# Chapter 5

## Protection Circuit Design

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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 lower the withstand capability get, the larger supply voltage and the higher junction temperature get.

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

![Fig. 5-1 Measuring circuit and waveform](a) Measuring circuit (b) representative short-circuit waveform

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### 1.2 Short-circuit modes and causes

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

<table>
<thead>
<tr>
<th>Short circuit mode</th>
<th>Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arm short circuit</td>
<td>Transistor or diode destruction</td>
</tr>
<tr>
<td>Series arm short circuit</td>
<td>Faulty control/drive circuit or noise induce malfunction</td>
</tr>
<tr>
<td>Short in output circuit</td>
<td>Miswiring or dielectric breakdown of load</td>
</tr>
<tr>
<td>Ground fault</td>
<td>Miswiring or dielectric breakdown of load</td>
</tr>
</tbody>
</table>
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 time from overcurrent detection to the complete turn-off in each circuit must be as short 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 inductive kick, and the IGBT may be destroyed by overvoltage (RBSOA destructions). Therefore, it is recommended that when cutting 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.

![Figure 5-2 Overcurrent detector insertion methods](image-url)
Table 5-2  Overcurrent detector insertion positions and function

<table>
<thead>
<tr>
<th>Detector insertion position</th>
<th>Features</th>
<th>Detection function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insertion in line with smoothing capacitor Fig.5-2/①</td>
<td>• AC current transformer available&lt;br&gt;• Low detection precision</td>
<td>• Arm short-circuit&lt;br&gt;• Short in output circuit&lt;br&gt;• Series arm short-circuit&lt;br&gt;• Ground fault</td>
</tr>
<tr>
<td>Insertion at inverter input Fig.5-2/②</td>
<td>• Necessary to use DC current transformer&lt;br&gt;• Low detection precision</td>
<td>• Arm short-circuit&lt;br&gt;• Short in output circuit&lt;br&gt;• Series arm short-circuit&lt;br&gt;• Ground fault</td>
</tr>
<tr>
<td>Insertion at inverter output Fig.5-2/③</td>
<td>• AC current transformer available for high frequency output equipment&lt;br&gt;• High detection precision</td>
<td>• Short in output circuit&lt;br&gt;• Ground fault</td>
</tr>
<tr>
<td>Insertion in line with switches Fig.5-2/④</td>
<td>• Necessary to use DC current transformer&lt;br&gt;• High detection precision</td>
<td>• Arm short-circuit&lt;br&gt;• Short in output circuit&lt;br&gt;• Series arm short-circuit&lt;br&gt;• Ground fault</td>
</tr>
</tbody>
</table>

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

This method can protect against all of the short-circuit types listed in Table5-1. 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 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](image)

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 $T_1$ 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. 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”. Fig. 5-4 shows an IGBT waveform during short circuit protection.
2MBI300UD-120
Ed=600V, VGE=+15V, –5V (EXB841), RG=3.3Ω, Tj=125°C
VCE=200V/div, IC=250A, VGE=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 high switching speed of IGBTs, at turn-off or during FWD reverse recovery, the current change rate (di/dt) is very high. Therefore the circuit wiring inductance to the module can cause a high turn-off surge voltage (V=L(di/dt)).

At an example, using the IGBT’s waveform at turn-off 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. 5-5, and the IGBT turn-off voltage and current waveforms are shown in Fig. 5-6.
The turn-off surge voltage peak $V_{CESP}$ can be calculated as follows:

$$V_{CESP} = Ed + (-L_S \cdot \frac{dI_c}{dt}) \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots .....

\begin{align*}
\text{d}I_c/\text{d}t: \text{Maximum collector current change rate at turn-off}
\end{align*}

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

---

Fig. 5-5  Chopper circuit

Fig. 5-6  Switching waveforms
2) Overvoltage suppression methods
Several methods for suppressing turn-off surge voltage, the cause for 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, place it as close as possible to 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").
   c. Place the electrolytic capacitor as close as possible to the IGBT in order to reduce the effective inductance of the wiring. Use a low impedance capacitor.
   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 5-3 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 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

<table>
<thead>
<tr>
<th>Snubber circuit schematic</th>
<th>Circuit features (comments)</th>
<th>Main application</th>
</tr>
</thead>
</table>
| **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 |
| ![RC snubber circuit diagram](image) | | |
| **Charge and discharge RCD snubber circuit** | • The effect on turn-off surge voltage is moderate.  
• As opposed to the RC snubber circuit, 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:  
\[ P = \frac{L \cdot I_o^2 \cdot f}{2} + \frac{C_s \cdot E_d^2 \cdot f}{2} \]  
L: Wiring inductance of main circuit,  
I_o: Collector current at IGBT turn-off,  
C_s: Capacitance of snubber capacitor,  
E_d: DC supply voltage,  
f : Switching frequency | Inverter |
| ![Charge and discharge RCD snubber circuit diagram](image) | | |
| **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:  
\[ P = \frac{L \cdot I_o^2 \cdot f}{2} \]  
L: Wiring inductance of main circuit  
I_o: Collector current at IGBT turn-off  
f : Switching frequency | |
Table 5-4  Lump snubber circuits

<table>
<thead>
<tr>
<th>Snubber circuit schematic</th>
<th>Circuit features (comments)</th>
<th>Main application</th>
</tr>
</thead>
<tbody>
<tr>
<td>C snubber circuit</td>
<td>• This is the simplest circuit&lt;br&gt;• The LC resonance circuit, which consists of a main circuit inductance coil and snubber capacitor, may cause the C-E voltage to oscillate.</td>
<td>Inverter</td>
</tr>
<tr>
<td></td>
<td><img src="image" alt="C snubber circuit schematic" /></td>
<td></td>
</tr>
<tr>
<td>RCD snubber circuit</td>
<td>• 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.</td>
<td>Inverter</td>
</tr>
<tr>
<td></td>
<td><img src="image" alt="RCD snubber circuit schematic" /></td>
<td></td>
</tr>
</tbody>
</table>

Table 5-5  Guidelines for determining lump C snubber circuit capacity

<table>
<thead>
<tr>
<th>Module rating</th>
<th>Drive conditions</th>
<th>$-V_{GE}(V)$</th>
<th>$R_G(\Omega)$</th>
<th>Main circuit wiring inductance (μH)</th>
<th>Capacitance of snubber capacitance Cs (μF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>600V</td>
<td>50A</td>
<td>15 max.</td>
<td>43 min.</td>
<td>-</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>75A</td>
<td></td>
<td>30 min.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100A</td>
<td></td>
<td>13 min.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>150A</td>
<td></td>
<td>9 min.</td>
<td>0.2 max.</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>200A</td>
<td></td>
<td>6.8 min.</td>
<td>0.16 max.</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>300A</td>
<td></td>
<td>4.7 min.</td>
<td>0.1 max.</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>400A</td>
<td></td>
<td>6 min.</td>
<td>0.08 max.</td>
<td>4.7</td>
</tr>
<tr>
<td>1200V</td>
<td>50A</td>
<td>15 max.</td>
<td>22 min.</td>
<td>-</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>75A</td>
<td></td>
<td>4.7 min.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100A</td>
<td></td>
<td>2.8 min.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>150A</td>
<td></td>
<td>2.4 min.</td>
<td>0.2 max.</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>200A</td>
<td></td>
<td>1.4 min.</td>
<td>0.16 max.</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>300A</td>
<td></td>
<td>0.93 min.</td>
<td>0.1 max.</td>
<td>3.3</td>
</tr>
</tbody>
</table>

*1: Typical standard gate resistance of V series IGBT is shown.
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.
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.

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

\[ V_{CESP} = E_d + V_{FM} + (-L_s \cdot \frac{dI_c}{dt}) \]

**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 inductance  
**\( \frac{dI_c}{dt} \):** Maximum collector current change rate at IGBT turn-off

\[ C_s = \frac{L \cdot I_o^2}{\left(V_{CEP} - E_d\right)^2} \]

**L:** Main circuit wiring inductance  
**I_o:** Collector current at IGBT turn-off  
**V_{CEP}:** 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:

\[ R_s \leq \frac{1}{2.3 \cdot C_s \cdot f} \]  

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.

Irrespective of the resistance, the power dissipation loss \( P(R_s) \) is calculated as follows:

\[ P(R_s) = \frac{L \cdot I_o^2 \cdot f}{2} \]

4) Snubber diode selection

A transient forward voltage drop in the snubber diode is one factor 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 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.

![Graph showing spike voltages dependency on collector current](image)

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.
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