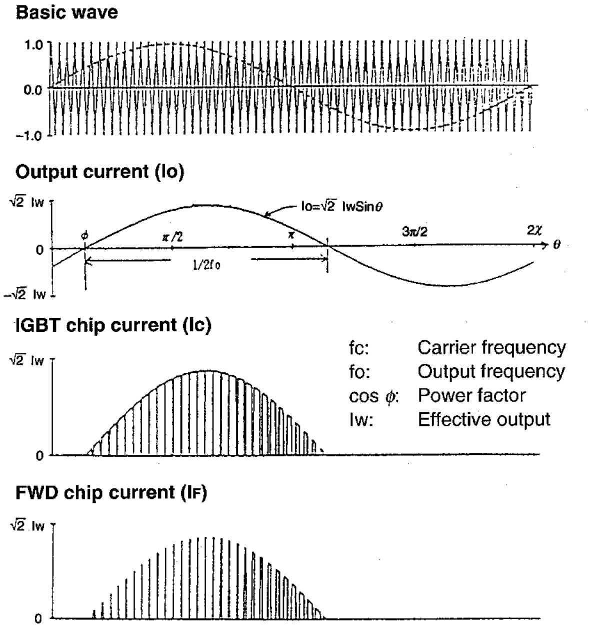


Fig. 2 PWM inverter output current

When using a VVVF inverter for a PWM control, the current value and operation pattern keep changing as shown in Fig. 3. Therefore, it is necessary to use computer simulations in order to make detailed power loss calculations. However, since computer simulations are very complicated, the following is an explanation of a simple method that generates approximate values.

1) Prerequisites

For approximate power loss calculations, the following prerequisites are necessary:

- Three-phase PWM-control VVVF inverter for sine-wave current output
- PWM control based on the comparison of sine-waves and sawtooth waves
- Output current in ideal sine-wave form

2) Calculating steady state power loss (P_{sat}, P_F)

As displayed below (Fig. 3), the output characteristics of the IGBT and FWD have been approximated based on the data contained in the module specification sheets.

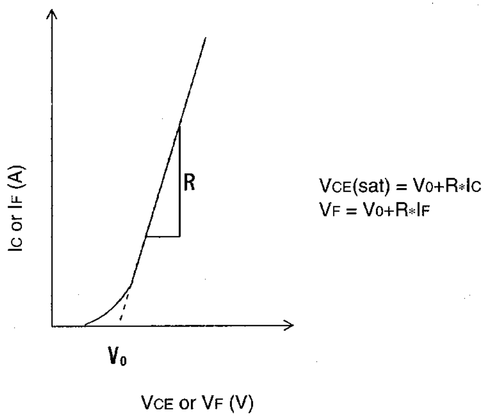


Fig. 3 Approximate output characteristics

Steady state power loss can be calculated as follows:
Steady state power loss in IGBT chip (P_{sat})

$$= DT\int_0^{\pi} I_C V_{CE}(sat)d\theta$$

$$= \frac{1}{2} DT \left[\frac{2\sqrt{2}}{\pi} I_M V_0 + I_M^2 R\right]$$

Steady state power loss in FWD chip (P_F)

$$= \frac{1}{2} DF \left[\frac{2\sqrt{2}}{\pi} I_M V_0 + I_M^2 R\right]$$

DT, DF: Average conductivity of the IGBT and FWD at a half wave of the output current. (Refer to Fig. 4)

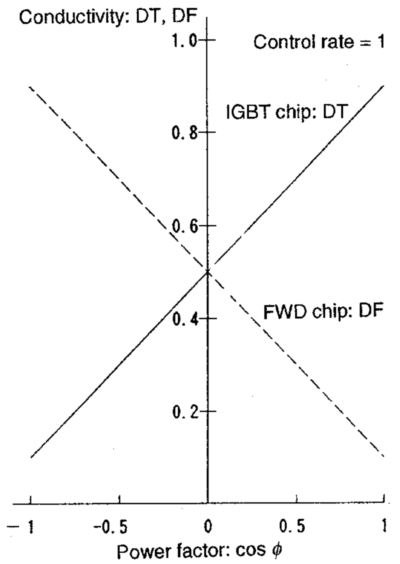


Fig. 4 Relationship between power factor of a sine-wave PWM inverter and conductivity

3) Calculating switching loss

The characteristics of switching loss vs. Ic are generally approximated using the following equations and Fig. 5 (Module specification sheet data).

$Eon = Eon'(Ic/\text{rated } Ic)^a$
$Eoff = Eoff'(Ic/\text{rated } Ic)^b$
$Err = Err'(Ic/\text{rated } Ic)^c$

a, b, c: Multiplier
Eon', Eoff', Err': Eon, Eoff and Err at rated Ic

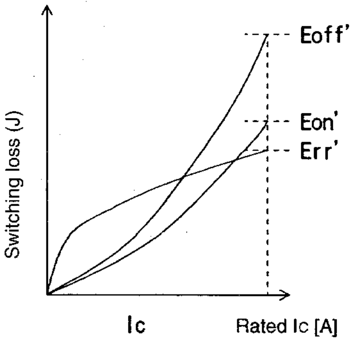


Fig. 5 Approximate switching loss

The switching loss can be represented as follows:

• Turn-on loss (Pon)

$$Pon = fo \sum_{k=1}^{n} (Eon)_k \quad \left(\text{n: Half-cycle switching count}=\frac{fc}{2\,fo}\right)$$

$$= fo\, Eon' \frac{1}{\text{Rated } Ic^a} \sum_{k=1}^{n} (Ic^a)_k$$

$$= fo\, Eon' \frac{n}{\text{Rated } Ic^a \times \pi} \int_0^{\pi} \sqrt{2}\, I_M{}^a \sin\theta \, d\theta$$

$$\fallingdotseq fo\, Eon' \frac{1}{\text{Rated } Ic^a}\, n\, I_M{}^a$$

$$= \frac{1}{2} fc\, Eon' \left[\frac{I_M}{\text{Rated } Ic}\right]^a$$

$$= \frac{1}{2} fc\, Eon\, (I_M)$$

$Eon(I_M)$: Ic = Eon at I_M

• Turn-off loss (Poff)

$$Poff \fallingdotseq \frac{1}{2} fc\, Eoff\, (I_M)$$

$Eoff(I_M)$:Ic=Eoff at I_M

• FWD reverse recovery loss (Prr)

$$Poff \fallingdotseq \frac{1}{2} fc\, Err\, (I_M)$$

$Err(I_M)$:Ic=Err at I_M

4) Calculating total power loss

Using the results obtained in 2) and 3),
The IGBT chip power loss: P_{Tr} = Psat + Pon + Poff
The FWD chip power loss: $P_{FWD} = P_F + P_{rr}$

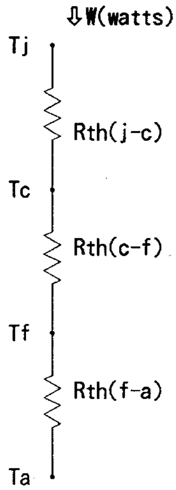
The DC supply voltage, gate resistance, and other circuit parameters will differ from the standard values listed in the module specification sheets.
Nevertheless, by applying the instructions of this section, the actual values can easily be calculated.

2 Selecting heat sinks

Most power diodes, IGBTs, transistors and other power devices, are designed to be insulated between electrodes and mounting bases. This type of module can be mounted and wired compactly in a variety of equipment, because several devices can be mounted on a single heat sink. However, in order to ensure safe operation, the power loss (heat) generated by each module must be dissipated efficiently. This is why heat sink selection is very important. The basics of heat sink selection will be illustrated in the following.

2.1 Thermal equations for steady state power loss calculations

The heat conduction of a semiconductor can be simulated in an electric circuit. For this example, with only one IGBT module mounted on the heat sink, the equivalent circuit is shown in Fig.6.



W : Module power loss
Tj : Junction temperature of IGBT chip
Tc : Module case temperature
Tf : Temperature of heat sink (Temperature closest to the mounting position of the module)
Ta : Ambient temperature
Rth(j-c): Thermal resistance between junction and case
Rth(c-f): Contact thermal resistance between case and heat sink
Rth(f-a): Thermal resistance between heat sink and ambient air

Fig. 6 Thermal resistance equivalent circuit

Using the above equivalent circuit, the junction temperature (Tj) can be calculated using the following thermal equation:

$$Tj = W * \left\{ Rth(j\text{-}c) + Rth(c\text{-}f) + Rth(f\text{-}a) \right\} + Ta$$

Note that the case temperature (Tc) and heat sink surface temperature mentioned here are measured from the base of the IGBT module directly below the chip. As shown in Fig. 7, the temperature measurements at all other points may be low due to the heat dissipation capability of the heat sink, and this needs to be taken into consideration during final heat sink selection.

Next, the equivalent circuit of an IGBT (2-pack module) and a diode bridge mounted on a heat sink is shown in Fig. 8. The thermal equations in this case are as follows:

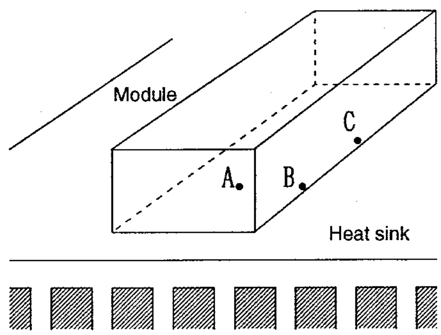
$$Tj(d) = Wd * [Rth(j\text{-}c)d + Rth(c\text{-}f)d] + [(Wd + 2WT + 2WD) * Rth(f\text{-}a)] + Ta$$

$$Tj(T) = WT * Rth(j\text{-}c)T + [(WT + WD) * Rth(c\text{-}f)T] + [(Wd + 2WT + 2WD) * Rth(f\text{-}a)] + Ta$$

$$Tj(D) = WD * Rth(j\text{-}c)D + [(WT + WD) * Rth(c\text{-}f)T] + [(Wd + 2WT + 2WD) * Rth(f\text{-}a)] + Ta$$

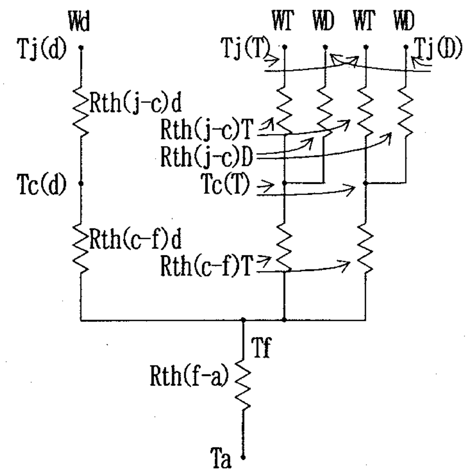
Use the above equations in order to select a heat sink that can keep the junction temperature (Tj) below Tj(max).

A: Directly below the chip on the base
B: Base, 14mm from point A
C: Base, 24mm from point A



	Point A	Point B	Point C
Case temperature Tc(°C)	51.9	40.2	31.4
Heat sink temperature Tf(°C)	45.4	36.9	30.2

Fig. 7 Example of case and heat sink temperature measurements



Wd, Tj(d), Tc(d), Rth( )d: Diode bridge (For one module)
WT, Tj(T), Tc(T), Rth( )T: IGBT(Each element)
WD, Tj(D), Tc(T), Rth( )D: FWD (Each element)

Fig. 8 Thermal resistance equivalent circuit

2.2 Thermal equations for transient power loss calculations

In general, as before, it is all right to base the steady state Tj on the average power loss. However, in actuality, repetitive switching causes power loss to pulse and the occurrence of temperature ripples as shown in Fig. 10. First consider the power loss as a train of constant cycles and constant-peak square pulses. Then calculate the approximate peak of the temperature ripples using the transient thermal resistance curve given in the module specification sheets.
Be certain to select a heat sink that will also keep the Tjp below Tj(max).

$$Tjp - Tc = P * [R(\infty) * \frac{t1}{t2} + (1 - \frac{t1}{t2}) * R(t1+t2) - R(t2) + R(t1)]$$

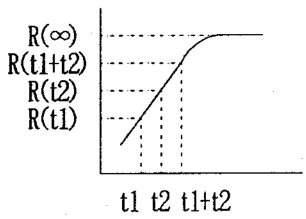


Fig. 9 Transient thermal resistance curve

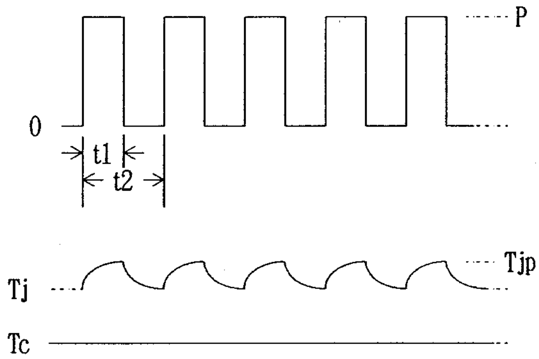


Fig. 10 Thermal ripples

6.3: Heat Sink Mounting Precausions

3 Heat sink mounting precautions

3.1 Heat sink mounting

Since thermal resistance varies according to an IGBT's mounting position, pay attention to the following points:

- When mounting only one IGBT module, position it in the exact center of the heat sink in order to minimize thermal resistance.
- When mounting several IGBT modules, determine the individual positions on the heat sink according to the amount of heat that each module generates. Allow more room for modules that generate more heat.

3.2 Heat sink surface finishing

The mounting surface of the heat sink should be finished to a roughness of 10μm or less and a warp between screw holes of 100μm or less. If the surface of the heat sink is not flat enough, there will be a sharp increase in the contact thermal resistance(Rth(c-f)). If the flatness of the heat sink does not meet the above requirements, then attaching (clamping) an IGBT to it will place extreme stress on the DBC substrate situated between the module's chips and metal base, possibly destroying this insulating barrier.

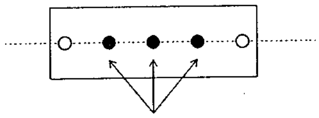
3.3 Thermal compound application

To reduce contact thermal resistance, we recommend applying a thermal compound between the heat sink and the IGBT's base plate. When applying the thermal compound, either to the heat sink or the module's base, do so as shown in the diagram below. When the module is screwed down, the thermal compound will spread and force out any air, thereby ensuring an even contact. Possible thermal compounds are listed below:

Product name	Manufacturer
G746	Shin-Etsu Chemical Co., Ltd.
SC102	Toray Dow-Corning Co., Ltd.
YG6260	Toshiba Silicone Co., Ltd.

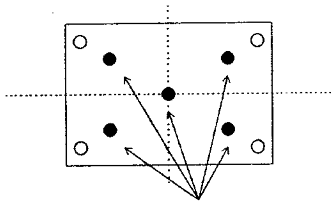
Thermal compound application

- **Two-point module mounting**



Thermal compound (approx. 0.5g)

- **Four-point module mounting**

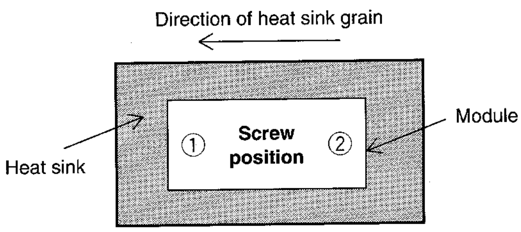


Thermal compound (approx. 0.5g)

3.4 Mounting procedure

Figure 11 and 12 diagrams are showing how to tighten an IGBT module's mounting screws. Each screw must be tightened using a specified torque. For the proper tightening torque, refer to the module specification sheets. An insufficient tightening torque may cause the contact thermal resistance to increase or the screws to come loose during operation. Conversely, an excessive tightening torque may damage the IGBT's case.

- **Two point mounting**

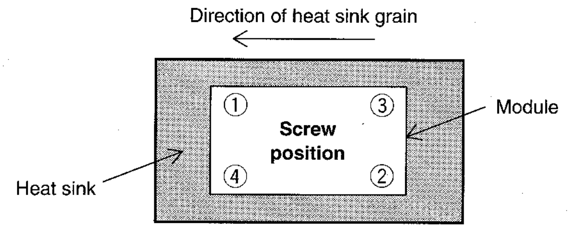


Clamping

	Torque	Sequence
Initial	1/3 specified torque	①→②
Final	Full specified torque	②→①

Fig. 11 IGBT module clamping

- **Four point mounting**



Clamping

	Torque	Sequence
Initial	1/3 specified torque	①→②→③→④
Final	Full specified torque	④→③→②→①

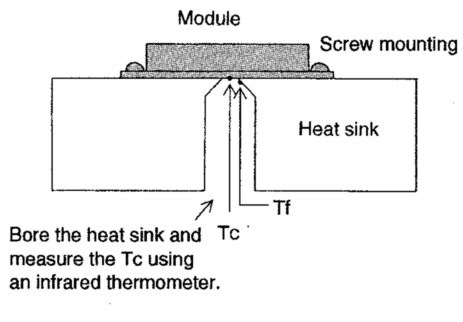
Fig. 12 IGBT module clamping

3.5 IGBT module mounting direction

When mounting the IGBT module, it is recommended to place the module lengthwise in the direction of the heat sink's grain. This reduces the effects of changes in the heat sink's shape.

3.6 Temperature verification

After deciding on a heat sink and mounting positions, measure the temperature of each area, and confirm that the junction temperature (Tj) of each module is within the required range.
For reference, the figure below is a diagram of how to measure the case temperature (Tc).



Chapter 7

Drive Circuit Design

CONTENTS Page

7.1: IGBT Drive Conditions and Main Characteristics

In order to maximize the performance of an IGBT, it is important to properly set the drive circuit constants.

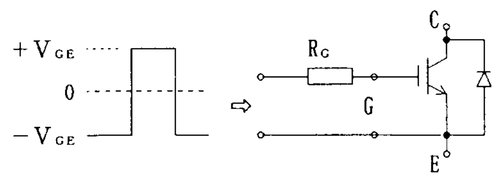
1 IGBT drive conditions and main characteristics

IGBT drive conditions and main characteristics are shown below. An IGBT's main characteristics change according to the values of V_{GE} and R_G, so it is important to use settings appropriate for the intended use of the equipment in which it will be installed.

IGBT drive conditions and main characteristics

Main characteristics	$+V_{GE}$ rise	$-V_{GE}$ rise	R_G rise
$V_{CE(sat)}$	↘	—	—
ton Eon	↘	—	↗
toff Eoff	—	↘	↗
Turn-on surge voltage	↗	—	↘
Turn-off surge voltage	—	↗	↘
dv/dt malfunction	↗	↘	↘
Current limit value	↗	—	↘
Short circuit withstand capability	↘	—	↗

(↗ Rise, ↘ Fall)



1.1 $+V_{GE}$ (On state)

Recommended value: +15V

- Set $+V_{GE}$ so that is remains under the maximum rated G–E voltage, $V_{GES}=\pm 20V$.
- It is recommended that supply voltage fluctuations are kept to within ±10%.
- The on-state C–E saturation voltage ($V_{CE(sat)}$) is inversely dependent on $+V_{GE}$, so the greater the $+V_{GE}$ the smaller the $V_{CE(sat)}$.
- Turn-on switching time and switching loss grows smaller as $+V_{GE}$ rises.
- At turn-on (at FWD reverse recovery), the higher the $+V_{GE}$ the greater the likelihood of surge voltages in opposing arms.
- Even while the IGBT is in the off-state, there may be malfunctions caused by the dv/dt of the FWD's reverse recovery and a pulse collector current may cause unnecessary heat generation. This phenomenon is called a dv/dt shoot through and becomes more likely to occur as $+V_{GE}$ rises.
- In N series IGBTs, the higher the $+V_{GE}$, the higher the current limit becomes.
- The greater the $+V_{GE}$ the smaller the short circuit withstand capability.

1.2 $-V_{GE}$ (Off-state)

Recommended value: −5V to −15V

- Set $-V_{GE}$ so that it remains under the maximum rated G–E voltage, $V_{GES}=\pm 20V$.
- It is recommended that supply voltage fluctuations are kept to within ±10%.
- IGBT turn-off characteristics are heavily dependent on $-V_{GE}$, especially when the collector current is just beginning to switch off. Consequently, the greater the $-V_{GE}$ the shorter the switching time and the smaller the switching loss.
- A high turn-off surge voltage can be controlled by reducing $-V_{GE}$.
- If the $-V_{GE}$ is too small, dv/dt shoot through currents may occur, so at least set it to a value greater than −5V. If the gate wiring is long, then it is especially important to pay attention to this.

1.3 R_G (Gate resistance)

Recommended value:
Listed in the product specification sheets under the heading of switching time.

- The switching characteristics of both turn-on and turn-off are dependent on the value of R_G, and therefore the greater the R_G, the longer the switching time and the greater the switching loss. Also, as R_G increases, the surge voltage during switching becomes smaller.
- The greater the R_G the more unlikely a dv/dt shoot through current becomes.
- N series IGBT modules have a built in overcurrent limiting capability, and this overcurrent limit as well as the short circuit withstand capability are dependent on the value of R_G . The greater the R_G the greater the short circuit withstand capability becomes, but conversely the current limit will drop. Therefore, it is important to set the overcurrent trip level of the equipment the modules will be installed in, to a value below this limit (explained in Fig. 2 of Chapter 5, "Protection Circuit Design").

7.2: Drive Current

1.2 Factors of current imbalances at turn-on and turn-off

The factors of current imbalances at turn-on and turn-off can be divided into module characteristics distribution and main circuit wiring inductance distribution.

1) Module characteristics distribution

An IGBTs' switching current imbalance is mostly determined by an on-state current imbalance, therefore if the on-state current imbalance is controlled, simultaneously, so will the switching voltage imbalance.

2) Main circuit wiring inductance distribution

Since the previously explained effect of resistance on current sharing is much the same as that of inductance on current sharing, inductance can be substituted for resistance in Fig. 2. As the collector current changes very suddenly during IGBT switching, a voltage is generated at both ends of inductance. The polarity of this voltage tends to hamper switching, so the switching time will increase. Therefore, if inductance is not controlled, then switching time will be delayed and the current will be concentrated into one of the modules. In order to reduce this imbalance, it is necessary to make the wiring on the emitter side as short and as uniform as possible.

2 Parallel connections

2.1 Wiring

The ideal parallel connection wiring is "both uniform and short", but when seen from the point of view of equipment mass production, it is often difficult to implement this fully. Therefore, it is necessary to design a layout as close to the ideal as possible. For this purpose, several basic points of caution are illustrated below.

1) Drive circuit wiring

When connecting IGBT modules in parallel, due to the gate circuit's wiring inductance and the IGBT's input capacitance, as the gate voltage rises a parasitic oscillation may occur. Therefore, in order to prevent this oscillation, a gate resistor should be series wired to each of the modules gates. (As illustrated in Fig. 3)

As stated previously, if the drive circuit's emitter wiring is connected in a different position from the main circuit, then the modules' transient current sharing (especially at turn-on) will become imbalanced. However, IGBT modules have an auxiliary emitter terminal for use by drive circuits. By using this terminal, the drive wiring of each module becomes uniform, and transient current imbalances attributed to drive circuit wiring can be controlled. Furthermore, be sure to lead the wiring out from the center of the modules parallel connection, tightly wind it together, and lay it out so that it is as far away from the main circuit as possible in order to avoid mutual induction.

2) Main circuit wiring

As stated previously, if the resistance or the inductance of the main circuit is not uniform, then the current sharing of the modules connected in parallel will be unbalanced. Furthermore, if the inductance of the main circuit is large, then the surge voltage at IGBT turn-off will also be high (for details, refer to Chapter 5, "Protection Circuit Design", of this manual). Therefore, for the purpose of reducing wiring induction and maintaining the temperature balance of each module, consider setting the modules that are to be connected in parallel as close together as possible and making the wiring as uniform as possible.
Also, take out the collector and emitter lead wires from the center of the parallel connection, and, in order to avoid mutual induction, do not wire them in parallel.

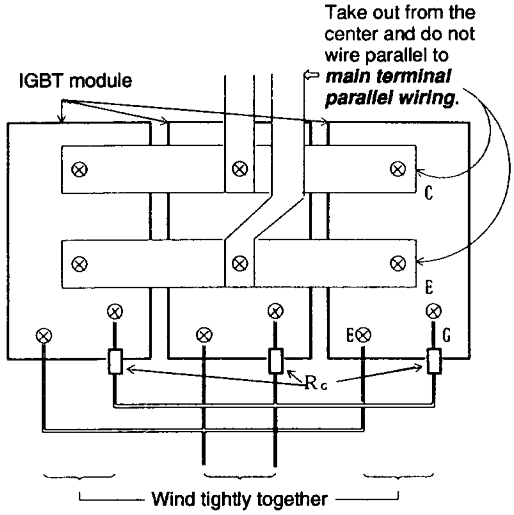


Fig. 3 Parallel connection layout example

7.3: Setting Dead-Time

N series IGBT module internal gate resistance Table 2

Module withstand voltage	Rated current	Internal gate resistance
600V	Up to 150A	0(None)
	200A to 400A	2.5Ω
	600A	1.25Ω
1200V	Up to 75A	0(None)
	100A, 150A	2.5Ω
	200A	2-pack 2.5Ω 1-pack 1.25Ω
	300A	2-pack 1.7Ω 1-pack 1.25Ω
	400A	1.25Ω

The slope of the gate charge characteristics (Refer to each modules technical specification sheets), rising from 0V is essentially the same as that of the input capacitance (Cies), and the reverse bias area can also be considered an extention of this. Therefore, the average value of the drive current I_G, using the gate charge characteristics (Fig.1), can be calculated as follows:

$$+I_G = -I_G = f_c * (Q_g + C_{ies} * |-V_{GE}|)$$

- fc: Carrier frequency
- Qg: Gate charge from 0V to $+V_{GE}$
- Cies: IGBT input capacitance

Consequently, it is important to set the output stage of the drive circuit in order to conduct this approximate current flow (I_{GP}, as well as $\pm I_G$).
Furthermore, If the power dissipation loss of the drive circuit is completely consumed by the gate resistance, then the drive power (Pd) necessary to drive the IGBT is shown in the following formula:

$$Pd(on) = f_c * \left(\frac{1}{2} Q_g\,|+V_{GE}| + \frac{1}{2} C_{ies}\,|-V_{GE}|^2\right)$$

$$Pd(off) = Pd(on)$$

$$Pd = Pd(off) + Pd(on) = f_c * (Q_g\,|+V_{GE}| + C_{ies}\,|-V_{GE}|^2)$$

Accordingly, a gate resistance is necessary that can charge this approximate capacity.

Be sure to design the drive circuit so that the above mentioned drive current and drive power can be properly supplied.

3 Setting dead-time

Recommended value ≧ 3μs
(at recommended drive conditions)

For inverter circuits and the like, it is necessary to set an on-off timing "delay" (dead time) in order to prevent short circuits. During the dead time, both the upper and lower arms are in the "off" state. Basically, the dead time (see Fig 3) needs to be set longer than the IGBT switching time (t_{off} max.). Accordingly, if R_G is increased, switching time also becomes longer, so it would be necessary to lengthen dead time as well. Also, it is necessary to consider other drive conditions as well as the modules distribution and temperature characteristics, etc. (at high temperatures, t_{off} becomes longer).
It is important to be careful with dead times that are too short, because in the event of a short circuit in the upper or lower arms, the heat generated by the short circuit current may destroy the module.

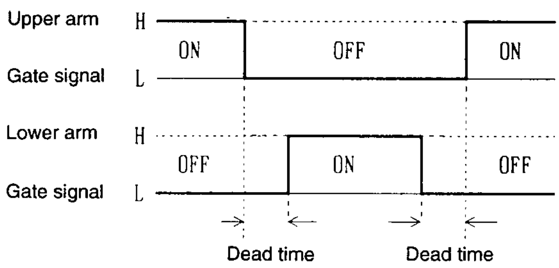


Fig. 3 Dead time timing chart

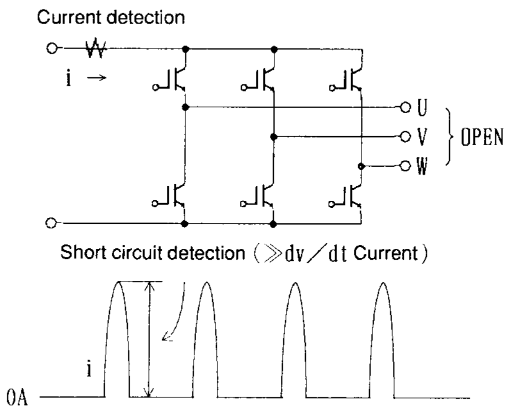


Fig. 4 Current detection methods for short circuits caused by insufficient dead time

7-4: Concrete Examples of Drive Circuits

One method of judging whether or not the dead time setting is sufficient or not, is to check the current of a no-load DC supply line.
In the case of a 3-phase inverter (as shown in Fig. 4), set the inverter's outputs to open, then apply a normal input signal, and finally measure the DC line current. A very small pulse current (dv/dt current leaving out the module's Miller Capacitance: about 5% of the normal rated current) will be observed, even if the dead time is long enough. However, if the dead time is insufficient, then there will be a short circuit current flow much larger than this. In this case, keep increasing the dead time until the short circuit current disappears. Also, for the same reasons stated above, we recommend testing at high temperatures.

4 Concrete examples of drive circuits

For inverter circuits and the like, it is necessary to electrically isolate the IGBT from the control circuit. An example of a drive circuit using this principle, is shown below.
Figure 5 shows an example of a drive circuit using a high speed opto-coupler. By using the opto-coupler, the input signal and the module are isolated from each other. Also, since the opto-coupler does not limit the output pulse width, it is suitable for changing pulse widths for PWM controllers, to wide ranges. It is currntly the most widely used. Furthermore, this way the turn-on and turn-off characteristics determined by gate resistance can be set separately, so it is commonly used to ensure the best settings.

High speed opto-coupler

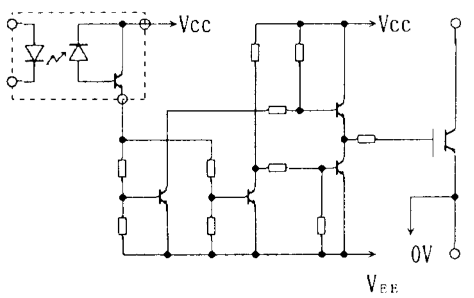


Fig. 5 Example of drive circuit using high speed opto-coupler

Fuji Electric is switching using opto-couplers to implement their Hybrid-ICs. (See Table below.)
Hybrid-ICs can drive with a single power supply, and also have a built in short circuit detection function as well as a soft cutoff circuit enabling them to provide the IGBT reliable protection in the event of a short circuit. For more complete details, refer to the Hybrid-IC Application Manual.
Aside from the above, there is also a signal isolation method using a pulse transformer. With this method the signal as well as the gate drive power can both be supplied simultaneously from the signal side, thereby allowing circuit simplification. However, this method has the limitations of an on/(off+on) time ratio of max. 50% , and reverse bias cannot be set, so its usefulness as a control method and switching frequency regulator is limited.

Hybrid ICs for driving IGBTs

IGBT type / Suitable hybrid IC	600V class Up to 150A 1200V class Up to 75A	600V class 200A to 400A 1200V class 100A to 300A
Medium speed type	EXB850	EXB851
High speed type	EXB840	EXB841
High dv/dt ruggedness	EXB*	EXB*

* The most suitable type for New 3rd-gen. IGBTs is currently under development
Medium speed type: Drive circuit signal transmission delay 4μs max.
High speed type: Drive circuit signal transmission delay 1.5μs max.

7.5: Drive Circuit Setting actual Implementation / Points of Caution

5 Drive circuit setting and actual implementation/Points of caution

5.1 Opto-coupler noise ruggedness

As IGBTs are high speed switching elements, it is necessary to select a opto-coupler for drive circuit that has a high noise ruggedness (e.g. HCPL4504). Also, to prevent malfunctions, make sure that the wiring from different sides doesn't cross. Furthermore, in order to make full use of the IGBT's high speed switching capabilities, we recommend using a opto-coupler with a short signal transmission delay.

5.2 Wiring between drive circuit and IGBT

If the wiring between the drive circuit and the IGBT is long, the IGBT may malfunction due to gate signal oscillation or induced noise. A countermeasure for this is shown below in Fig. 6.

- Make the drive circuit wiring as short as possible and finely twist the gate and emitter wiring. (Twist wiring)
- Increase R_G. However, pay attention to switching time and switching loss.
- Separate the gate wiring and IGBT control circuit wiring as much as possible, and set the layout so that they cross each other (in order to avoid mutual induction).
- Do not bundle together the gate wiring of other phases.

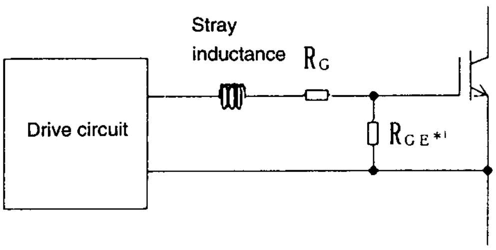


Fig. 6 Gate signal oscillation countermeasure

*1 R_{GE}
If the gate circuit is bad or if the gate circuit is not operating (gate in open state)*2 and a voltage is applied to the power circuit, the IGBT may be destroyed. In order to prevent this destruction, we recommend placing a 10kΩ resistance R_{GE} between the gate and emitter.

*2 Switch-on
When powering up, first switch on the gate circuit power supply and then when it is fully operational, switch on the main circuit power supply.

5.3 Gate overvoltage protection

It is necessary that IGBT modules, like other MOS based elements, are sufficiently protected against static electricity. Also, since the G–E absolute maximum rated voltage is ±20V, if there is a possibility that a voltage greater than this may be applied, then as a protective measure it is necessary to connect a zenner diode between the gate and emitter as shown in Fig. 7.

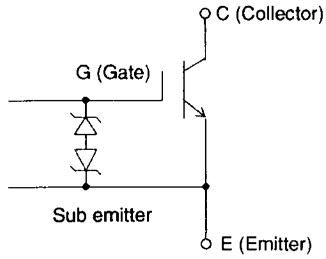


Fig. 7 G—E overvoltage protection circuit example

Chapter 8

Parallel Connections

CONTENTS Page

8.1: Factors that inhibit Current-Sharing

When connecting IGBT modules in parallel, it is necessary to properly manage the elements' characteristics. Otherwise, a current sharing imbalance may occur depend on the characteristics distribution between the parallel connected modules.

1 Factors that inhibit current sharing

1.1 On-state current imbalance

An on-state current imbalance may be caused by the following two factors:

- $V_{CE(sat)}$ distribution
- Main circuit wiring resistance distribution

1) Current imbalance caused by $V_{CE(sat)}$ distribution

As shown in Fig. 1, a difference in the output characteristics of two IGBT modules connected in parallel can cause a current imbalance.

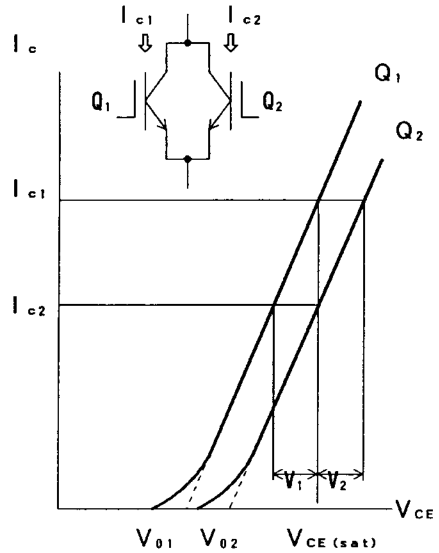


Fig. 1 Example of a $V_{CE(sat)}$ pair

The output characteristics of Q1 and Q2 shown in Fig. 1, can be approximated as follows:

$V_{CEQ1} = V_{01} + r_1 * I_{C1}$

$r_1 = V_1/(I_{C1}-I_{C2})$

$V_{CEQ2} = V_{02} + r_2 * I_{C2}$

$r_2 = V_2/(I_{C1}-I_{C2})$

Based on the above, if the I_{Ctotal} ($=I_{C1}+I_{C2}$) collector current is made to flow through the circuit of Q_1 and Q_2 connected in parallel, then the IGBT's collector current becomes the following:

$I_{C1} = (V_{02} - V_{01} + r_2 \times I_{Ctotal}) / (r_1 + r_2)$

$I_{C2} = (V_{01} - V_{02} + r_1 \times I_{Ctotal}) / (r_1 + r_2)$

and $V_{CE(sat)}$ becomes a major factor in causing current imbalances. Therefore, in order to ensure the desired current sharing, it is necessary to pair modules that have a similar $V_{CE(sat)}$.

2) Main circuit wiring resistance distribution

The effect exerted on current sharing by the main circuit's wiring resistance can be seen in Fig. 2. The effect is larger with emitter resistance than with collector resistance, so collector resistance has been omitted here. If there is resistance in the main circuit, then the parity of the slope of the IGBT modules' output characteristics will lessen, and the collector current will drop. So, depending on how well the collector current can flow through this resistance, an electrical potential difference may appear, the actual gate-emitter voltage drop ($V_{GE} = V-V_E$), the IGBTs' output characteristics change and the collector current decline. Therefore, if $R_{E1}>R_{E2}$, then the slope of the Q_1 output characteristics will lessen and if $I_{C1}<I_{C2}$ then a current sharing imbalance will appear.
In order to reduce this imbalance, it is necessary to make the wiring on the emitter side as short and as uniform as possible.

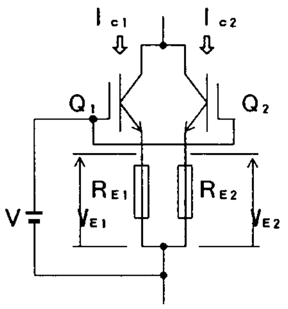


Fig. 2 The effect of main circuit wiring resistance

8.2: Parallel Connections

1.2 Factors of current imbalances at turn-on and turn-off

The factors of current imbalances at turn-on and turn-off can be divided into module characteristics distribution and main circuit wiring inductance distribution.

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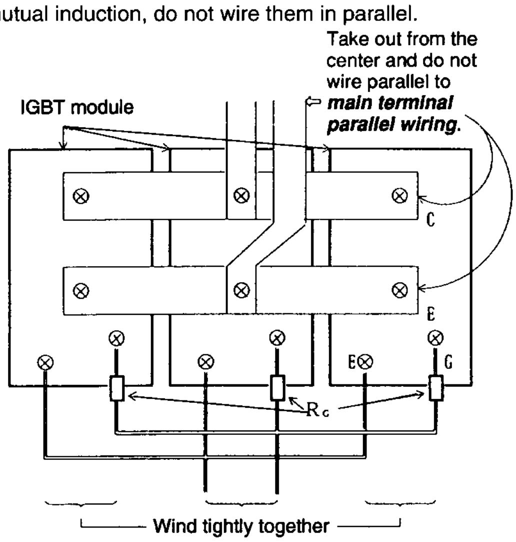

Fig. 3 Parallel connection layout example