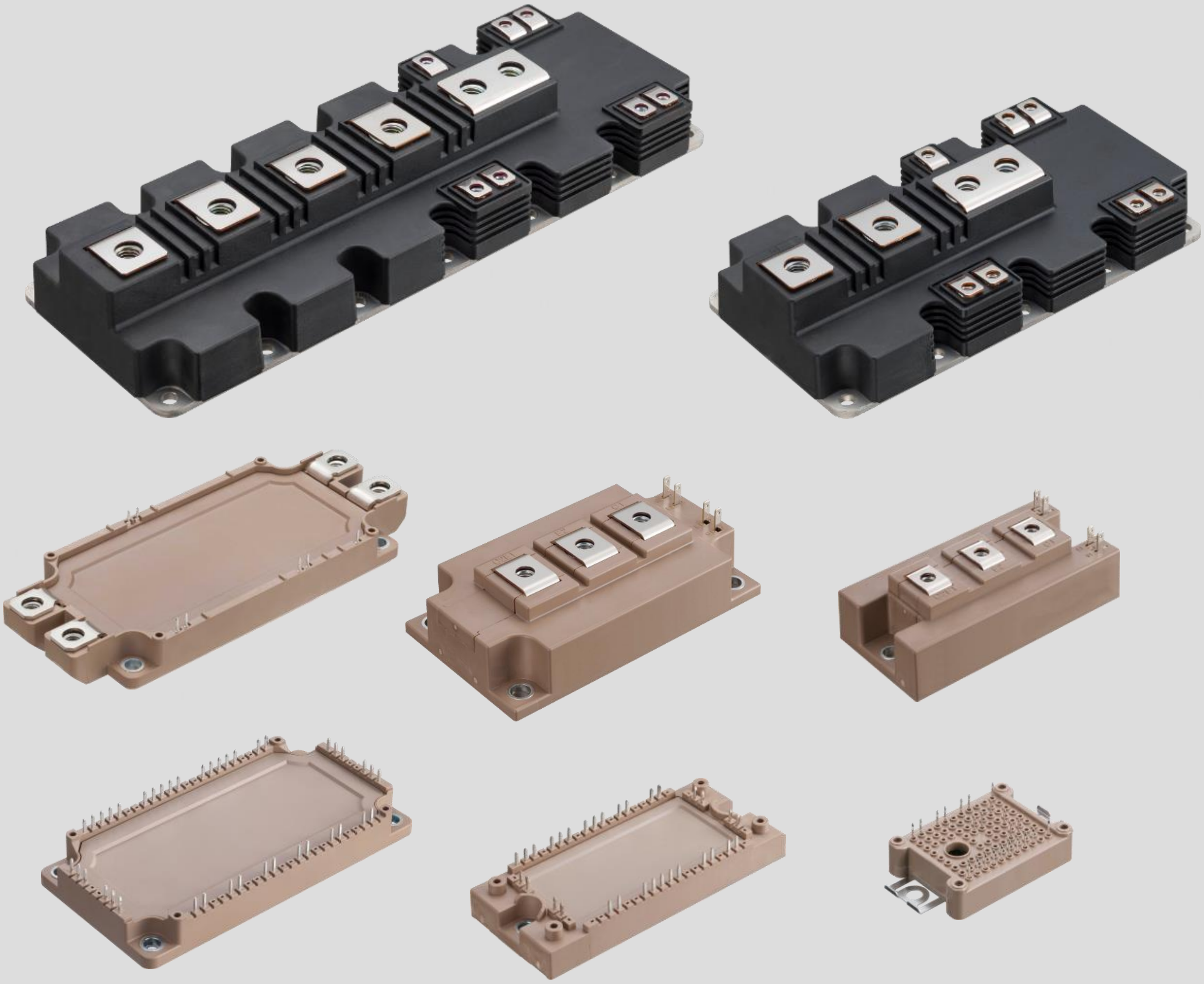

Fuji IGBT Module

Application Manual

March, 2023

Fuji Electric Co., Ltd.

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Chapter 4 Typical Troubles and Troubleshooting

This chapter describes typical troubles and how to deal with them.

1. Troubleshooting

Abnormality such as incorrect wiring or mounting of IGBT modules in inverter circuit, etc., could cause module destruction. Because there are many failure modes, it is important to first determine the cause of the problem, and take the necessary countermeasures. Table 4-1 shows how to determine a module's failure modes as well as the causes by observing the module external abnormalities. First of all, check the estimated failure mode from Table 4-1. If the cause cannot be determined using this table, use the detailed analysis charts in Fig. 4-1. In addition, method to determine whether the module is broken is described in section 4.2, and typical troubles and their countermeasures are described in section 4.3. These can be used to assist in finding the cause.

Table 4-1 Failure mode and cause estimation

External abnormalities		Cause		Failure mode	Checkpoints
Short circuit	Arm short circuit	Surge voltage during short circuit protection exceeds SCSOA.		SCSOA (surge voltage)	Check that short circuit waveform (locus) and device ruggedness match.
	Series arm short circuit	Insufficient dead time	Insufficient $-V_{GE}$ Dead time setting error	Overheating	Check that device t_{off} and dead time match.
		dv/dt malfunction	Insufficient $-V_{GE}$ Gate wiring too long	SCSOA and overheating	Check for false turn-on caused by dv/dt.
		Noise, etc.	Logic or gate drive circuit malfunction		Check for circuit malfunction.
	Output short circuit	Miswiring, abnormal wire contact, or load short circuit.			Check conditions at time of failure. Check that device ruggedness and protection circuit match. Check wiring condition.
	Ground fault	Miswiring, abnormal wire contact			
Overload (overcurrent)		Logic circuit malfunction		Overheating	Check logic circuit.
		Overcurrent protection circuit setting error			Adjust overcurrent protection level.
Overvoltage	Excessive DC voltage	C-E voltage exceeds voltage rating	Excessive input voltage	C-E overvoltage	Adjust overvoltage protection level.
			Overvoltage protection setting error		
	Excessive surge voltage	Surge voltage during turn-off exceeds RBSOA		RBSOA	Check that turn-off waveform (locus) and RBSOA match. Review snubber circuit.
		Surge voltage during FWD reverse recovery exceeds voltage rating		C-E overvoltage	Check that surge voltage and voltage rating match. Review snubber circuit.
		Short on-pulse reverse recovery	Logic or gate drive circuit malfunction due to noise		Check logic circuit.
			Interference to gate signal from the main circuit, etc.		Check gate signal. Use twisted pair wire. Check distance between main circuit and signal wire.
Drive supply voltage drop		V_{GE} drops resulting in increased heat (loss) generation	DC-DC converter malfunction	Overheating	Check for circuit malfunction.
			Drive voltage rise is too slow.		
			Disconnected wire		
Gate overvoltage		Static electricity applied to gate		G-E overvoltage	Check operating conditions (anti-static protection).
		Surge voltage due to excessive length of gate wiring			Check gate voltage.
Driving IGBT with gate open		Applying voltage at C-E with the gate open		Overheating	Check gate voltage.
Overheating	Insufficient heat dissipation	T_{vj} exceeds maximum value	Loose screws	Overheating	Check cooling conditions.
			Insufficient thermal grease		
			Cooling fan stopped		
	Increased loss	Logic circuit malfunction			Check logic circuits.
Stress	Stress	Soldering inside the module disconnected due to stress fatigue	Stress from external wiring	Disconnection of internal circuit (open)	Check the generated stress. Check the mounting condition of the module and other mounting parts.
	Vibration		Stress from vibration of other mounting parts		
Reliability (Lifetime)		The application conditions do not match the reliability of the module		Failure mode is different for each case	Refer to Fig. 4-1.

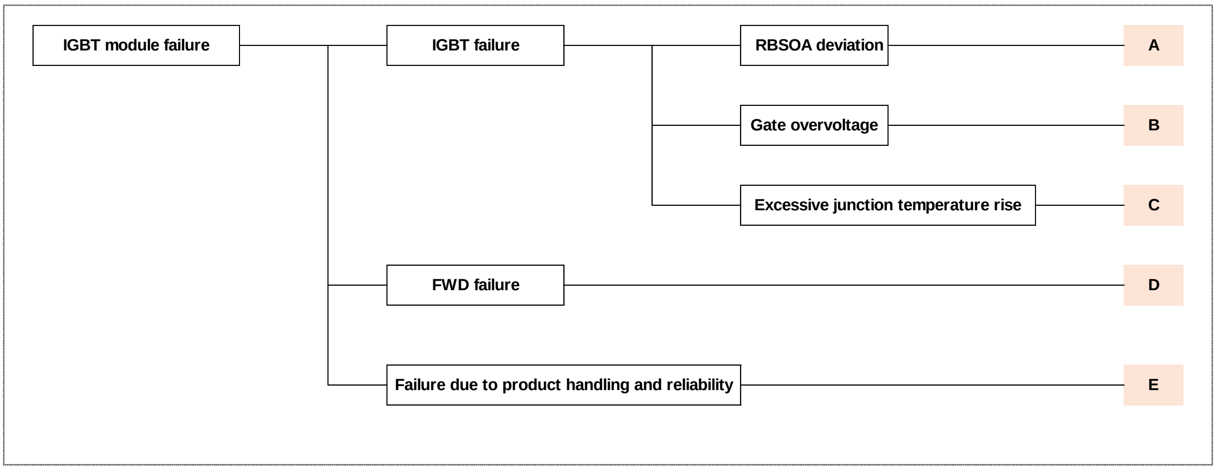


Fig. 4-1(a) IGBT module failure analysis chart (* Symbols A to D are linked to the charts below)

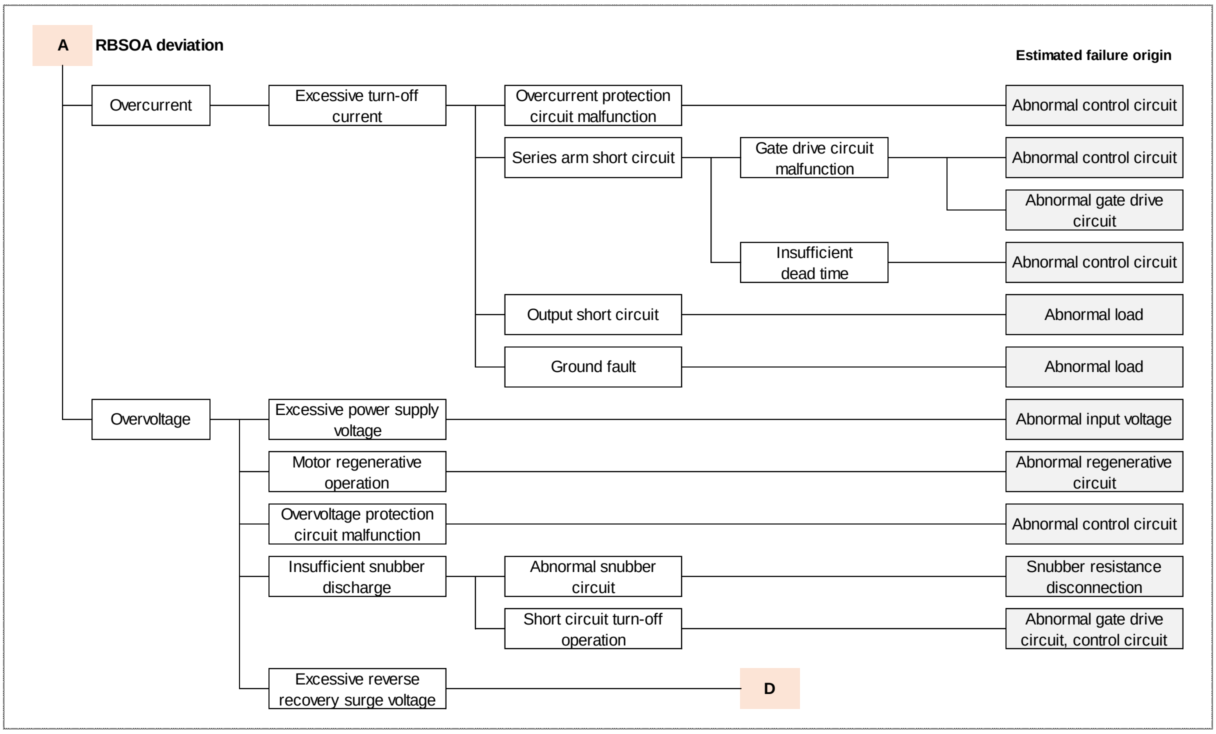


Fig. 4-1(b) Mode A: RBSOA deviation

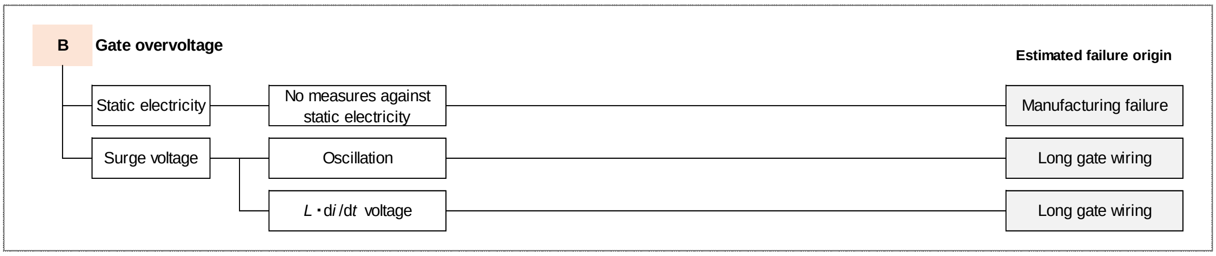


Fig. 4-1(c) Mode B: Gate overvoltage

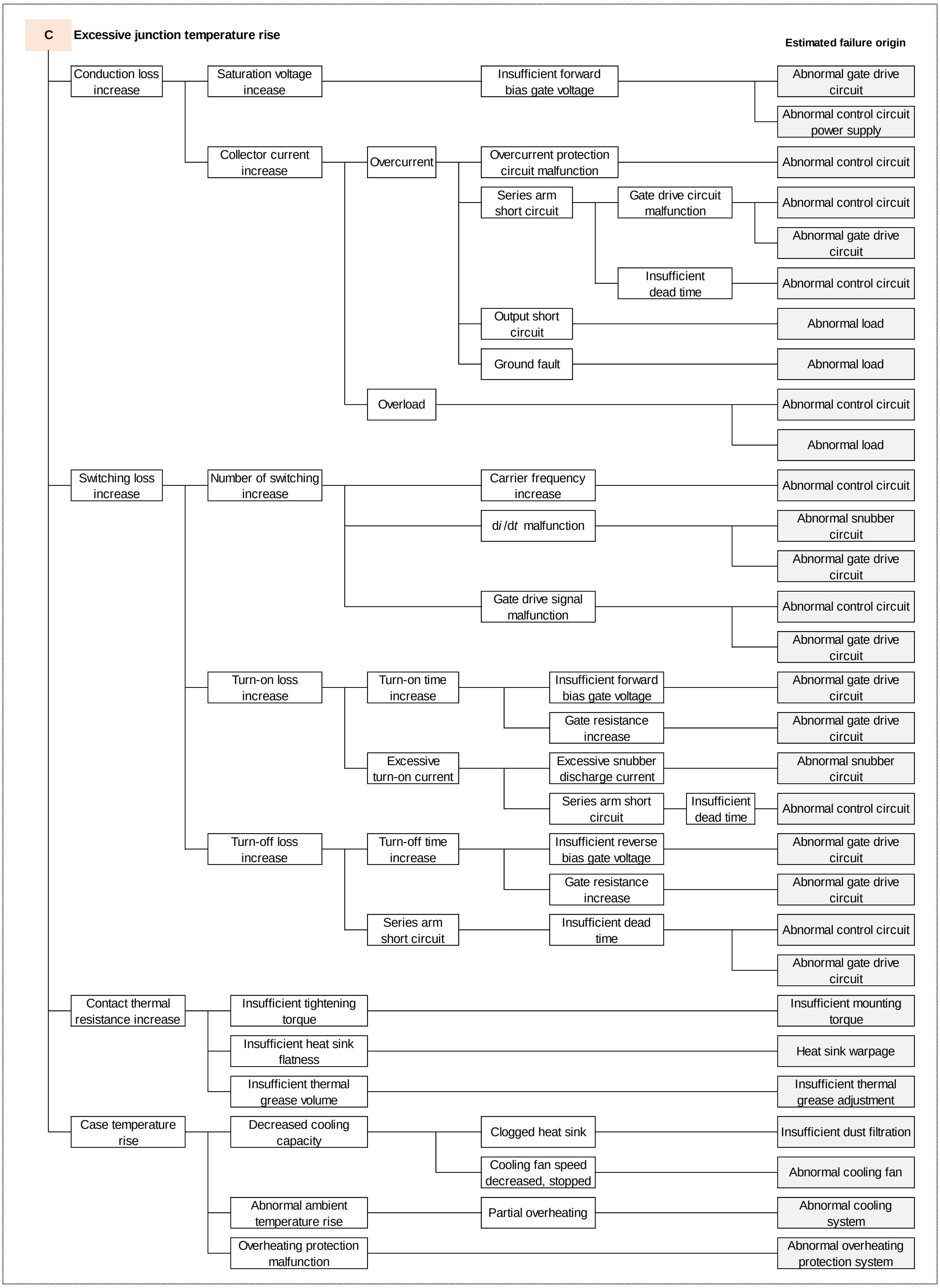


Fig. 4-1(d) Mode C: Excessive junction temperature rise

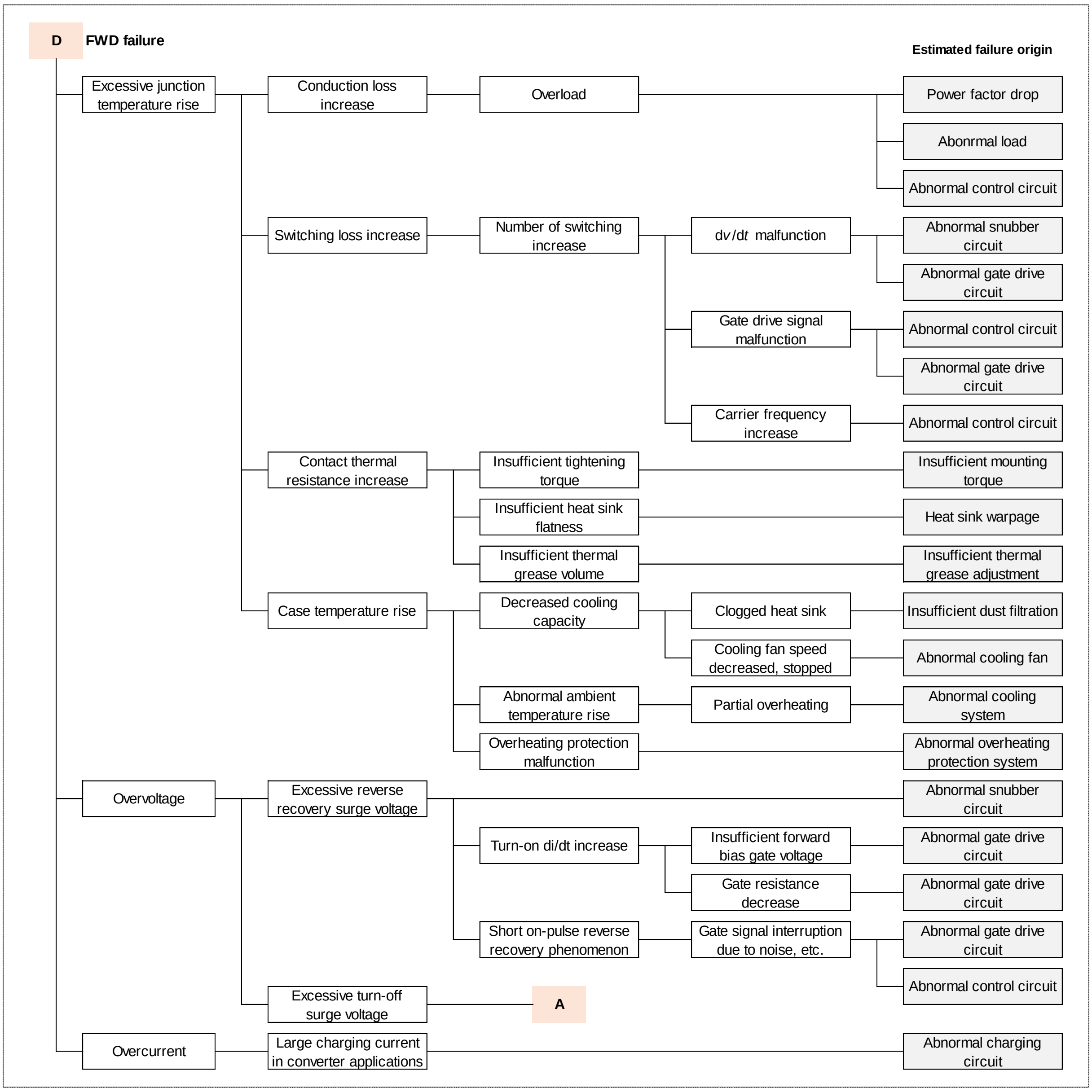


Fig. 4-1(e) Mode D: FWD failure

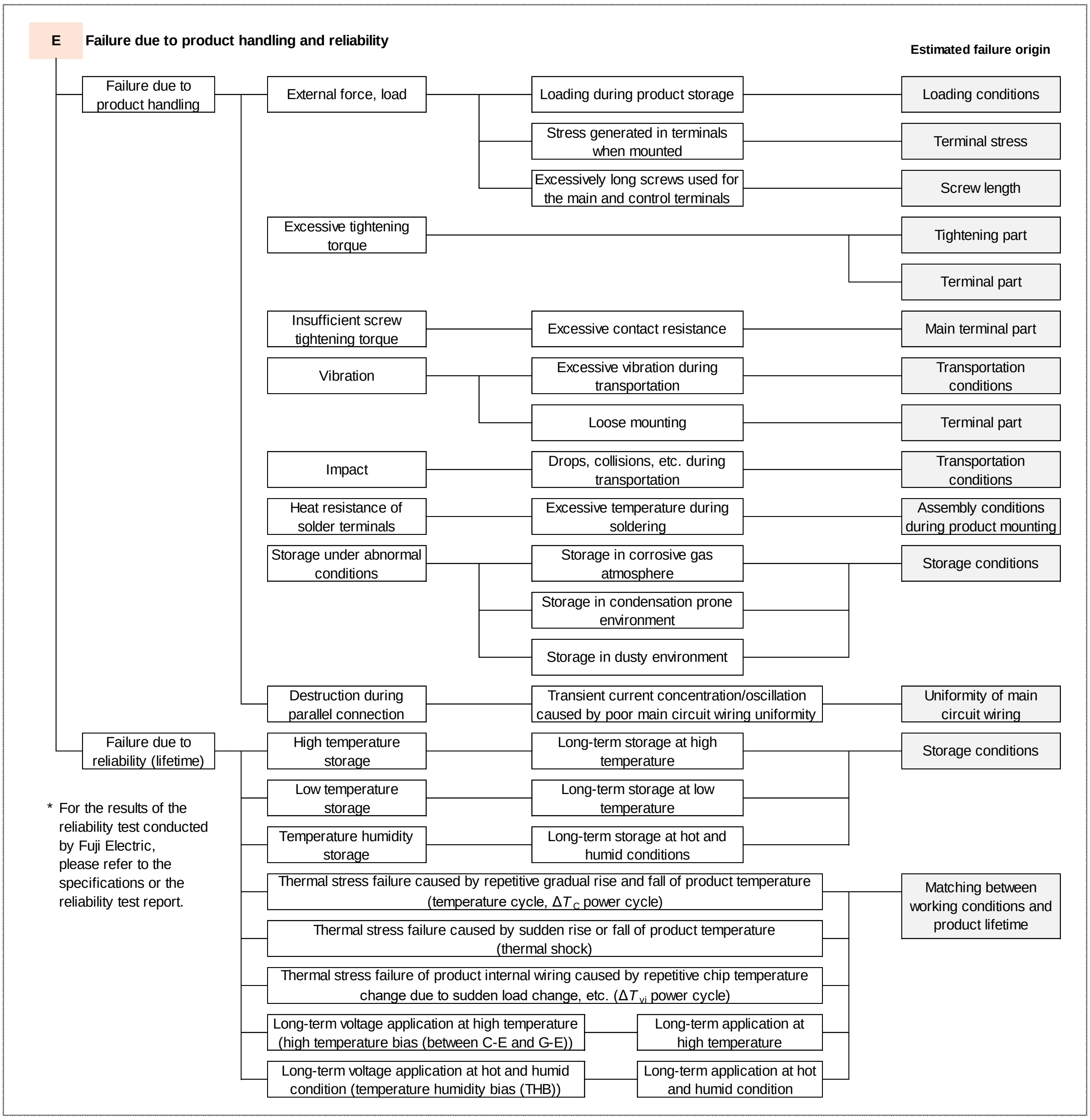


Fig. 4-1(f) Mode E: Failure due to product handling and reliability

2. IGBT Test Procedures

An IGBT module that has been found to be faulty can be checked by using a transistor characteristics measuring device called a ‘transistor curve tracer (CT)’.

(1) G-E leakage current

(2) C-E leakage current (short G-E)

If a CT is not available, other test equipment such as a tester that is capable of measuring voltage/resistance can be used to help to diagnose the module.

2.1 G-E leakage current check

As shown in Fig.4-2, measure the leakage current or resistance between G-E, with C-E shorted. (Do not apply a voltage in excess of 20V between G-E. If a tester is used, make sure that the internal battery voltage is less than 20V.)

If the module is normal, the leakage current reading will be on the order of several 100nA (if a tester is used, the resistance reading will be on the order of 10MΩ to infinity). Otherwise, the device has most likely destroyed (generally, if a device is destroyed, G-E will be short-circuited).

2.2 C-E leakage current check

As shown in Fig.4-3, measure the leakage current or resistance between C-E, with G-E shorted. Be sure to connect C to (+) and E to (-). If the polarity is reversed, the FWD will conduct and shorts C-E.

If the module is normal, the leakage current reading should read below the I_{CES} maximum value specified in the datasheet (if a tester is used, the resistance reading will be on the order of 10MΩ to infinity). Otherwise, the device has most likely destroyed (generally, if a device is destroyed, C-E will be short-circuited).

Caution: Never perform withstand voltage measurement between C-G. It might cause the dielectric breakdown of the oxide layer due to excessive voltage.

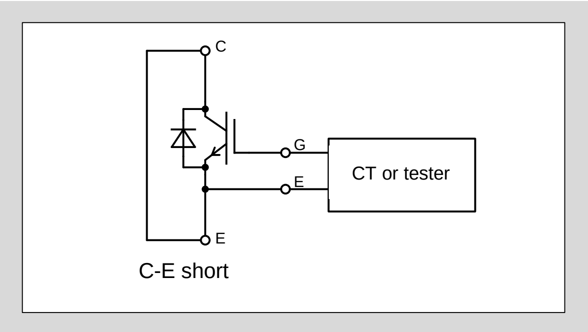


Fig. 4-2 G-E check

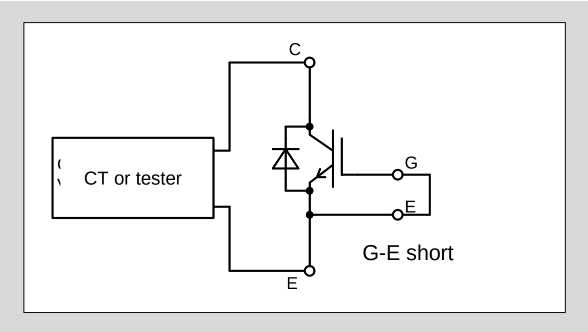


Fig. 4-3 C-E check

3. Typical Troubles and Troubleshooting

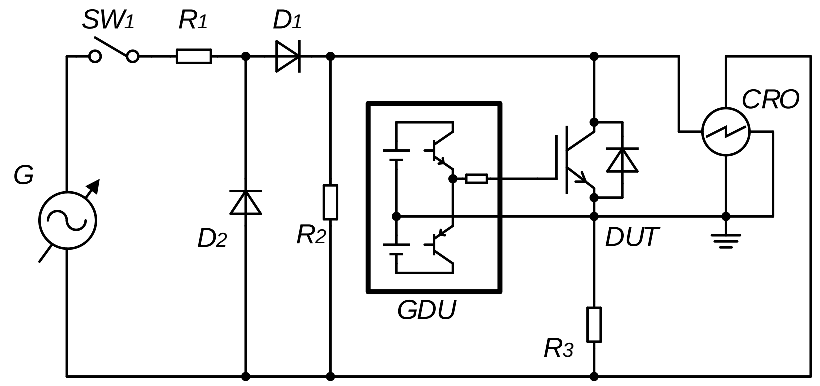
3.1 Main circuit voltage application with G-E open

If main circuit voltage is applied with G-E open, the IGBT would be turned on autonomously, triggering a large current flow and cause device destruction. This phenomenon occurs when the G-E capacitance is charged through the feedback capacitance C_{res} of the IGBT, raising the gate potential and causing the IGBT to be turned on. Take measures such as connecting a resistor of about 10kΩ to G-E to prevent G-E from being opened (refer to Chapter 3, item 2).

If the gate signal line is switched using a mechanical switch, such as a rotary switch during product acceptance testing or on similar occasions, the G-E may open instantaneously at the time of switching, which could cause device destruction if voltage is applied to C-E.

When the mechanical switch chatters, a similar period is generated, leading to device destruction. To prevent this, be sure to discharge the main circuit voltage to 0V before switching the gate signal. Furthermore, when conducting characteristics test, such as acceptance test on a product comprising multiple devices (two or more), be sure to short G-E of the devices other than the one under test.

Fig. 4-4 shows an example of an on-voltage measurement circuit. The measurement procedure is described using this circuit. First, turn off the gate drive unit (GDU) ($V_{GE} \leqq 0V$), then turn on SW_1 to apply voltage to C-E. Next, apply a predefined forward bias voltage to G-E from the GDU to turn-on the IGBT and measure the on voltage. Finally, turn off the gate circuit and then turn off SW_1. This sequence allows for safe measurement of device characteristics without risking destruction.



DUT:IGBT under test, *GDU*:Gate drive unit, *G*:Variable AC power supply
CRO:Oscilloscope, R_1,R_2:Protective resistance, R_3:Current measurment non-inductive resister
D_1,D_2:Diode, SW_1:Switch

Fig. 4-4 On voltage measurement circuit

3.2 Destruction caused by mechanical stress

If the module terminals are subjected to stress from a large external force or vibration, the internal electrical wiring of the product could be destroyed. Be careful not to apply such stress when mounting the module.

Fig. 4-5 shows an example of mounting a gate drive printed circuit board (PCB) on top of the module. As shown in Fig. 4-5(a), if the gate drive PCB is mounted without fixing it, the PCB might vibrate due to vibration during transportation. This vibration may apply stress to the module terminals, causing internal electrical wiring damage. To prevent this, it is recommended to fix the PCB as shown in Fig 4-5(b). Use a dedicated fixing material with sufficient strength.

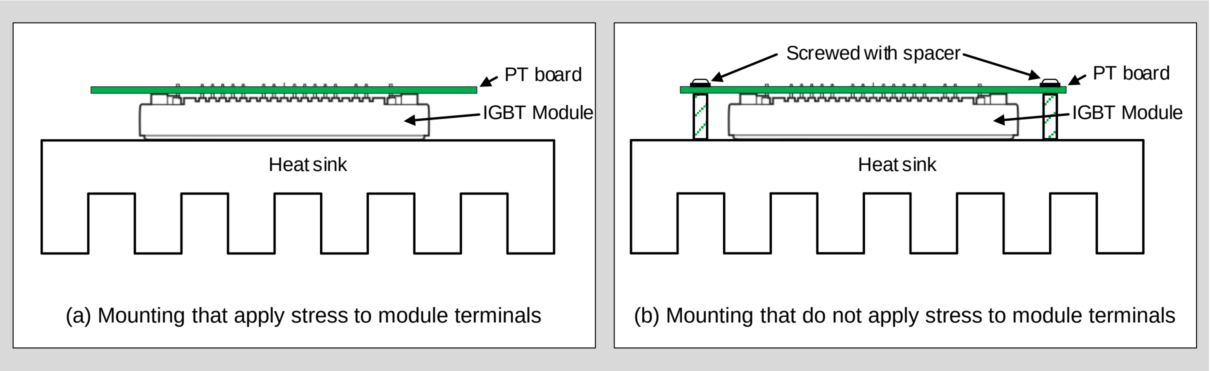


Fig. 4-5 Fixing a PCB

Fig. 4-6 shows an example of main circuit wiring using a laminated bus bar. If there is a step difference between the (+) and (-) conductors as shown in Fig. 4-6(a), the terminals are continually exposed to upward tensile stress, which may cause disconnection of the internal electrical wiring. To prevent this problem, it is recommended to insert a conductive spacer to eliminate the step difference as shown in Fig. 4-6(b). Furthermore, in the PCB structure, if the wiring height is misaligned, large tensile stress or external force will be applied to the terminals, which may cause similar problems. Thus, laminated bus bar or PCB needs to be mounted without tensile stress.

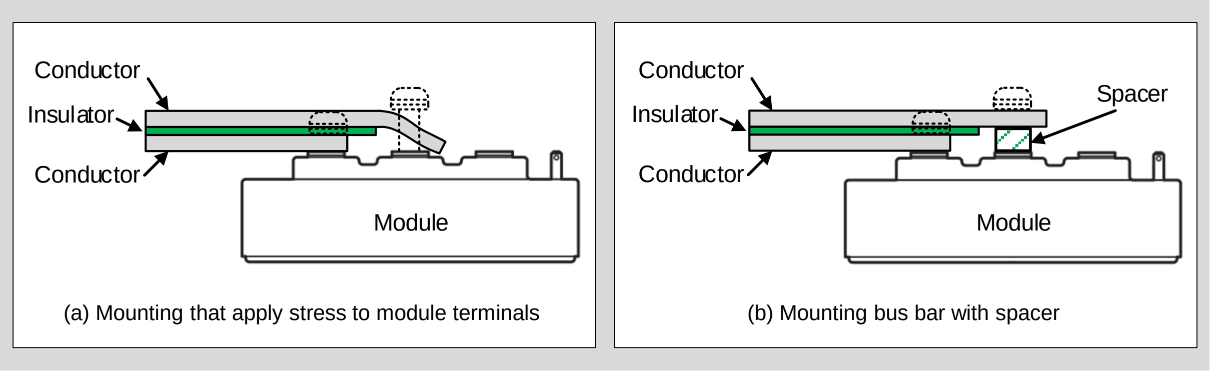


Fig. 4-6 Mounting with laminated bus bar

3.3 False turn-on of the IGBT caused by insufficient -V_{GE}

Insufficient reverse bias gate voltage -V_{GE} induces false turn-on of the IGBT, resulting in short circuit of both the upper and lower arm IGBTs. The product may be destroyed by the surge voltage or loss generated when the short circuit current is cut off. Therefore, make sure that false turn-on does not happen when designing the equipment (recommended -V_{GE}=15V). In addition, please refer to Chapter 7, section 1.4 for the details of the malfunction occurrence mechanism due to the d*v*/d*t* when -V_{GE} is insufficient.

Fig. 4-7 shows an example of how to check the presence of short circuit current in the upper and lower arms. First, disconnect the output terminals (U, V, W) of the inverter (open, no load). Next, start the inverter and drive each IGBT. At this time, if the current flowing from the power supply line is detected as shown in the figure., the presence of short circuit current can be checked. If –V_{GE} is sufficient, only a very small pulse current (about 5% of the rated current) that charges the junction capacitance of the device will be observed. However, if -V_{GE} is insufficient and short circuit occurs, this current will increase. To make an accurate judgment, it is recommended to perform this current measurement with -V_{GE}=15V first, and then measure the current again with the specified –V_{GE}. If the current of both cases have the same value, it means that there is no false turn-on.

If false turn-on is confirmed by the above method, countermeasures include increasing -V_{GE} until the short circuit current disappears, or connect a capacitor (C_{GE}) with capacitance of about twice the value of C_{ies} described in the specifications between G-E. Is recommended to connect C_{GE} close to the gate terminals.

However, simply adding C_{GE} will increase the switching time and loss. In order to have equivalent switching time and loss before C_{GE} addition, it is recommended to decrease the R_G value to about half of that before C_{GE} addition.

Another cause of short circuit through the upper and lower arms is insufficient dead time. When this happens, short circuit current will be observed in the test. If the short circuit current does not decrease even when -V_{GE} is increased, increasing the dead time is necessary. Please refer to Chapter 7, section 3 for a detailed explanation of dead time.

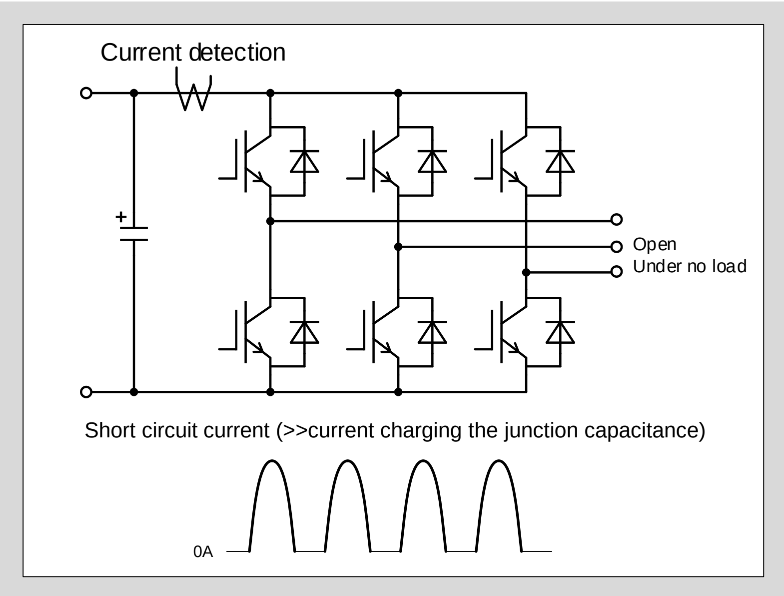


Fig. 4-7 Short circuit current measuring circuit

3.4 Diode reverse recovery from a transient on state (short on-pulse reverse recovery)

The IGBT module contains built-in FWD. Paying close attention to the behavior of this FWD is very important for designing a reliable equipment. This section describes the short on-pulse reverse recovery phenomenon, which is likely to lead to module destruction.

The short on-pulse reverse recovery phenomenon is a phenomenon in which the gate signal is interrupted due to noise, etc. when driving the IGBT, resulting in a very large reverse recovery surge voltage. Fig. 4-8 shows the waveforms of short on-pulse reverse recovery. If a very short off-pulse (T_w) with respect to the on period (T_{ON}) of IGBT is generated, the FWD on the opposite arm will enter reverse recovery in a very short time after it is turned on. Normally, reverse recovery starts after sufficient carriers are accumulated in the FWD, whereas in the short on-pulse reverse recovery, reverse recovery starts without sufficient carrier accumulation in the FWD. As a result, the depletion layer of FWD expands at a rapid speed, causing steep di/dt and dv/dt. This causes a very large reverse recovery surge voltage to occur between C-E (K-A). If the surge voltage exceeds the module rated voltage, it may lead to module destruction.

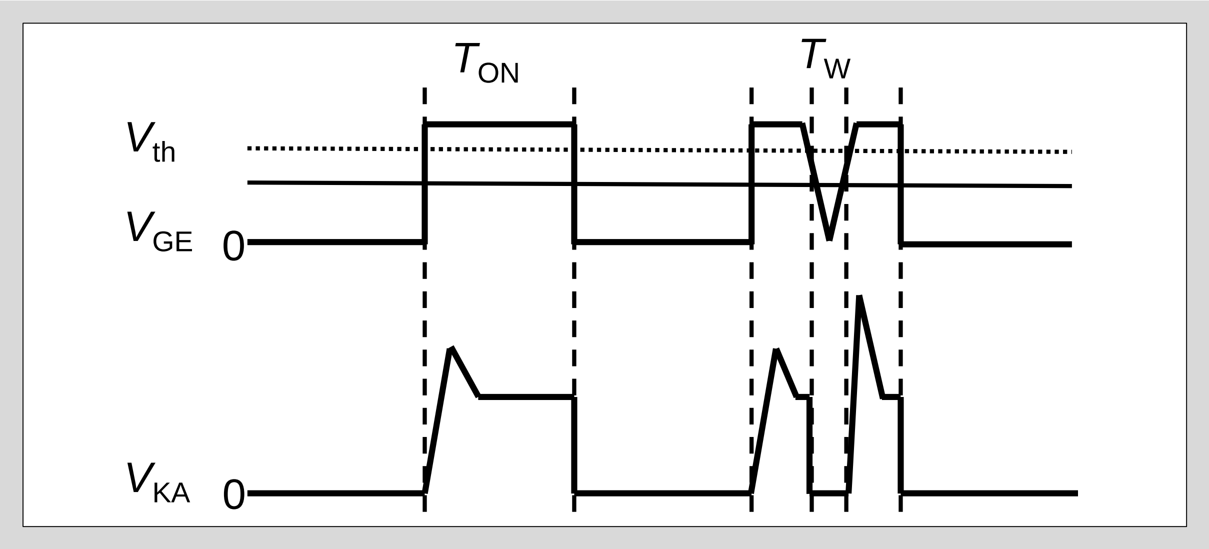


Fig. 4-8 Waveforms at short on-pulse reverse recovery

Our tests confirmed that a surge voltage increases sharply when $T_w < 1\mu s$. Be sure not to design a circuit that will generate such short gate signal off pulses.

For equipment with operation mode of $T_w < 1\mu s$, verify that the surge voltage at minimum T_w does not exceed the module rated voltage. If the surge voltage exceeds the module rated voltage, take countermeasures to reduce surge voltage as follows.

- Increase R_G
- Reduce circuit inductance
- Enhance snubber circuit
- Add C_{GE}
- Add active clamping circuit

Fig. 4-9 shows the waveforms of short on-pulse reverse recovery of 6MBI450U-120 (1200V, 450A). As shown in the waveforms, surge voltage can be decreased by increasing R_G from 1.0Ω to 5.6Ω.

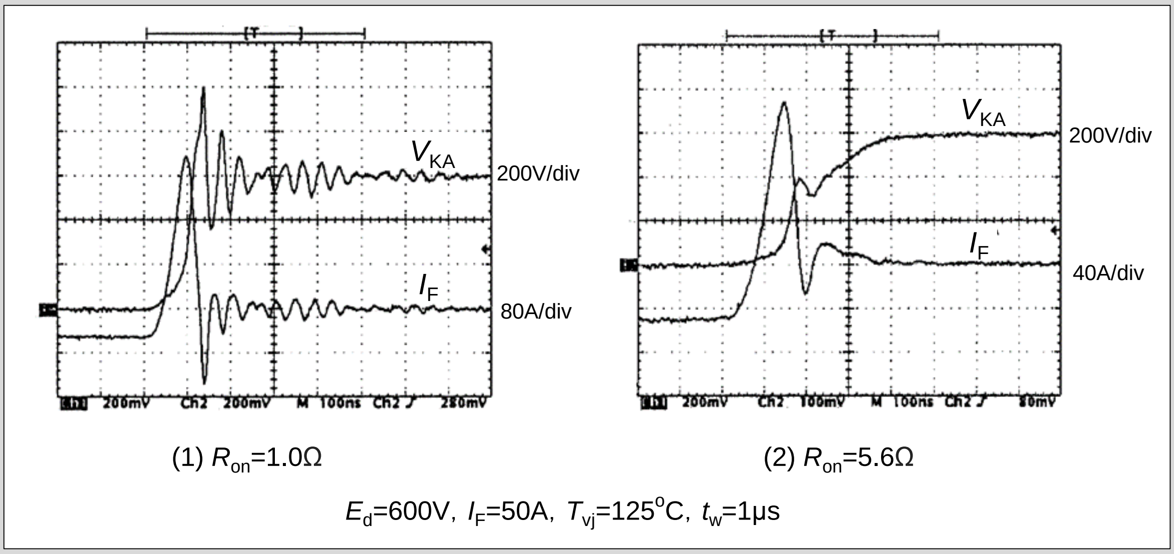


Fig. 4-9 Waveforms of short on-pulse reverse recovery

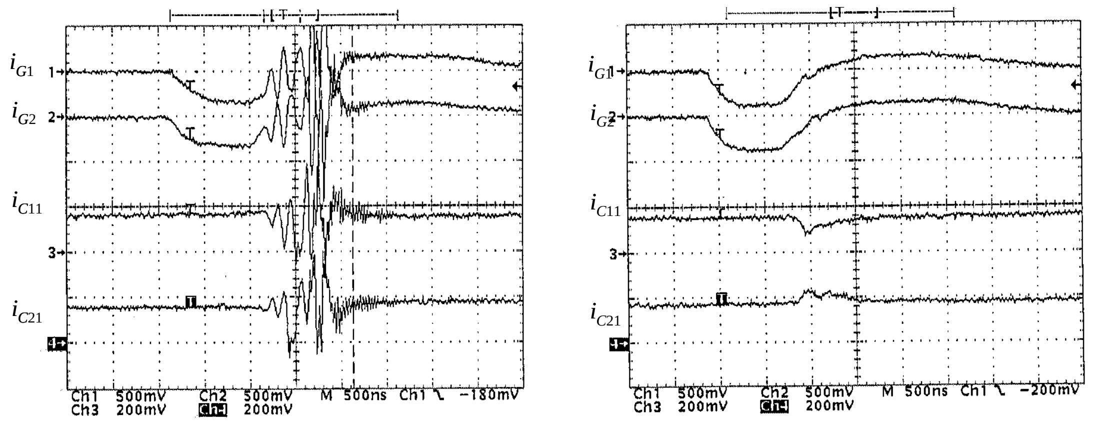
3.5 Oscillation during parallel connection

When connecting modules in parallel, the uniformity of the main circuit wiring is very important. If the wiring is unbalanced, current will concentrate on the module with a shorter wiring, which could lead to module destruction or deterioration of long-term reliability.

Also, if the main circuit wiring is not uniform, the overall main circuit inductance will also be unbalanced for each devices. Consequently, di/dt during switching generate voltages of varied potentials in the individual wiring inductances, producing abnormal oscillating current such as a loop current, which could lead to module destruction.

Fig. 4-10(a) shows the oscillation phenomenon when the wiring inductance of the emitter is made extremely unbalanced. This oscillation happens due to oscillating current flows through the wiring loop of emitters connected in parallel, causing the IGBT gate voltage to oscillate, resulting in IGBT turn-on and turn-off at high speed. A ferrite core (common mode) can be inserted in each G-E wiring to suppress or eliminate the emitter loop current. Fig. 4-10(b) shows the waveforms with ferrite core inserted to each G-E wiring. As shown in the waveforms, oscillation is suppressed.

It is necessary to maintain circuit uniformity when designing the main circuit wiring of parallel connection.



(a) When emitter inductance is extremely unbalanced (b) When ferrite mode core is inserted to G-E wiring

(i_{G1},i_{G2}: 5A/div, i_{C11},i_{C21}: 100A/div, t: 0.5ms/div, E_d=600V 1200V/300A/IGBT 2 parallel connection)

Fig. 4-10 Waveforms of 2 parallel connection

3.6 Notes on the soldering process

When soldering the gate drive circuit or control circuit to the terminals of the module, if the solder temperature is excessively high, problems such as melting of the case resin material may occur. Avoid soldering process that exceeds the heat resistance test conditions defined in the specifications.

Terminal heat resistance test conditions in the general product specifications documents are shown below for reference.

Solder temperature: 260±5°C
Time: 10±1s
Cycles: 1

3.7 Using IGBT Module in converter application

Diodes used in the IGBT modules have I^2t rating. I^2t is the limit of the forward, non-repetitive overcurrent capability of current pulses with a very short duration (less than 10ms). For a sinusoidal half-wave pulse current, I denotes the RMS current, and t indicates the pulse duration. If the IGBT module is used in a rectifier circuit or converter circuit, an inrush current flows at startup. Do not exceed the I^2t limits. If I^2t is exceeded, take measures such as connecting a starter circuit with resistor and conductor connected in parallel between the AC power supply and the IGBT module.

3.8 EMC noise countermeasures

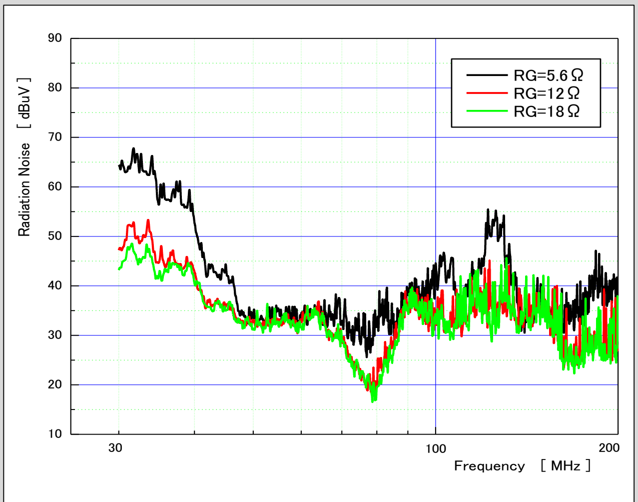
Amid the ongoing effort to comply with European CE marking for IGBT module-based converters, such as inverters and UPS, and with VCCI regulations in Japan, electromagnetic compatibility (EMC), suppressing EMI noise (conductive and radiating noises emitted from devices during operation) below the specifications has become an essential aspect of circuit design.

As IGBT modules continue to offer enhanced characteristics with each generation, including faster switching and lower loss, high dv/dt and di/dt during switching can cause radiation noise. Radiation noises are primarily associated with harmonic LC resonance between stray capacitances, such as semiconductor device junction capacitances, and wiring stray inductances, triggered by high dv/dt and di/dt generated from the IGBTs during turn-on (reverse recovery of the opposing arm FWD).

In order to decrease the radiation noise, it is effective to soften (lower speed) the switching characteristics, especially the turn-on characteristics, by changing the drive conditions. Refer to Chapter 7 for explanation of drive conditions.

Fig. 4-11 shows example of radiation noise characteristics when switching speed is changed with R_G. In this case, the standard R_G is 5.6Ω, but the radiation noise can be decreased by more than 10dB by doubling the R_G value (12Ω).

However, softening the switching characteristics to decrease radiation noises tends to increase the switching loss. Thus, it is important to design the drive conditions while considering the balance with the equipment operating conditions, module cooling conditions and other relevant conditions.



15kW inverter, 1200V/150A module

Fig. 4-11 Radiation noise (R_G dependence)

Table 4-2 shows example of general countermeasures against radiation noise. Because the cause and noise level are different according to the wiring structure, material and the circuit configuration of the equipment, it is necessary to verify which of the countermeasures is effective.

Table 4-2 Countermeasures of radiation noise

Countermeasure	Description	Remarks
Review drive conditions (reduce dv/dt and di/dt)	Increase the R_G (particularly, turn-on side).	Switching time and switching loss increase.
	Connect a capacitor between G-E (C_{GE}).	Switching time and switching loss increase.
Connect the snubber capacitor as near as possible with the IGBT module	Minimize the wiring between the snubber capacitor and the IGBT module (connect snubber capacitor directly on module terminals).	Effective in suppressing surge voltage and dv/dt during switching.
Reduce wiring inductances	Use laminated bus bars to reduce inductances.	Effective in suppressing surge voltage and dv/dt during switching.
Filtering	Connect noise filters to the input and output of the equipment.	Various filters are commercially available
Cable shielding	Shield the input/output cables to reduce radiation noise from the cables.	
Metalize the equipment case	Metalize the equipment housing to suppress noise emitted from the device	