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Applied Power Electronics Conference and Exposition (APEC), 2014 Twenty-Ninth Annual IEEE
Year: 2014
Pages: 2550 - 2555, DOI: 10.1109/APEC.2014.6803662

Monitoring IGBT's Health Condition via Junction Temperature Variations

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***Abstract*—Insulated gate bipolar transistor (IGBT) failures are a major issue in modern power electronics applications. Two most dominated failure mechanisms of IGBTs are solder fatigue and bond wire wear-out. This paper proposes a new method to online monitor an IGBT's health condition by using the instantaneous junction temperature variation between present and the first operating cycles of the IGBT with the same operating current. In this work, the instantaneous junction temperature of an IGBT is estimated from a thermal network model. The proposed method is validated by experimental results obtained from accelerated aging tests for IGBTs.**

I. INTRODUCTION

Power semiconductor devices are playing a more and more important role in modern industry. Among various power devices, the insulated gate bipolar transistors (IGBTs) are dominant in the medium- and high-power applications because of their high input impedances and low on-state resistances. During the last two decades, the performance of IGBTs has been greatly improved. However, failures of IGBT modules are still one of the key reliability issues in modern power electronic systems [1]. Two major failure mechanisms observed in the IGBTs with the traditional direct bond copper (DBC) structure (see Fig. 1) are solder fatigue and bond wire wear-out. These failure mechanisms are caused by mismatch of the coefficients of thermal expansion (CTE) of different materials in the chip package [2]. Particularly, bond wire damage is the root cause of most device failures, even though solder fatigue arises firstly in specific operating conditions [3].

It is believed that the development of these major failures will change the electrical and thermal behaviors of IGBTs. Therefore, if the variations of some electrical and thermal parameters of IGBTs can be monitored online accurately, the condition of the devices can be evaluated online and maintenance or replacement can be scheduled before a serious deterioration or breakdown occurs. It has been proposed to use the collector-emitter saturation voltage $V_{CE(sat)}$, on-state resistance R_{ON}, gate-emitter threshold gate voltage $V_{GE(th)}$, and internal thermal resistance R_{th} to monitor the degradation of IGBTs [4], [5]. However, it is difficult or not cost-effective to measure these parameters accurately in real time for online monitoring of the health condition of IGBTs. For example, the $V_{CE(sat)}$ of an IGBT with a rated current of 1000 A has only approximately a 30 mV variation between healthy and degraded states. Accurately measuring $V_{CE(sat)}$ requires an additional complex circuit to generate a specific current, during which the IGBT has to be stopped [6]-[8].

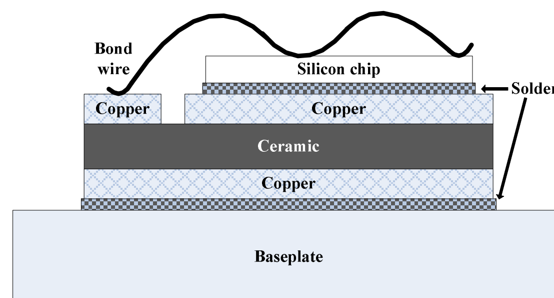

Fig. 1. The DBC structure of an IGBT.

This paper proposes a new method of using the junction temperature variation for online monitoring of the health condition of IGBTs during their entire lifetime, where the junction temperature is estimated by using a thermal network model.

II. FUNDAMENTAL BACKGROUND

The junction temperature (T_J) is an important parameter reflecting the operating state of power devices, especially IGBTs. The value of T_J is affected by both solder fatigue and bond wire wear-out. However, because the junctions of modern IGBTs are not accessible in practice, it is not feasible to acquire the real-time information of T_J directly by using sensors. Currently, there are mainly three methods for monitoring the junction temperature of IGBTs: optical method, electrical method, and thermal model method [9]. The optical method uses expensive equipment, including infrared radiation (IR) sensors, optical fibers, IR microscope and an IR camera to measure T_J directly. The other two

This work was supported in part by a Layman Award and a College of Engineering Edgerton Innovation Award of the University of Nebraska−Lincoln.

978-1-4799-2325-0/14/$31.00 ©2014 IEEE

methods are economical to detect junction temperature and are briefly described in the next two subsections.

A. Estimating T_J Using a Thermal Model

Thermal models are commonly used to interpret the thermal behavior of power devices. The most popular thermal model is the equivalent resistance-capacitance (RC) ladder network owing to its simplicity and computational efficiency. In this work, a Cauer-type thermal network consisting of seven pairs of thermal RCs is used, as shown in Fig. 2. Each group of R and C represents different layers of the thermal conduction path, from the heat source to the base plate in the DBC structure shown in Fig. 1. The values of the thermal RCs can be calculated by using the material and geometry properties, including the thickness, effective cross section area, thermal conductivity, specific heat capacity, mass density of each layer of the device. The input current source of the equivalent RC network represents the instantaneous power dissipated in the semiconductor chip. This connects the thermal model with the electrical behavior of an IGBT. The junction temperature is the node voltage of the input current source; while the case temperature T_C represents the reference node voltage of the network. The relation between the T_J and T_C meets the following equation.

$$T_J = T_C + P_{diss} \cdot Z_{th(JC)} \quad (1)$$

where P_{diss} is the instantaneous power dissipated in the IGBT and connected with the collector-emitter voltage V_{CE} and conduction current I_C, and $Z_{th(JC)}$ is the equivalent thermal impedance between the junction and case of the IGBT as described in Fig. 2.

B. Measuring T_J via Thermo-Sensitive Electrical Parameters

Currently, using thermo-sensitive electrical parameters (TSEPs) is the only way to carry out fast measurement of T_J for packaged power devices with a time interval shorter than 100 μs [9]. The $V_{CE(sat)}$ is a commonly used TSEP for IGBTs. The $V_{CE(sat)}$ can be used to estimate T_J effectively if it can be measured accurately. In this method, a direct-current (DC) source is used to supply a small continuous collector current, which is sufficient to raise the collector-emitter voltage above the saturation value. The $V_{CE(sat)}$ of the IGBT is measured at different ambient temperatures, which are equal to the junction temperatures when the IGBT is placed in a constant-temperature test chamber for a long time. Then the relationship between $V_{CE(sat)}$ and T_J can be obtained by curve fitting. This curve is a good reference to verify the accuracy of T_J estimated from the thermal model. However, it is difficult to directly use $V_{CE(sat)}$ as a parameter for online condition monitoring of IGBTs in industrial applications due to the reasons stated in Section I. Another problem is that $V_{CE(sat)}$ will change its thermal property from a positive temperature coefficient to a negative one when the operating current decreases below a certain value [9].

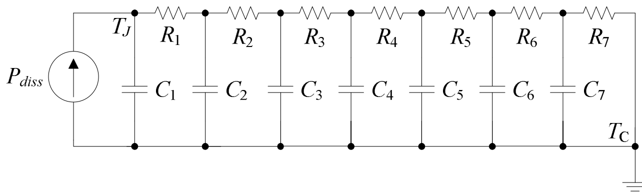

Fig. 2. Schematic of an equivalent RC ladder network for IGBTs.

III. PROPOSED METHOD FOR MONITORING THE HEALTH CONDITION OF IGBTS

According to (1), the value of T_J depends on T_C, P_{diss} (which depends on V_{CE} and I_C), and $Z_{th(JC)}$. Therefore, the variation of T_J (i.e., ΔT_J) of the current operating cycle t with respect to a previous operating cycle t_0 of an IGBT can be defined as a function below.

$$\Delta T_J(t) = T_J(V_{CE}(t), Z_{th(JC)}(t), T_C(t), I_C(t)) - T_J(V_{CE}(t_0), Z_{th(JC)}(t_0), T_C(t_0), I_C(t_0)) \quad (2)$$

The values of V_{CE} and $Z_{th(JC)}$ usually increase during an IGBTs' aging process. For example, the two primary IGBTs' failure mechanisms, bond wire wear-out and solder fatigue, will result in the increase of $V_{CE(sat)}$ and R_{th}, respectively. Therefore, the value of ΔT_J obtained at the same operating current condition (i.e., $I_C(t) = I_C(t_0)$) during an IGBT's operation can be used as an indicator to evaluate the health

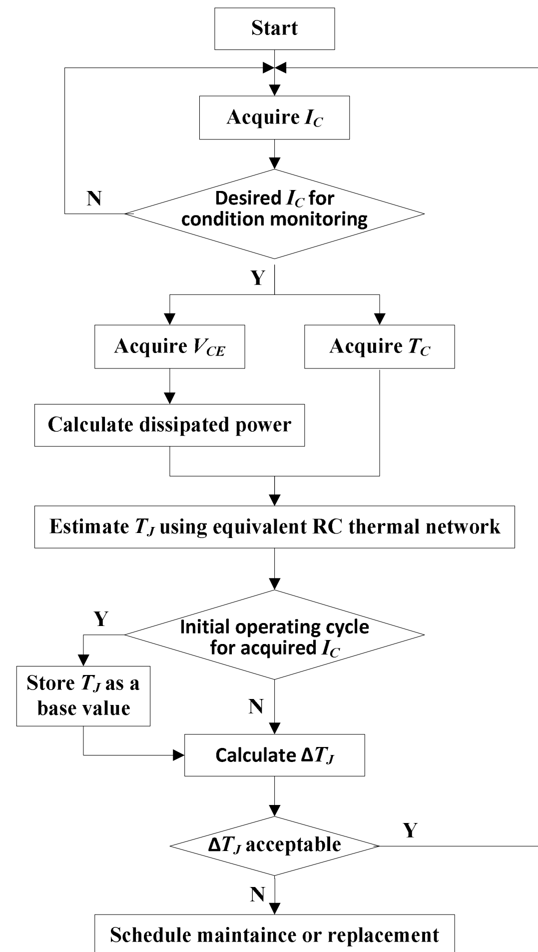

Fig. 3. Flowchart of the proposed method for monitoring the health condition of IGBTs.

condition of the IGBT during the entire lifetime.

This section presents a new method of using the ΔT_J defined in (2) for online evaluation of the health condition for an IGBT, where the values of T_J are instantaneous and obtained at the same operating current condition. The flow chart of the proposed method is shown in Fig. 3, where T_J is estimated by (1) using the equivalent RC thermal network; the dissipated power including conduction and switching power losses can be calculated by using electrical quantities, such as I_C and V_{CE}; the thermal resistances and capacitances between the junction and case are calculated from the material and geometry properties of the IGBT [10]; and T_C is acquired by applying a thermal sensor at the bottom surface of the baseplate under the IGBT chips to improve the accuracy of T_J estimation. Moreover, T_C can be used to evaluate the variation of R_{th} to reflect IGBT's health condition affected by the solder fatigue [6]. Then, T_J can be calculated from the equivalent RC thermal network. The value of ΔT_J with respect to the first operating cycle (i.e., the device is new) in the same operating current condition is then recorded. Although the value of T_J estimated by the equivalent RC thermal network may have errors, the trend of ΔT_J variation as the number of operating cycles increases will reflect the real situation of the IGBT's aging. In practice, the value of ΔT_J can be monitored from time to time at the same operating current conditions according to the fatigue state of the IGBT. Compared with the methods in [7], [8], the proposed method does not need any additional power supply, DSP, or isolation and, therefore, is more feasible with less cost.

IV. Validation of The Proposed Method

In order to validate the proposed method, TSEP test and pulsed-current tests, and accelerated aging test are performed for a Mitsubishi CM400-DU IGBT, which have the maximum operating junction temperature of 150 °C specified by the datasheet.

A. Experimental Setup

The experimental setup for the IGBT tests is shown in Fig. 4. The setup consists of an oscilloscope for transient electrical signal acquisition, such as I_C and V_{CE}, a DC source for generating gate signals, a programmable 600 A DC source for providing continuous and pulsed operating currents, a temperature test chamber for providing a stable ambient temperature, a National Instruments (NI) data acquisition system for acquiring the case temperature T_C from a thermocouple, and a control system developed in LabVIEW™ operating in a laboratory computer for controlling the testing process. The case temperature is measured on the surface of the bottom baseplate located on the package directly under the chip by using a thermocouple with a high accuracy of ±0.005 °C.

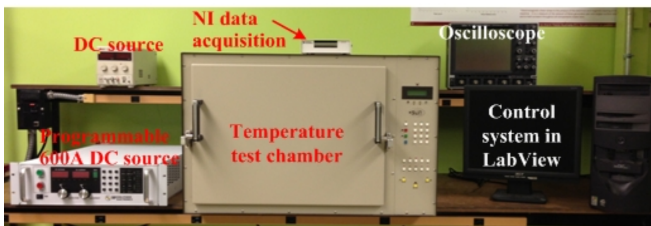

Fig. 4. Experimental setup for IGBT tests.

B. TSEP Test

The TSEP test is first performed to obtain the real-time relationship between T_J and $V_{CE(sat)}$. The test circuit is shown in Fig. 5, and the current applied to the test IGBT is 1 A. The use of such a low current limits self-heating to a negligible value and improves the accuracy of the measurement of T_J. The result is shown in Fig. 6. The curve provides the value of T_J, which is called the measured T_J, from the measured $V_{CE(sat)}$ at 1 A rating. The measured T_J will be used as a reference to compare with T_J estimated from the thermal model used in other tests described below.

C. Pulsed-Current Tests

Pulsed-current tests are performed during different stages of the accelerated aging test of the IGBT to emulate the operating cycles in real-world applications to acquire the measured and estimated T_J. The pulsed-currents are applied between the collector and emitter of the IGBT. In each test cycle four high-current pulses with the same amplitude of hundreds of amperes are applied. Each of the first three high-current pulses lasts for 1 second with a 50% duty ratio. The ON-state of the last high-current pulse lasts for 0.5 second and then the current drops to 1 A for 3 seconds before becoming zero. The $V_{CE(sat)}$ measured at the moment when the

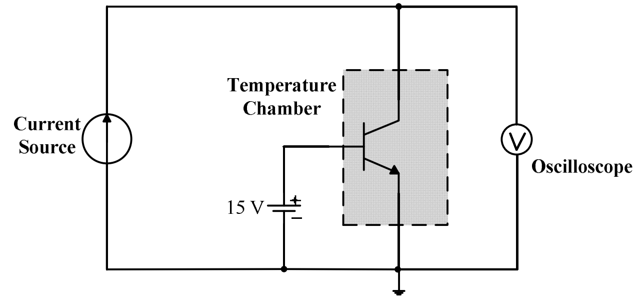

Fig. 5. TSEP test circuit.

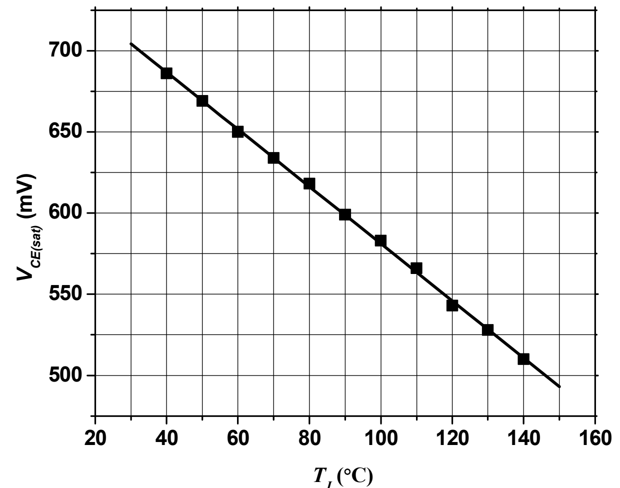

Fig. 6. Measured $V_{CE(sat)}$ as a function of T_J for the test IGBT.

1 A current is applied is used to acquire the measured T_J from the curve in Fig. 6. In order to investigate the effect of the operating current (i.e., power level) on the variation of T_J, high-current pulses with three different amplitudes of 200, 300 and 400 A are applied sequentially, while all other test conditions are the same. A sufficient time interval is applied between two consecutive cycles of high-current pulses with different amplitudes to ensure T_J of the IGBT drops back to room temperature, which means the initial T_J is same for every pulsed-current test. The values of V_{CE} and case temperature T_C are also recorded during the entire pulsed-current test to calculate the instantaneous power dissipated in the IGBT and estimate T_J by using the equivalent RC thermal network.

D. Accelerated Aging Test

Various factors, such as failure modes, failure mechanisms, and their effects [11], must be considered when designing the accelerated aging test. The random failure modes of IGBTs, e.g., short circuits, increased leakage current, cosmic ray damage, and loss of gate control, are not in the scope of this work. This work focuses on the failure mechanisms of IGBTs caused by module aging during long-term power cycles. Therefore, the IGBT is tested in a controlled environment (i.e., controlled temperature and current) with thermal-electrical stresses to monitor it degradation process using the proposed method. The aging process of the test IGBT is accelerated by removing its heat sink, which reduces the heat transfer capability (*i.e.*, increases the thermal stress) of the IGBT [12].

In the accelerated aging test, a 15 V constant voltage is applied to the gate of the IGBT, and aging power cycles are applied to the IGBT continuously. Each power cycle lasts for 10 seconds, which consists of a 400 A ON-state for 2.5 seconds, following by a 1 A ON-state for 1 second and then a 6.5 seconds OFF-state, where the conduction current is supplied by the programmable DC source and applied through the collector-emitter terminals. The 400 A current generates power dissipation in the IGBT, which heats the chip. The following 1 A current is used to acquire the junction temperature T_J according to the TSEP method, which helps control T_J close to the maximum value allowed during the test.

This test design does not use any gate control circuit, which prevents the influence of unexpected gate control failures on the testing results. In the whole aging process of the IGBT, it takes approximately 20,000 cycles before the IGBT enters a fatigue stage [6] and approximately 40,000 cycles when the $V_{CE(sat)}$ acquired during the pulsed-current test cycles has increased 15% over its nominal value. In this case the IGBT is considered to be in severe degradation [13]. After 50,000 cycles, the IGBTs are close to failure when the measured $V_{CE(sat)}$ has increased 20% over its nominal value. Therefore, the first 20,000 cycles are called "healthy stage", between 20,000 and 40,000 cycles are called "fatigue stage", and from 40,000 cycles until 50,000 cycles are called "dangerous stage."

The accelerated aging test is stopped temporarily about every 10,000 cycles to perform the pulsed-current test to obtain the measured and estimated values of T_J for the test IGBT in real time.

E. Results of ΔT_J Variation during the IGBT Aging Process

The initial T_J measured or estimated before the accelerated aging test is used as a base value. The variation of T_J (i.e., ΔT_J) measured or estimated during different stages of the following aging test with respect to its corresponding base value is acquired. Fig. 7 compares the curve of ΔT_J estimated from the thermal network vs. aging power cycle number with that obtained from the measured $V_{CE(sat)}$ for three different operating currents. Both the estimated and measured values of ΔT_J are obtained by using the measurements taken at the moment when the 1 A current is applied during each pulsed-current test cycle. The same variation trend is observed in all the cases, i.e., the value of ΔT_J increases monotonically with the number of aging power cycles, although the errors between the estimated and measured ΔT_J curves are non-negligible. The estimated value of ΔT_J in the 400 A operating current scenario increases dramatically, about 20 °C at the end of the IGBT's fatigue. The same tendency is shown for the cases of 200 A and 300 A operating currents. Therefore, the increase of ΔT_J with respect to the first aging power cycle is a good indicator for online evaluation of the health condition of IGBTs.

The percentages of ΔT_J measured or estimated during different stages of the IGBT aging process with respect to their corresponding base values are summarized in Table I for the three different operating current scenarios. The data in Table I show that both the measured and estimated values of ΔT_J increase along with the IGBT's fatigue process and the operating current. When the IGBT is in the healthy stage, the percentage of ΔT_J is small in all scenarios, the largest one being less than 1.26%. When the fatigue stage starts, from around the 20,000th aging power cycle, the percentage of the estimated ΔT_J has an apparent increase, such as 5.18% in the 400 A operating current scenario, which is much larger than that of 1.26% estimated at the 10,000th aging power cycle during the healthy stage. During the fatigue stage, both the measured and estimated ΔT_J continuously increase, and a remarkable change is observed when the IGBT enters the dangerous stage. At this point in the device's lifetime the

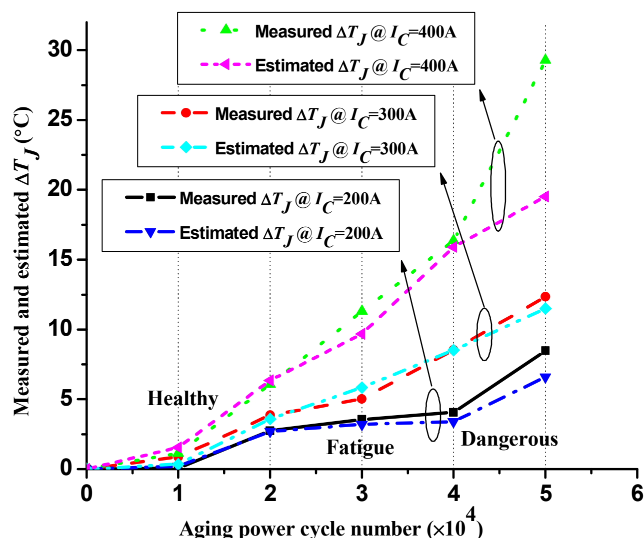

Fig. 7. Comparison between measured and estimated ΔT_J during aging.

TABLE I. PERCENTAGES OF MEASURED AND ESTIMATED ΔT_J WITH RESPECT TO CORRESPONDING BASE VALUES FOR DIFFERENT OPERATING CURRENT SCENARIOS DURING AGING PROCESS.

Aging Power Cycles	Percentage of Measured ΔT_J (%)			Percentage of Estimated ΔT_J (%)		
	I_c = 200A, Base value 65.75°C	I_c = 300A, Base value 90.25°C	I_c = 400A, Base value 127°C	I_c = 200A, Base value 63.7°C	I_c = 300A, Base value 91.79°C	I_c = 400A, Base value 122.45°C
10,000	0.11	0.95	0.88	0.31	0.37	1.26
20,000	4.18	4.27	4.76	4.24	3.90	5.18
30,000	5.40	5.56	8.90	5.02	6.35	7.91
40,000	6.16	9.45	12.87	5.34	9.27	12.98
50,000	12.90	13.67	23.06	10.36	12.52	15.93

percentages of the estimated ΔT_J in the 400 A operating current scenario are 12.98% by the 40,000th power cycle and 15.93% at the 50,000th power cycle, which are 2 to 3 times the value at the beginning of the fatigue stage. The same tendency is observed in the 200 A and 300 A operating current scenarios. When the IGBT is close to failure, that is, at the 50,000th power cycle, the percentages of the estimated ΔT_J are in the range of 10–16% for the three operating current scenarios.

F. IGBT Remaing Useful Lfie Prediction

The estimated T_J and ΔT_J can be used to predict the remaining useful life of the IGBT module according to the Coffin-Manson law [14], [15] expressed as follows.

$$N_f = A \cdot f^{-a} \cdot \Delta T^{-b} \cdot e^{\frac{Ea}{k_B \cdot Tm}} \tag{3}$$

where N_f is the remaining useful life of the IGBT, which is represented by the number of power cycles to fail; A, a and b are coefficients; f is the frequency of the power cycle; ΔT is the temperature variation during a power cycle; E_a is the activation energy, which is a constant related to the chemical property of the material; k_B is the Boltzman's constant; and T_m is the mean value of T_J during a power cycle. At the same operating current condition, $\Delta T(t) = \Delta T_J(t) + \Delta T(t_0)$, where $\Delta T_J(t)$ is the variation of the junction temperature in the present power cycle t with respect to a previous power cycle t_0. Therefore, (3) can reflect the reduction of the remaining useful life of the IGBT when the junction temperature variation ΔT_J is taken into account.

The curves of the predicted remaining useful life N_f of the IGBT module vs. aging power cycle number are plotted in Fig. 8. The three curves N_{fm}, N_{fe} and N_{fed} for each operating current condition represent the values of N_f predicted from (3) by using the measured T_J, the T_J estimated by the thermal network, and the T_J estimated by using the V_{CE} from the datasheet, respectively. When a constant V_{CE} from the datasheet is used, the value of N_{fed} is constant during the aging process and is close to N_{fm} and N_{fe} only before the first 10,000 aging power cycles. This indicates that the T_J estimated by using the datasheet data cannot reflect the aging status of the IGBT module. It is observed that the curves of N_{fm} and N_{fe} have the same variation trend, that is, the predicted remaining useful life decreases with the aging

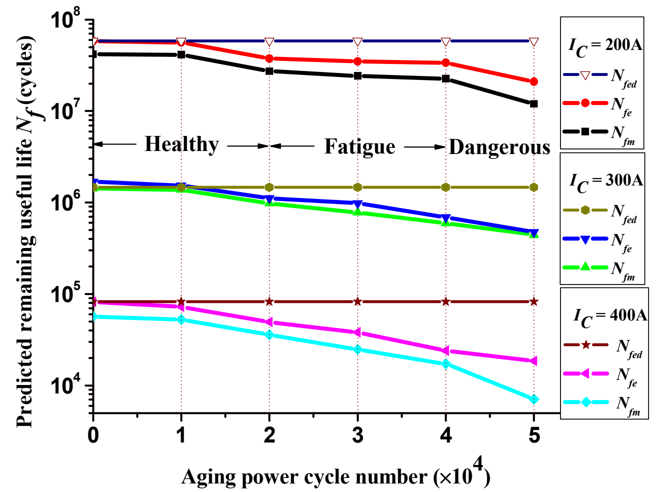

Fig. 8. Comparison of predicted remaining useful life N_f among measured T_J, estimated T_J by thermal network and estimated T_J by datasheet during aging.

process. The predicted N_{fe} at the 400 A condition using the T_J estimated by the thermal network accurately reflects the actual remaining useful life of the IGBT. The difference of N_{fm} and N_{fe} can be eliminated or reduced by taking into account the variations of the thermal model parameters due to the aging of the IGBT. This issue will be investigated in the future work.

V. CONCLUSION

This paper has proposed a new method of using the variation of T_J at a certain operating current condition to monitor the health condition of an IGBT module while online, where the value of T_J can be estimated from a computationally-efficient thermal network model of the IGBT module. The proposed method offers an effective means for online condition monitoring of IGBTs over the entire lifetime and predicting the remaining useful life of the devices. Experimental results have demonstrated the effectiveness of the proposed method.

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