Chapter 5

Protection Circuit Design

This section explains the protection circuit design.

1 Short circuit (overcurrent) protection

1-1 Short circuit withstand capability

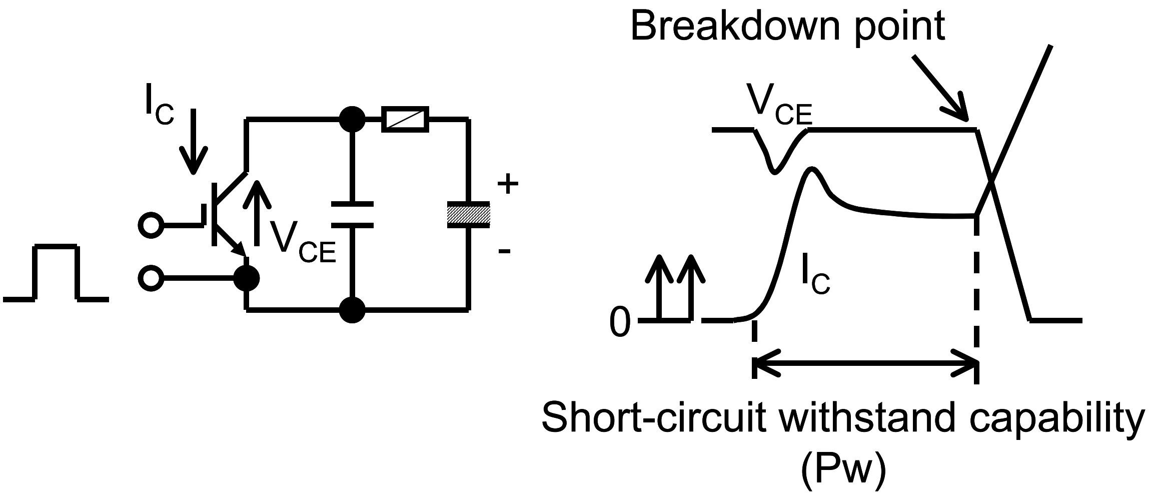
In the event of a short circuit, first the IGBT's collector current will rise, once it has reached a certain level, the C-E voltage will spike. Depending on the device's characteristics, during the short-circuit, the collector current can be kept at or below a certain level, however the IGBT will still continue to be subjected to a heavy load, that is, high voltage and high current. Therefore, this condition must be removed as soon as possible.

However, 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, which is determined by the amount of time, as illustrated in Fig. 5-1. The IGBT's short circuit withstand capability is defined as the start of the short-circuit current until the module is destroyed. Therefore, when the IGBT is short-circuited, large current is need to be cut off within the short circuit withstand capability.

The withstand capability depends on collector to emitter voltage V_{CE}, gate to emitter voltage V_{GE} and/or junction temperature T_j.

In general, , the larger supply voltage and/or the higher junction temperature are, the lower the withstand capability will be.

For more information on withstand capability, referred to the application manual or technical data.



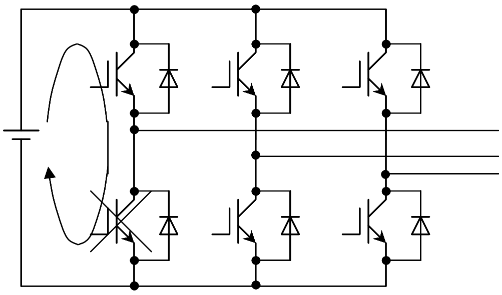
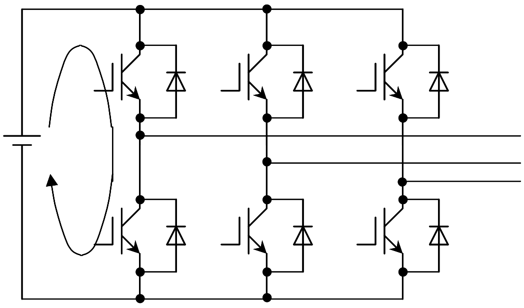
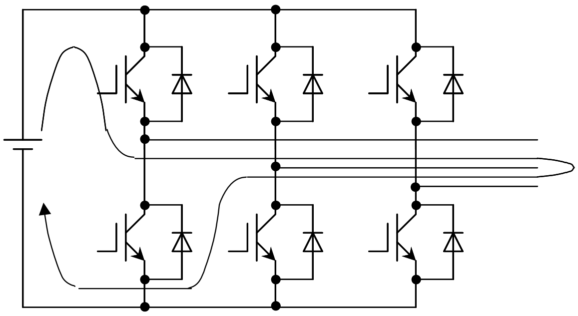
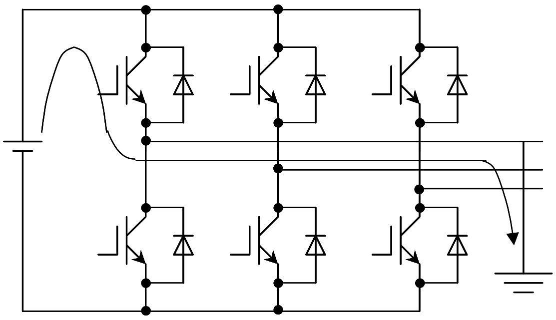
(a) Measuring circuit (b) representative short-circuit waveform

Fig. 5-1 Measuring circuit and waveform

1-2 Short-circuit modes and causes

Table 5-1 lists the short-circuit modes and causes that occur in inverters.

Table 5-1 Short circuit mode and cause

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

1-3 Short-circuit (overcurrent) detection

1) Detection in the circuit

As described previously, in the event of a short-circuit, the IGBT must be protected as soon as possible. Therefore, the time from overcurrent detection to the complete turn-off in each circuit must work effectively as fast as possible.

Since the IGBT turns off very quickly, if the overcurrent is shut off using an ordinary drive signal, the collector-emitter voltage will rise due to the back-emf from parasitic inductances, and then the IGBT would have chance to be destroyed by overvoltage (RBSOA destructions). Therefore, it is recommended that when shutting off the overcurrent that the IGBT be turned off gently (Soft turn-off).

Figure 5-2 shows the insertion methods for overcurrent detectors, and Table 5-2 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 of detection.

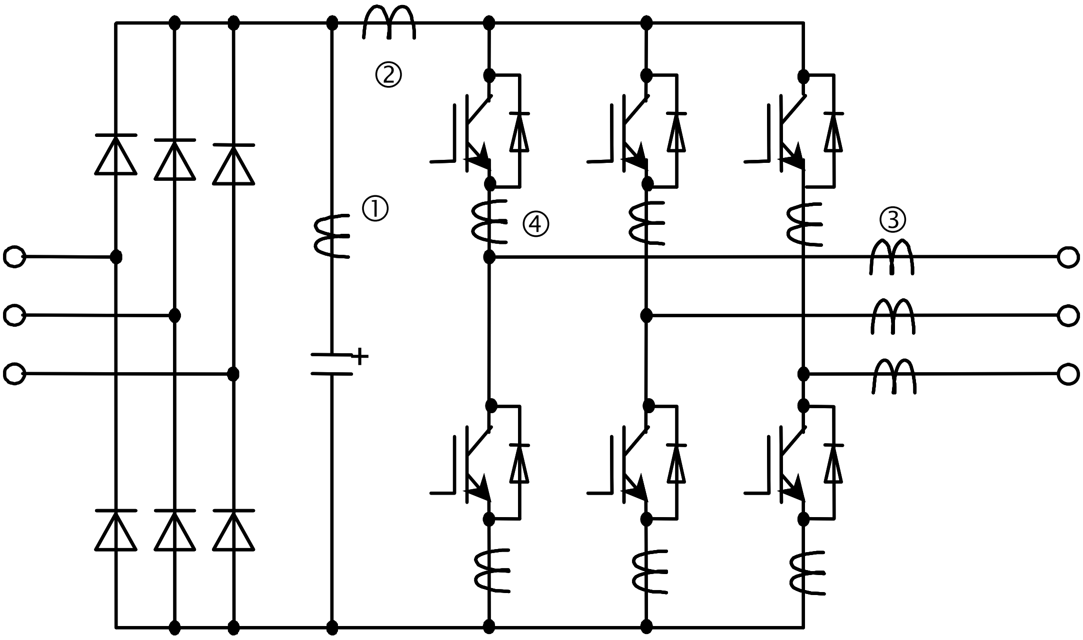


Fig. 5-2 Overcurrent detector insertion methods

Table 5-2 Overcurrent detector insertion positions and function

Detector insertion position	Features	Detection function
Insertion in line with smoothing capacitor Fig.5-2/①	• 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.5-2/②	• 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.5-2/③	• AC current transformer available for high frequency output equipment • High detection precision	• Short in output circuit • Ground fault
Insertion in line with switches Fig.5-2/④	• Necessary to use DC current transformer • High detection precision	• Arm short-circuit • Short in output circuit • Series arm short-circuit • Ground fault

2) Detecting using $V_{CE(sat)}$

This method has a feature of protection against all possible short-circuit types listed in Table5-1. Since all operations from overcurrent detection to protection are done on the drive circuit side, the fastest protection is possible. A short-circuit protection schematic, based in $V_{CE(sat)}$ detection, is shown in Fig.5-3.

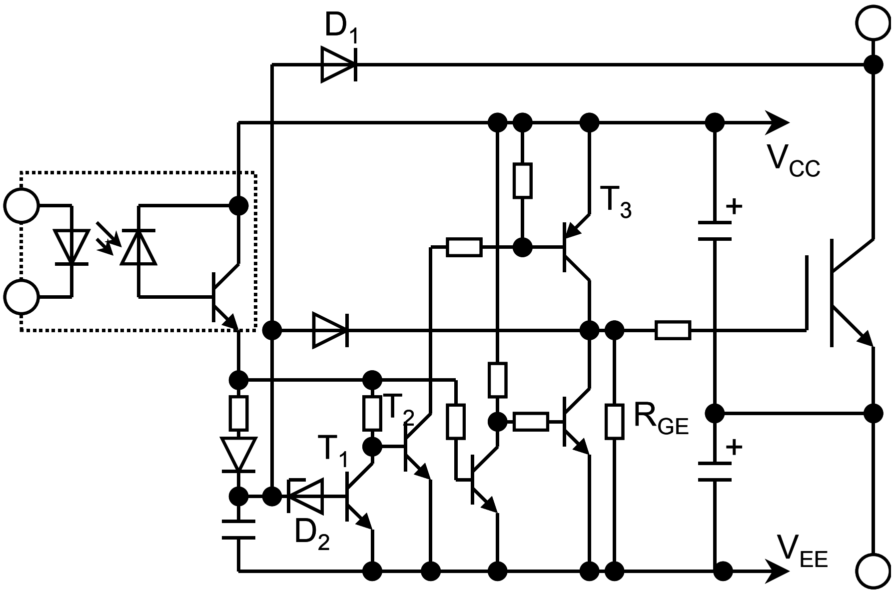
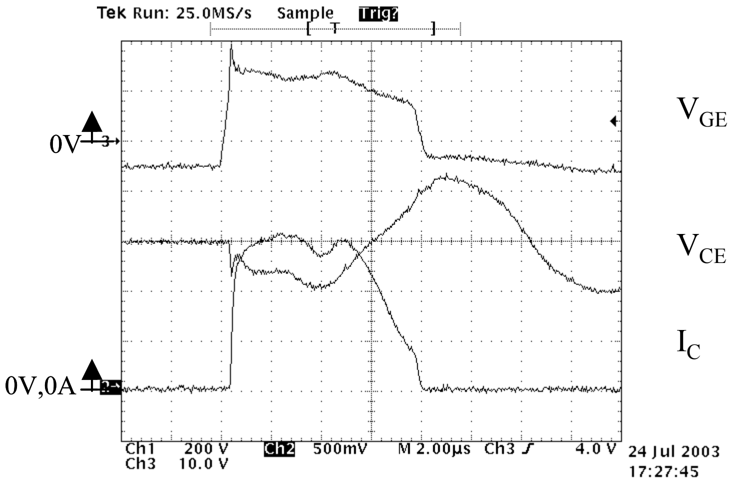


Fig. 5-3 Short-circuit protection schematic based in VCE(sat) detection

This circuit uses D_1 to constantly monitor the collector-emitter voltage, so if during operation the IGBT's collector-emitter voltage rises above the limit at D_2, then a short-circuit condition will be detected and T1 will be switched on while T_2 and T_3 are switched off. At this time, the accumulated charge at the gate is slowly released through the R_{GE}, so a large voltage spike is prevented when the IGBT is turned off. Gate driver hybrid IC_S (model VLA517) have similar kind of protective circuit built in, thereby simplifying the drive circuit design. For more details, refer to Chapter 7 "Drive Circuit Design". Fig. 5-4 shows an example of IGBT waveforms in short circuit protection.



2MBI300UD-120

Ed=600V, V_{GE}=+15V, –5V (VLA517), R_G=3.3Ω, Tj=125°C

V_{CE}=200V/div, I_C=250A, V_{GE}=10V/div, t=2µs/div

Fig. 5-4 Waveforms during short circuit protection

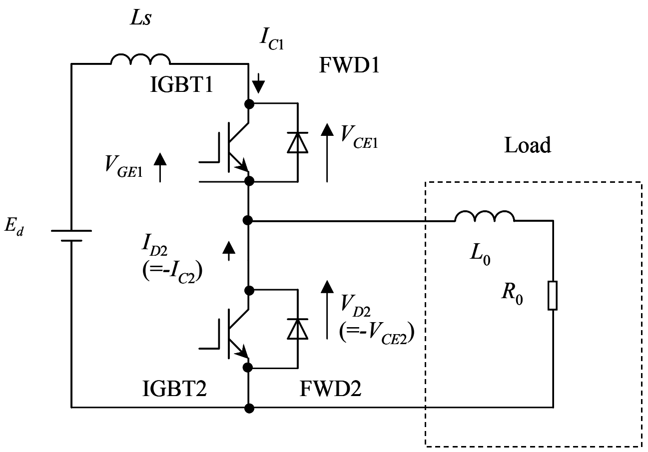
2 Overvoltage protection

2.1 Overvoltage causes and their suppression

1) Overvoltage causes

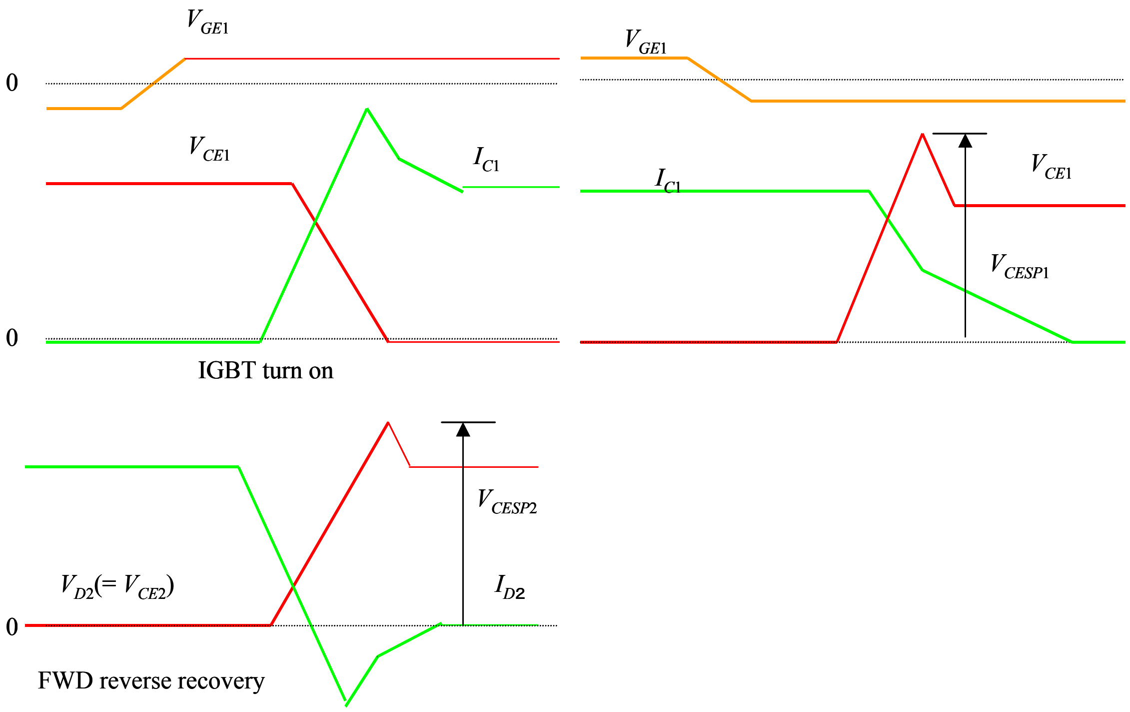
Due to the fast switching feature of IGBTs at turn-off and/or during FWD reverse recovery, the instantaneous rate in current over time (di/dt) would have very high value. Therefore the parasitic inductances to the module would produce a high turn-off surge voltage (V=L(di/dt)).

In this section, an example of solutions both for IGBT and FWD are described with explanation of the root causes and practical methods to suppress the surge voltage with typical IGBT waveforms at turn-off To demonstrate the turn-off surge voltage, a simplified chopper circuit and the IGBT turn-off voltage and current waveforms are shown in Fig. 5-5 and 5-6, respectively.



E_d: DC supply voltage, L_S: Main circuit parasitic inductance, Load:L_0,R_0

Fig. 5-5 Chopper circuit



(1) Waveforms of reverse recovery.

(2) Waveforms of turn-off.

Fig. 5-6 Switching waveforms

The turn-off surge voltage peak V_{CESP} can be calculated as follows:

$$V_{CESP} = Ed + (-L_S \bullet dIc/dt) \cdots\cdots\cdots\cdots ①$$

dIc/dt: Instantaneous rate in current over time

If V_{CESP} exceeds the maximum C-E (V_{CES}) rating of IGBT, IGBT module would be destroyed.

2) Overvoltage suppression methods

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

a. Control the surge voltage with an additional protection circuit (snubber circuit) to the IGBT.
A film capacitor in the snubber circuit, which is connected as close as possible to the IGBT, works to bypass the high frequency surge currents.

b. Adjust the IGBT drive circuit's – V_{GE} and/or R_G in order to reduce the di/dt value. (Refer to Chapter 7, "Drive Circuit Design".)

c. Place the electrolytic capacitor as close as possible to the IGBT in order to reduce the parasitic inductance of the wiring. A low impedance capacitors have better effect.

d. To reduce the inductance of the main circuit as well as the snubber circuit parasitic inductances, thicker and shorter connections are recommended. Laminated bus bars are best solution to reduce parasitic inductances.

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 5-3 shows the schematic of each type of individual snubber circuit, its features, and an outline of its main applications.

2) Lump snubber circuits

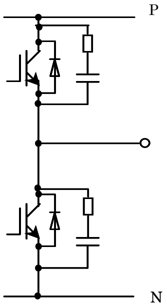
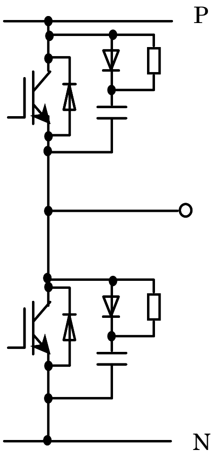
Examples of typical snubber circuits are listed below.

a) C snubber circuits
b) RCD snubber circuits

Lump snubber circuits are becoming increasingly popular due to circuit simplification.

Table 5-4 shows the schematic of each type of lump snubber circuit, its features, and an outline of its main applications. Table 5-5 shows the capacity selection of a C type snubber circuit. Fig. 5-7 shows the current and voltage turn-off waveforms for an IGBT connected to a lump snubber circuit.

Table 5-3 Individual snubber circuits

Snubber circuit schematic	Circuit features (comments)	Main application
RC snubber circuit 	• Very effective on turn-off surge voltage suppression • Best for chopper circuits • For high power IGBTs, the low resistance snubber resistance is necessary, which results increase in turn-off collector current and higher IGBT load.	Welding Switching power supply
Charge and discharge RCD snubber circuit 	• The moderate effect in turn-off surge voltage suppression. • In contrast to the RC snubber circuit, additional snubber diodes connected paralley to the snubber resistance.. This diode enable not to use low snubber resistance. consequently preventing the IGBT higher load turn-on issue in RC snubber solution above. • Since the power dissipation of the snubber circuit (primarily caused by the snubber resistance) is much higher than that of a discharge suppressing snubber circuit below, it is not considered suitable for high frequency switching applications. • The power dissipation caused by the resistance of this circuit can be calculated as follows: $P = \frac{L \bullet Io^2 \bullet f}{2} + \frac{C_S \bullet Ed^2 \bullet f}{2}$ L: Parasitic inductance of main circuit, Io: Collector current at IGBT turn-off, Cs: Capacitance of snubber capacitor, Ed: DC supply voltage, f :Switching frequency	

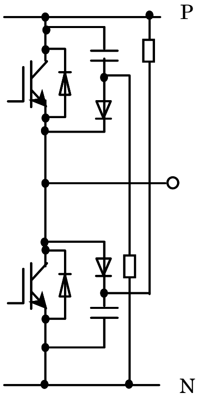
Discharge suppressing RCD snubber circuit  	• Limited effect on turn-off surge voltage suppression • Suitable for high-frequency switching • Small power dissipation of snubber circuit i. • The power dissipation caused by the resistance of this circuit can be calculated as follows: $$P = \frac{L \bullet Io^2 \bullet f}{2}$$ L: Parasitic inductance of main circuit Io: Collector current at IGBT turn-off f :Switching frequency	Inverter

Table 5-4 Lump snubber circuits

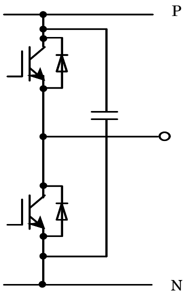
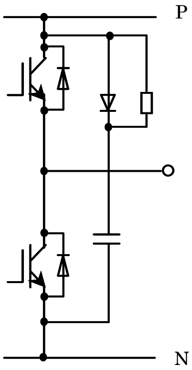
Snubber circuit schematic	Circuit features (comments)	Main application
C snubber circuit  	• The simplest topology. • The LC resonance circuit, which consists of a main circuit parasitic inductance and snubber capacitor, may have a chance of the C-E voltage oscillation.	Inverter
RCD snubber circuit  	• In case inappropriate snubber diode is used, a high spike voltage and/or the output voltage oscillation in the diodes reverse recovery would be observed	Inverter

Table 5-5 Guidelines for designing the lump C snubber circuit capacitance

Item Module rating		Drive conditions[*1]		Main circuit wiring inductance (μH)	Snubber capacitance Cs (μF)
		$-V_{GE}$(V)	R_G(Ω)		
600V	50A	max 15V	min.43Ω	-	0.47μF
	75A		min.30 Ω		
	100A		min.13 Ω		
	150A		min.9 Ω	max 0.20μH	1.5 μF
	200A		min.6.8 Ω.	max.0.16 μH	2.2 μF
	300A		min.4.7 Ω	max.0.10 μH.	3.3 μF
	400A		min.6.0 Ω	max.0.08 μH.	4.7 μF
1200V	50A	max 15V	min.22 Ω	-	0.47 μF
	75A		min.4.7 Ω		
	100A		min.2.8 Ω		
	150A		min.2.4 Ω	max.0.20 μH.	1.5 μF
	200A		min.1.4 Ω	max.0.16 μH.	2.2 μF
	300A		min.0.93 Ω	max.0.10 μH.	3.3 μF

[*1]: Typical external gate resistance of V series IGBT are shown.

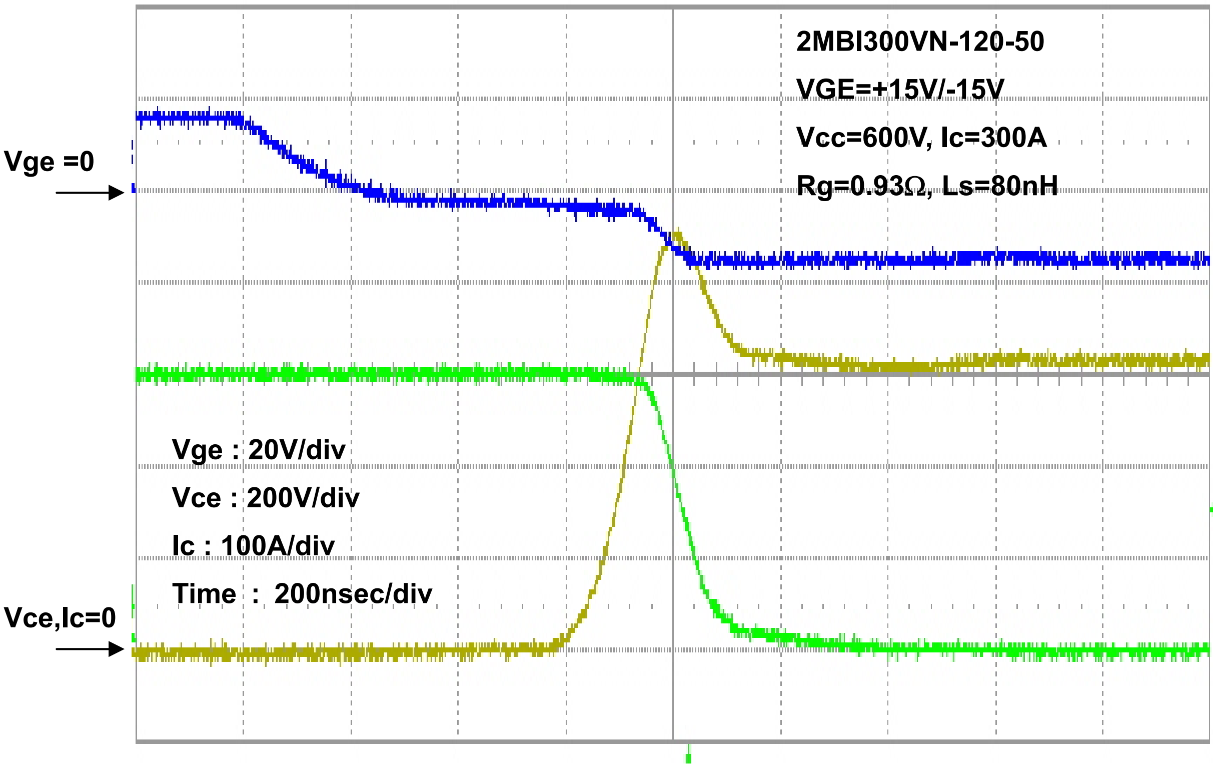


Fig. 5-7 Current and voltage waveforms of IGBT with lump snubber circuit at turn-off

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 5-8 is the turn-off locus waveform of an IGBT in a discharge-suppressing RCD snubber circuit. Fig. 5-9 shows the IGBT current and voltage waveforms at turn-off.

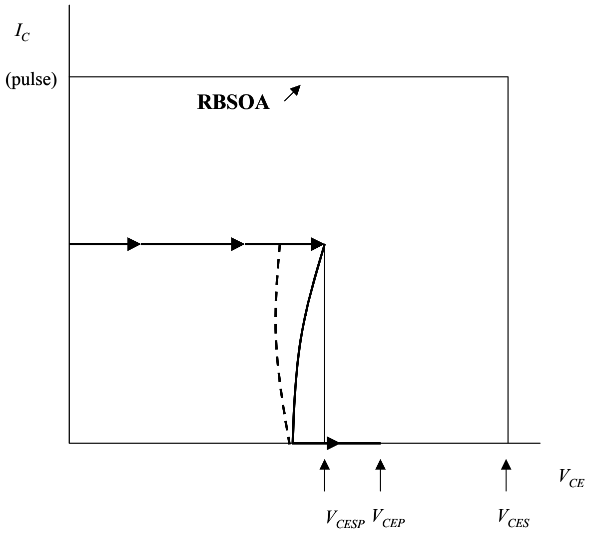


Fig. 5-8 Turn-off locus waveform of IGBT

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 diagram Fig. 5-8 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. 5-8.

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

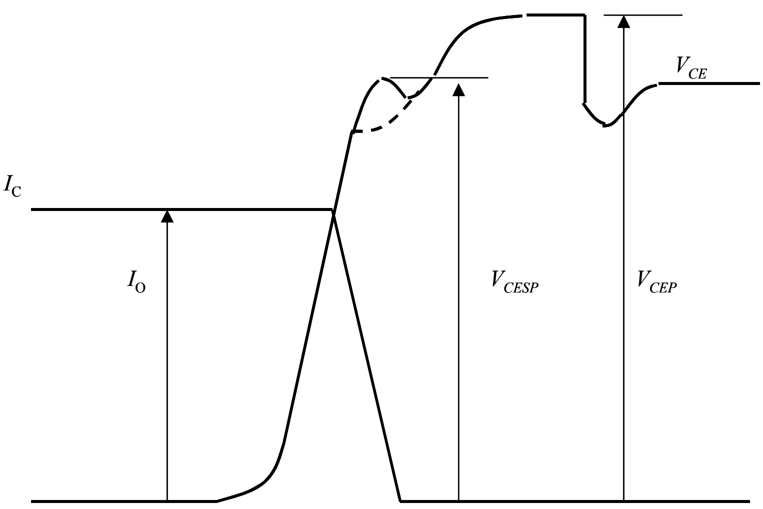


Fig. 5-9 Voltage and current waveforms at turn-off

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

$$V_{CESP} = Ed + V_{FM} + (-L_S \bullet dIc/dt) \cdots\cdots\cdots\cdots ②$$

Ed: Dc supply voltage
V_{FM}: Transient forward voltage drop in snubber diode
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
Ls: Snubber circuit wiring parasitic inductance
dIc/dt: The instantaneous rate in collector current over time in IGBT turn-off

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

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

$$C_S = \frac{L \bullet Io^2}{(V_{CEP} - Ed)^2} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots ③$$

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

VCEP must be lower than IGBT C-E breakdown voltage. High frequency capacitors such as film capacitors are recommended.

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 event.

To discharge 90% of the accumulated energy by the next IGBT turn-off event, the snubber resistance must be as follows:

$$R_S \leq \frac{1}{2.3 \bullet C_S \bullet f} \cdots\cdots\cdots\cdots\cdots\cdots\cdots ④$$

f: Switching frequency

If the snubber resistance is set too low, the snubber circuit current will oscillate and the peak collector current at the IGBT turn-off will increase. Therefore, set the snubber resistance in a range below the value calculated in the equation.

Independently to the resistance, the power dissipation loss P (Rs) is calculated as follows:

$$P(R_S) = \frac{L \bullet Io^2 \bullet f}{2} \cdots\cdots\cdots\cdots\cdots\cdots\cdots ⑤$$

4) Snubber diode selection

A transient forward voltage drop in the snubber diode is one factor that would 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 will also be 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 voltage, therefore it is important to design the circuit with the lowest inductance possible.

2-4 Example of characteristic of spike voltage

The spike voltage shows various behaviors depending on the operation, drive and circuit conditions. Generally, the spike voltage becomes higher when the collector voltage is higher, the circuit inductance is larger, and the collector current is larger. As an example of spike voltage characteristic, the current dependence of spike voltage at IGBT turn-off and FWD reverse recovery is shown in Figure 5-10.

As this figure shows, the spike voltage at IGBT turn-off becomes higher when the collector current is higher, but the spike voltage at FWD reverse recovery becomes higher when the current is low. Generally, the spike voltage during reverse recovery becomes higher when the collector current is in the low current area that is a fraction of the rated current.

The spike voltage shows various behaviors depending on the operation, drive and circuit conditions. Therefore, make sure that the current and voltage can be kept within the RBSOA described in the specification in any expected operating condition of the system.

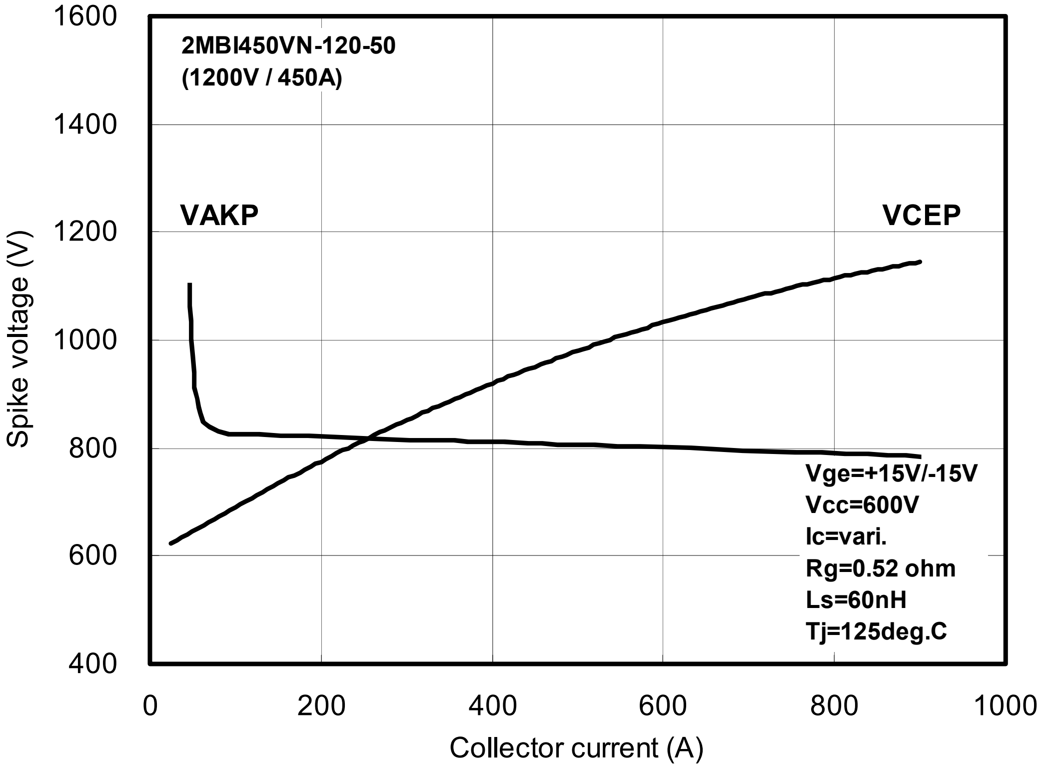


Fig. 5-10 Spike voltages dependency on collector current

2-5 Spike voltage suppression circuit - clamp circuit -

In general, spike voltage generated between collector to emitter can be suppressed by means of decreasing the stray inductance or installing snubber circuit. However, it may be difficult to decrease the spike voltage under the hard operating conditions.

For this case, it is effective to install the active clamp circuits, which is one of the spike voltage suppressing circuits.

Fig. 5-11 shows the example of active clamp circuits.

In the circuits, Zenner diode and a diode connected with the anti-series in the Zenner diode are added.

When the Vce over breakdown voltage of Zenner diode is applied, IGBT will be turned-off with the similar voltage as breakdown voltage of Zenner diode. Therefore, installing the active clamp circuits can suppress the spike voltage.

Moreover, avalanche current generated by breakdown of Zenner diode, charge the gate capacitance so as to turn-on the IGBT. As the result, di/dt at turn-off become lower than that before adding the clamp circuit (Refer to Fig. 5-12). Therefore, because switching loss may be increased, apply the clamp circuit after various confirmations for design of the equipment.

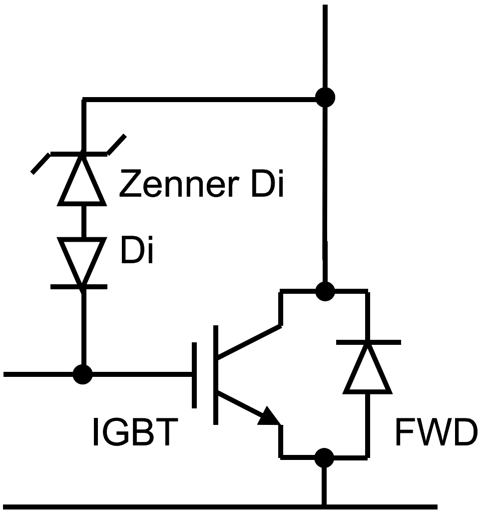


Fig. 5-11 Active clamp circuit

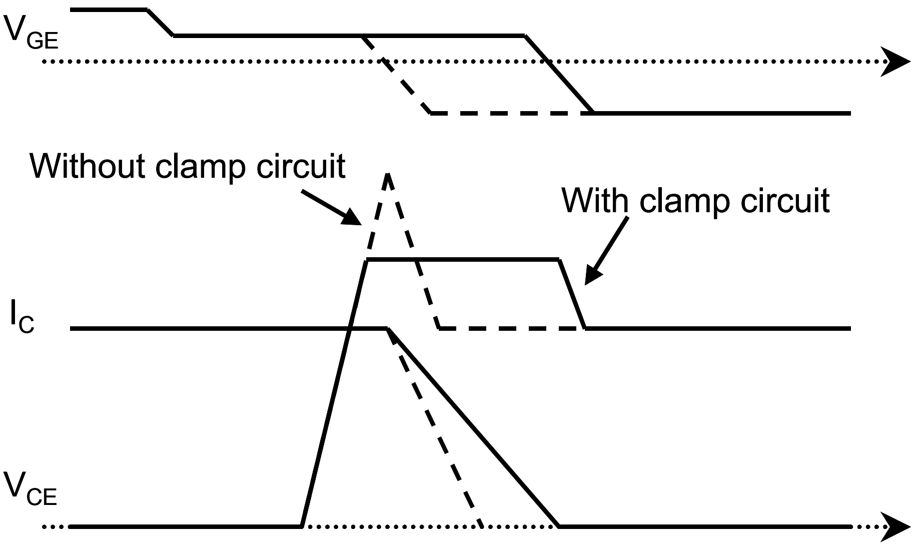


Fig. 5-12 Schematic waveform for active clamp circuit

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