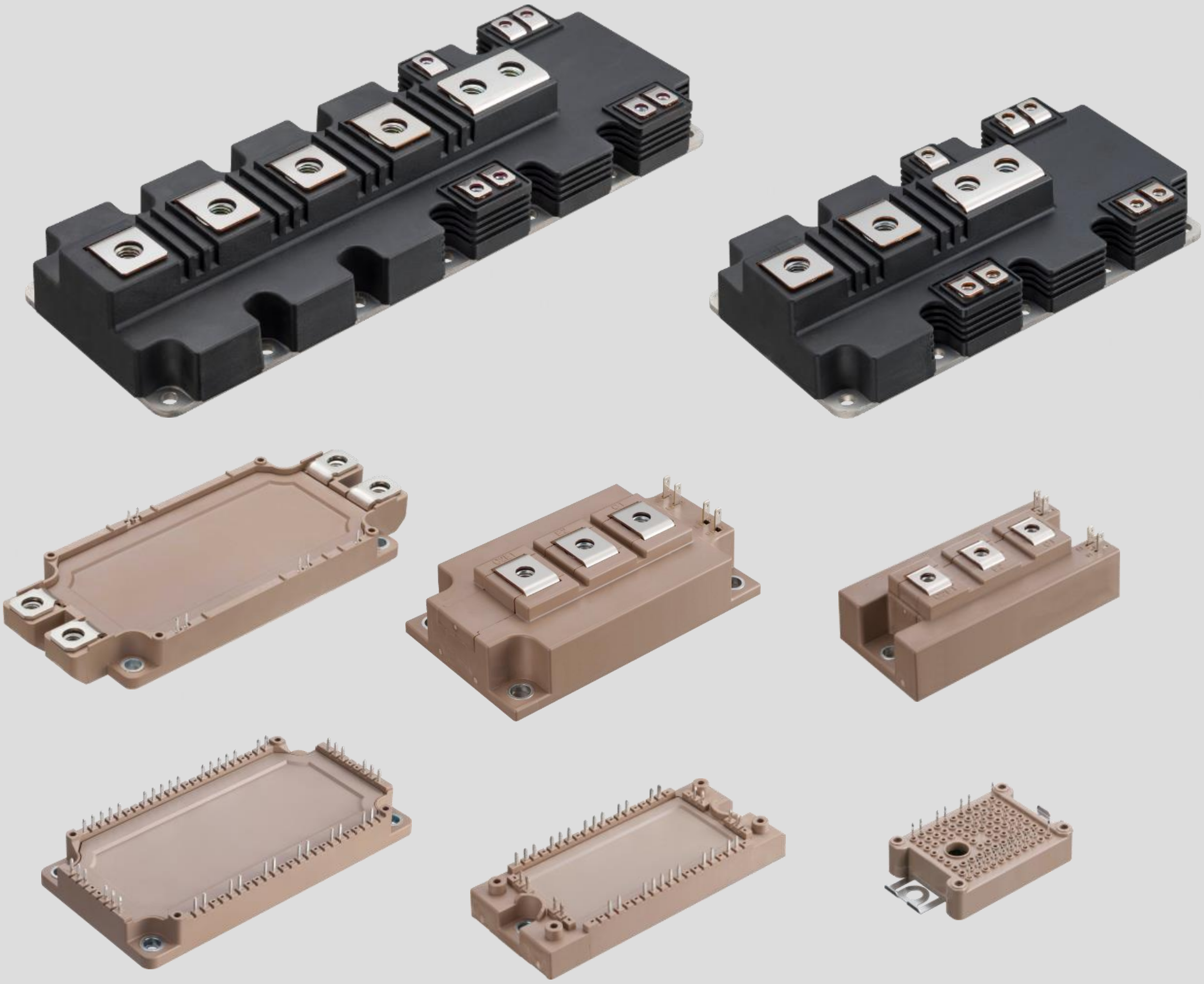

Fuji IGBT Module

Application Manual

March, 2023

Fuji Electric Co., Ltd.

⚠Cautions

This manual contains the product specifications, characteristics, data, materials, and structures as of March 2023.
The contents are subject to change without notice for specification changes or other reasons. When using a product listed in this manual, be sure to obtain the latest specifications.

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Chapter 11 Reliability of Power Module

The market for power modules is not limited to general-purpose inverters, servo motors, NC machines, elevators, etc., but is expanding into new applications such as electric vehicles, solar, wind and fuel cell power generation systems.

Fuji Electric has developed various power modules to meet the market demands. In the future, as the market expands further, the performance requirements for these power modules are expected to become even more diverse and sophisticated.

To meet these demands, it is necessary to pay attention to ensuring the reliability of the power modules. This chapter describes the reliability of power modules, especially IGBT modules.

1. Basis of Reliability

In general, the failure rate of electronic devices and components such as IGBT modules follows a bathtub-shaped failure rate curve as shown in Fig. 11-1. This failure rate curve is shown in three periods: the early failures period, random failures period, and wear-out failures period.

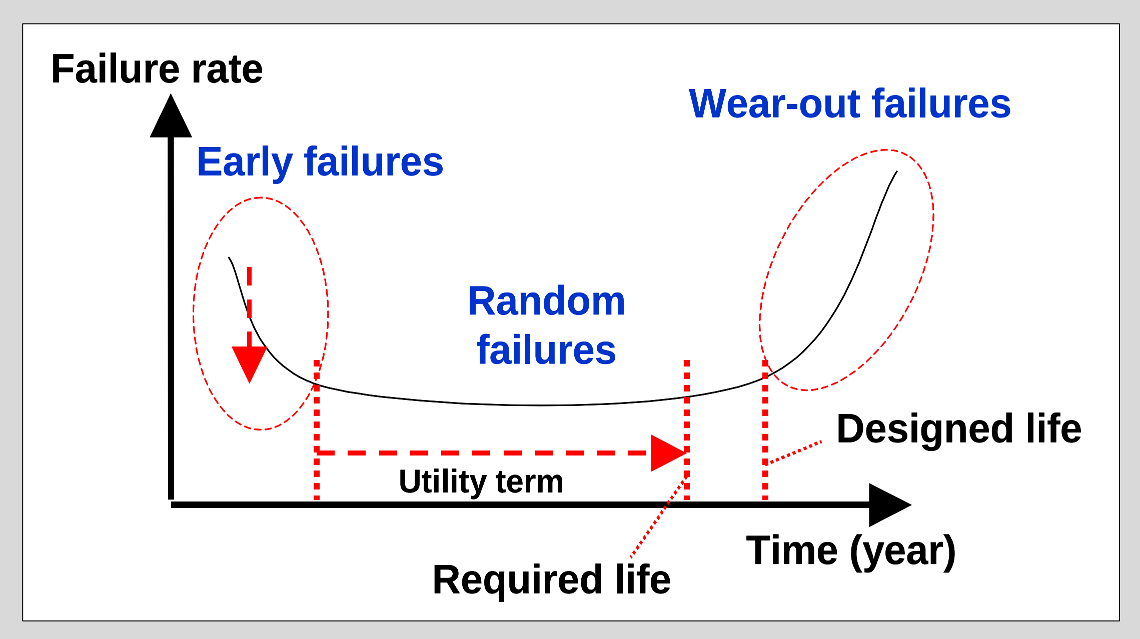


Fig. 11-1 Change in failure rate of semiconductor devices over time

Early failures in IGBT modules are caused by microscopic defects such as minute defects in IGBT/FWD, cracking in DCB, wire contact, and human error, etc.

Such defects and errors can be reduced by continuing the quality improvement using various design methods in IGBT/FWD chip design, module structure design, chip manufacturing process design, and assembly process design. However, it is very difficult to completely eliminate these at the design state, thus screening test (outgoing test) is required.

Fuji Electric is working to reduce the early failure rate by applying screening tests.

The failure rate in the random failures period of the failure rate curve settles down to a constant level because early failures products are removed. Duration of this random failures period varies depending on the operating conditions and environment of the entire system, which is composed of IGBT modules and other components, and corresponds to the system specific reliability. Random failures that occur during this period are generally caused by excessive stress exceeding the product maximum ratings being applied, such as overvoltage (between G-E, between C-E), overcurrent, and overheating.

In order to reduce the failure rate in the random failures period, it is necessary to design and confirm that various characteristics do not exceed the maximum ratings under the worst operating conditions of the system. Therefore, it is recommended to derate the operating conditions such as operating voltage and current from the maximum ratings described in the specifications.

The failures during wear-out failures period of the failure rate curve are due to the product lifetime, and caused by wear and fatigue. Therefore, in order to ensure the long-term reliability of IGBT modules, it is necessary to design that the product reaches the end of its lifetime before the wear-out failures period.

Fuji Electric verifies the long-term reliability test shown in the next section onwards during the design stage. In particular, the power cycling lifetime is verified using two models, the ΔT_{vj} power cycling (ΔT_{vj}-P/C) and the ΔT_C power cycling (ΔT_C-P/C) as shown in section 3 of this Chapter. When designing the lifetime of IGBT module, consider and design within this power cycling lifetime.

Also, the product lifetime varies greatly depending on the environment and operating conditions, thus it is necessary to take this into consideration when designing.

2. Reliability Test Conditions

In order to ensure long-term reliability, Fuji Electric conducts various reliability tests for design verification. Table 11-1 and Table 11-2 show the representative reliability tests for the 7th generation IGBT modules, X series. Refer to the product specification for details.

Table 11-1 Reliability tests of X series (environment tests)

Test categories		Test items	Test methods and conditions	Reference norms JEITA ED-4701 (Aug.-2013 edition)	Number of sample	Acceptance number
Environment Tests	1	High Temperature Storage	Storage temp. : 125±5°C Test duration : 1000hr.	Test Method 201A	5	(0:1)
	2	Low Temperature Storage	Storage temp. : -40±5°C Test duration : 1000hr.	Test Method 202A	5	(0:1)
	3	Temperature Humidity Storage	Storage temp. : 85±2°C Relative humidity : 85±2% Test duration : 1000hr.	Test Method 103A Test code C	5	(0:1)
	4	Temperature Cycle	Test temp. : High temp. 125+15/-0°C Low temp. -40+0/-10°C Minimum soak time : 15 min. Number of cycles : 100cyc	Test Method 105A	5	(0:1)
	5	Thermal Shock	Test temp. : High temp.100+10/-2°C Low temp. 0+2/-10°C Used liquid : Water with ice and boiling water Dipping time : 5min. per each temp. Transfer time : 10sec. Number of cycles : 10cycles	Test Method 307B Condition code B	5	(0:1)

Table 11-2 Reliability tests condition of X series (endurance tests)

Test categories		Test items	Test methods and conditions		Reference norms JEITA ED-4701 (Aug.-2013 edition)	Number of sample	Acceptance number
Endurance Tests	1	High Temperature Reverse Bias (IGBT/FWD chip)	Test temp. Bias voltage Bias method Test duration	: T_{vj} = 175±5°C : V_{CE} = 0.8 x V_{CES} : Applied DC voltage to C-E V_{GE} = 0V : 1000hr.	Test Method 101A	5	(0:1)
	2	High Temperature Bias (for Gate)	Test temp. Bias voltage Bias method Test duration	: T_{vj} = 175±5°C : V_{GE} = +20V or -20V : Applied DC voltage to G-E V_{CE} = 0V : 1000hr.	Test Method 101A	5	(0:1)
	3	Temperature Humidity Bias (IGBT/FWD chip)	Test temp. Relative humidity Bias voltage Bias method Test duration	: 85±2°C : 85±5% : V_{CE} = 0.8 x V_{CES} : Applied DC voltage to C-E V_{GE} = 0V : 1000hr.	Test Method 102A Condition code C	5	(0:1)
	4	Intermitted Operating Life (Power Cycle) (for IGBT)	ON time OFF time Test Temp. Number of cycles	: 2 sec. : 18 sec. : ΔT_{vj} = 100±5 deg. T_{vj} ≤ 175°C, T_S = 75±5°C : 60000 cycles.	Test Method 602	5	(0:1)

3. Power Cycling Lifetime

The temperature of IGBT module rises and falls according to the operating conditions. As the temperature fluctuates, the internal structure of the IGBT module is exposed to thermal stress, causing fatigue and deterioration. This fatigue and deterioration is greatly dependent on the temperature fluctuation range, thus the lifetime of the IGBT module varies depending on the operating and environmental conditions. This thermal stress lifetime is called power cycling lifetime (power cycling capability). The power cycling lifetime can be calculated from the power cycling lifetime curve that shows the relationship between the temperature change ΔT and the number of repeated cycles. There are two types of curves.

One is the ΔT_{vj}-P/C lifetime curve, which is related to the chip junction temperature fluctuation. In this case, the dominant failure modes are failure due to the deterioration of the aluminum wire joints on the chip surface, and deterioration of the solder joints directly under the chip.

The other is the ΔT_C-P/C lifetime curve, which is related to the case temperature (mainly the copper baseplate temperature) fluctuation due to the junction temperature fluctuation. In this case, the dominant failure mode is failure due to deterioration of the solder joints between the DCB insulating substrate and the copper baseplate.

The following sections describe the measurement method and the power cycling lifetime curves for ΔT_{vj}-P/C and ΔT_C-P/C.

3.1 ΔT_{vj}-P/C lifetime curve

Fig. 11-2 shows the current pattern of the ΔT_{vj}-P/C test. Fig. 11-3 and Fig. 11-4 show the equivalent test circuit diagram and the schematic diagram of the T_C and T_f measurement positions, respectively. During the ΔT_{vj}-PC test, T_{vj} is rapidly increased and decreased in a relatively short cycle. Therefore, thermal stress occurs between the power chip and the DCB, and between the power chip and the aluminum wire due to the temperature difference. For this reason, the ΔT_{vj}-PC mainly indicates the lifetime of the aluminum wire joints on the chip surface, and the solder joints directly under the chip.

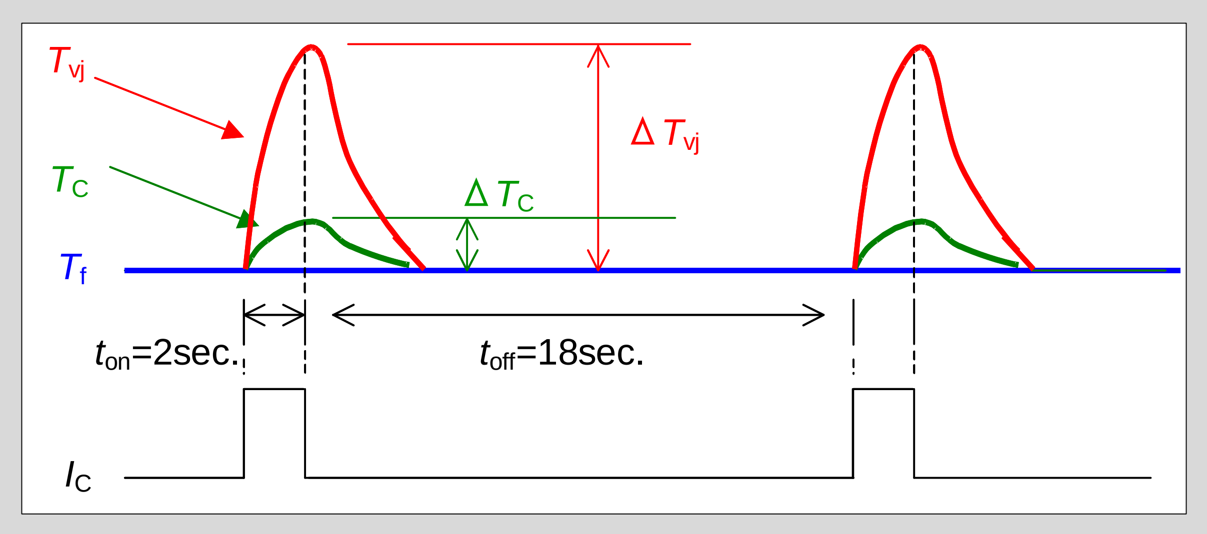


Fig. 11-2 ΔT_{vj}-P/C test current pattern and temperature changes

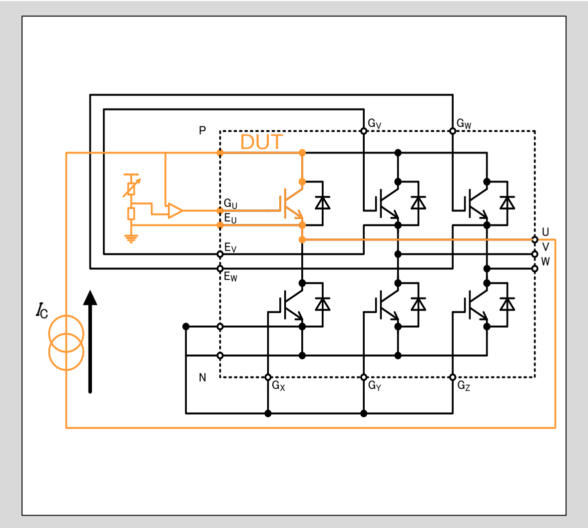


Fig. 11-3 Equivalent test circuit for ΔT_{vj}-PC test

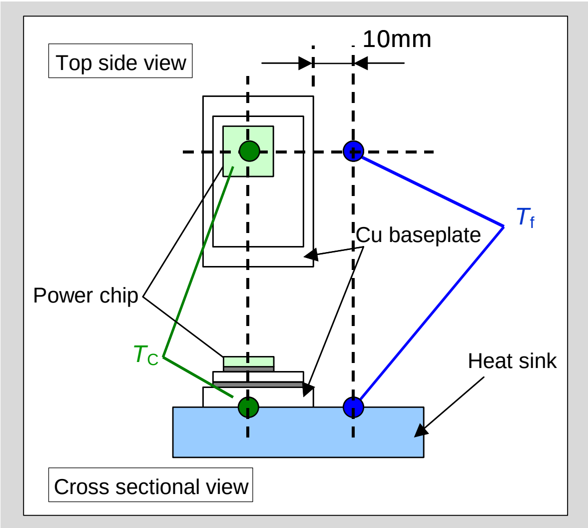


Fig. 11-4 T_C and T_f measurement positions

As example, Fig. 11-5 shows the ΔT_{vj}-PC lifetime curves of U series and V series. In this figure, the $T_{vj(min)}$=25° C line indicates the lifetime when the chip junction temperature is changed while the temperature of the heat sink is kept at 25° C. For example, when ΔT_{vj} = 50° C, the chip junction temperature reaches 75° C while the heat sink temperature is 25° C. On the other hand, the $T_{vj(max)}$ =150° C line shows the lifetime when the heat sink temperature is changed while the chip junction temperature is kept at 150° C. For example, when ΔT_{vj} = 50° C, the chip junction temperature reaches 150° C while the heat sink temperature is 100° C. Thus, even if ΔT_{vj} is the same, the higher the heat sink temperature and the chip junction temperature, the shorter the lifetime.

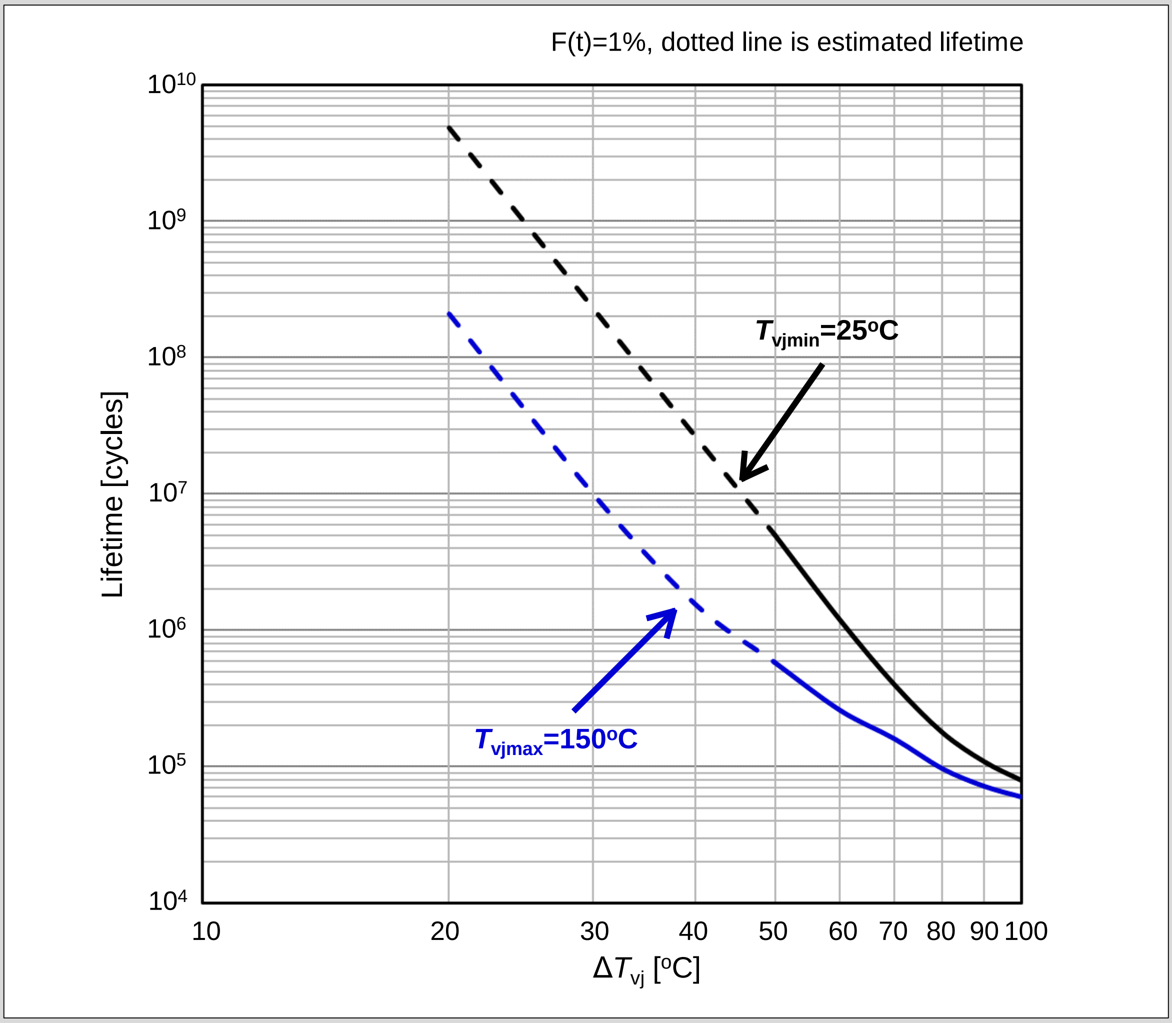


Fig. 11-5 Example of ΔT_{vj}-P/C lifetime curve

3.2 ΔT_{vj}-P/C lifetime in actual equipment

For example, in the equipment shown in Fig. 11-6 where the motor accelerates/decelerates, starts/stops frequently, calculate the ΔT_{vj}-PC lifetime with ΔT_{vj} as the difference between the maximum junction temperature T_{vj} and the heat sink temperature T_f (see Fig. 11-2), and confirm that the lifetime is sufficiently longer than the target lifetime of the equipment. Do not calculate the ΔT_{vj}-PC lifetime under such operating conditions from ΔT_{vj} during steady-state operation. The ΔT_{vj} during acceleration, deceleration, starting and stopping are greater than during steady-state operation, and the lifetime is determined by this ΔT_{vj}. In addition, in an inverter system with low speed operation such as 0.5Hz, note that the ΔT_{vj} changes significantly, thus it is necessary to calculate the lifetime with ΔT_{vj} at this condition.

If there are multiple acceleration, deceleration or low speed operation within one operation cycle of the equipment, refer to the calculation method described later in section 3.4, “P/C lifetime when there are multiple temperature rise peaks in one operation cycle”.

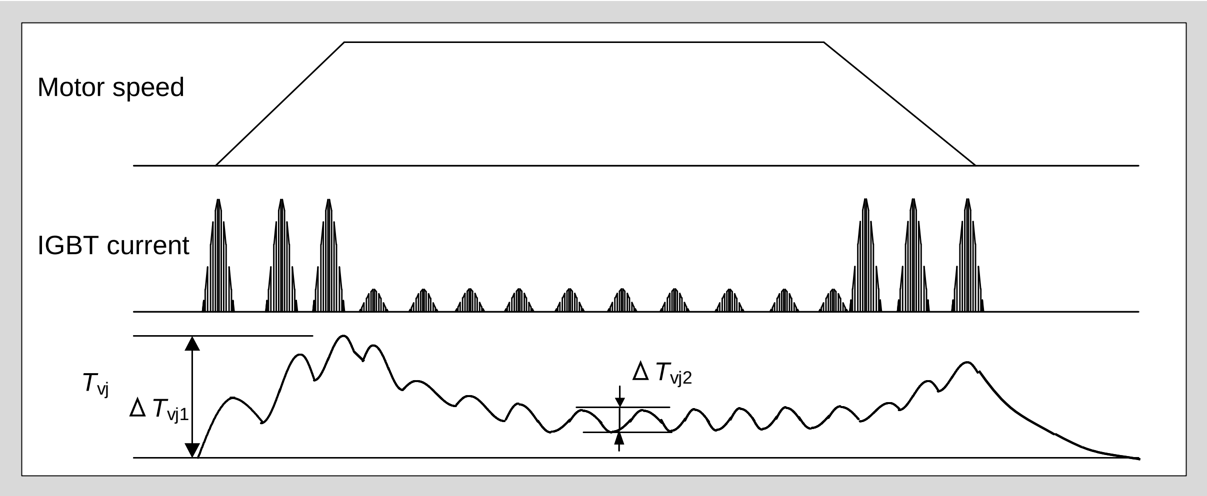


Fig. 11-6 Operation in actual equipment (example)

3.3 ΔT_C-P/C lifetime curve

Fig. 11-7 shows the current pattern of the ΔT_C-P/C test.

Fig. 11-8 shows the equivalent test circuit diagram for ΔT_C-PC test of a 6-Pack module. During the test, all the phases are energized, and the temperature of the entire case (copper base) rises and falls. The case temperature T_C is raised and lowered in a relatively long cycle so that the temperature difference between T_{vj} and T_C becomes small. This is different from the conditions in the ΔT_{vj}-PC test. When such temperature change occurs, large stress strain becomes predominant between the copper base and the DCB insulating substrate. Thus, the ΔT_C-PC mainly indicates the lifetime of the solder joints under the DCB insulating substrate.

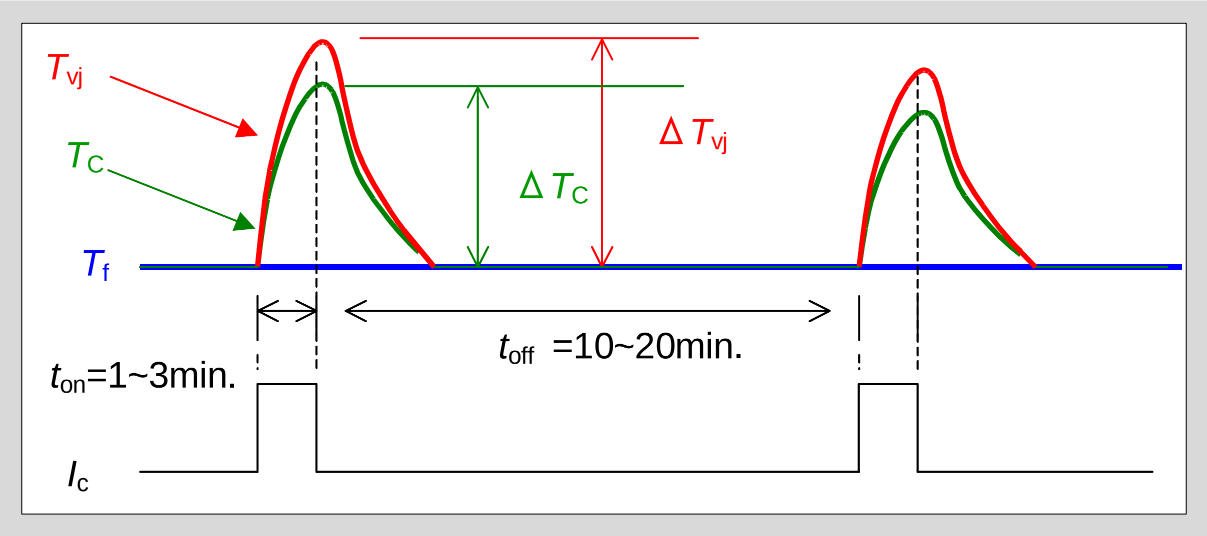


Fig. 11-7 ΔT_C-P/C test current pattern and temperature changes

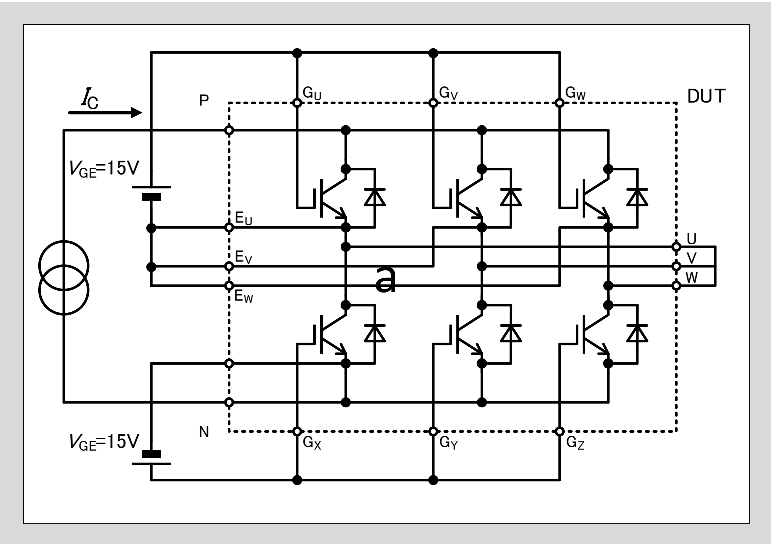
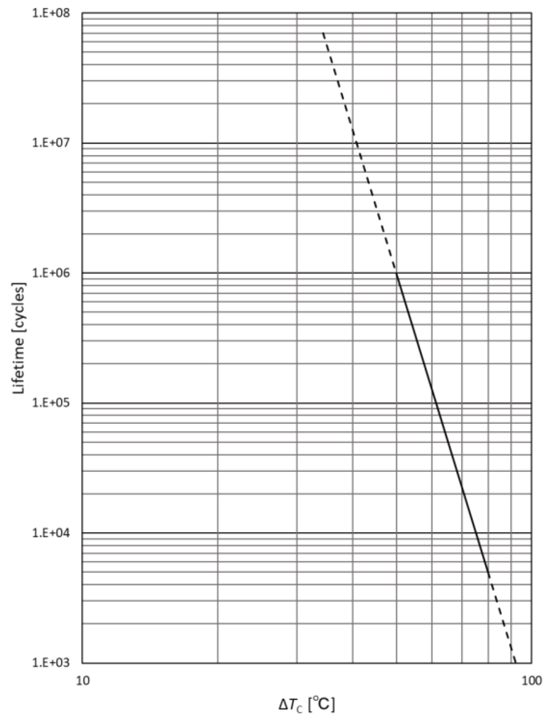


Fig. 11-8 Equivalent test circuit for ΔT_C-P/C test

The failure mode of ΔT_C-PC can be explained as follows. When T_C is raised and lowered, the largest stress strain occurs at the solder joints between the copper base and the DCB insulating substrate due to the difference in thermal expansion coefficient between them. Repeated temperature changes cause cracks in the solder joints due to stress strain. When the crack progresses and reaches the bottom part of the DCB insulating substrate where the chips are mounted, the heat dissipation of the chips deteriorate (thermal resistance R_{th} increases). As a result, T_{vj} rises and may exceed T_{vjmax}, leading to thermal destruction.

Fig. 11-9 shows the ΔT_C-PC lifetime curve of an IGBT module. When the temperature difference between T_{vj} and T_C is small, and T_C rises and falls frequently, make sure that the ΔT_C-PC lifetime of the module is sufficiently longer than the target lifetime of the equipment.



1. The failure criteria is when the thermal resistance becomes 1.2 times of more of the initial value.
2. The heat sink used in the test and the mounting condition for the modules is based on Fuji's standards.
3. The lifetime curve shows the data at F(t)=20% of the accumulated failure rate by Weibull analysis.
4. The lifetime curve shows the test result of multiple types modules.
5. The dashed line shows the estimated lifetime.

(DCB insulating substrate: Al2O3
Solder under DCB: Sn-based lead-free solder)

Fig. 11-9 Example of ΔT_C-PC lifetime

3.4 P/C lifetime when there are multiple temperature rise peaks in one operation cycle

The P/C lifetime of the IGBT module depends on the temperature rise peak and the maximum junction temperature. Therefore, when there is only one temperature rise peak in one operation cycle, the number of cycles calculated from the P/C lifetime curve is the lifetime of the IGBT module. However, when there are multiple temperature rise peaks in one operation cycle, the lifetime becomes shorter due to the impact of multiple temperature rises.

The calculation method of P/C lifetime when there are multiple different temperature rise peaks is shown below. When there are n times of temperature rises in one operation cycle, the combined P/C lifetime can be expressed by the following formula, where P/C(k) is the P/C lifetime for the k-th (k=1, 2, 3, …., n) temperature rise.

$$P/C = 1\Big/\left(\sum_{k=1}^{n} \frac{1}{P/C(k)}\right)$$

For example, when n=4 and the P/C lifetime for the respective temperature rise are 3.8 x 10^6, 1.2 x 10^6, 7.6 x 10^5 and 4.6 x 10^5, the combined P/C lifetime can be calculated as follows.

$$P/C = 1\Big/\left(\frac{1}{3.8 \times 10^6} + \frac{1}{1.2 \times 10^6} + \frac{1}{7.6 \times 10^5} + \frac{1}{4.6 \times 10^5}\right) = 2.2 \times 10^5$$

The P/C lifetime can be obtained from the product of the P/C lifetime calculated in this way and one operation cycle (time). For example, when one operation cycle is 1800 seconds (30 minutes), the lifetime is calculated as follows.

$$2.2 \times 10^5 \times 1800/(60 \times 60 \times 24 \times 365) = 12.55 \fallingdotseq 12\ years\ and\ 6\ months$$