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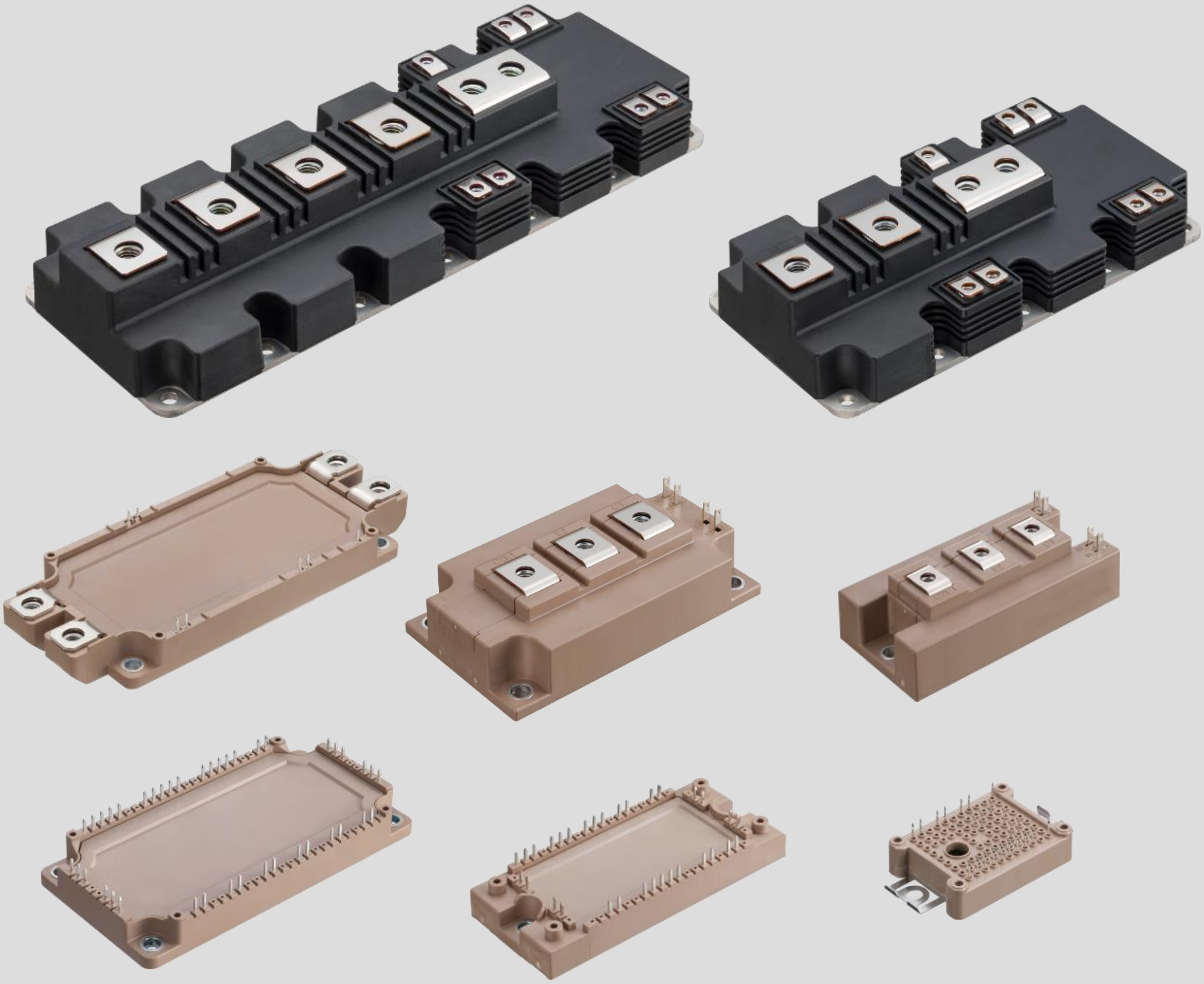

Fuji IGBT Module

Application Manual

March, 2023

Fuji Electric Co.,Ltd.

REH984f

⚠ Cautions

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Chapter 5 Protection Circuit Design

This chapter describes about the protection circuit design.

1. Short Circuit (Overcurrent) Protection

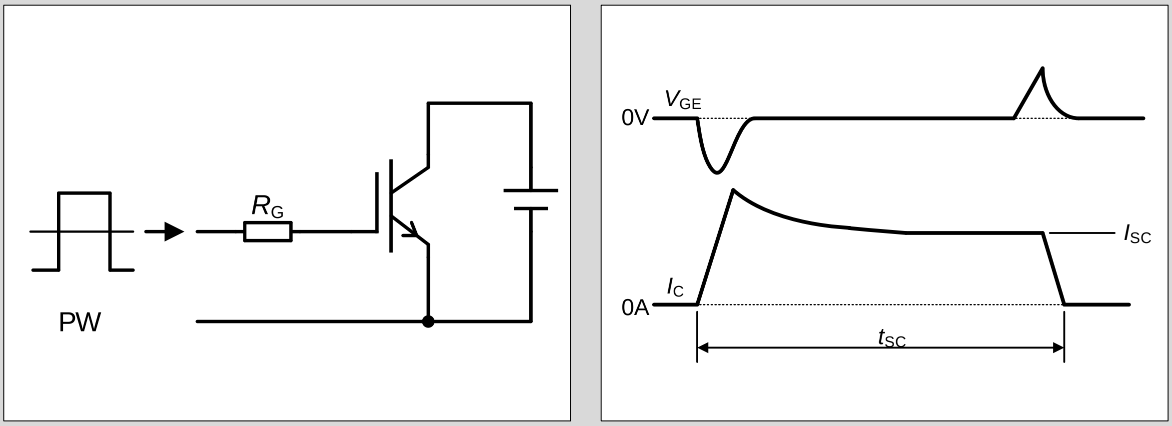
1.1 Short circuit withstand capability t_{sc}

In the event of a short circuit, the IGBT's collector current I_C will rise, and if it exceeds a certain level, the C-E voltage V_{CE} will increase sharply. Due to this characteristic, the I_C can be kept at or below a certain level during short circuit. However, the IGBT will still continue to be subjected to a heavy load of high voltage and high current. If this abnormal state continues, the IGBT will be destroyed. The time that the IGBT can withstand a short circuit without destruction is specified as short circuit withstand capability t_{sc}. The gate drive circuit must be designed so that the delay time from short circuit detection until the short circuit current cut off is shorter than t_{sc}.

The concept of short-circuit withstand capability for arm short circuit and output short circuit is explained below.

(1) Arm short circuit

Fig. 5-1 shows an arm short circuit test circuit and waveform example. As for the arm short circuit, the I_C rises sharply at the start of the short circuit and drops slightly after saturation. The short circuit (saturation) current value I_{SC} is determined by V_{GE}, device output characteristics, and T_{vj}, and is almost independent of V_{DC}, R_G, and P_W. The short circuit withstand capability is expressed by the energization time P_W and is specified after specifying the V_{GE}, T_{vj}, and V_{DC} conditions. Design the protection circuit so that when a short circuit occurs, it will be cut off within the specified short circuit withstand capability.



(a) Arm short circuit test circuit

(b) Arm short circuit waveform example

Fig. 5-1 Arm short circuit test circuit and waveform

(2) Output short circuit

Fig. 5-2 shows the output short circuit test circuit and waveform example. In the output short circuit, the short circuit wire has inductance component, thus the current waveform at the start of the short circuit is different from that in the case of the arm short circuit. In this case, the current rise rate d*i*/d*t* can be expressed as follows.

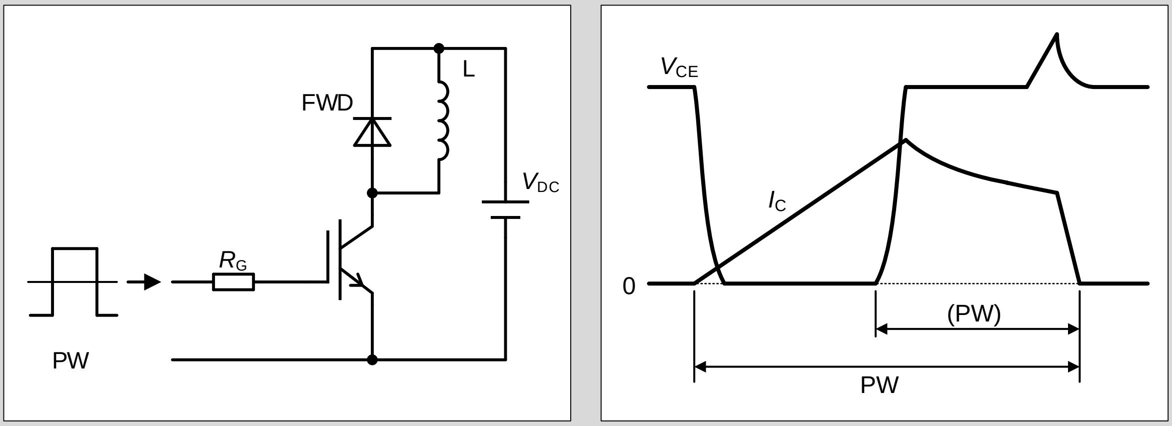
$$d_i/d_t = V_{DC}/L \ \ (A/sec)$$

If the time from the start of the short circuit is given as *t* (sec), I_C can be expressed as follows.

$$I_C = d_i/d_t \cdot t \ (A)$$

The I_C peak value depends on the inductance and the drive circuit (transient V_{GE} rise). After reaching the peak value and saturating, V_{CE} rises sharply. From here, it becomes the same situation with an arm short circuit.

The short circuit withstand capability in the case of output short circuit is shown in Fig. 5-2(b) as (P_w). During I_C rise, V_{DC} is applied to the inductance L, and the voltage across the IGBT is about $V_{CE\ (sat)}$, thus the load on the IGBT is extremely low compared to the arm short circuit. Therefore, this period is not included in the short circuit withstand capability.



(a) Output short circuit test circuit (b) Output short circuit waveform example

Fig. 5-2 Output short circuit test circuit and waveform

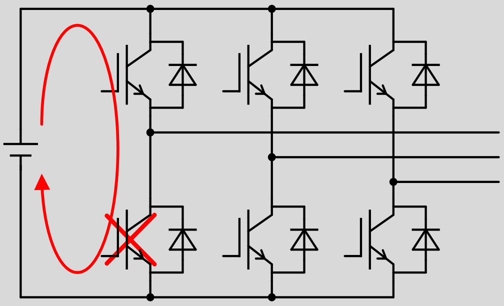
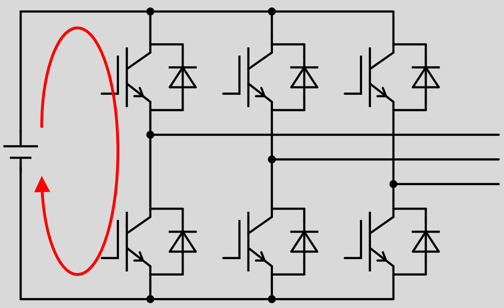
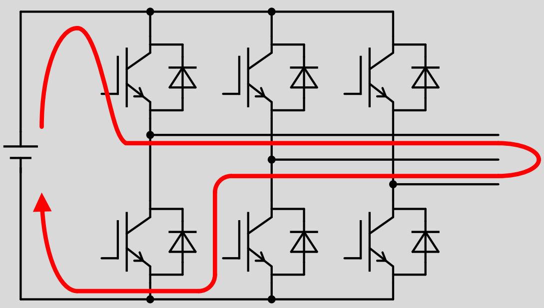
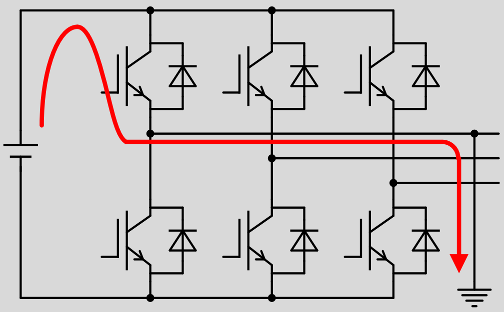
Short circuit withstand capability depends on conditions such as V_{CE}, V_{GE}, and T_{vj}. Generally, the higher the V_{DC} and the higher the T_{vj}, the shorter the short circuit withstand capability.

Also, please note that V_{GE} may rise during short circuit. Please refer to the application manual or technical document for the short circuit capability of each IGBT series.

1.2 Short circuit modes and causes

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

Table 5-1 Short circuit modes and causes

Short circuit mode	Cause
Arm short circuit 	IGBT or diode destruction.
Series arm short circuit 	Control circuit / drive circuit failure or malfunction due to noise.
Output short circuit 	Miswiring or dielectric breakdown of load
Ground fault 	Miswiring or dielectric breakdown of load

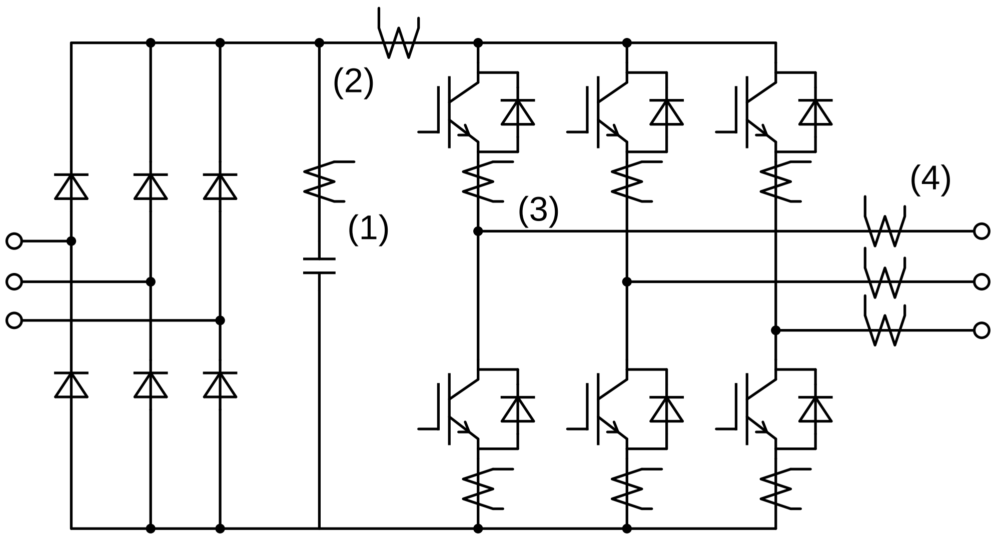
1.3 Short circuit (overcurrent) detection method

(1) Detection by overcurrent detector

As mentioned, in the event of a short circuit, the IGBT must be turned off as soon as possible. Therefore, the time from short circuit detection to the completion of turn-off must be as short as possible.

Since the IGBT turns off very fast, if the short circuit is turned off with a normal gate drive signal, a large surge voltage will be generated, and the IGBT may be destroyed by overvoltage (RBSOA destruction). Therefore, it is recommended to turn off the IGBT slowly (soft turn-off).

Fig. 5-3 shows the overcurrent detectors position in an inverter circuit, and Table 5-2 shows the features and the types of short circuit that can be detected by each method. Consider what kind of protection is necessary, and select the most appropriate form of detection.



Overcurrent detector position	Types of short circuits that can be detected
(1), (2), (3)	・Arm short circuit ・Series arm short circuit ・Output short circuit ・Ground fault
(4)	・Output short circuit ・Ground fault

Fig. 5-3 Overcurrent detector position

Table 5-2 Overcurrent detector positions and their features

Overcurrent detector position	Feature	Types of short circuits that can be detected
In series with smoothing capacitor Fig. 5-3/(1)	• AC current transducer can be used • Low detection precision	• Arm short circuit • Series arm short circuit • Output short circuit • Ground fault
At inverter input Fig. 5-3/(2)	• DC current transducer is required • Low detection precision	• Arm short circuit • Series arm short circuit • Output short circuit • Ground fault
In series with each IGBT Fig. 5-3/(3)	• DC current transducer is required • High detection precision	• Arm short circuit • Series arm short circuit • Output short circuit • Ground fault
At inverter output Fig. 5-3/(4)	• AC current transducer can be used for equipment with high frequency output • High detection precision	• Output short circuit • Ground fault

(2) Detection by $V_{CE(sat)}$

This method can protect against all types of short circuit shown in Table 5-1. Since the operations from overcurrent detection to protection are done on the drive circuit side, this method offers the fastest protection possible. Fig. 5-4 shows an example of short circuit protection circuit using $V_{CE(sat)}$ detection method.

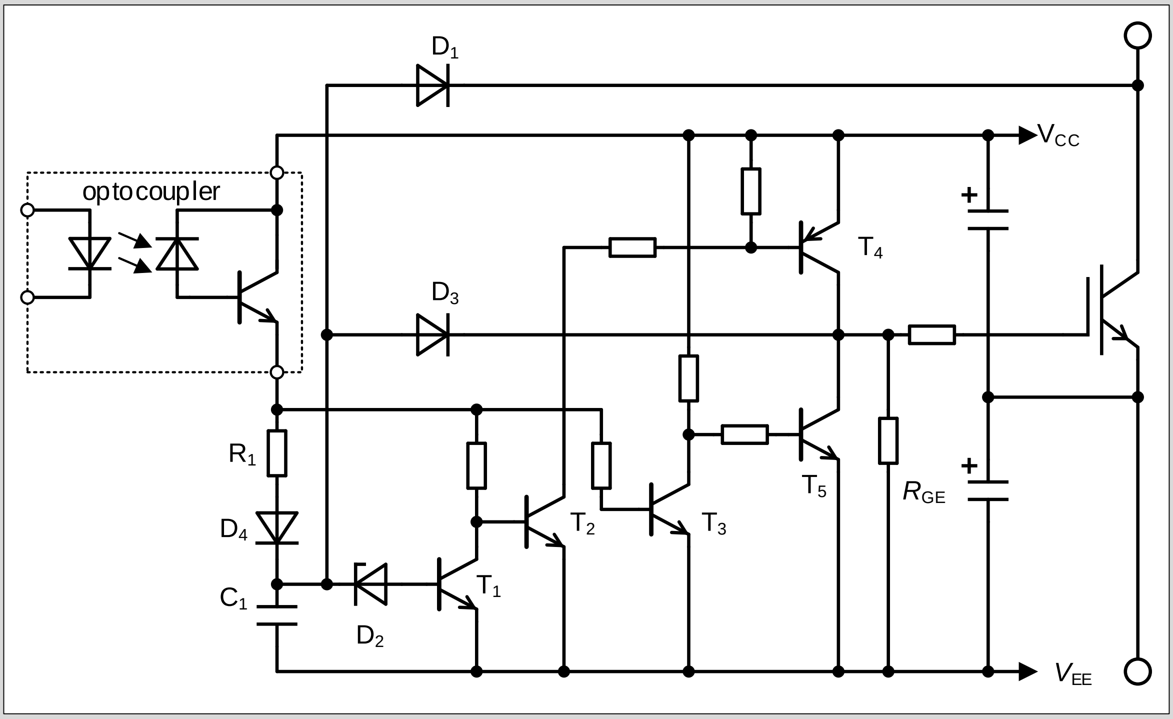


Fig. 5-4 Short-circuit protection circuit using $V_{CE(sat)}$ detection method

This circuit uses diode D_1 to constantly monitor the C-E voltage.

When the optocoupler is turned on, transistors T_2 and T_4 are turned on and a positive gate voltage is applied to the IGBT. Also, the capacitor C_1 is charged through the resistor R_1 and diode D_4. The operation changes depending on the voltage of capacitor C_1.

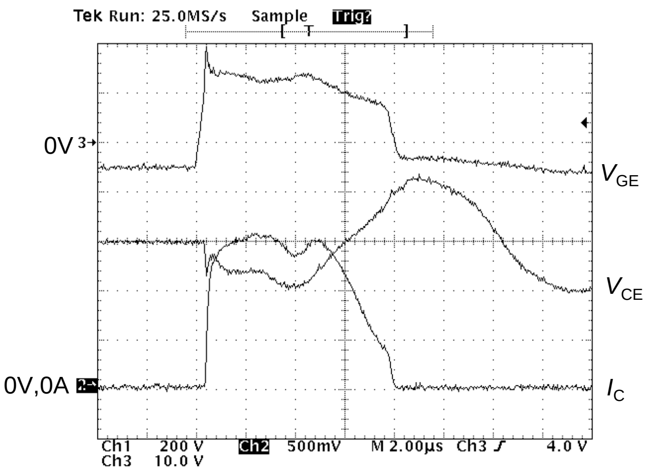
【Short circuit protection operation】

If a short circuit occurs after the IGBT is turned on, the V_{CE} of the IGBT rises. When V_{CE} becomes higher than the voltage of [C_1 - D_1 (V_F - V_{EE})], diode D_1 is turned off and the voltage of capacitor C_1 rises again. When the voltage of capacitor C_1 becomes higher than [V_Z of Zener diode D_2 + V_{BE} of transistor T_1], short circuit protection operates.

In the short circuit protection operation, a current flows through Zener diode D_2 to the base of transistor T_1, turning it on. When transistor T_1 is turned on, transistors T_2 and T_4 are turned off, and the applied positive gate voltage is cut off. Since the optocoupler is on, the transistor T_3 is on and transistor T_5 is off. Since the transistors T_4 and T_5 are turned off at the same time, the gate accumulated charge is slowly discharged through the R_{GE}. This effect can suppress the generation of excessive surge voltage when the IGBT turns off. Fig. 5-5 shows an example of the short circuit protection waveform.

【Normal operation】

After the IGBT is turned on, the IGBT is kept on by keeping the voltage of capacitor C_1 below [V_Z of the Zener diode D_2 + V_{BE} of transistor T_1]. When the optocoupler is turned off, the transistors T_2, T_4 turn off, transistor T_3 turns off, and transistor T_5 turns on, applying a negative gate voltage to the IGBT. The charge on capacitor C_1 is discharged through diode D_3 and transistor T_5 and reset to 0V. As can be seen from the above operation sequence, short circuit protection is monitored on each pulse.



E_d=600V, V_{GE}=+15V/-5V, R_G=3.3Ω, T_{vj}=125°C

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

Fig. 5-5 Waveforms during short circuit protection

2. Overvoltage Protection

2.1 Cause of overvoltage and suppression methods

(1) Cause of overvoltage

Due to the high switching speed of IGBTs, during turn-off or FWD reverse recovery, the current change rate d*i*/d*t* is very high. Therefore, the circuit wiring inductance around the module L_S can generate a high surge voltage $V_{CEP}=L_S\cdot(di/dt)$.

Fig. 5-6 shows a chopper circuit for measuring the turn-off surge voltage, and Fig. 5-7 shows the switching waveforms.

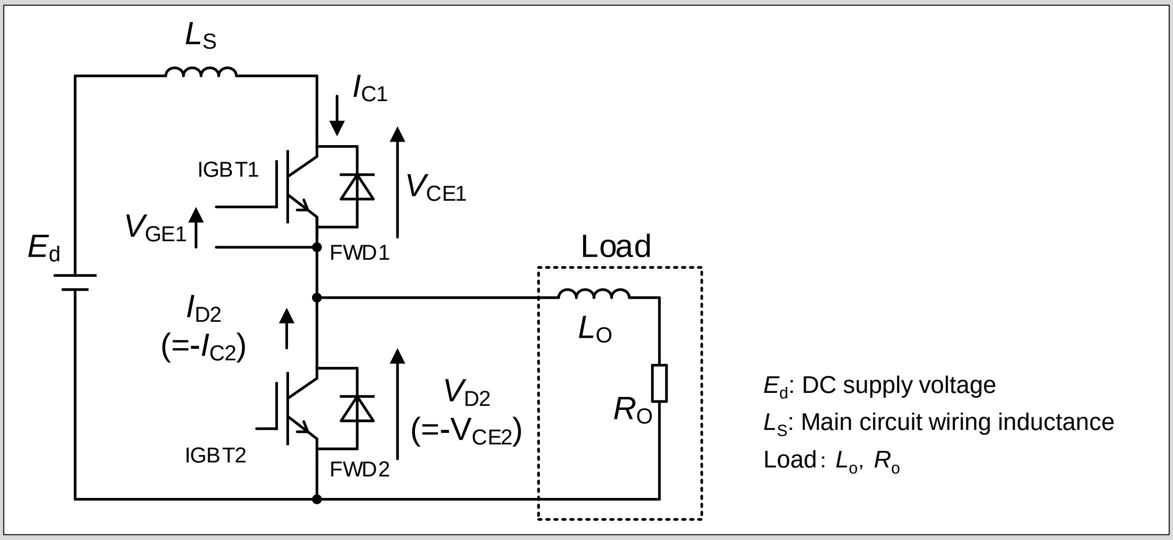


Fig. 5-6 Chopper circuit

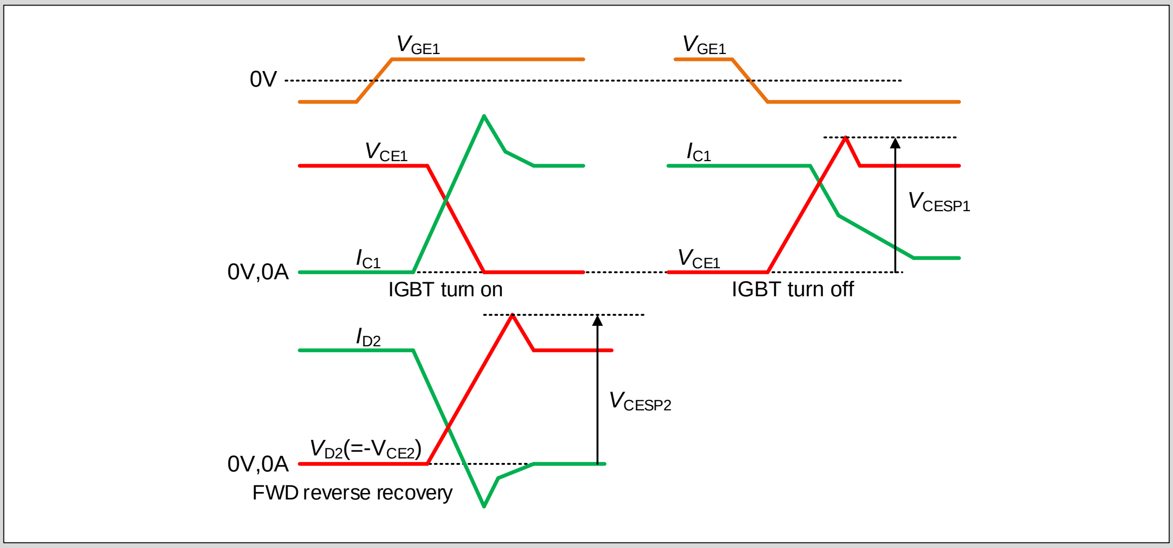


Fig. 5-7 Switching waveforms

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

$$V_{CESP} = E_d + (-L_S \cdot \frac{dI_C}{dt})$$

dI_C/dt: Maximum I_C change rate at turn-off

If V_{CESP} exceeds the V_{CES} rating, the module will be destroyed.

(2) Overvoltage suppression methods

The following methods are available for suppressing turn-off surge voltage.

a. Suppress the surge voltage by adding a protection circuit such as a snubber circuit to the IGBT. Use a film capacitor and place it as close as possible to the IGBT in order to suppress high frequency surge voltage.
b. Adjust the $-V_{GE}$ and R_G of the drive circuit in order to reduce the d*i*/d*t*. (For details, refer to Chapter 7, 'Gate Drive Circuit Design')
c. Place the DC capacitor as close as possible to the IGBT in order to reduce L_S. Use a low impedance type capacitor.
d. Reduce the L_S of the main circuit and snubber circuit by using thicker and shorter wires. It is also very effective to use laminated bus bars.
e. Use an active clamp circuit. The surge voltage is suppressed to approximately equal to the Zener voltage of the Zener diode.

2.2 Types of snubber circuits and their features

Snubber circuits can be classified into two types: individual snubber circuit and lump snubber circuit. 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 as follows.

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

Table 5-3 shows the schematic and features of each type of individual snubber circuit.

(2) Lump snubber circuits

Examples of typical lump snubber circuits are as follows.

a. C snubber circuit
b. RCD snubber circuit

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

Table 5-4 shows the schematic and features of each type of lump snubber circuit. Table 5-5 shows the guideline for determining lump C snubber capacitance. Fig. 5-8 shows an example of turn-off waveforms of IGBT with lump C snubber circuit.

Table 5-3 Individual snubber circuits

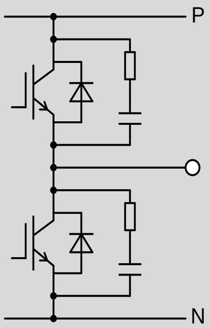
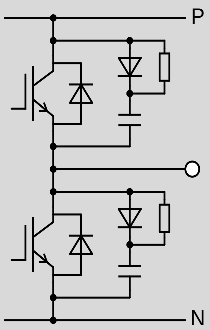
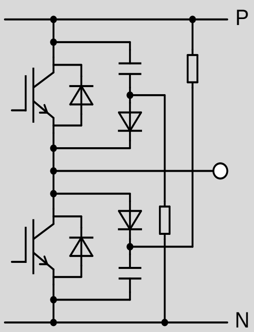
Snubber circuit schematic	Features (Notes)
RC snubber circuit 	• The surge voltage suppression effect is greater than that of a lump snubber circuit. • When applied to large capacity IGBTs, the snubber resistance must be low. As a result, the current at turn-on increases and increase the IGBT load.
Charge-discharge RCD snubber circuit 	• Unlike the RC snubber circuit, a snubber diode is added. Thus, snubber resistance can be increased, and decrease the IGBT load at turn-on . • The power dissipation loss by the snubber resistance of this circuit can be calculated as follows. $P = \frac{L_S \cdot I_O^2 \cdot f}{2} + \frac{C_S \cdot E_d^2 \cdot f}{2}$ L_S: Wiring inductance of main circuit I_O: Collector current at IGBT turn-off C_S: Capacitance of snubber capacitor E_d: DC power supply voltage f: Switching frequency
Discharge-suppressing RCD snubber circuit 	• Power dissipation loss of snubber circuit is small. • The power dissipation loss by the snubber resistance of this circuit can be calculated as follows. $P = \frac{L_S \cdot I_O^2 \cdot f}{2}$ L_S: Wiring inductance of main circuit Io: Collector current at IGBT turn-off f :Switching frequency

Table 5-4 Lump snubber circuits

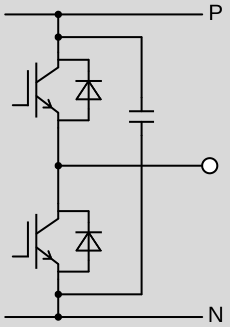
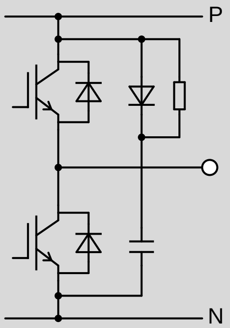
Snubber circuit schematic	Features (Notes)
C snubber circuit 	• This is the simplest snubber circuit. • The LC resonance circuit, which consists of main circuit inductance and snubber capacitor, may cause the C-E voltage to oscillate.
RCD snubber circuit 	• If the snubber diode is selected incorrectly, a high surge voltage will be generated or the voltage may oscillate during reverse recovery of the snubber diode.

Table 5-5 Guideline for determining lump C snubber capacitance

Item / Module rating		Gate drive conditions [*1] $-V_{GE}$ (V)	Gate drive conditions [*1] R_G (Ω)	Main circuit inductance (μH)	Snubber capacitance C_S (μF)
600V	50A	≦15	≧43	-	0.47
	75A		≧30		
	100A		≧13		
	150A		≧9	≦0.2	1.5
	200A		≧6.8	≦0.16	2.2
	300A		≧4.7	≦0.1	3.3
	400A		≧6	≦0.08	4.7
1200V	50A	≦15	≧22	-	0.47
	75A		≧4.7		
	100A		≧2.8		
	150A		≧2.4	≦0.2	1.5
	200A		≧1.4	≦0.16	2.2
	300A		≧0.93	≦0.1	3.3

*1: Standard gate drive conditions of V series IGBT is shown

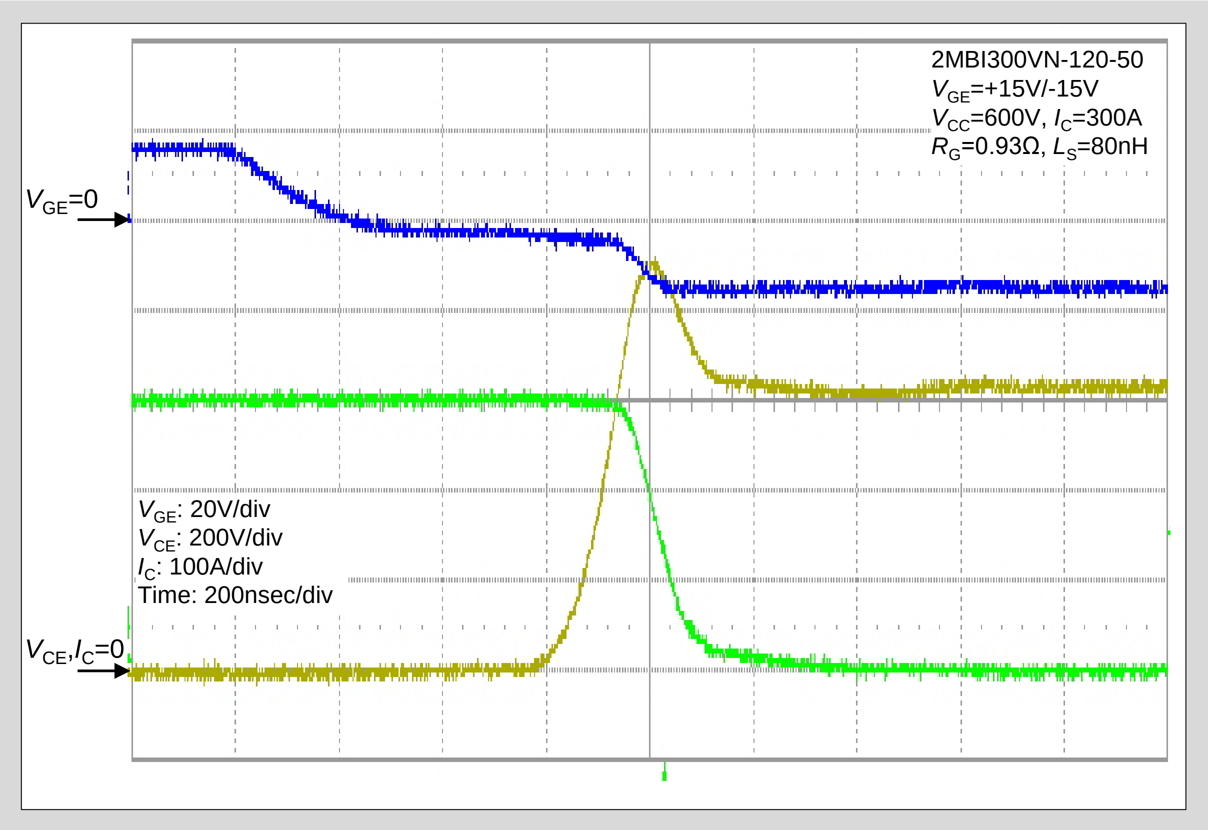


Fig. 5-8 Turn-off waveforms of IGBT with lump C snubber circuit

2.3 Discharge-suppressing RCD snubber circuit design

The discharge-suppressing RCD snubber circuit is considered the most suitable snubber circuit for IGBT. The basic design method of this circuit is as follows.

(1) Study of applicability

Fig. 5-9 shows the turn-off locus of IGBT with discharge-suppressing RCD snubber circuit. Fig. 5-10 shows the IGBT turn-off waveform.

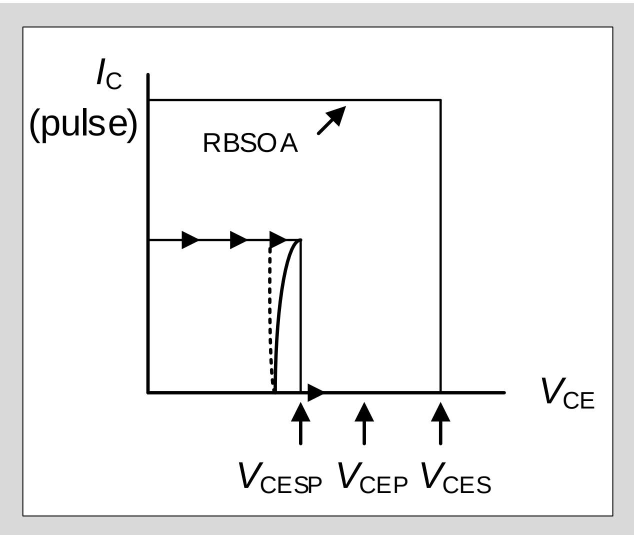


Fig. 5-9 Turn-off locus of IGBT

In the discharge-suppressing RCD snubber circuit operates after V_{CE} of the IGBT exceeds the DC power supply voltage. The ideal operation trajectory is shown by the dotted line.

However, in actual equipment, there is surge voltage at turn-off due to the wiring inductance of the snubber circuit and the transient forward voltage of the snubber diode, thus the actual waveform is as shown by the solid line.

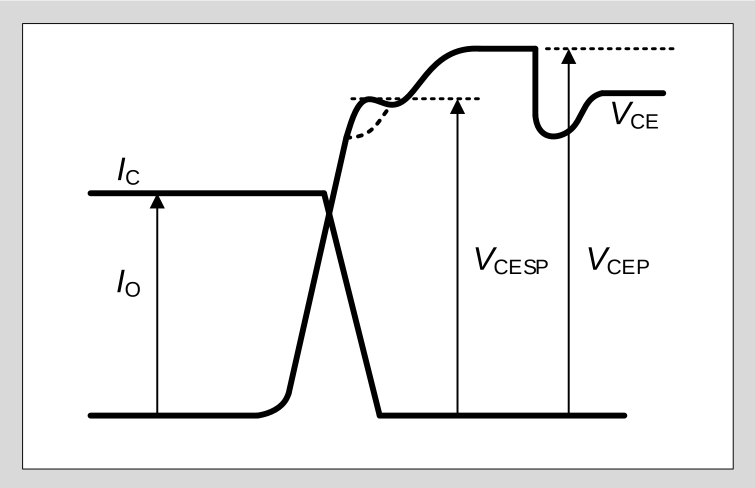


Fig. 5-10 Turn-off waveform with discharge-suppressing RCD snubber circuit

The discharge-suppressing RCD snubber circuits applicability is decided by whether the turn-off locus after applying the snubber circuit is within the RBSOA.

The surge voltage at IGBT turn-off is calculated as follows.

$$V_{CESP} = E_d + V_{FM} + (-L \cdot \frac{dI_c}{d_t})$$

E_d :DC power supply voltage
V_{FM} :Transient forward voltage of snubber diode
The reference values are as follows.
600V class: 20 to 30V
1200V class: 40 to 60V
L :Snubber circuit wiring inductance
dI_c/d_t :Maximum I_C change rate at IGBT turn-off

(2) Calculating the snubber capacitance (C_S)

The capacitance of the snubber capacitor is calculated as follows.

$$C_S = \frac{L_S \cdot I_O^2}{(V_{CEP} - E_d)^2}$$

L_S :Main circuit wiring inductance
I_o :Collector current at IGBT turn-off
V_{CEP} :Snubber capacitor peak voltage
E_d :DC power supply voltage

V_{CEP} must be limited to less than V_{CES} of the IGBT. Use a snubber capacitor with good high-frequency characteristics such as a film capacitor.

(3) Calculating the snubber resistance (R_S)

The function of the snubber resistor is to discharge the accumulated charge in the snubber capacitor before the next IGBT turn-off. To discharge 90% of the accumulated charge by the next IGBT turn-off, the snubber resistance is calculated as follows.

$$R_S \leq \frac{1}{2.3 \cdot C_S \cdot f}$$

R_S :Snubber resistance
C_S :Snubber capacitance
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 as high as possible within the calculated range.

Irrespective of the resistance value, the power dissipation of the snubber resistor $P(R_S)$ is calculated as follows.

$$P(R_S) = \frac{L_S \cdot I_O^2 \cdot f}{2}$$

$P(R_S)$:Power dissipation of snubber resistor
L_S :Main circuit wiring inductance
I_o :Collcetor current at IGBT turn-off
f :Switching frequency

(4) Snubber diode selection

The transient forward voltage of the snubber diode is one of the cause of surge voltage at IGBT turn-off. If the reverse recovery time of the snubber diode is too long, the power dissipation loss of the snubber diode will also be much higher during high frequency switching. Also, if the reverse recovery of the snubber diode is too hard, then the IGBT C-E voltage will oscillate greatly.

Therefore, select a snubber diode that has a low transient forward voltage, a short reverse recovery time, and asoft reverse recovery.

(5) Snubber circuit wiring precautions

The snubber circuit wiring inductance is one of the main cause of surge voltage, therefore it is important to reduce the wiring inductance, as well as considering the layout of circuit components.

2.4 Example of surge voltage characteristics

Surge voltage characteristics depend on the operation, drive conditions, circuit conditions, etc. Generally, surge voltage tends to increase when V_{CE} is higher, the circuit inductance is larger, and I_C is larger.

As an example, the current dependency of surge voltage during IGBT turn-off and FWD reverse recovery is shown in Fig. 5-11. As shown in this figure, the surge voltage at IGBT turn-off becomes higher when current is higher, but the surge voltage during FWD reverse recovery tends to increases at the low current region. Generally, the surge voltage during reverse recovery increases at low current that is about 1~10% of the rated current.

The surge voltage shows various characteristics depending on the operation, drive conditions, circuit conditions, etc. Therefore, it is necessary to confirm that the current and voltage are within the RBSOA described in the specification under all operating conditions of the system.

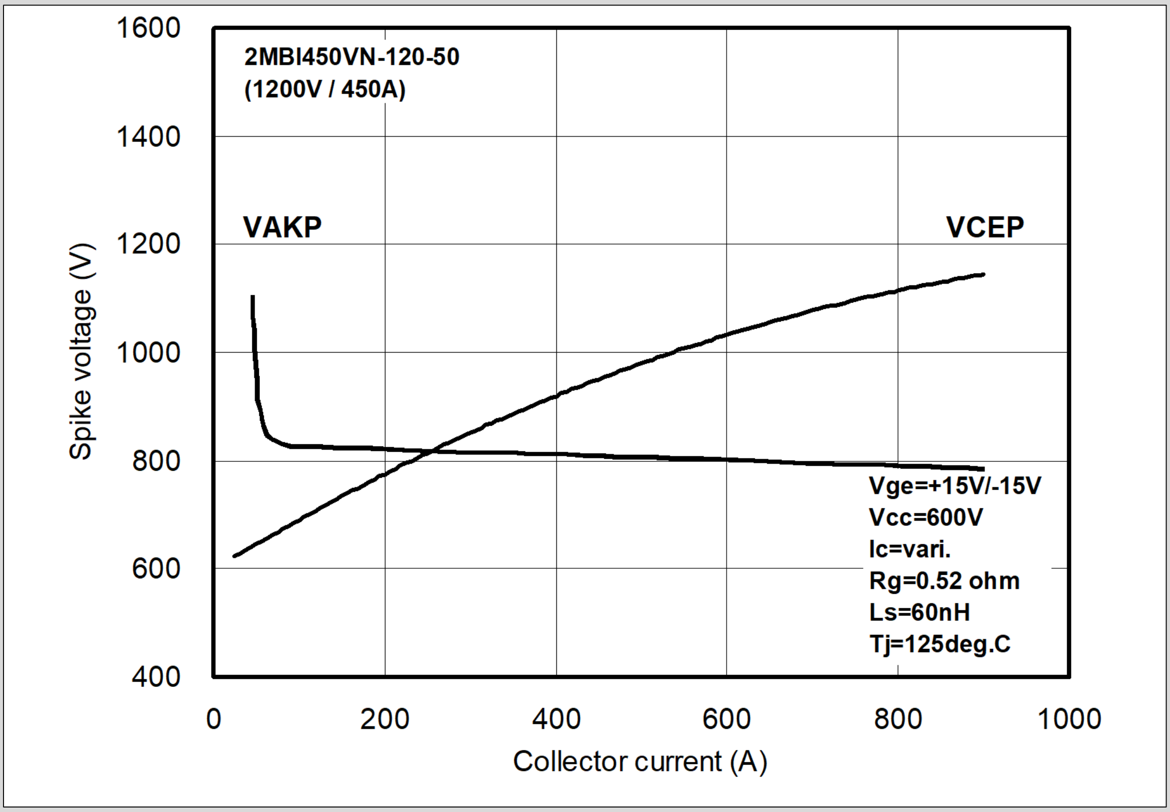


Fig. 5-11 Current dependency of surge voltage during IGBT turn-off and FWD reverse recovery

2.5 Overvoltage suppression circuit -example of clamp circuit configuration-

In general, surge voltage can be suppressed by means of decreasing the stray inductance or installing a snubber circuit. However, it may be difficult to suppress the surge voltage under depending on the operating conditions of the equipment. For such cases, it is effective to use active clamp circuits.

Fig. 5-12 shows an example of active clamp circuit. The circuit configuration adds a Zener diode at C-G of the IGBT, and connect a diode in anti-series with the Zener diode.

When voltage exceeding the Zener voltage of the Zener diode is applied on C-E, the Zener diode breakdown and current flows from collector to the IGBT gate. Positive voltage is added to V_{GE} by this current flowing through R_G. When V_{GE} exceeds the gate threshold voltage $V_{GE(th)}$, I_C flows through the IGBT, and V_{CE} is clamped to approximately equal to the Zener voltage of the Zener diode. In thi s way, surge voltage can be suppressed.

On the other hand, since the active clamp circuit turn on the IGBT, the d*i*/d*t* at turn-off becomes slower than before the addition of the clamp circuit, resulting in a longer turn-off time (refer to Fig. 5-13). As this will increase the switching loss, make sure to apply the clamp circuit after verifying if this has no problem with the design of the equipment.

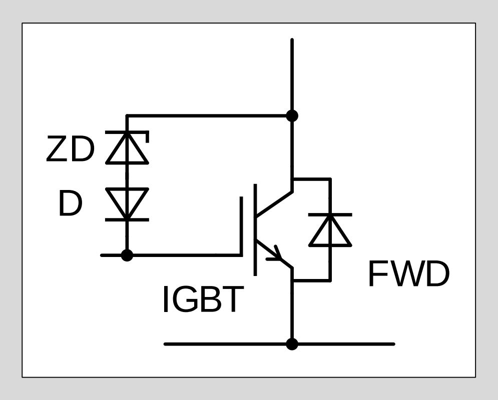


Fig. 5-12 Active clamp circuit

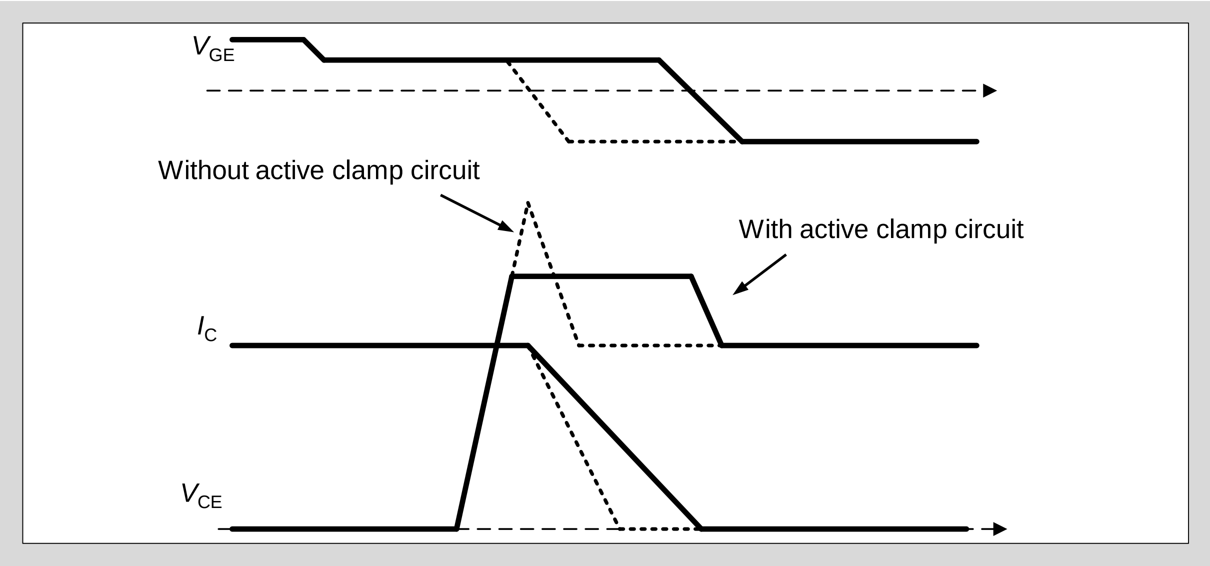


Fig. 5-13 Waveform example when active clamp circuit is applied