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PROTECTION OF IGBT MODULES IN INVERTER CIRCUITS

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1. FOREWORD

For general-purpose inverters, NC machine tools, uninterrupted power supplies, and other power converters, small size, light weight, low acoustics noise, and high efficiency are demanded. Various high-speed, low loss devices have been developed and commercialized to meet this need. The IGBT is a device with the low saturation voltage characteristic of a power bipolar transistor and the high switching speed characteristic of a MOSFET and is the power device which is currently attracting the most attention.

Application of this IGBT to a VVVF inverter is taken as an example and the overvoltage and overcurrent generation mechanism and the related element characteristics and destructive withstand capability and basic protection method are described.

2. OVERVOLTAGE PROTECTION

2.1 Main causes of overvoltage generation

Figure 1 shows the an IGBT application circuit example and *Fig. 2* shows the operation waveforms at IGBT turn-off.

When the IGBT is turned off, a high voltage is induced in the stray inductance of the main circuit by the abrupt change of the main circuit current and a switching surge voltage is generated.

Fig. 1 Example of application to VVVF inverter

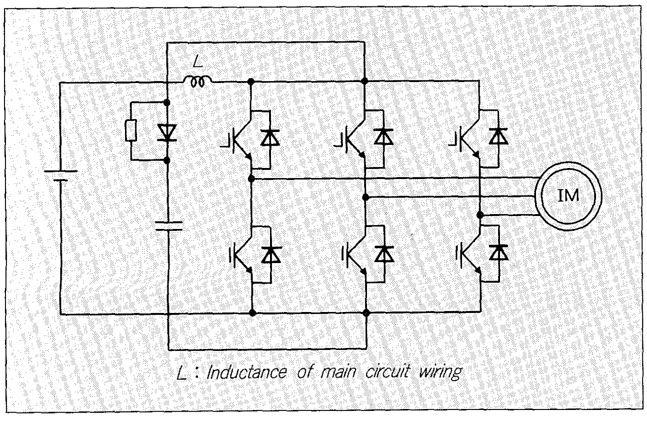


Fig. 2 IGBT turn-off operation waveforms

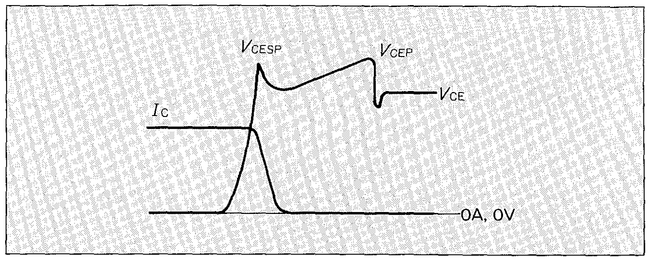
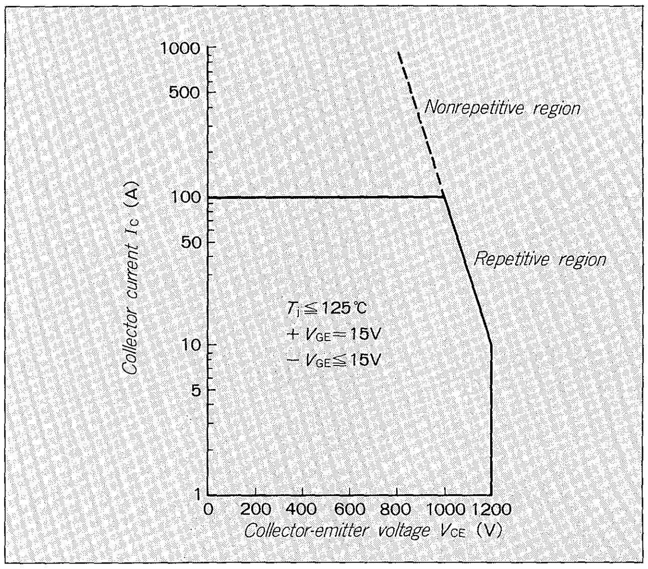


Fig. 3 IGBT RBSOA (2MBI50-120)

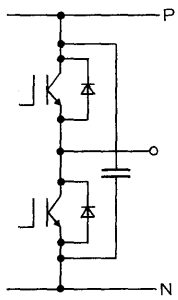
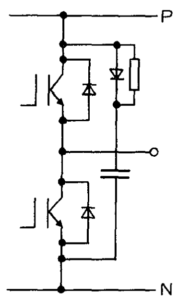
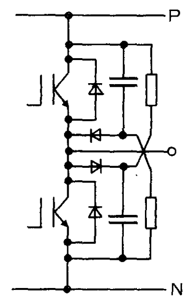


The protection method against this switching surge voltage is described here.

2.2 Snubber circuit

The RBSPA (Reverse Biased Safe Operating Area) of a IGBT is shown in *Fig. 3*. When the turn off locus exceeds the RBSOA due to the previously mentioned switching surge voltage, the element is destroyed. A snubber circuit is used to keep the turn-off locus within the RBSOA by controlling the switching surge voltage.

Table 1 Examples of snubber circuit

	(a)	(b)	(c)
Connection diagram (for one phase)			
Application objective	Small capacity IGBT (~ 50A)	Medium capacity IGBT (~ 200A)	Large capacity IGBT (300A ~)
Notes	A voltage is oscillated easily by the resonant circuit consisting of the main circuit inductance and the snapper capacitor.	If the snapper diode is selected incorrectly, a high spike voltage will be generated and a voltage will be oscillated at snapper diode reverse recovery.	If the snapper diode is selected incorrectly, a high spike voltage will be generated and a voltage will be oscillated at snappe snapper diode reverse recovery.

2.3 Types of snubber circuits

Specific snubber circuits and application objectives and notes are shown in *Table 1.*

2.4 Snubber circuit basic design method

The discharge-restraint snubber is the most practical IGBT snubber . Its basic design is described below.

(1) Snubber circuit basic design method

The capacitance (C_s) of the snubber capacitor is found from the following equation:

$$C_s = \frac{LI_o^2}{(V_{CEP} - E_d)^2} \quad \cdots\cdots\cdots\cdots\cdots\cdots \quad (1)$$

where, L : Stray inductance of main circuit
I_o : Collector current at IGBT turn-off
V_{CEP} : Ultimate value of snubber capacitor voltage
E_d : DC power supply voltage

(Note that the allowable V_{CEP} differs with the current as shown by the RBSOA.)

(2) Snubber resistance (R_s) design

The function demanded of a snubber resistor is that is discharge the charge stored in the snubber capacitor until the IGBT performs the next turn-off operation. When the snubber resistance is found under the condition which discharges 90% of the stored charge before the next turn-off operation, the following equation is obtained:

$$R_s \leqq \frac{1}{2 \times 3 \times C_s \times f} \quad \cdots\cdots\cdots\cdots\cdots\cdots \quad (2)$$

where, f : Switching frequency

However, if the snubber resistor is too small, the snubber circuit current will oscillate and the peak collector current at IGBT turn-on will also increased and, therefore, it should be made the largest value in the range which satisfies Eq. (2).

The snubber resistor power loss is unrelated to the snubber resistor value and is found from Eq. (3).

$$P_s = \frac{L_s \times I_o^2 \times f}{2} \quad \cdots\cdots\cdots\cdots\cdots\cdots \quad (3)$$

where, L_s : Snubber circuit inductance

(3) RBSOA consideration method

The spike voltage V_{CEP} during the IGBT turn-off process is found from Eq. (4).

$$V_{CEP} = E_d + V_{FM} + L_s \cdot di/dt \quad \cdots\cdots\cdots\cdots \quad (4)$$

where di/dt : Collector current rate of change during drop period
V_{FM} : Snapper diode transient forward voltage drop of snapper diode (Generally, 20-30V for 600V class snapper diode and 40-60V for 1 200V class snapper diode)

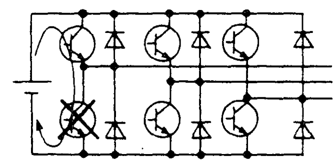
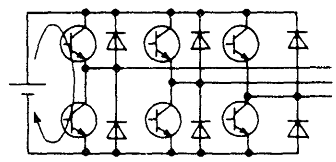
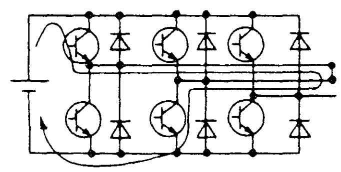
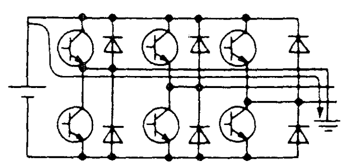
This V_{CEP} must be in the RBSOA. To suppress the V_{CEP}, the high-speed diode with a small transient forward voltage drop must be selected and the inductance of snubber circuit must be kept as possible.

3. OVERCURRENT PROTECTION

3.1 Main causes of overcurrent generation

With a VVVF inverter, the rush current at motor starting, erroneous operation of the control circuit, or drive circuit, erroneous wiring, etc. may cause arm short circuit, output short circuit, etc. and an overcurrent may flow in the IGBT. Of these, for short circuits and other troubles, the current change is very fast and a very high voltage and large current duty is imposed on the elements

Table 2 Short circuit phenomena and main generation causes

Short circuit path	Cause
Arm short circuit 	Destruction of transistor or diode
Series short circuit 	Control circuit, drive circuit trouble or erroneous operation by noise.
Output short circuit 	Wiring operation, etc. man-made mistake and destruction of load insulation.
Ground short circuit 	Same as above.

and, therefore, an overcurrent must be detected quickly and the inverter self-trip so that the elements are not destroyed.

The short circuit phenomena and main generation causes at an inverter circuit are shown in *Table 2*. Short circuit phenomena can be grouped into the following four kinds:

(1) Arm short circuit
(2) Series short circuit
(3) Output short circuit
(4) Ground short circuit

The 2MBI50–120 is taken as an example and the withstand capability at various short circuits is studied and protection methods are described here.

3.2 IGBT short circuit withstand capability

The DC supply voltage at an inverter circuit is shown by Eq. (5).

$$E_d = V_{ac} \times 1.1 \times \sqrt{2} \quad \ldots\ldots\ldots\ldots\ldots \quad (5)$$

where, power supply voltage rate of change = 10%

For AC input 480V used by a 1200V IGBT, the DC supply voltage is 747V and an elements that will not be destroyed even if a short circuit is generated at this voltage is necessary.

Fig. 4 Measurement circuit simulating arm short circuit

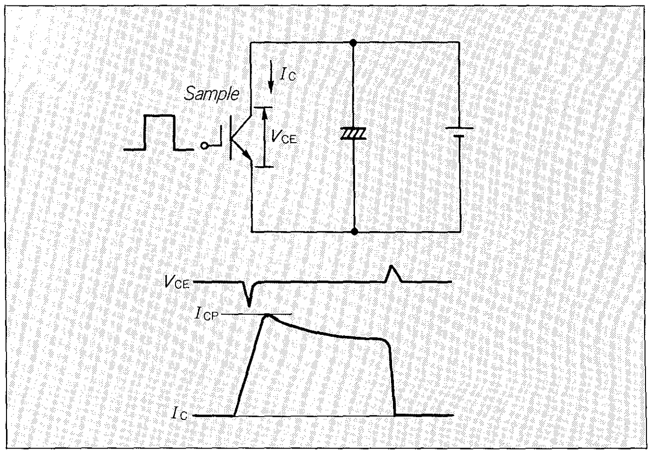


Fig. 5 Output characteristics at short circuit

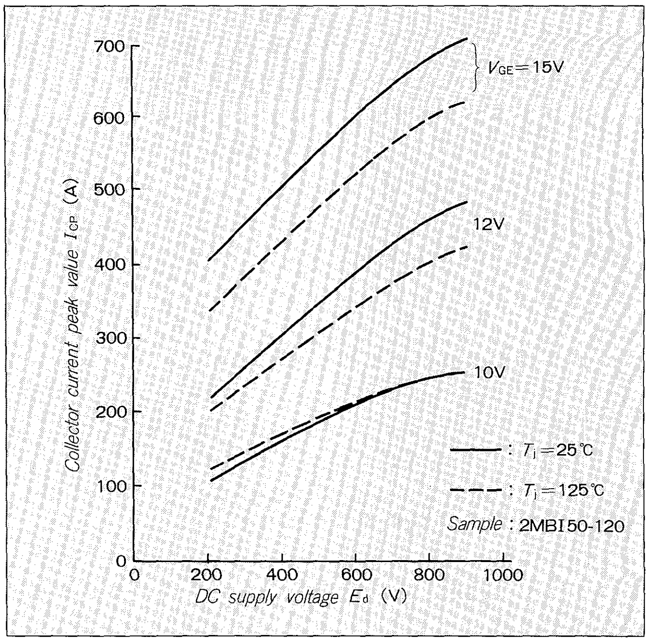


Fig. 6 Short circuit withstand capability when arm short circuit simulated

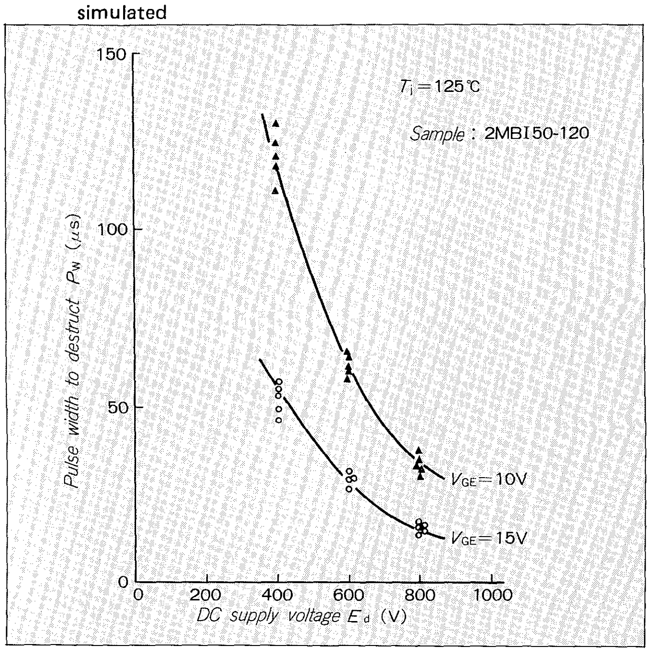


Fig. 7 Series short circuit simulation measurement circuit and operation waveforms

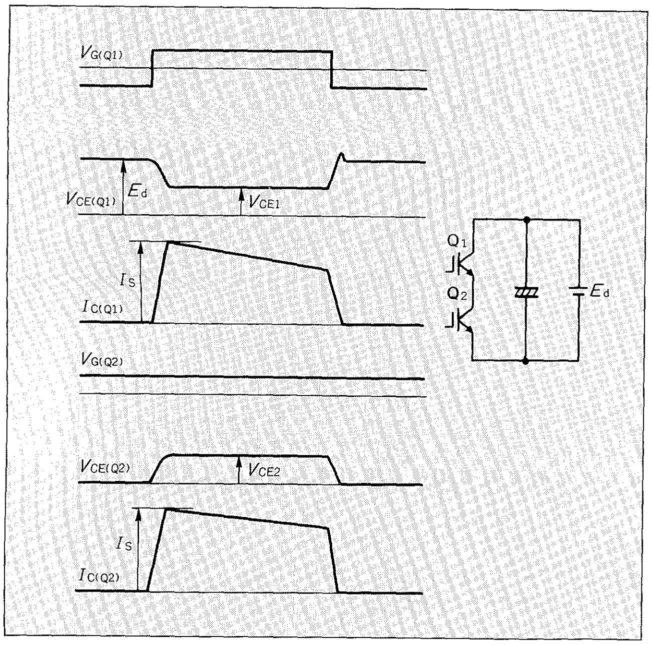


Fig. 8 IGBT output characteristics at series short circuit

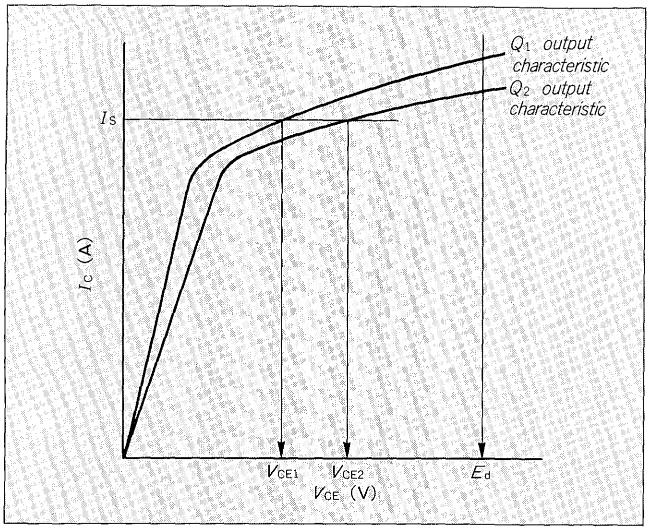


Fig. 9 Short circuit withstand capability when series short circuit simulated

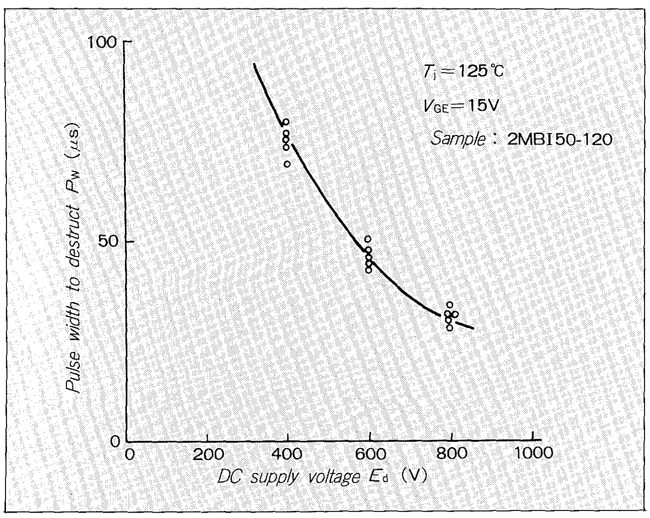


Fig. 10 Short circuit withstand capability when output short circuit simulated

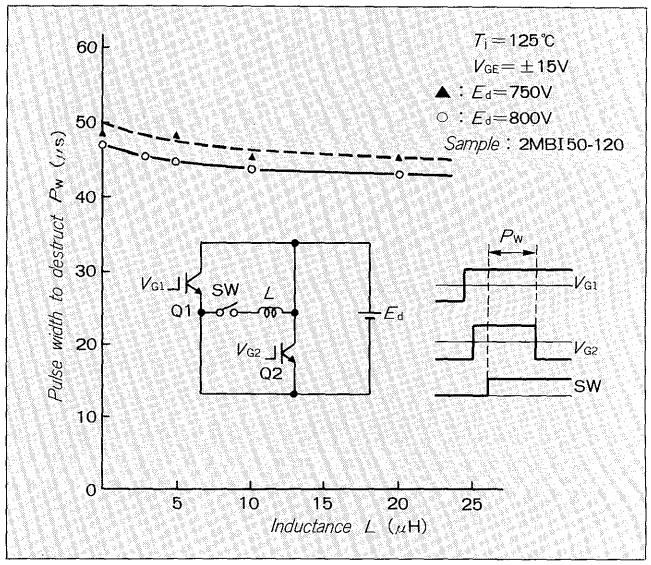
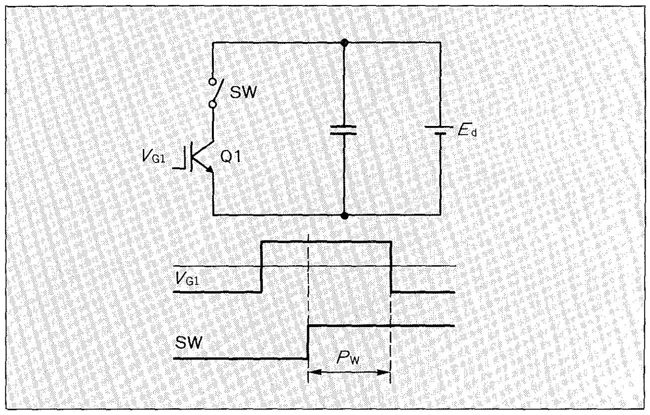


Fig. 11 Measurement circuit simulating ground short circuit



(1) Arm short circuit

A measurement circuit simulating an arm short circuit is shown in *Fig. 4* and the DC supply voltage and short circuit current change are shown in *Fig. 5*. As shown in *Fig. 5*, the collector current at short circuit is limited by the output characteristic of the IGBT and does not become a large value such as that determined by the circuit impedance. However, if E_d = 750V is taken as an example, the peak collector current becomes approximately 600A and is 12 times the rate current.

The results of measuring the pulse width to destruct at the circuit of *Fig. 4* are shown in *Fig. 6*.

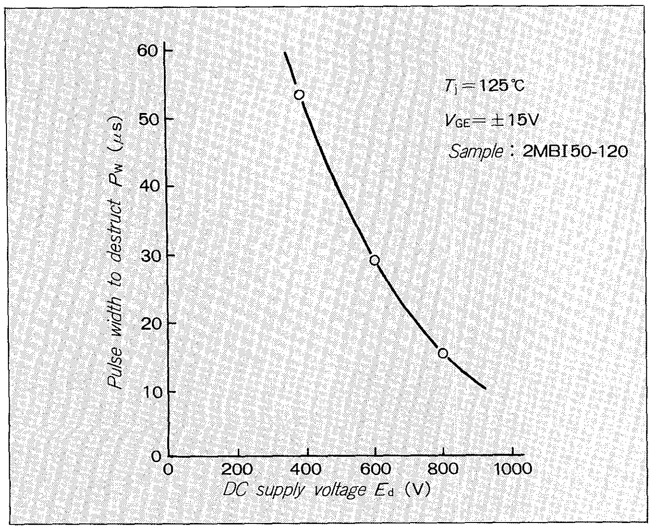
(2) Series short circuit

The waveforms for series short circuit with two elements are shown in *Fig. 7*. For series short circuit of two elements, as shown in *Fig. 8*, the DC voltage is divided between V_{CE1} and V_{CE2} by the output characteristic of each element and the collector current is also considered to be lower than for an arm short circuit. The destruct withstand capability data for series short circuit is shown in *Fig. 9*.

(3) Output short circuit

For an output short circuit, since the wiring inductance

Fig. 12 Short circuit withstand capability when ground short circuit simulated



from the standpoint of the short circuit path differs with the length of the output wire and the short circuit location, the short circuit current rise ratio (di_C/dt) is not constant. Therefore, it have been reported for bipolar transistor that the short circuit withstand capability become small due to the peak collector current increasing at small wiring inductance. The relationship between IGBT output short circuit withstand capability and inductance is shown in *Fig. 10.* For an IGBT, there is no wiring inductance dependence and the withstand capability does not change. Moreover, when compared by time up to destruction, it has a withstand capability of about 4 times that of *Fig. 4* which simulated an arm short circuit.

(4) Ground short circuit

A measurement circuit simulating a ground short circuit is shown in *Fig. 11.* For a ground short circuit, the sum of the reverse electromotive force and the DC supply voltage (E_{d2}) may be impressed on the IGBT and is considered to be the most severe condition of the short circuit phenomena shown in *Table 2.* The results of measurement of the pulse width to destruct means of the circuit of *Fig. 11* are shown in *Fig. 12.* If the supply voltage is the same, the short circuit withstand capability at arm short circuit (*Fig. 4*) and ground short circuit (*Fig. 11*) is about the same.

From the study results above, for an IGBT, protection against almost all short circuit phenomena is considered to be possible by evaluating the short circuit withstand capability and quickly cutting off the gate within that withstand capability.

3.3 Protection circuit example

As previously described, whereas, compared to a bipolar transistor, an IGBT is sufficient if evaluated by one kind of circuit (*Fig. 4*) for various short circuit phenomena, its pulse width to destruct is short so that high speed cutoff is necessary.

Fig. 13 Short circuit protection circuit example

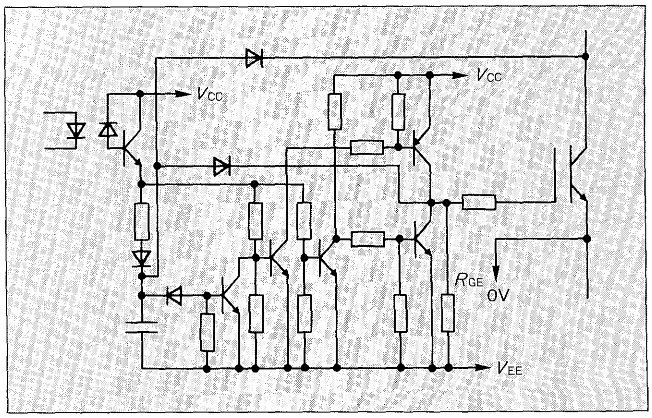


Fig. 14 IGBT RBSOA and operation orbit at short circuit

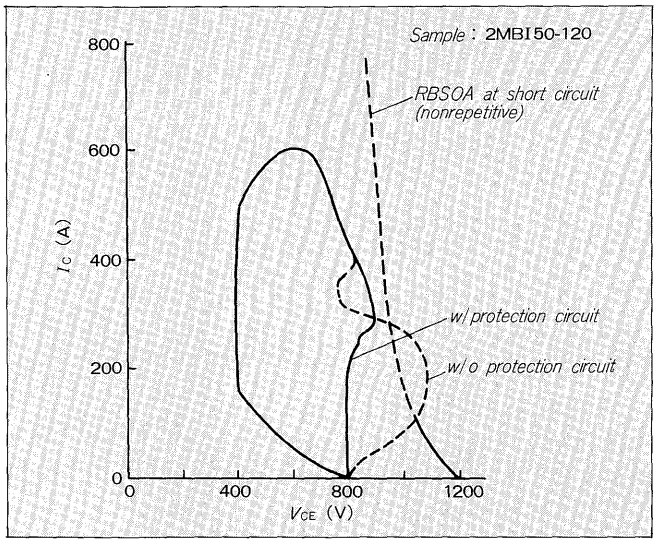
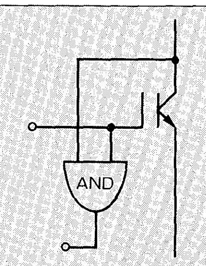


Table 3 Drive hybrid IC series table

Applicable IGBT	600V IGBT drive		1200 IGBT drive	
	~ 150A	~ 400A	~ 75A	~ 300A
Medium speed type	EXB850	EXB851	EXB850	EXB851
High speed type	EXB840	EXB841	EXB840	EXB841

Medium speed type: Drive circuit signal propagation delay Max 4μs
High speed type: Drive circuit signal propagation delay Max 1.5μs

Fig. 15 Overcurrent detection circuit



Item	V_{CE} low	V_{CE} high
On signal	Normal operation	Overcurrent
Off signal	—	Normal operation

Fig. 16 Soft cutoff operation waveforms

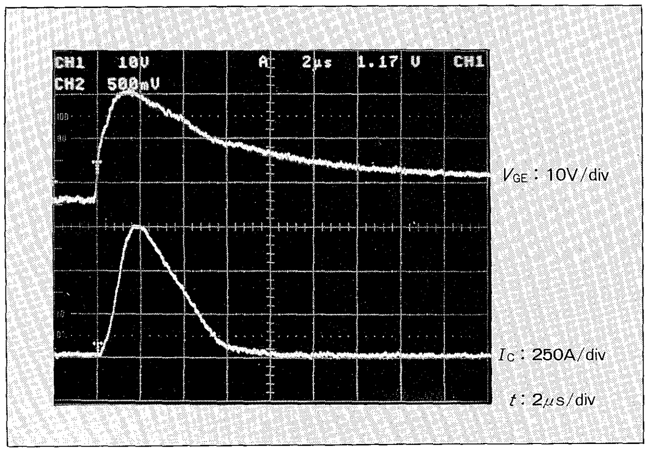
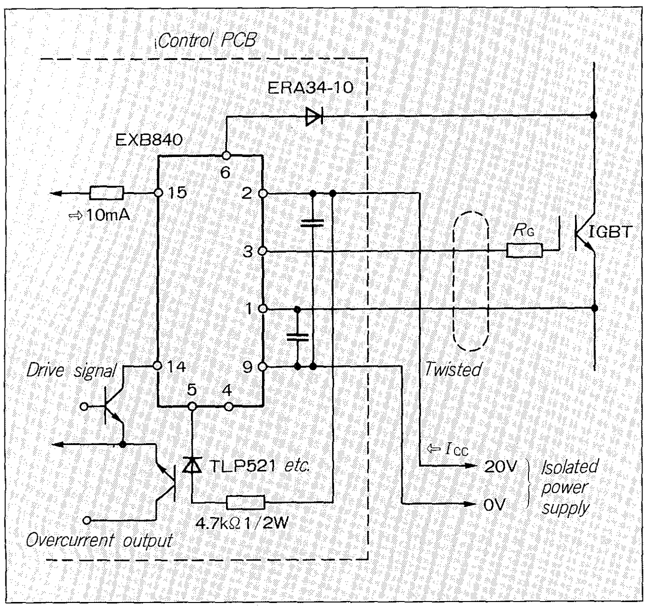


Fig. 17 EXB840 application circuit example



However, especially with large current devices, when the overcurrent at short circuit is cutoff at high speed by an IGBT, the surge voltage applied between the collector and emitter go across the RBSOA shown in *Fig. 3* and the element may be destroyed. Turning off the IGBT at slow speed at short circuit only is effective in avoiding this.

Fig. 13 is an example of a drive circuit for performing this operation. This circuit controls the turn off speed of IGBT by the conparatively high resistance when the short circuit occure, both of the output stage transistor (RGE), in the drive circuit are turned off at the sametime, and to electric charge in the gate capacitor of IGBT is discharged through high resistance (RGE), so that the IGBT turns off slowly. *Fig. 14* shows the turn off locus when this circuit is applied and not applied.

3.4 Drive hybrid IC application example

Fuji Electric has commercialized drive hybrid IC with built-in overcurrent protection circuit. An example of a circuit using this hybrid circuit is introduced here.

(1) Product series

The product series is shown in *Table 3*. Two types each by applicable IGBT current serialized for the medium and high speed types for a total of 4 types. Selection of the best driver for the application can be selected.

(2) Application circuit example

These hybrid ICs have the overcurrent detector shown in *Fig. 15* and the soft cutoff circuit at overcurrent shown in *Fig. 16* built-in.

They also have a built-in off gate reverse bias power supply circuit and since they are operated by a single power supply (20V), simplification of the drive circuit is easy.

An application circuit example using the EXB840 is shown in *Fig. 17*.

4. CONCLUSION

The overvoltage and overcurrent production technology for the IGBT module was described above. The main points are summarized below.

(1) Overvoltage protection: The operation locus is kept in the RBSOA by optimum design of the snubber.

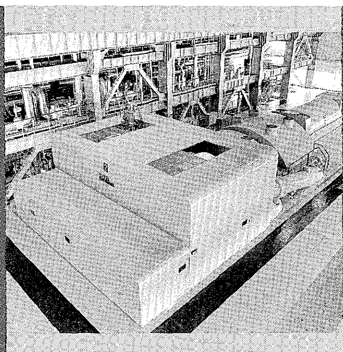
(2) Overcurrent protection: Short circuit overcurrent protection is performed by performing element evaluation by a circuit that simulates an arm short circuit and cutting off the IGBT quickly enough that the element is not destroyed. Soft cutoff is effective in keeping the operation locus in the RBSOA at this time.

Development of technology for the application of IGBT modules to inverter circuits is said to have just started and the authors will be happy if this paper assists in the IGBT module protection circuit design.

We will put our efforts into the development of new products capable of simplifying and expanding the protection range of protection circuit further in the future.

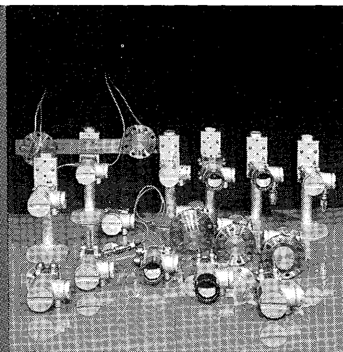
Outline of Products

Power and Industrial Electrical Machinery



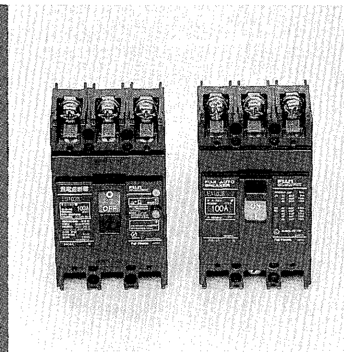
- Nuclear Power
- Power Generation and Distribution
- Transportation
- Environmental Equipment
- Industry
- Electrical Installation
- Mechatronics Equipment

Instrumentation



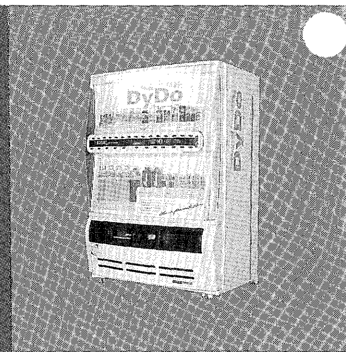
- Industrial Instrumentation
- Water Treatment
- Data Process Engineering

Standard Electrical Products



- IC (Integrated Circuit)
- Semiconductors
- Rotating Machines
- Standard Electrical Equipment

Vending Machines and Specialty Appliances



- Vending Machines
- Freezing & Refrigerating Open Showcases
- P.O.S. for Versatile Purpose Appliances
- Air Conditioning