

Chapter 3 Overvoltage Protection (Main Circuit)

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Overvoltage is applied to IGBT and FWD when the current is cut off, and the overvoltage may destroy the device. This chapter describes the overvoltage protection (main circuit).

1. Overvoltage Causes and Suppression Method

Fig.3-1 shows the inverter circuit for one phase. The overvoltage is generated at the wiring inductance L_s of the main circuit due to a sudden change in the main circuit current when the IGBT is turned-off. Fig.3-2 shows a typical IGBT1 turn-off waveform and FWD2 reverse recovery waveform. If this overvoltage exceeds V_{CES} , the IGBT and FWD might be destroyed.

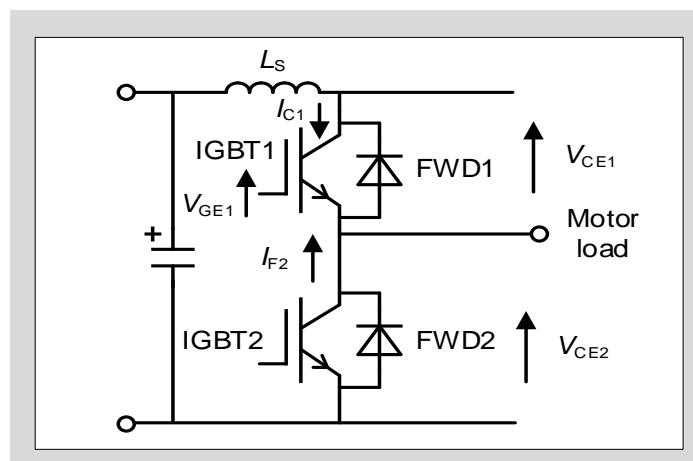


Fig.3-1 Inverter circuit for one phase

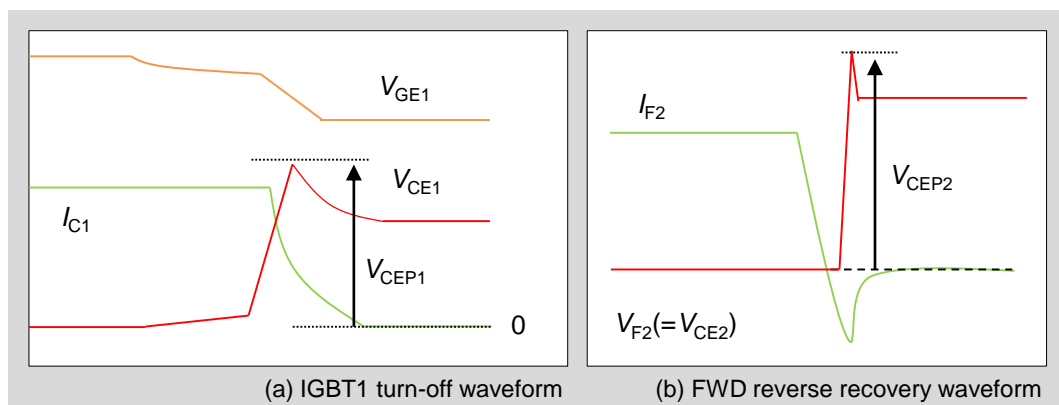


Fig. 3-2 Switching waveforms

<Overvoltage suppression methods>

The methods for suppressing the overvoltage are shown below.

(a) Snubber circuit placement

Place the snubber circuit close to the terminals to reduce the effect of wiring inductance.

(b) Adjustment of reverse biased voltage ($-V_{GE}$) and gate resistance (R_G) of IGBT drive circuit

By reducing $-V_{GE}$ and increasing R_G , di/dt at the time of turn-off can be reduced and overvoltage can be suppressed. (See Chapter 4, Drive Circuit Design for details)

(c) Shortening the distance between the electrolytic capacitor and the IGBT

Place the electrolytic capacitor as close as possible to the IGBT in order to reduce the wiring inductance. It is even more effective to use a capacitor with low impedance.

(d) Adjustment of main circuit

To reduce the inductance, use thicker and shorter wires. It is also very effective to use laminated copper bars .

(e) Application of active clamp circuit

By applying an active clamp circuit to the gate drive circuit, it is possible to suppress the overvoltage to approximately equal to the Zener Voltage of the Zener diode.

2. Types of Snubber Circuits and Their Features

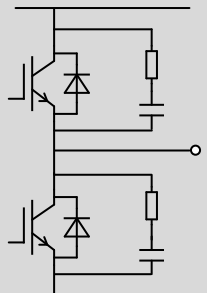
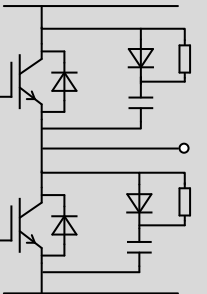
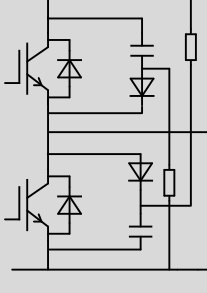
Individual snubber circuits are connected to each IGBT, while lump snubber circuits are connected between the DC power-supply bus and the ground for centralized protection.

<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.3-1 Individual snubber circuits

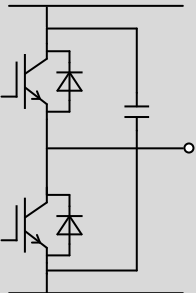
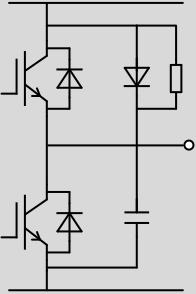
Snubber circuit schematic	Circuit features (comments)
<p>(a) RC snubber circuit</p> 	<ul style="list-style-type: none"> • This circuit has greater overvoltage suppression effect than the lump snubber circuit. • When applied to large capacity IGBT, the snubber resistance must be low. Consequently however, the above condition causes the load conditions at turn-on to become more severe.
<p>(b) Charge and discharge RCD snubber circuit</p> 	<ul style="list-style-type: none"> • This circuit has overvoltage suppression effect. • As opposed to the RC snubber circuit, a snubber diode has been added. This allows the snubber resistance to increase and consequently avoids the IGBT load conditions at turn-on problem. • The power dissipation loss caused by the snubber resistance can be calculated as follows: <ul style="list-style-type: none"> L : Wiring inductance of main circuit I_o : I_C at IGBT turn-off C_s : Capacitance of snubber capacitor E_d : DC supply voltage f : Switching frequency $P = \frac{L \cdot I_o^2 \cdot f}{2} + \frac{C_s \cdot E_d^2 \cdot f}{2}$
<p>(c) Discharge suppressing RCD snubber circuit</p> 	<ul style="list-style-type: none"> • This circuit has overvoltage suppression effect. • Snubber circuit power dissipation is small. • The power dissipation loss caused by the snubber resistance can be calculated as follows: <ul style="list-style-type: none"> L : Wiring inductance of main circuit I_o : I_C at IGBT turn-off f : Switching frequency $P = \frac{L \cdot I_o^2 \cdot f}{2}$

<Lump snubber circuits>

Examples of typical snubber circuits are listed below.

(a) C snubber circuit (b) RCD snubber circuit

Fig.3-2 Lump snubber circuits

Snubber circuit schematic	Circuit features (comments)
<p>(a) C snubber circuit</p> 	<ul style="list-style-type: none"> • This is the simplest circuit. • The LC resonance circuit, which consists of main circuit inductance and snubber capacitance, may cause the voltage to oscillate.
<p>(b) RCD snubber circuit</p> 	<ul style="list-style-type: none"> • If the wrong snubber diode is used, high overvoltage will be generated and the output voltage will oscillate during reverse recovery.

3. Discharge-suppressing RCD Snubber Circuit Design

This section describes the basic design method of the discharge-suppressing RCD snubber circuit.

<Study of applicability>

Fig.3-3 shows the turn-off locus waveform of IGBT in a discharge-suppressing RCD snubber circuit. Fig.3-4 shows the I_C and V_{CE} waveforms at turn-off. This circuit is activated when V_{CE} starts to exceed the DC supply voltage. The dotted line in Fig. 3-3 shows the ideal operating locus of the IGBT. In an actual application, the wiring inductance of the snubber circuit or a transient forward voltage drop in the snubber diode can cause overvoltage at IGBT turn-off. This overvoltage causes the sharp-cornered locus indicated by the solid line in Fig.3-3. This snubber circuit applicability is decided by whether or not the IGBT operating locus is within the RBSOA at turn-off.

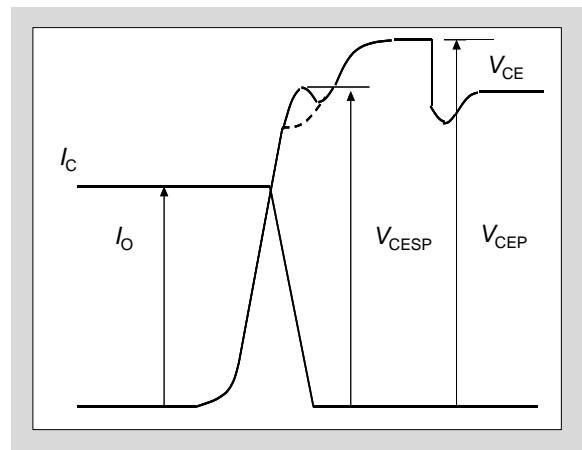
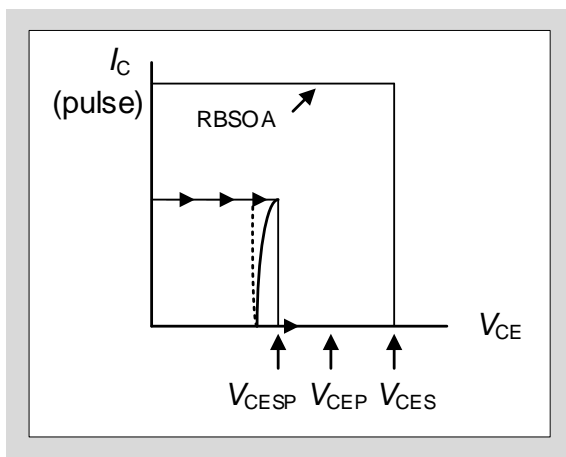


Fig.3-3 Turn-off locus waveform of IGBT Fig.3-4 Voltage and current waveforms at turn-off

The overvoltage at IGBT turn-off is calculated as follows:

$$V_{CESP} = E_d + V_{FM} + \left(-L_S \frac{di_C}{dt}\right) \dots\dots\dots ①$$

E_d : DC supply voltage
 V_{FM} : Transient forward voltage drop in snubber diode
 L_S : Snubber circuit wiring inductance
 di_C/dt : Max. I_C change rate 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

<Calculating the capacitance of the snubber capacitor (Cs)>

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

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

L : Main circuit wiring inductance
 I_O : I_C at IGBT turn-off
 V_{CEP} : Snubber capacitor peak voltage
 E_d : DC supply voltage

V_{CEP} must be limited to less than or equal to the IGBT C-E withstand voltage. Also, select a snubber capacitor with good high-frequency characteristics (film capacitor, etc.).

<Calculating snubber resistance (R_s)>

The snubber resistance is required 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:

$$R_s \leq \frac{1}{2.3 \cdot C_s \cdot f} \dots\dots\dots \textcircled{3}$$

R_s : Snubber resistance
 C_s : Snubber capacitor
 f : Switching frequency

If the snubber resistance is set too low, the snubber circuit current will oscillate and the peak I_C at the IGBT turn-off will increase. Therefore, set the snubber resistance in a range below the value calculated in equation ③.

Irrespective of the resistance value, the snubber resistance loss $P(R_s)$ can be calculated as follows:

$$P(R_s) = \frac{L \cdot I_0^2 \cdot f}{2} \dots\dots\dots \textcircled{4}$$

$P_{(R_s)}$: Loss of snubber resistance
 L : Main circuit wiring inductance
 I_0 : I_C at IGBT turn-off
 f : Switching frequency

<Snubber diode selection>

Transient forward voltage drop in the snubber diode is one factor that can cause overvoltage. 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 fast, then the IGBT C-E voltage will increase drastically and oscillate. Select a snubber diode that has a low transient forward voltage, short reverse recovery time and a soft recovery.

<Snubber circuit wiring precautions>

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

4. Active Clamp Circuit

Other than the reduction of main circuit inductance and application of snubber circuit, applying an active clamp circuit to the gate drive circuit (GDU) is an effective method of suppressing overvoltage. Fig.3-5 shows the example of active clamp circuits. In the circuit, a zener diode and a diode connected in anti-series are added in between C-G. If a voltage exceeding the breakdown voltage of the zener diode is applied to C-G, the zener diode breakdown, and the IGBT will be turned-off with C-G voltage equal to the breakdown voltage of the zener diode. Fig.3-6 shows an example of the waveform when the active clamp circuit is applied. i_c rate of change di_c/dt at turn-off is slower than before the active clamp circuit was applied, thus the turn-off time is longer. Since the application of the active clamp circuit causes an increase in loss, it is recommended to perform various design verifications.

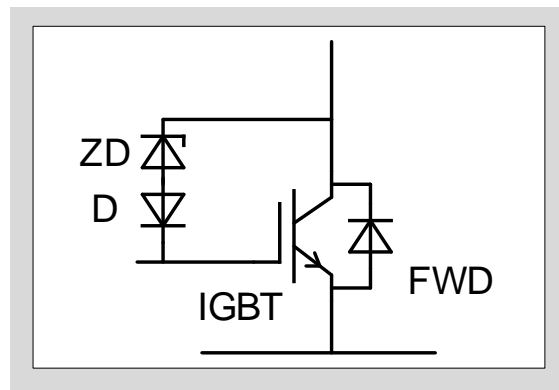


Fig.3-5 Active clamp circuit

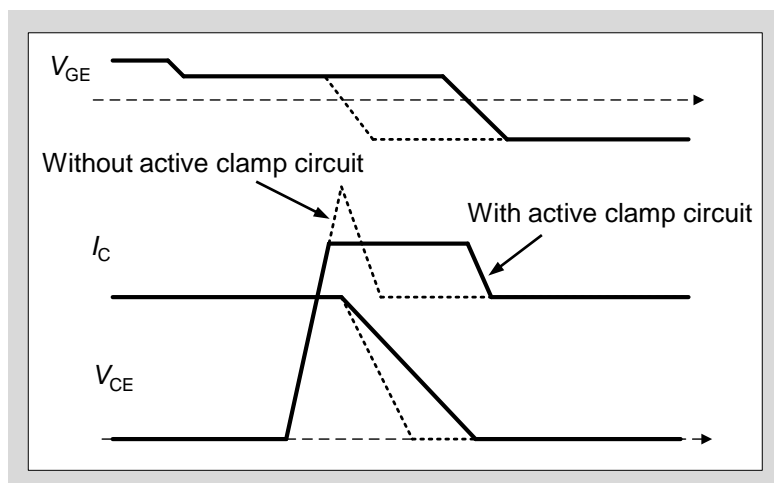


Fig.3-6 Schematic waveform for active clamp circuit