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# Chapter 11

## Reliability of power module

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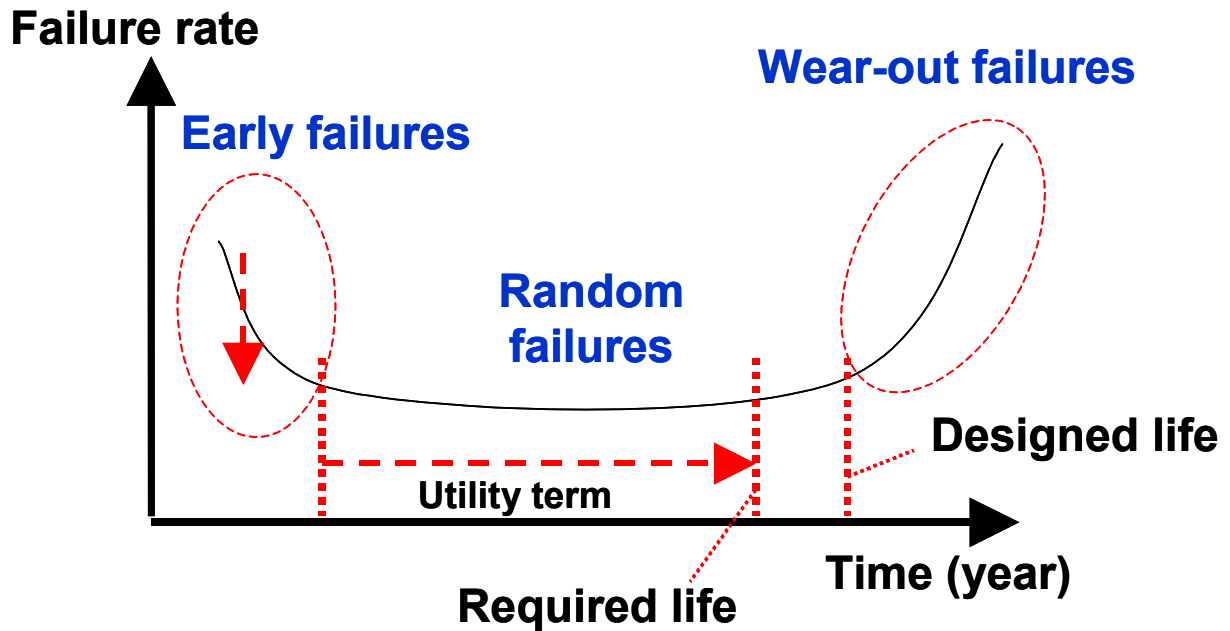
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Market of the power modules has widely been spread among the various applications, such as green energy conversion and electric vehicle in addition to conventionally used general purpose inverter, servo, NC and elevator applications. Up to now, Fuji electric has tried to match the market demand for the power modules. In future, preferred properties for various applications are expected to have more varieties and/or higher functionality depending on the market growth. The reliability of power modules are getting more and more important to match these demands.

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

## 1 Basis of the reliability

In general, the time-dependent change in the failure rate of electronics parts and components including power modules is known as bathtub curve as shown in Fig.1. The curve can be comprised three parts of early failures, random failures and wear-out failures.



Early failures in IGBT modules would be caused by micro 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 these inconveniences are very difficult, screening tests in out-going procedure are necessary to reject such early failures. Fuji Electric is continuing to prevent defective products leaving out from factory..

Failure rate of random failures coming after the early failures is relatively stable. Duration of random failure depends on operating conditions including environments of whole systems where IGBT modules and other components are installed. 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.

The unlikely failures during wear-out part are difficult to control procedures above because it is caused by wear or fatigue of the products.

It is important to select type of IGBT module to match the lifetime design in system taking into account of wear-out duration of IGBT module. Even though IGBT modules are fabricated on the well controlled production process, the product lifetime not only depends on the operating conditions and/or environments, but also depends on how much design margin left in practical system.

## 2 Reliability test conditions

As described the previous section, the various reliability tests are performed to decrease failure rates of random failure, these tests are also for confirmation of new design.

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. : $125 \pm 5$ °C Test duration : 1000hr.	Test Method 201	5	(0 : 1)
	2 Low Temperature Storage	Storage temp. : $-40 \pm 5$ °C Test duration : 1000hr.	Test Method 202	5	(0 : 1)
	3 Temperature Humidity Storage	Storage temp. : $85 \pm 2$ °C Relative humidity : $85 \pm 5$ % Test duration : 1000hr.	Test Method 103 Test code C	5	(0 : 1)
	4 Unsaturated Pressurized Vapor	Test temp. : $120 \pm 2$ °C Test humidity : $85 \pm 5$ % 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. : $\left\{ \begin{array}{l} \text{High temp. } 100^{+0}_{-5} \text{ °C} \\ \text{Low temp. } 0^{+5}_{-0} \text{ °C} \end{array} \right.$ 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 $-20\text{V}$ 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 : ; 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, it should be noted that high temperature reverse bias and high temperature bias to gate are done at junction temperature of  $150^{\circ}\text{C}$  in order to guarantee  $150^{\circ}\text{C}$  continuous operation.

### 3 Power cycle curve

The IGBT module has temperature swing depending on its operating conditions. The mechanical stress in each internal structure of the IGBT module will be accumulated over thermal stress and then it results mechanical fatigue and deterioration. This fatigue and deterioration strongly depend on the amount of temperature swing of up and down and it also limits the IGBT product lifetime depending on the operating and environmental conditions. This type of temperature cycle is typically called as "power cycle life (power cycle capability)". The power cycle life can be estimated from the power cycle capability curves indicating the relation between the temperature swing  $\Delta T$  and the number of cycles. There are two types of curves are practically important for system design.

One is the  $\Delta T_j$  power cycle ( $\Delta T_j$ -P/C) capability curves, which are the life curves made when the junction temperature rapid rises and falls. In these curves, failure caused by deterioration at the interface between the aluminum bonding wire and chip surface interconnection. The other is the  $\Delta T_c$  power cycle ( $\Delta T_c$ -P/C) capability curves, which predict the product lifetime curve which is limited by the change in the case temperature (mainly the base plate temperature). In this case, a predominant failure caused by deterioration of the soldered joints between the insulated substrate DCB and the copper base plate.

The following sections describe the measurement method and the power cycle capability curves for the  $\Delta T_j$ -P/C and  $\Delta T_c$ -P/C power cycles, respectively.

#### 3.1 $\Delta T_j$ power cycle ( $\Delta T_j$ -P/C) capability curves

Figure 11-2 shows the patterns of current flow in the  $\Delta T_j$  power cycle ( $\Delta T_j$ -P/C) test. Figures 11-3 and 11-4 show the equivalent schematic circuit in the  $\Delta T_j$  power cycle test and the schematic view of the  $T_c$  and  $T_f$  measurement positions, respectively. During the  $\Delta T_j$  power cycle test, the junction temperature goes up and down in a short-time cycle. Therefore, outstanding temperature difference between silicon chip and DCB or bonding wires results thermal stress. For this reason, the  $\Delta T_j$  power cycle lifetime is mainly limited by the aluminum bonding wire joints and the soldered layer under the chip.

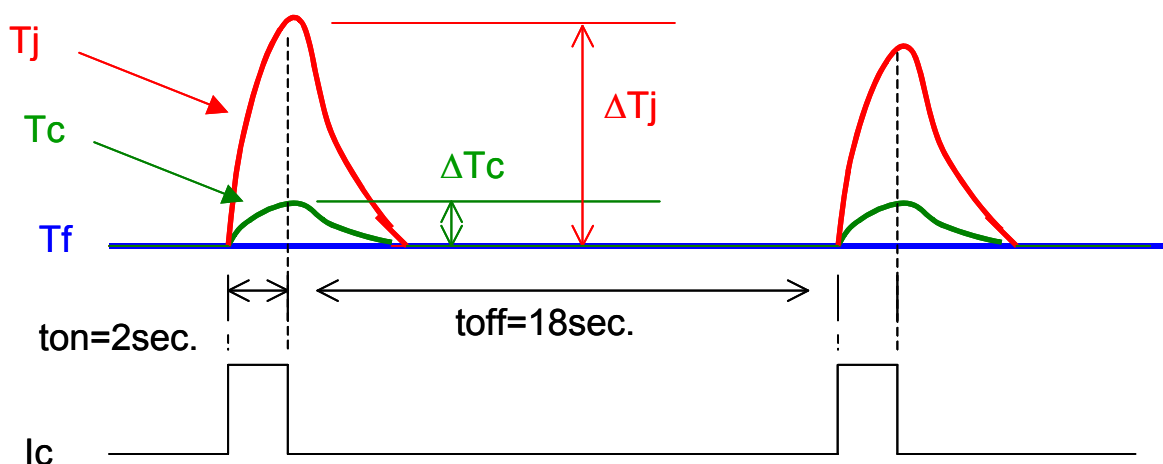


Fig. 11-2 Pattern diagram of current flow of  $\Delta T_j$  power cycle and temperature change

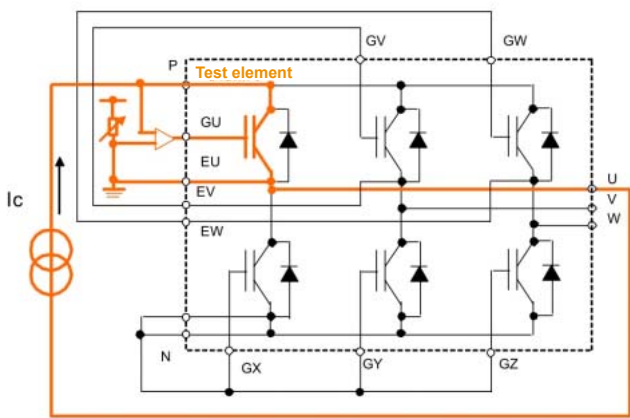


Fig. 11-3 Equivalent circuit for  $\Delta T_j$  power cycle test

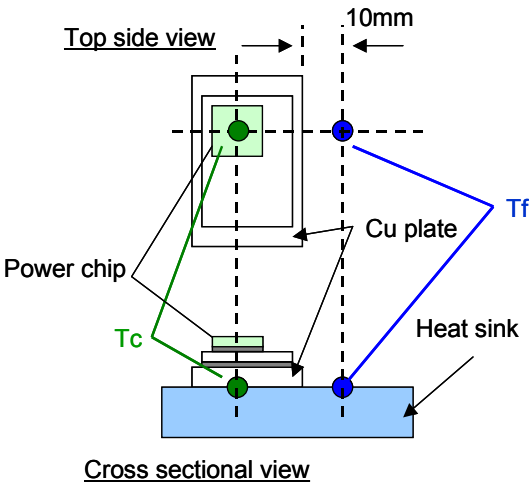


Fig. 11-4 Schematic view of  $T_c$  and  $T_f$  measurement positions

Figure 11-5 shows the curves of U series and V series as an example of  $\Delta T_j$  power cycle capability curve of the IGBT module. In this figure, the  $T_{jmin}=25^\circ\text{C}$  line indicates the life cycle of fixed minimum temperature. The chip temperature is changed while the temperature of the cooling fin is kept at  $25^\circ\text{C}$ . For example, when  $\Delta T_j = 50^\circ\text{C}$ , the chip temperature reaches  $75^\circ\text{C}$  while the cooling fin temperature is  $25^\circ\text{C}$ . On the other hand, the  $T_{jmax}=150^\circ\text{C}$  line shows the life cycle of fixed maximum temperature. The temperature of cooling fin is changed but the maximum junction temperature of the chip is fixed to  $150^\circ\text{C}$ . For example, when  $\Delta T_j = 50^\circ\text{C}$ , the chip maximum junction temperature is  $150^\circ\text{C}$  while the temperature of the cooling fin is  $100^\circ\text{C}$ . As shown in the figure, even at the same  $\Delta T_j$ , the higher the temperature of the cooling fin and the achieving temperature of the

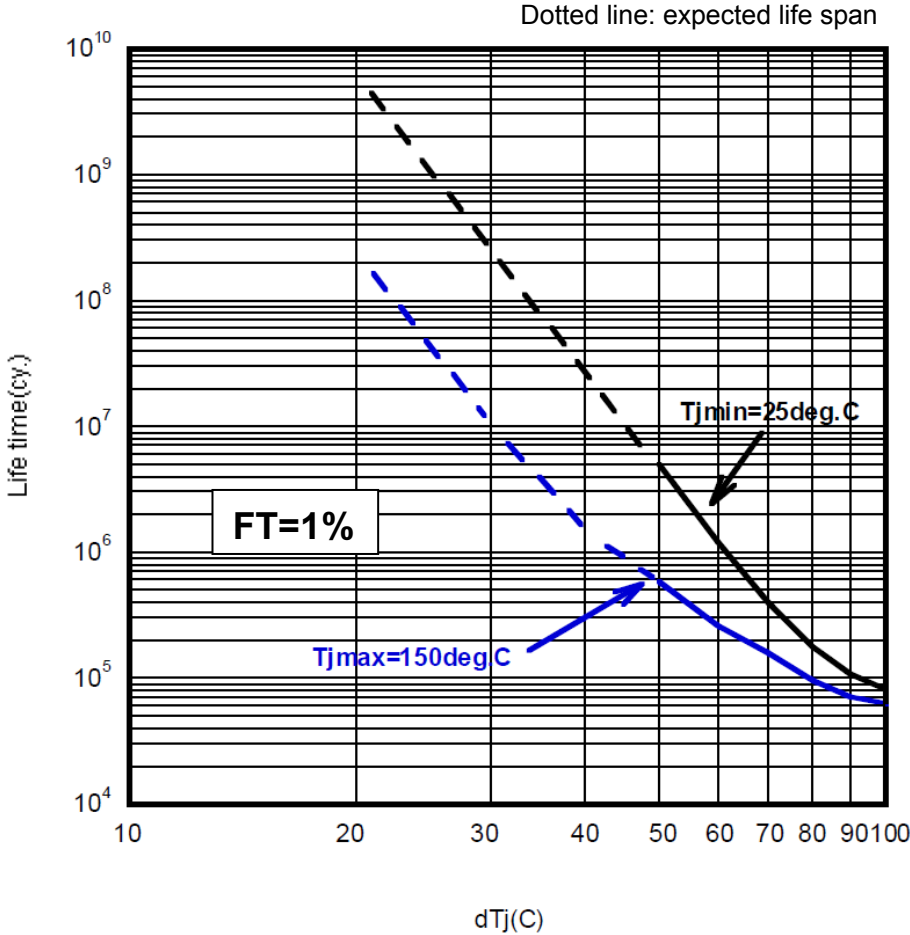


Fig. 11-5 Example of  $\Delta T_j$  power cycle capability curve  
 ( $F(t) = 1\%$  Chips connected in parallel are excluded.  
 The dotted lines indicate the expected life span.)

chip are, the shorter the estimated life span will be.

For safe life design of the IGBT module in practical system, it is important to check  $\Delta T_j$  in various operating conditions of the equipment to make sure the power cycle life with the chart provided above so that the IGBT expected product lifetime has longer enough than the specific life span of the product.

It should be noted that for the system, which have frequent acceleration/deceleration or frequent system start/stop such as Fig 11-6 as one of examples, should be careful in reliability lifetime prediction.

In such equipment,  $\Delta T_j$  should be defined as the difference between the maximum junction temperature  $T_j$  and the fin temperature  $T_f$  (see Figure 11-2), and then make sure that its life is longer enough than the targeted life span of the product. It is important for such system not to use parameters in steady-state. Because the product lifetime is limited by much higher temperature swing at acceleration/deceleration or start/stop compared to the steady state.

In addition, drive systems which run low speed operation such as 0.5Hz output should have similar notice since the temperature swing at low speed operation may have much higher than steady-state.

If there are multiple load profile of acceleration, deceleration and/or low-speed operation temperatures within one operation cycle of the equipment, calculate the power cycle life according to the "Calculation of life span when there are multiple temperature rises" described later.

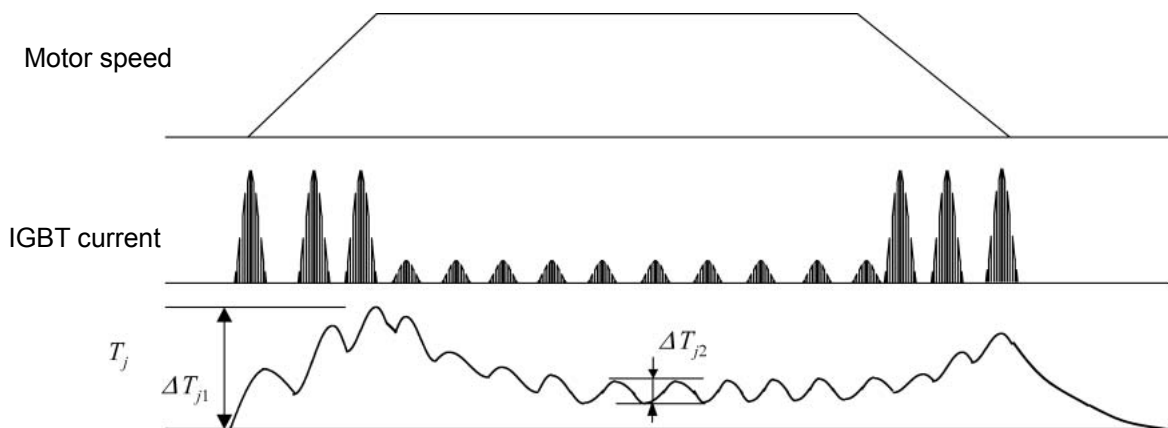


Fig. 11-6 Operation in actual inverter (example)

### 3.2 $\Delta T_c$ power cycle ( $\Delta T_c$ -P/C) capability curve

Figure 11-7 shows the current flow pattern of  $\Delta T_c$  power cycle ( $\Delta T_c$ -P/C) in Fuji IGBT reliability test. Figure 11-8 shows the equivalent schematic circuit in the  $\Delta T_c$  power cycle test for the 6in1 module. During the  $\Delta T_c$  power cycle test, all switches (6 switches in the 6in1 module, and 2 switches in the 2in1 module) are electrically active state, and the temperature of the entire case (mainly the copper base) can be controlled to 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  $\Delta T_j$  power cycle test. When such temperature change occurs, the significant stress strain becomes predominant between the base and the insulated substrate DCB. The power cycle of this operation mode is limited by the soldered joints under the insulated substrate DCB.

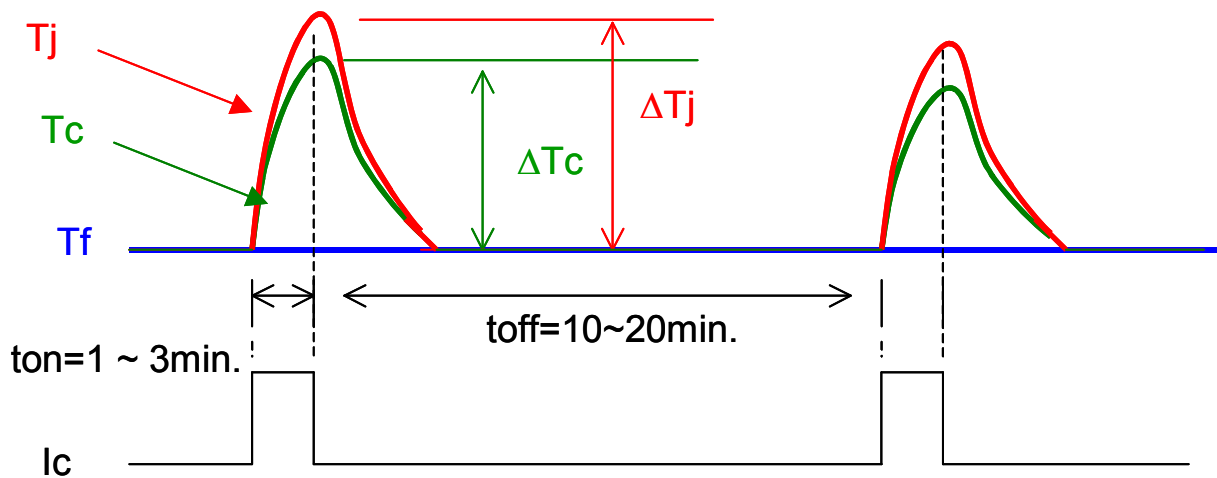


Fig. 11-7 Current flow pattern of  $\Delta T_c$  power cycle

The failure mode of the  $\Delta T_c$  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  $T_{jmax}$  and thermal destruction may result.

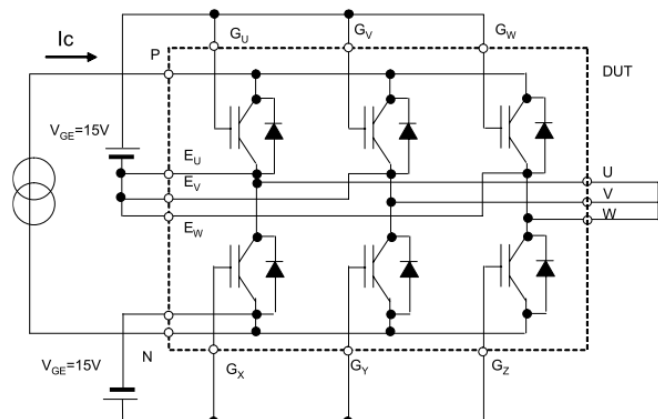


Fig. 11-8 Equivalent circuit for  $\Delta T_c$  power cycle test

Figure 11-9 shows the  $\Delta T_c$  power cycle curve in the IGBT module. When the temperature difference between the joint and the case 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  $\Delta T_c$  power cycle curve, is longer enough than the targeted design life of the product.

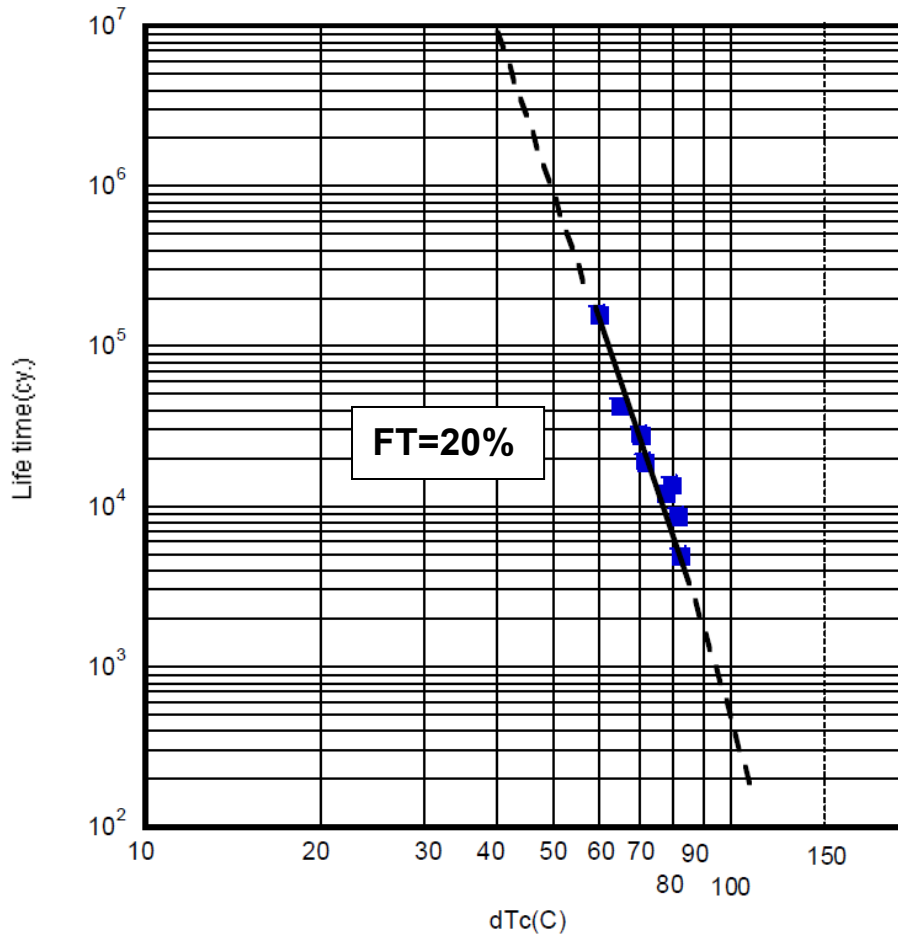


Fig. 11-9 Example of  $\Delta T_c$  power cycle capability  
(DCB substrate:  $Al_2O_3$  / lower part of DCB soldered: Sn type lead-free solder)

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

The power cycle life of the IGBT module depends on height the temperature swing (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  $3.8 \times 10^6$ ,  $1.2 \times 10^6$ ,  $7.6 \times 10^5$  and  $4.6 \times 10^5$ , 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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