
Chapter 11

Reliability of power module

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Market of the power modules will widely spread towards the various applications such as green energy generation and electric vehicle as well as widely used inverters. Until now, Fuji Electric has been responded to the market demand for the power modules. In future, required performance for them is going to be advanced depending on the wider market. It is important to pay attention to the reliability to respond for these demands.

In this section, reliability for power modules, especially IGBT modules, will be expresses.

1 Basis of the reliability

Time-dependent change of the failure rate for electronics parts and components including power modules is shown in Fig.1. Generally, it is described a curve like bathtub. There are three durations of early failures, random failures and wear-out failures in this failure rate curve.

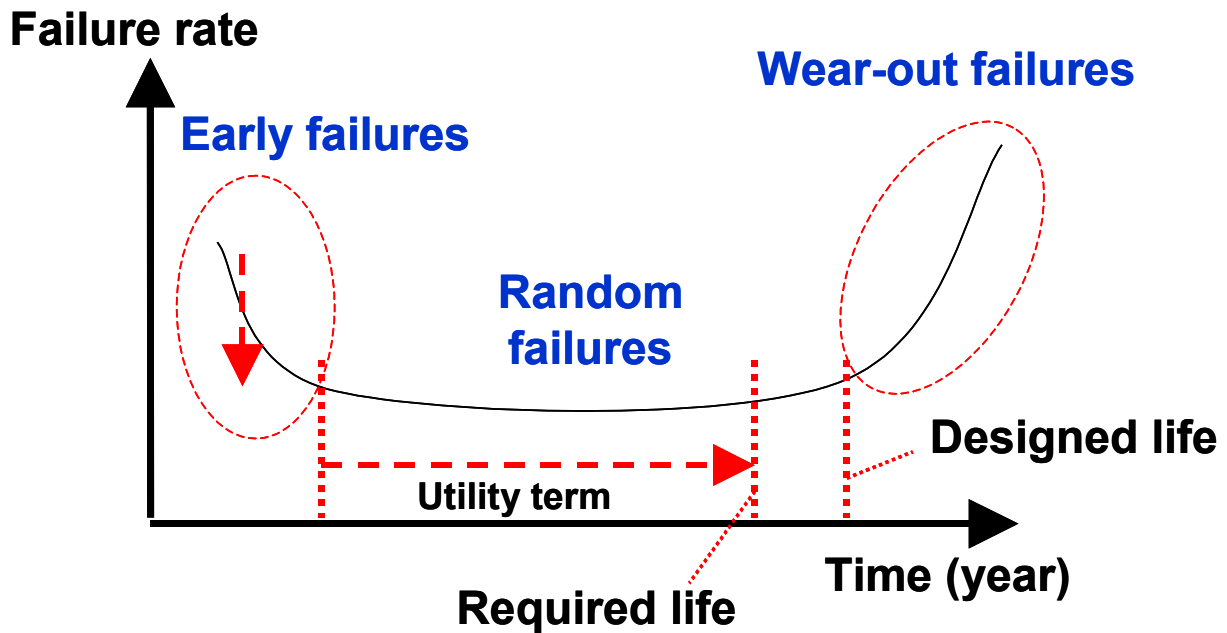


Fig.1 Time-dependent change of the failure rate for semiconductor devices

Early failures in IGBT modules would be caused by microscopic defects or human errors, which are originated defects in IGBTs and FWDs, cracking in DCBs, touch of gate and emitter wiring and so on.

Continuing the quality improvement activity can reduce such defects or errors. However, since complete removal of them cannot be avoided, removing the early failures is needed. They can be removed by suitable screening condition at outgoing tests. Fuji electric is continuing to prevent outflow of the early failures by suitable outgoing test.

Failure rate of random failures is almost fixed by removing the early failures. Duration of random failure is varied on operating condition or under environments of whole systems composed of IGBT modules and other components. This means that failure rate of random failures is equivalent to the system-specific reliability. Therefore, random failures are in general caused by excessive stresses over maximum rating such as overvoltage, overcurrent, overheat and so on. The various reliability tests have been performed to decrease failure rates during random failure, result in confirming the designs.

The failure during wear-out failures can be not serious because it is caused by wear or fatigue of the products.

IGBT module products need to be selected so as to reach the required life within wear-out duration. Even if IGBT modules were fabricated on the similar condition, life is varied depending on the operating conditions or environments. In addition, it is varied by margin including in operating condition or design. Therefore, IGBT modules on the systems must be selected by taking the operating condition and reliability into consideration.

2 Reliability test condition

As described the previous section, the various reliability tests have been performed to decrease failure rates during random failure, result in confirming the designs.

Tables 1-1 and 1-2 show some parts of representative reliability test condition for the six-generation V-IGBTs. These conditions are governed by JEITA. Refer to the specification sheets in details.

Table 1-1 Reliability test condition (environment tests)

Test categories	Test items	Test methods and conditions	Reference norms EIAJ ED-4701 (Aug.-2001 edition)	Number of sample	Acceptance number
Environment Tests	1 High Temperature Storage	Storage temp. : 125 ± 5 °C Test duration : 1000hr.	Test Method 201	5	(0 : 1)
	2 Low Temperature Storage	Storage temp. : -40 ± 5 °C Test duration : 1000hr.	Test Method 202	5	(0 : 1)
	3 Temperature Humidity Storage	Storage temp. : 85 ± 2 °C Relative humidity : 85 ± 5 % Test duration : 1000hr.	Test Method 103 Test code C	5	(0 : 1)
	4 Unsaturated Pressurized Vapor	Test temp. : 120 ± 2 °C Test humidity : 85 ± 5 % Test duration : 96hr.	Test Method 103 Test code E	5	(0 : 1)
	5 Temperature Cycle	Test temp. : $\left\{ \begin{array}{l} \text{Low temp. } -40 \pm 5 \text{ °C} \\ \text{High temp. } 125 \pm 5 \text{ °C} \\ \text{RT } 5 \sim 35 \text{ °C} \end{array} \right.$ Dwell time : High ~ RT ~ Low ~ RT 1hr. 0.5hr. 1hr. 0.5hr. Number of cycles : 100 cycles	Test Method 105	5	(0 : 1)
	6 Thermal Shock	Test temp. : $\left\{ \begin{array}{l} \text{High temp. } 100^{+0-5} \text{ °C} \\ \text{Low temp. } 0^{-0+5} \text{ °C} \end{array} \right.$ Used liquid : Water with ice and boiling water Dipping time : 5 min. par each temp. Transfer time : 10 sec. Number of cycles : 10 cycles	Test Method 307 method I Condition code A	5	(0 : 1)

Table 1-2 Reliability test condition (endurance tests)

Test categories	Test items	Test methods and conditions	Reference norms EIAJ ED-4701 (Aug.-2001 edition)	Number of sample	Acceptance number
Endurance Tests	1 High temperature Reverse Bias	Test temp. : $T_j = 150^{\circ}\text{C} (-0^{\circ}\text{C}/+5^{\circ}\text{C})$ Bias Voltage : $VC = 0.8 \times VCES$ Bias Method : Applied DC voltage to C-E $V_{GE} = 0\text{V}$ Test duration : 1000hr.	Test Method 101	5	(0 : 1)
	2 High temperature Bias (for gate)	Test temp. : $T_j = 150^{\circ}\text{C} (-0^{\circ}\text{C}/+5^{\circ}\text{C})$ Bias Voltage : $VC = V_{GE} = +20\text{V}$ or -20V Bias Method : Applied DC voltage to G-E $V_{CE} = 0\text{V}$ Test duration : 1000hr.	Test Method 101	5	(0 : 1)
	3 Temperature Humidity Bias	Test temp. : $85 \pm 2^{\circ}\text{C}$ Relative humidity : $85 \pm 5\%$ Bias Voltage : $VC = 0.8 \times VCES$ Bias Method : Applied DC voltage to C-E $V_{GE} = 0\text{V}$ Test duration : 1000hr.	Test Method 102 Condition code C	5	(0 : 1)
	4 Intermitted Operating Life (Power cycle) (for IGBT)	ON time : 2 sec. OFF time : 18 sec. Test temp. : $100 \pm 5^{\circ}\text{deg}$ $T_j \leq 150^{\circ}\text{C}$, $T_a = 25 \pm 5^{\circ}\text{C}$ Number of cycles : 15000 cycles	Test Method 106	5	(0 : 1)

As shown in table 1-2, both high temperature reverse bias and high temperature bias to gate are confirmed on the condition at junction temperature of 150°C , these results can be guaranteed for operating temperature of 150°C .

3 Power cycle curve

The temperature of IGBT module rises and falls according to the operating conditions. The interior structure of the IGBT module is exposed to the heat stress caused by this temperature rise and fall and suffers fatigue and deterioration. This fatigue and deterioration depend heavily on the change width of temperature rise and fall and so the life span of the IGBT modules varies depending on the operating and environmental conditions. This heat cycle life is called power cycle life (power cycle capability). The power cycle life can be calculated from the power cycle capability curve that shows the relation between the temperature change ΔT and the number of cycles, and there are two types of curve.

One is the ΔT_j power cycle (ΔT_j -P/C) capability curve, which is the life curve made when the element temperature rises and falls suddenly. In this curve, a failure caused by deterioration of the aluminum wire joints on the chip surface becomes predominant. The other is the ΔT_c power cycle (ΔT_c -P/C) capability curve, which is the life curve made when the change of the case temperature (mainly the copper base plate temperature) follows the temperature rise and fall of the element. In this case, in this curve, a failure caused by deterioration of the soldered joints between the insulated substrate DCB and the copper base plate becomes predominant.

The following sections describe the measurement method and the power cycle capability curve for the ΔT_j -P/C and ΔT_c -P/C power cycles, respectively.

3.1 ΔT_j power cycle (ΔT_j -P/C) capability curve

Figure 11-2 shows the pattern of current flow in the ΔT_j power cycle (ΔT_j -P/C) test. Figures 11-3 and 11-4 show the equivalent circuit schematic in the ΔT_j power cycle test and the schematic view of the T_c and T_f measurement positions, respectively. During the ΔT_j power cycle test, the temperature of the element joints is increased and decreased in a short-time cycle. Therefore, a difference is made in temperature between the silicon chip and the DCB or between the silicon chip and the aluminum wire and so heat stress is caused between them. For this reason, the ΔT_j power cycle shows mainly the life span of the aluminum wire joints and the soldered section under the chip.

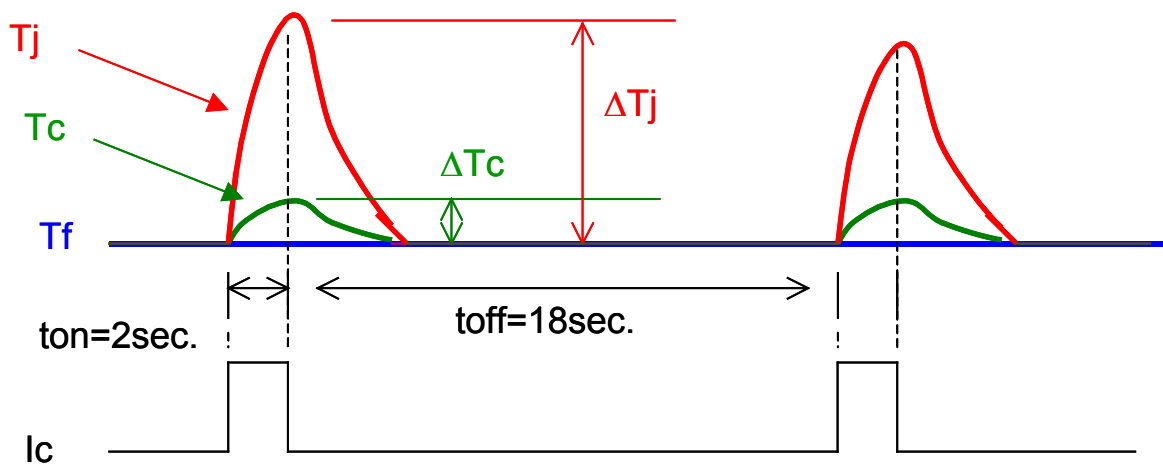


Fig. 11-2 Pattern diagram of current flow of ΔT_j power cycle and temperature change

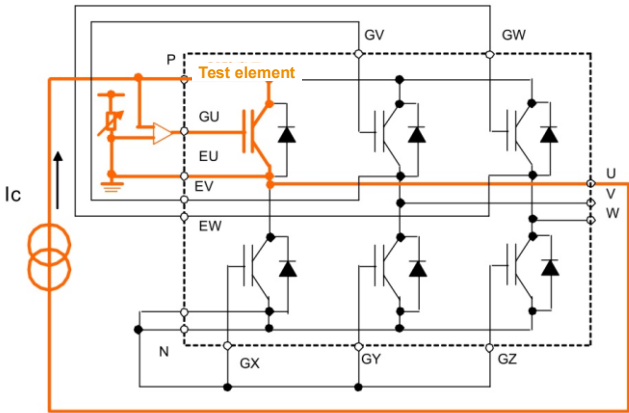


Fig. 11-3 Equivalent circuit for ΔT_j power cycle test

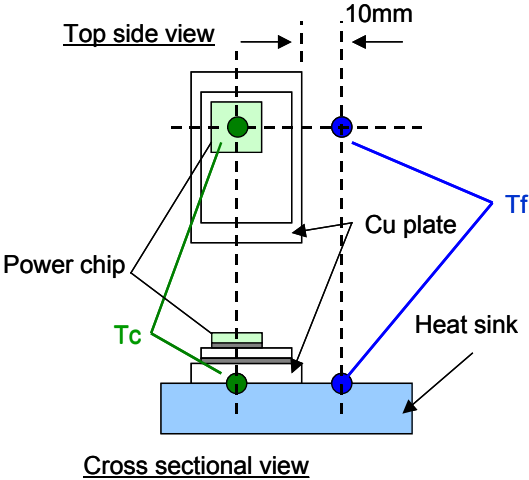


Fig. 11-4 Schematic view of T_c and T_f measurement positions

Figure 11-5 shows the curves of U series and V series as an example of ΔT_j power cycle capability curve of the IGBT module. In this figure, the $T_j(\text{min})=25^\circ\text{C}$ line indicates the life cycle when the chip temperature is changed while the temperature of the cooling fin is kept at 25°C . For example, when $\Delta T_j = 50^\circ\text{C}$, the chip temperature reaches 75°C while the cooling fin temperature is 25°C . On the other hand, the $T_j(\text{max})=150^\circ\text{C}$ line shows the life cycle when the temperature of cooling fin is changed while the achieving temperature of the chip is kept at 150°C . For example, when $\Delta T_j = 50^\circ\text{C}$, the chip temperature reaches 150°C while the temperature of the cooling fin is 100°C . As shown, even if ΔT_j is the same, the higher the temperature of the cooling fin and the achieving temperature of the chip are, the shorter the life span is.

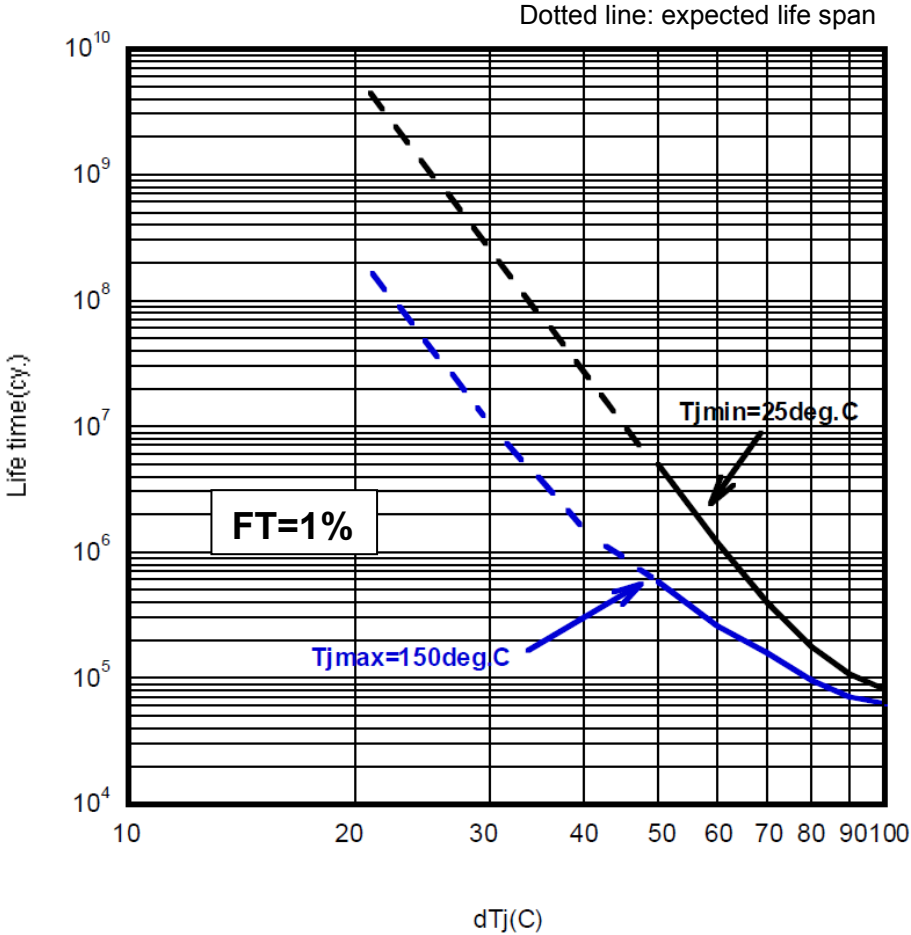


Fig. 11-5 Example of ΔT_j power cycle capability curve ($F(t) = 1\%$. Chips connected in parallel are excluded. The dotted lines indicate the expected life span.)

For safe life design of the IGBT module in actual equipment, check ΔT_j in the operating conditions of the equipment and make sure that the power cycle life, which is obtained from the ΔT_j power cycle capability curve, is longer enough than the required life span of the product.

For example, as shown in Figure 11-6, in equipment, in which the motor is accelerated, decelerated, started and stopped repeatedly, obtain the ΔT_j power cycle life where ΔT_j is the difference between the maximum junction temperature T_j and the fin temperature T_f (see Figure 11-2), and make sure that its life is longer enough than the targeted life span of the product.

For life design in such operating conditions, however, do not obtain ΔT_j during steady operation. This is because the temperature change caused while the motor is accelerated, decelerated, started and stopped is bigger than the one caused while it is operated steadily, and the life span is affected by such temperature change.

In addition, since the temperature change becomes bigger in a drive system, in which low speed operation such as 0.5Hz is performed, be careful enough of ΔT_j during the operation when you design the product life.

If there are multiple acceleration, deceleration or low-speed operation temperatures within one operation cycle of the equipment, calculate the power cycle life according to the “Calculation of power cycle life when there are multiple temperature rises in one operation cycle” described later.

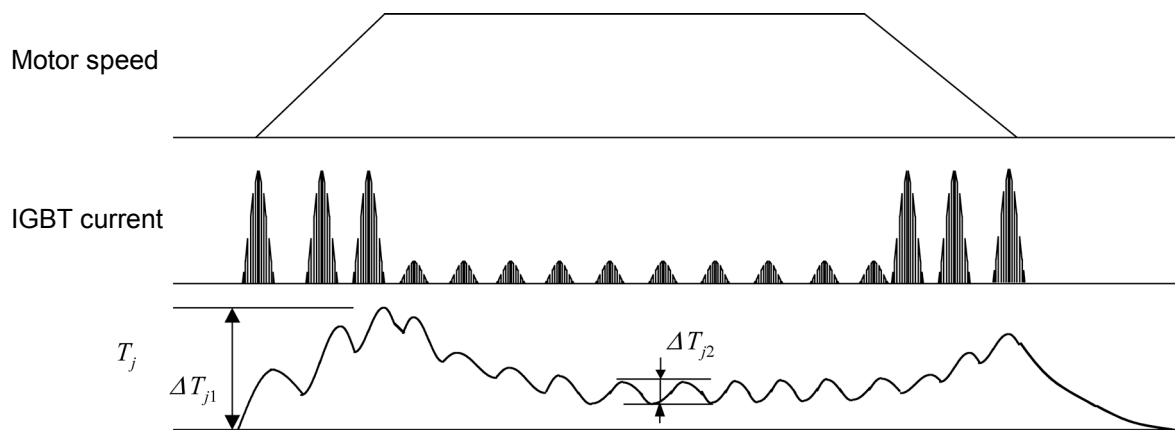


Fig. 11-6 Operation in actual inverter (example)

3.2 ΔT_c power cycle (ΔT_c -P/C) capability curve

Figure 11-7 shows the current flow pattern of ΔT_c power cycle (ΔT_c -P/C) conducted by us. Figure 11-8 shows the equivalent circuit schematic in the ΔT_c power cycle test for the 6in1 module. During the ΔT_c power cycle test, all the phases (6 phases in the 6in1 module, and 2 phases in the 2in1 module) are energized, and the temperature of the entire case (mainly the copper base) is increased and decreased. However, the case temperature T_c is increased and decreased in a relatively long-time cycle so that the difference between the junction temperature T_j and the case temperature T_c becomes small. This is different from the conditions in the ΔT_j power cycle test. When such temperature change occurs, the significant stress strain becomes predominant between the base and the insulated substrate DCB and so the power cycle shows mainly the life span of the soldered joints under the insulated substrate DCB.

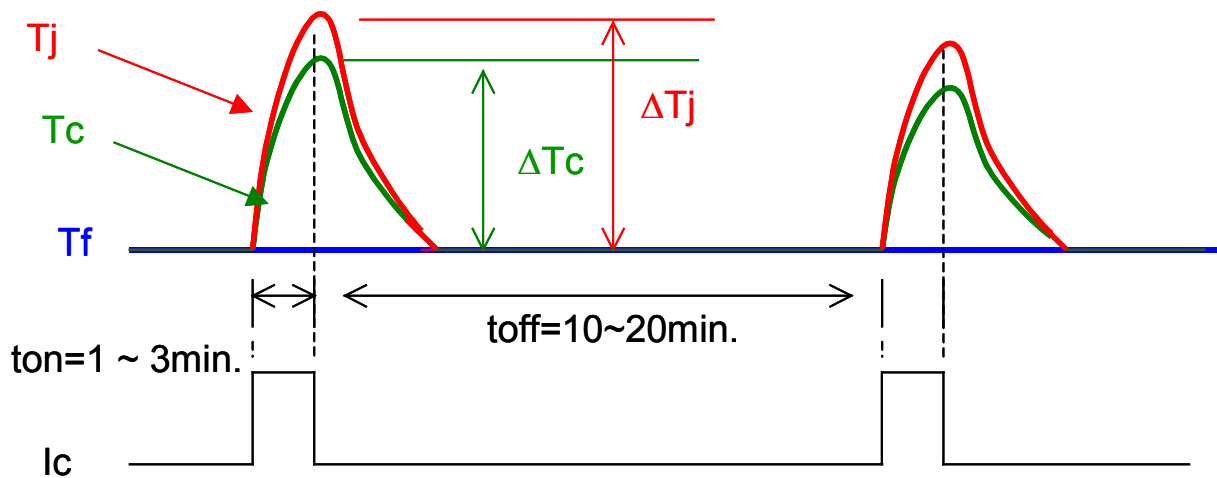


Fig. 11-7 Current flow pattern of ΔT_c power cycle

The failure mode of the ΔT_c power cycle can be explained as follows. When the case temperature T_c is increased and decreased, the largest stress strain is caused in the soldered joint between the insulated substrate DCB and the base due to the difference in thermal expansion coefficient between them. When this heat change is repeated, the soldered joint is cracked due to the stress strain. When this crack advances up to the lower part of the insulated substrate DCB, on which the silicon chip is installed, the chip junction temperature T_j rises because the heat radiation of the silicon chip is deteriorated (the thermal resistance R_{th} increases). As a result, the chip junction temperature T_j may exceed $T_j(\max)$ and thermal destruction may result.

Figure 11-9 shows the ΔT_c power cycle curve in the IGBT module. When the temperature difference between the junction temperature T_j and the case temperature T_c is small and the temperature of the case rises and falls repeatedly, make sure in design that the operation life of the module, which is obtained from the ΔT_c power cycle curve, is longer enough than the targeted design life of the product.

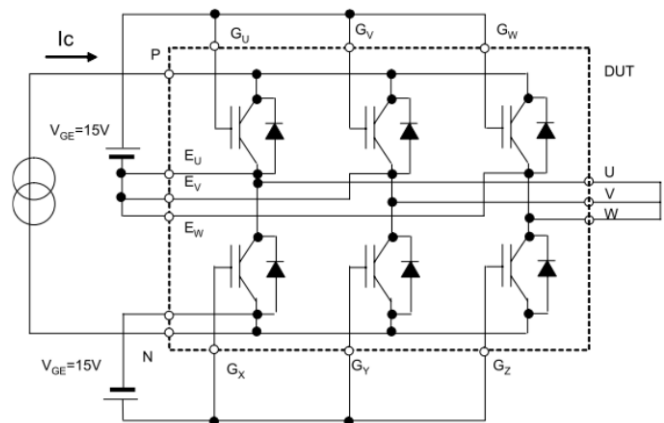
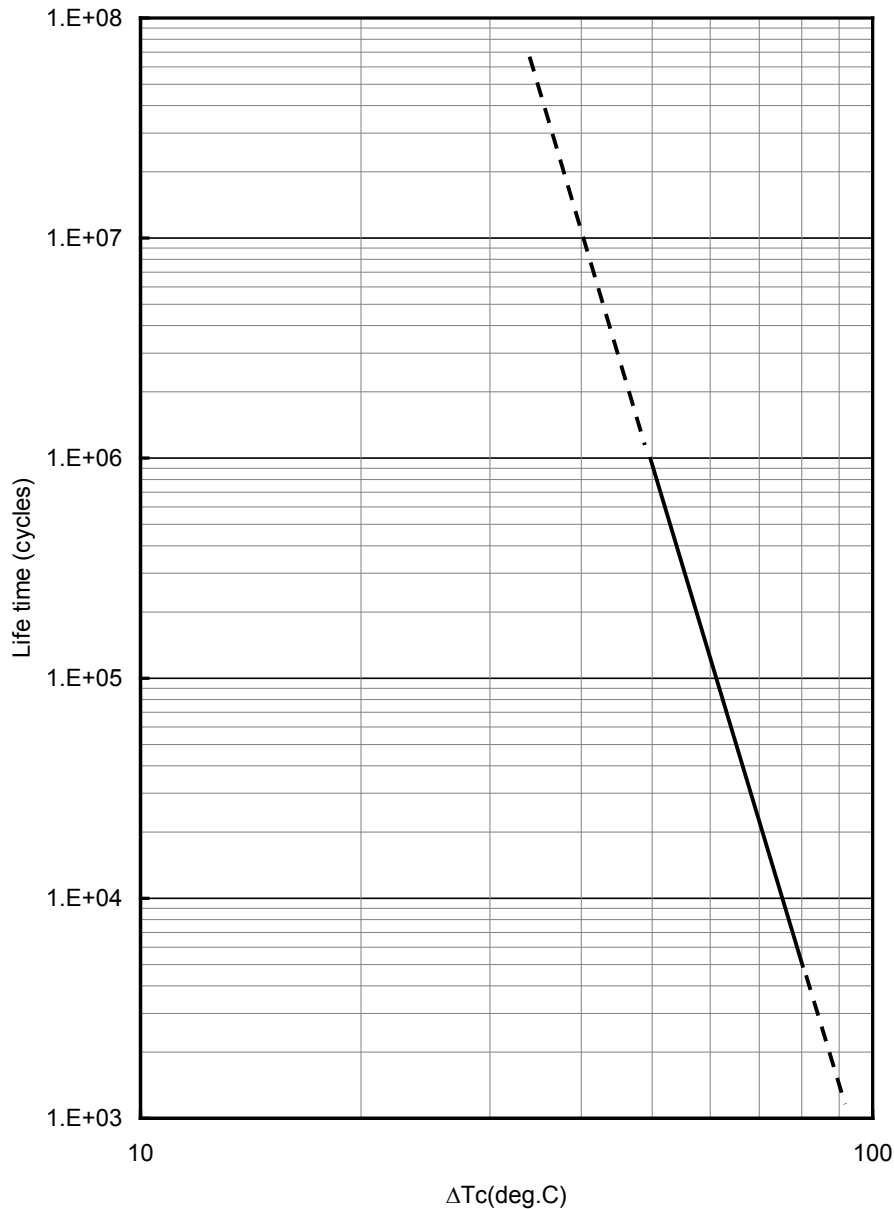


Fig. 11-8 Equivalent circuit for ΔT_c power cycle test



- *1). The definition of the failure criteria in this test is at $R_{th} > 1.2$ times of an initial value.
- *2). The heat sink used in the test and the mounting condition for the modules is accordance to Fuji standard
- *3). The life time curve with black color shown in figure is at $F(t) = 20\%$ of the accumulated failure rate by weibull analysis chart.
- *4). The life time shown in this figure is the tested results used several type of the modules
- *5). The dotted line shows the estimated life time.

Fig. 11-9 Example of ΔT_c power cycle capability

(DCB substrate: Al_2O_3 , solder between copper base plate and DCB : Sn type lead-free solder)

3.3 Calculation of power cycle life when there are multiple temperature rises in one operation cycle

The power cycle life of the IGBT module depends on the temperature rise width (and the maximum temperature) during power cycle. Therefore, when there is only one temperature rise peak of the IGBT module in one operation cycle of the inverter, the number of times calculated from the power cycle life curve is the life cycle of the IGBT module.

However, when there are multiple temperature rise peaks in one operation cycle of the inverter, the life cycle becomes shorter because the module is influenced by the multiple temperature rises. The calculation method of power cycle life when there are multiple different temperature rise peaks is shown below.

When there are n times of temperature rises in one operation cycle of inverter, the combined power cycle life can be expressed in the following formula, where $PC(k)$ is the power cycle life for the k -th ($k=1, 2, 3, \dots, n$) temperature rise.

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

For example, when $n=4$ and the power cycle numbers for the respective power rise peaks are 3.8×10^6 , 1.2×10^6 , 7.6×10^5 and 4.6×10^5 , calculation is made as follows:

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

Therefore, the power cycle lifetime can be obtained from the product of the power cycle life calculated in this way and one cycle (time) of operation mode.

For example, when one cycle of the above operation mode is 1800sec (30min), the lifetime is calculated as follows:

$$2.2 \times 10^5 \times 1800 / (60 \times 60 \times 24 \times 365) = 12.55 \approx 12 \text{ years and 6 months.}$$

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