On-Line Estimation Method of Junction Temperature of Inverter's Power Devices with Due Consideration to Device's Deterioration

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Abstract

Power converters (inverters) are used in fields such as industrial facilities and infrastructures, with a need for improved reliability. Temperature protection is one method for improving inverter reliability, however, it is difficult to directly measure the junction temperature T_j of the power devices – a major component of the inverter. One technique for estimating T_j is to compare the voltage-T_j characteristics of the power device with the voltage and current values during the operation of the inverter. With this method, however, as the power device deteriorates, the characteristics obtained in advance change resulting in temperature estimation errors.

We, therefore, developed a method to estimate the deterioration of power devices using electrical resistance values, and confirmed that the accuracy of temperature estimation was improved.

1 Preface

Power devices used in power converters (inverters) are actively being studied for application in a wide range of fields where reliability is required. One way to improve inverter reliability is to estimate the junction temperature T_j of power devices while the inverter is running. By estimating T_j during operation, it is possible to avoid a power device malfunction due to overheating above the rated temperature level. One method[1] for estimating T_j is to calculate the loss of the power device and estimate it from the heat equivalent circuit, however, a high-precision heat equivalent circuit is required.

There is also a V_{ce} measurement method[2] that estimates T_j by comparing the measured on-voltage V_{ce} and on-current I_c with the previously obtained V_{ce}-T_j characteristic for I_c. Generally, the components that make up a power device have different coefficients of linear expansion. When T_j changes due to the use of power devices, the solder at the junction is deteriorated[3]. Due to this deterioration, the V_{ce}-T_j characteristic with respect to I_c changes from the previously obtained characteristics. When using the V_{ce} measurement method during the operation of the inverter, errors occur in the T_j estimation. In this paper, we introduce a method to improve the accuracy of the T_j estimation by estimating the deterioration of power devices as resistance values.

2 T_j Estimation Method Using V_{ce}

2.1 System Configuration

Fig. 1 shows a system configuration for the T_j estimation method using Value V_{ce}. In this system, values of V_{ce}, load current *iload*, and package temperature T_c are measured with the use of the detec-

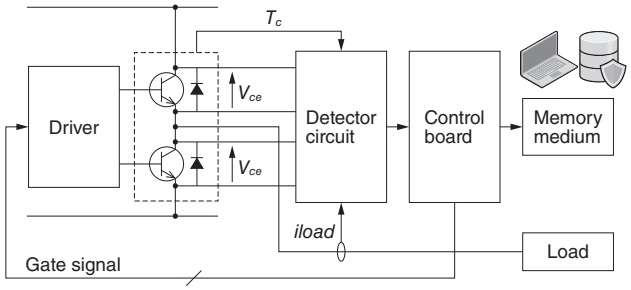

Fig. 1 System Configuration for T_j Estimation Method

The detector circuit is connected to each power device to measure on-state voltage V_{ce}, load current *iload*, and package temperature T_c. The measured data are saved in the memory medium to support long term monitoring.

tor circuit. After the measured values are converted into digital signals by using the analog-digital converter, the data is saved in the memory medium through the control board. To estimate the value T_j during operation of inverters, values of V_{ce}, I_c, and T_c are measured at the cycle of some tens of a microsecond. Value I_c is assumed to be identical with the absolute value of the load current and derived from the direction of *iload* and on-state period of the power device. Since the measured data is saved in the memory medium, long-term monitoring of power devices is possible.

2.2 T_j Estimation Approach Using V_{ce} Estimation Method

Fig. 2 shows the V_{ce}-T_j Characteristics of I_c. Each line falls on a V_{ce}-T_j characteristic of the respective I_c values. The power device employed is a 2-in-1 module of a rated voltage 1200 V and a rated continuous current 75 A. Regarding the characteristics in Fig. 2, there is a condition of I_c (cross point current I_{c_cp} hereafter) such that V_{ce} is kept constant irrespective of T_j. In addition, the trends of V_{ce} variation with T_j can differ around the boundary of currents I_{d_min} and I_{d_max} near I_{c_cp}. For the V_{ce} measurement approach, the V_{ce}-T_j characteristics of I_c are acquired in advance under multiple I_c conditions. Value T_j is then estimated by comparing the I_c and V_{ce} values measured during inverter operation with the characteristics acquired in advance.

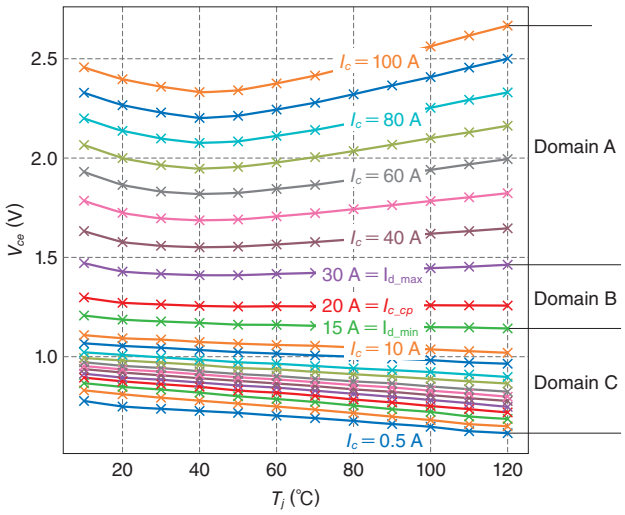

Fig. 2 V_{ce}-T_j Characteristic of I_c

Each line of characteristics shows the V_{ce}-T_j characteristic of each I_c. The V_{ce}-T_j characteristic varies in conformity with I_c. Based on the I_c value, the V_{ce}-T_j characteristic is split into three domains A, B, and C so that T_j is estimated with a different algorism for each domain.

Accordingly, when I_c is greater than I_{d_max}, the V_{ce}-T_j characteristics become nonlinear, and T_j cannot be uniquely estimated from V_{ce} and I_c.

For a solution, the area in Fig. 2 is split into three domains (A∼C) and T_j is estimated with a different algorism in each domain. Fig. 3 shows a flowchart of the T_j estimation by the V_{ce} measurement approach. Firstly, in the system of Fig. 1, V_{ce}, I_c, and T_c are measured. Then, a domain shown in Fig. 2 is identified using measured I_c. The T_j estimation algorisms in respective domains are as follows:

(1) Domain A condition: $I_c > I_{d_max}$

This domain is for a condition where the current condition is higher than the I_{c_cp} level. Here in this domain, the V_{ce} variations are nonlinear for T_j. For this reason, T_j is estimated by comparing the measured V_{ce} and I_c with the V_{ce}-T_j characteristic of I_c acquired in advance.

(2) Domain B condition: $I_{d_min} < I_c \leqq I_{d_max}$

This domain is of I_{d_max} and I_{d_min} where V_{ce} is almost kept constant for T_j changes in the vicinity of I_{c_cp}. Since the temperature estimation accuracy is poor, Value T_j is employed that is estimated based on the V_{ce} and I_c values measured before the last measuring cycle.

(3) Domain C condition: $I_c \leqq I_{d_min}$

This domain for the I_c values lower than those of Domain B. In this domain, V_{ce} is monotonously decreased with T_j and, therefore, T_j can be uniquely obtained by making comparison of measured V_{ce} and I_c values with the V_{ce}-T_j characteristics of I_c acquired in advance.

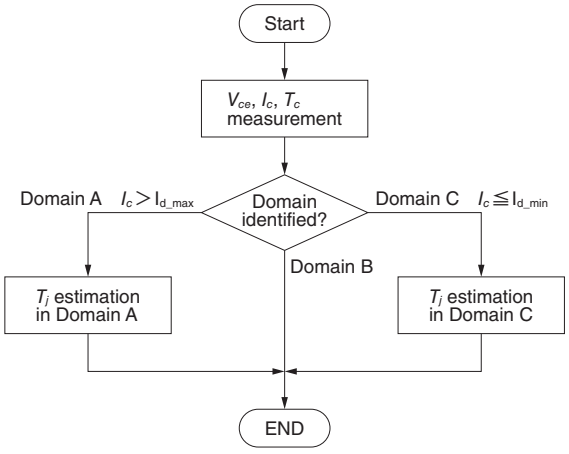

Fig. 3 Flowchart of T_j Estimation by V_{ce} Measurement Approach

This flowchart identified a domain based on the measured values of V_{ce} and I_c. The measured values of V_{ce} and I_c are compared with the V_{ce}-T_j characteristic of I_c acquired in advance to estimate the T_j value.

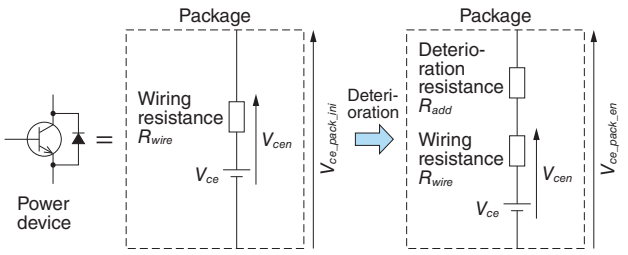

Fig. 4 Equivalent Circuit in Power Device Package

The equivalent circuit in the power device package is composed of wiring resistance and V_{ce}. When inverters are operated for a long time, deterioration occurs, and wiring resistance is increased. The increased component of resistance is defined as deterioration resistance.

3 T_j Estimation Compensation Method by Estimating Deteriorated Resistance of Power Devices

Fig. 4 shows an equivalent circuit in the power device package. The V_{ce}-T_j characteristics of I_c acquired in advance can be expressed by the equivalent circuit before deterioration shown on the left of Fig. 1. By the effect of T_j variation due to power device usage, a junction between a wire bonding and a chip is deteriorated. As a result of this deterioration, resistance is increased and this causes an increase in on-state voltage $V_{ce_pack_en}$ in consideration of a voltage drop. Consequently, the on-state voltage is given by Expression (1) with the use of on-state voltage V_{cen}, deteriorated resistance R_{add}, and I_c at the time of characteristic data acquisition before deterioration. In this case, however, the voltage drop component due to wiring resistance R_{wire} of wire bonding before deterioration is included in V_{cen}.

$$V_{ce_pack_en} = V_{cen}\,(T_j, I_c) + R_{add}\,I_c \cdots\cdots\cdots\cdots (1)$$

As suggested by Expression (1), a voltage drop is caused by the increased resistance due to deterioration and $V_{ce_pack_en}$ of V_{ce} measured value is increased. This is because the relationship changes between the measured data and the V_{ce}-T_j characteristic of I_c, thus generating an error in the T_j estimation value. For this reason, it is necessary to estimate the resistance value R_{add} that is increased to reduce this error. Since V_{cen} is changed by T_j and I_c, the rise of $V_{ce_pack_en}$ cannot be a marker to identify whether it is a sign of a rise of T_j or deterioration. Consequently, R_{add} is estimated using V_{ce} measured value of I_{c_cp} where V_{ce} is not changed by T_j. Measured values V_{ce} and $V_{ce_pack_ini}$ of I_{c_cp} before deterioration and the measured value $V_{ce_pack_en}$ of V_{ce} after deterioration can be given by Expressions (2) and (3) below.

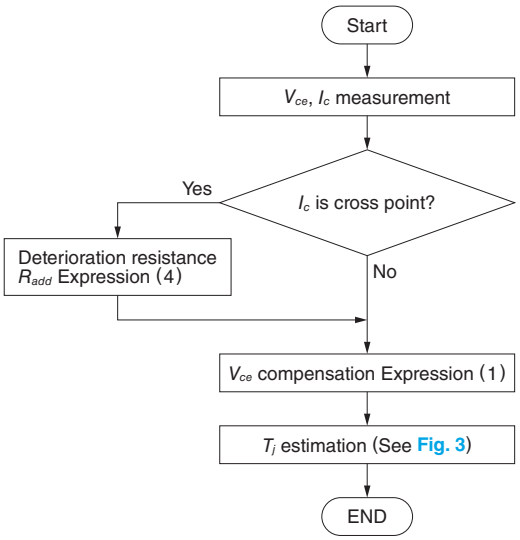

Fig. 5 Flowchart of Proposed Deterioration Resistance Estimation

Deterioration resistance is estimated based on the current value (cross point current) where V_{ce} is not changed by T_j.

$$V_{ce_pack_ini} = V_{cen}\,(I_{c_cp}) \cdots\cdots\cdots\cdots\cdots\cdots (2)$$
$$V_{ce_pack_en} = V_{cen}\,(I_{c_cp}) + R_{add}\,I_{c_cp} \cdots\cdots\cdots\cdots (3)$$

When Expression (3) is substituted into Expression (2) to get a solution for Value R_{add}, this R_{add} can be estimated.

$$R_{add} = \frac{V_{ce_pack_en} - V_{ce_pack_in}}{I_{c_cp}} \cdots\cdots\cdots\cdots\cdots (4)$$

When V_{cen} in Expression (1) is derived with the use of the estimated resistance value, estimation error of T_j due to deterioration can be compensated. Fig. 5 shows a flowchart of deterioration resistance estimation. The resistance value R_{add} due to deterioration is estimated at a timing when I_c becomes I_{c_cp}.

4 Experimental Results and Analysis Results

4.1 Test Conditions

To confirm the adequacy of our proposed methods, a testing using a three-phase inverter was carried out. Fig. 6 shows a configuration of the test circuit. Fig. 7 shows the testing system. Inductors are used as a load. A three-phase inverter is operated by current control so that a load current of 70 Arms is generated at an output frequency of 0.8 Hz. A water-cooled system is adopted to chill the heat sink. The chiller is controlled so that the

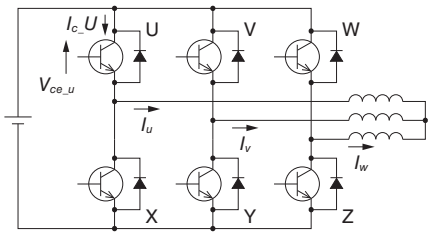

Fig. 6 Configuration of Test Circuit

This is a three-phase inverter system composed of three legs in Fig. 1. Inductors are used in the load block.

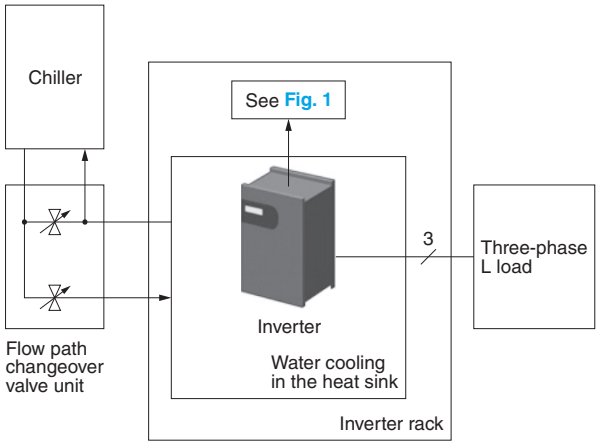

Fig. 7 Testing System

A water cooling system is adopted for the power device. The chiller controls the water temperature at 10℃. The flow path changeover valve unit controls to switch over the flow path of cooling water to increase the maximum value of T_j.

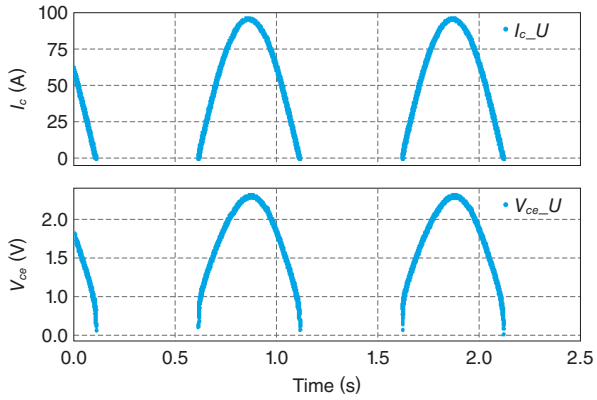

Fig. 8 Result of V_{ce}, I_c Measurements during Inverter Operation

Measured values of V_{ce} and I_c are changing in compliance with the AC waveforms of inverters. This fact implies that an approach by V_{ce} measurement is adequate.

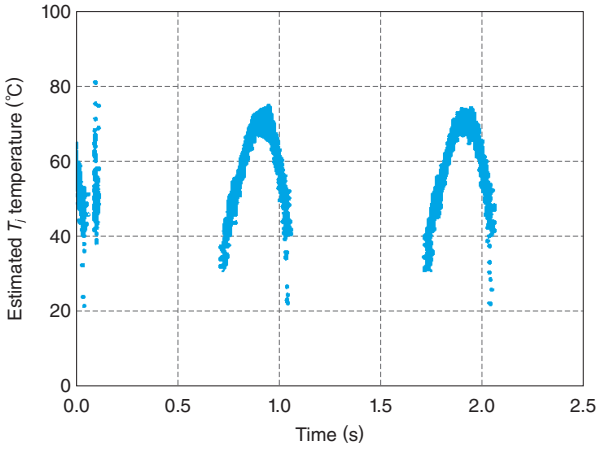

Fig. 9 Result of T_j Estimation during Inverter Operation

Value T_j can be estimated based on the measured values of V_{ce} and I_c.

cooling water temperature is kept at 10℃. Regarding the driving pattern for the inverter, it runs for 20 seconds and then stops for 5 seconds in a single operational cycle. During the stop period of the inverter, the flow path changeover valve unit is actuated to circulate the cooling water in the heat sink. While during the inverter driving period, the circulation of cooling water is suspended in the heat sink. In such a process, the maximum value of T_j can be increased, and the deterioration of the power device is accelerated.

4.2 Result of T_j Estimation

Fig. 8 shows the result of V_{ce}, I_c measurements during the inverter operation. In the power device, current flows only in the predetermined direction. For this reason, the current I_c_U flows only when the power device is in the ON state and the load current *Iu* is positive. It is recognized that the measured value of V_{ce}_U changes in conjunction with the waveform of the inverter current and, therefore, measurement of V_{ce} is adequate. Fig. 9 shows the result of T_j estimation based on the measured values of V_{ce} and I_c. During the ON state period of the power device, T_j can be estimated except for an area adjacent to the cross point. It is, however, important that the estimated T_j value is greatly changed in the vicinity of I_c zero. This is because the measured I_c value is close to Domain B and the temperature estimation accuracy is poor. If the range of Domain B is adjusted, sharp changes in T_j value may be controlled.

4.3 Result of T_j Estimation Compensation Considering Module Deterioration

Fig.10 shows the long-term trend of the Max. T_j value Estimation in a single cycle of the drive

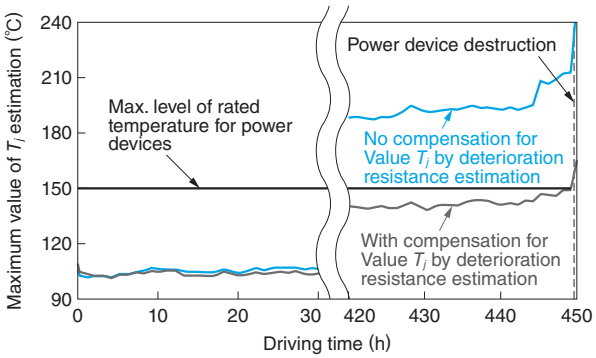

Fig. 10 **Long-Term Trend of Max. T_j Value Estimation in a Single Cycle of Drive Pattern**

As a result of application of this method, it has been known that the T_j value at the time of power device destruction coincides with the rated maximum temperature.

pattern. Based on the driving time, the T_j estimation value is raised and the power device is destroyed 450 hours thereafter. It is considered that the rise of T_j estimation value is caused by the deterioration around the junction between the chip and the wire bonding. Shortly after the start of inverter operation, the T_j estimation value is kept the same in both cases whether compensation for deterioration resistance estimation is provided or not provided. Nevertheless, compared with the case of compensation, the result of no compensation tends to show a higher estimation value of T_j as deterioration develops. In the case of no compensation, the estimated T_j value stays around 240℃ shortly before power device destruction. Such a temperature is over the rated maximum temperature of 150℃ for the power device used. In the case with compensation, however, the estimated temperature stays around 150℃ at the time of power device destruction.

Judging from these results, the excess of rated temperature is considered a cause of power device destruction and we concluded that our proposed method is adequate.

5 Postscript

We proposed a method to improve the T_j estimation accuracy by estimating power device deterioration as electrical resistance. In addition, we confirmed the effect of improving T_j estimation accuracy from our experiments using a three-phase inverter.

Going forward, we will promote further evaluation for the application of our approaches to our products.

・All product and company names mentioned in this paper are the trademarks and/or service marks of their respective owners.

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