Review of IGBT Junction Temperature Extraction and Estimation Methods

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Abstract. IGBT is widely used in photovoltaic power generation, aerospace, electric vehicles, ships and other power electronic equipment due to its advantages such as simple driving, high power level, low power consumption, and good thermal stability. As the core component of power electronic equipment, IGBT has always been a major concern for manufacturers and users. Excessive temperature is considered to be the main cause of IGBT failure. In order to meet the needs of high reliability in these applications, it is important to manage and control the temperature of the IGBT. Therefore, how to estimate or measure the junction temperature of IGBT is the focus of research on IGBT reliability. This article introduces several published methods for measuring junction temperature, focuses on the Temperature sensitive electrical parameters (TSEP) method and thermal resistance network method, and conducts experimental verification through the IGBT double-pulse test platform. Trying to provide help for future junction temperature detection work.

1. Introduction
In the past few decades, due to the rapid development of power electronics technology, the power density of power electronics equipment has increased significantly [1-2]. The working environment and working conditions that IGBTs confront are becoming increasingly complex. In system applications, the factors that affect the life of an IGBT module are electrical load and environmental conditions (temperature, humidity, dust, cosmic rays, mechanical vibration, etc.). Studies have shown that about 60% of IGBT failures are caused by temperature, and the probability of failure of IGBT doubles every time the temperature rises by 10 °C [3]. The aging failure of IGBT power module is closely related to health state change. If the failure mechanism is different, the state change of the module will also be different [4]. Using the state parameters of the IGBT power module can monitor the state of the module, which is a key link for subsequent state assessment and reliability analysis. Because IGBT modules are composed of multiple materials, these materials have different coefficients of thermal expansion (CTE). Temperature fluctuations caused by IGBT operation will generate thermomechanical stress in adjacent layers. This kind of thermomechanical stress is the root cause of material aging and failure in IGBT modules. Typical failure points include: bonding wire root, chip metallization layer, and solder layer between DCB and chip or copper substrate. Therefore, in order to improve the reliability of power electronic equipment, temperature management and control of IGBT is very important. At present, the methods for generally evaluating the junction temperature include
optical measurement method, physical contact method, thermal electrical parameter method and thermal resistance model prediction method [5]. This article focuses on the TSEP method and thermal resistance network method, and analyzes the advantages and disadvantages of different thermistor parameters in the fields of feasibility, resolution, etc. through simulation experiments.

2. Temperature Sensitive Electrical Parameters (TSEP)
Some IGBT operating electrical parameters have a linear relationship with junction temperature. Such electrical parameters are called temperature sensitive electrical parameters (TSEP). The method of measuring the IGBT junction temperature by using the mapping relationship between the Temperature sensitive electrical parameters and the junction temperature is called the thermally sensitive electrical parameter method. Compared with infrared measurement, this method can measure the junction temperature without damaging the IGBT package structure [6].

2.1. Static Parameters

2.1.1. On-State Voltage at Low Current ($V_{ce(on)low}$). The most commonly used temperature sensitive electrical parameter is the on-state saturation voltage at a low current, which essentially reflects the temperature sensitive characteristics of the PN junction on-voltage drop [7]. When the collector current is less than a certain value, the on-state saturation voltage drop is negatively related to the junction temperature [8]. As shown in figure 1, a constant current of 1-100 mA (or 1/1000 of the rated current) is injected into the IGBT collector. According to the measurement, the on-state saturation voltage drop of the IGBT collector and emitter is mapped to the junction temperature [9]. In silicon devices, this parameter usually exhibits a negative temperature dependence of about -2 mV/°C [10]. In actual working conditions, this parameter can only be measured when the IGBT module is in an off-work state. Therefore, this parameter is not suitable for online detection.

![Figure 1. Tj-Vces at low current.](image)

2.1.2. On-State Voltage at High Current ($V_{ce(on)high}$). Using on-state voltage at low current method requires an additional constant current source generating circuit [11]. On-state voltage at high current method measures the collector current at on-line condition, and uses an offline database to calculate the junction temperature [12]. As shown in figure 2, 1.2 kV/400A IGBT module work at a specific collector current point, the IGBT on-state saturation voltage drop will show the boundary between the positive temperature coefficient and the negative temperature coefficient [13]: When the electrode current is less than this current, the saturation voltage drop is negatively related to the junction temperature. When the collector current is greater than this current, the saturation voltage drop is positively related to the junction temperature. However, when the collector current is near the boundary, the saturation voltage drop is not sensitive to the junction temperature. This method may cause detection failure near the current point. Because the junction area of the positive and negative
temperature coefficients is usually within the rated operating current range, to extract the junction temperature using the large current injection method, it is necessary to detect the detection blind area in advance and establish a corresponding avoidance strategy in actual operation [14]. The circuits described in Refs. [9, 15] can measure the saturation voltage drop. Ref. [16] compensated for the voltage drop on the interconnection parameters of the IGBT, and improved the accuracy of measuring the junction temperature by the large current injection method.

![I-V characteristics of IGBT modules (1.2 kV/400A) at different junction temperatures.](image)

**Figure 2.** I-V characteristics of IGBT modules (1.2 kV/400A) at different junction temperatures.

2.1.3. **Short-Circuit Current (Isc).** Short-circuit current method is used as a thermally sensitive electrical parameter and is negatively related to the junction temperature [17]. Ref. [18] proposed a method for measuring junction temperature using the negative temperature characteristic of short-circuit current (-0.345 A/°C). This method only tests the output, and it needs to ensure that the short circuit can be opened in time so that the stress will not exceed the capacity of the device.

2.2. **Dynamic Parameters**

It mainly studies the working parameters during the switching transient, such as switching delay time, switching time, switching voltage and current change rate, switching loss, etc.

2.2.1. **Turn-off Delay Time (t\text{doff}).** As shown in figure 3, when the drive voltage \(V_{ge}\) drops by 10% and the collector voltage \(V_{ce}\) rises to 90% of the bus voltage, this time interval is the turn-off delay time \(t_{doff}\) [13]. Its temperature-sensitive characteristic is actually the temperature-sensitive characteristic of the gate voltage during the Miller plateau time [19].

![Definition of Turn-off delay time](image)

**Figure 3.** Definition of Turn-off delay time [20].

As shown in figure 4, when the bus voltage and load current are the same, an increase in junction
temperature will cause an increase in the IGBT turn-off delay \((1-2 \text{ ns/}°\text{C})\) \[11\]. Ref. \[21\] established a junction temperature detection model based on the turn-on and turn-off delay time considering the influence of voltage and current. Reference \[22\] designed a circuit to convert the starting and ending moments of the Miller platform into pulse output. Ref. \[23\] studied a time-to-digital converter (TDC) based on FPGA. It is used for measuring Miller delay time. These signs indicate that recent attempts by researchers to apply this relationship to achieve online detection of junction temperature have made some progress. But the turn-off delay time is also affected by the collector current. This method needs to compensate the current.

**Figure 4.** Relation between turn-off delay time and junction temperature (load current \(i_L = 40\text{A}\)).

### 2.2.2. Maximum Change Rate of Turn-off Current

The rate of change of IGBT turn-off current increases approximately linearly with increasing temperature \[24\]. Ref. \[25\] proposed a method based on parasitic inductance to extract the maximum change rate of the off current. As shown in figure 5, this method converts the rate of change of current into the induced voltage on the parasitic inductance \(V_{E_{\text{max}}}\) that can be observed (its sensitivity is about 25 mV/°C), but the voltage spike signal is sensitive to noise.

**Figure 5.** With change of junction temperature and current density, (a)(dIc/dt) max fitted curve and (b) Induction voltage spike fitting curve.

### 2.2.3. Turn-off Loss (Eoff)

IGBT turn-off loss is directly related to temperature. Qiu \[26\] verified its positive correlation in the simulation condition platform. Figure 6 shows the prediction effect of the method in a certain 1200V 75A module. The method has good linearity and sensitivity. Only by collecting the voltage and current signals of the collector, the junction temperature information can be extracted online.
2.2.4. Turn-on Parameters. Turn-on parameters such as turn-on time and turn-on delay have small numerical values, low temperature sensitivity, and other reasons. Few researchers have used it as a thermoelectric parameter to predict junction temperature. Zhang [27] has found that the turn-on time is directly related to the oxygen degradation of the IGBT gate.

3. Thermal Resistance Model Prediction

3.1. Finite Element Method

Some scholars input IGBT parameters into finite element analysis software such as ANSYS, Icepak, and Flotherm for modeling and temperature field analysis. This method is usually based on the 7-layer structure of the IGBT module, and it is necessary to input the thermal conductivity parameters and dimensions of each layer of materials, the power of the IGBT and the diode, the convection coefficient, and the ambient temperature. Software such as ANSYS can be used to simulate the heating of each layer of the IGBT. The simulation results are shown in figure 7. Fang [28] and others used ANSYS to simulate the IGBT thermal distribution field and compared with the results of the infrared imager. The error was within the allowable error range of 0.075%. Xiao [29] studied the effect of voids on the thermal stability of the device through finite element simulation. Wang [30] used Icepack for the heat dissipation design of the drive controller, compared the results of IGBT junction temperature simulation and theoretical calculation, and obtained a calculation error of less than 2%. Zhang [31] calculated the maximum junction temperature and maximum thermal stress of the IGBT module package using ANSYS as the platform. Li [32] used Flotherm to establish high-quality simulation models of IGBT components and complete heat sinks, and calculated the flow velocity distribution of the radiator fins and water-cooled pipes, and the temperatures of the IGBT components and heat sinks by software simulation calculation distributed.

The disadvantage of this method is that it requires detailed equipment material properties, and the analytical solution is mathematically complex and requires a lot of calculation time. Therefore, it is difficult to apply in actual working conditions.

Figure 6. Eoff-Tj-Ic 3D prediction diagram.

Figure 7. ANSYS simulation effect diagram [28].
3.2. Electrothermal Coupling Model
The principle of the IGBT thermal network model is to compare the thermal characteristics of the device to electrical characteristics. The loss is equivalent to the current source input, the thermal resistance is equivalent to the resistance, the thermal capacity is equivalent to the capacitance, and the node voltage is equivalent to the temperature of each layer. The heat conduction process inside the device is likened to the transfer of power in the circuit [33]. The thermal characteristics of IGBTs can be represented by equivalent RC thermal network model circuits. You can use MATLAB simulink, saber, multisim, POSIM and other simulation tools to build an equivalent thermal network model of the device.

3.2.1. Selection of Electric Heating Network and Determination of Thermal Resistance Parameters.
Common thermal resistance networks include the fourth-order Foster model [34] and the seventh-order Cauer model [35]. The Cauer thermal network is calculated based on the actual impedance values of the materials of each layer of the IGBT module, and is generally used for the physical modeling and analysis of the module. The Foster thermal network is a centralized equivalent of the module’s heat transfer process, and the parameters are easy to obtain. Generally, the fourth-order RC thermal network parameters of the IGBT module are given by device manufacturers, and the thermal network value provided by the data-sheet is used to quickly establish a thermal network model. Chen [36] proposed a thermal resistance network considering junction surface thermal resistance and diffusion thermal resistance as shown in figure 8 based on the 7th-order Cauer model. Compared with the traditional heat transfer model, only the thermal resistance of the material with constant thermal conductivity is considered. With higher accuracy, Li [37] and others established a thermal network model considering the influence of chip thermal coupling. When the distance is increased to 8 mm, the thermal resistance between the chips is almost zero. In this article, the IGBT module parallel chip spacing is 10 mm. Half-bridge IGBT and diode chips simplify the model.

![Figure 8. Thermal network model with diffusion thermal resistance added [36].](image)

The basic idea of the experimental method for extracting thermal resistance is to place the IGBT module in a constant temperature environment and heat the module to a stable state by constant power. Then remove the heating source and allow the module to cool to a stable temperature. Record the temperature change during the cooling process, and extract the thermal resistance and heat capacity parameters of the n-order thermal resistance network from equation (1) by using the cooling curve.

\[
Z_{th} = \sum_{i=1}^{n} R_i [1 - \exp(-t/\tau)]
\] (1)

3.2.2. IGBT Module Loss Calculation. IGBT module loss includes IGBT loss and anti-parallel diode FWD loss. IGBT losses consist of resistance losses, on-state losses, turn-on losses, and turn-off losses. Diode loss includes conduction loss, resistance loss, and reverse recovery loss. Resistance losses are often neglected compared to other losses. IGBT on-state loss and modulation strategy under different operating conditions, and switching loss are also strongly related to temperature [38]. Therefore, the
accurate calculation of real-time losses of IGBT modules is the key and difficult point in the thermal resistance network method.

Yang [39] and others directly obtained the loss by multiplying the RMS value of the voltage and current of the oscilloscope and power analyzer. Yin [40] obtained the on-state loss for the operation logic of the 6 units MMC submodule, and used the curve of IGBT switching loss, diode reverse recovery loss and junction temperature in the data sheet to obtain the total loss. The maximum error between calculated loss and actual loss is less than 3%. Li [41] combined the actual operating characteristics of doubly-fed wind power converters to establish a steady state model of IGBT module power loss and junction temperature at the machine and grid sides. Li [42] analyzed the power consumption of the inverter circuit IGBT and chopper IGBT based on the motor characteristics and control strategy. Yao [43] added a temperature influence factor to the on-state loss calculation of the wind power converter. The switching loss also increased the temperature influence factor based on the data sheet, thereby improving the accuracy. Li [44] used an iterative algorithm based on the thermoelectric coupling model to analyze the junction temperature calculation method of the switching cycle and iteratively calculate the junction temperature of the fundamental frequency cycle. Ding [45] and others used Infineon’s IPOSIM software to calculate the loss of the two-level inverter, and used the thermal resistance network to iteratively calculate the junction temperature.

4. Simulation Comparison Experiment

In order to compare the temperature characteristics and sensitivity of different thermal electrical parameters laterally, a certain 1200V/75A IGBT device is taken as an example, and a simulation test circuit of the module is established on the Saber simulation platform. The simulation test circuit is shown in figure 9. The upper tube Q1 is locked. Two pulses are applied to Q2. The first pulse on-time determines the magnitude of the current flowing through the collector of Q2. The falling edge of the first pulse is used to capture the Q2 shutdown process. The rising edge captures the turn-on of Q2. In this way, extraction of static parameters and extraction of dynamic parameters under high current are realized. It can also be achieved by connecting a small current source in parallel with Q2 to achieve static parameter extraction at low current. Compare on-state voltage at low current(10mA), on-state voltage at high Current(75A), turn-off delay time $\text{tdoff}$, turn-off time $\text{toff}$, turn-off loss $\text{Eoff}$, turn-on time $\text{ton}$, turn-on loss $\text{Eon}$ The simulation results are shown in table 1.

In order to visualize the sensitivity of the temperature characteristics of each thermoelectric parameter, the data is normalized and the sensitivity horizontal comparison chart shown in figure 10 is drawn. The analysis shows that the linearity of the on-voltage drop of the static parameters is good, but the overall rate of change is low, the sensitivity is low, and the on-voltage drop at low current is not suitable for online detection. In the dynamic parameters, the turn-on loss is non-linearly related to temperature, the turn-on delay and turn-on time are almost constant with temperature, and the sensitivity is low. The turn-off time is positively related to the turn-off loss, both of which have a change rate of more than 30%, and the overall linearity is good. The turn-off delay time does not change significantly at low temperatures, and has good linearity and highest sensitivity at high temperatures.

![Figure 9. IGBT junction temperature detection simulation test schematic diagram.](image-url)
### Table 1. TSEP temperature characteristics horizontal comparison table.

| Temperature (°C) | 30      | 50      | 70      | 90      | 110     | 130     | 150     |
|------------------|---------|---------|---------|---------|---------|---------|---------|
| VCEon (10mA) (V) | 1.0855  | 1.0433  | 1.0006  | 0.9577  | 0.9142  | 0.8705  | 0.8263  |
| VCEon (75A)      | 1.999   | 2.0328  | 2.0684  | 2.1035  | 2.1424  | 2.1805  | 2.2222  |
| Toff (ns)        | 1742    | 1851    | 1971    | 2097    | 2224    | 2372    | 2508    |
| Eoff (mJ)        | 53.3    | 56.7    | 59.7    | 62.8    | 66.1    | 69.6    | 73.3    |
| Ton (ns)         | 113     | 116     | 119     | 120     | 123     | 126     | /       |
| Eon (mJ)         | 3.1817  | 3.2854  | 3.3851  | 3.86    | 3.5091  | 3.5733  | /       |
| Tdoff (ns)       | 157     | 157     | 156     | 155     | 136     | 119     | 99      |
| Tdon (ns)        | 303     | 306     | 309     | 313     | 316     | 319     | /       |

![Figure 10. Comparison diagram of junction temperature sensitivity of different TSEP.](image)

### 5. Discussion and Outlook

This article systematically reviews and compares several methods for measuring IGBT junction temperature in detail. Although the method of measuring the junction temperature using optical fiber has high accuracy, it has high application cost and needs to damage the IGBT module, which is difficult to apply to the online detection of junction temperature. The thermal electrical parameter method does not need to destroy the IGBT module and has a fast response speed suitable for on-line monitoring. However, the thermal sensitivity, linearity, and resolution of different parameters vary greatly, and some parameters have great requirements on the measurement circuit. The saturation voltage linearity of the static parameters under small current is good, the resolution is high (~2 mV/°C), but additional constant current source injection is needed, and it is not suitable for online detection. The saturation voltage drop under high current is easy to extract, but there is a non-temperature-sensitive region near the critical current, and the internal interconnect resistance has a greater effect under high current. The short-circuit current is negatively related to temperature, has higher resolution, but requires higher device over-stress capabilities, and the short-circuit itself may cause IGBT failure and damage. Among the dynamic parameters, the off-delay time has a good linearity and a resolution of 1-2 ns/°C. The disadvantage is that it requires high-speed and high-precision sampling equipment, which is not convenient for extraction. The on-gate peak current avoids the detection of high voltage and high current, which reduces the design of the acquisition circuit but is affected by the aging of the IGBT module. Choosing suitable thermistor electrical parameters and designing high-speed and high-precision online measurement circuits are the research directions in the future. The finite element thermal simulation method can accurately calculate the temperature field of the IGBT module, but it requires detailed equipment material properties and a large amount of calculation time, and is not suitable for online calculation. The thermoelectric...
coupling model method is convenient for importing real-time simulation software and is easy to calculate online. However, the accurate calculation of losses under different operating conditions and control strategies is a major difficulty. How to find the best advantage between calculation accuracy and calculation time is also a great challenge.

6. Conclusion
Effective IGBT junction temperature on-line detection method provides important reference for the reliability of power electronic equipment. Optical or physical direct measurement methods have failed to resolve the breakthrough in non-invasiveness and fastness, and it is not easy to monitor the junction temperature online. The thermal electrical parameter method does not need to destroy the IGBT module and has a fast response speed suitable for on-line monitoring. However, the thermal sensitivity, linearity, and resolution of different parameters vary greatly, and some parameters have great requirements on the measurement circuit. The thermal resistance model prediction method can accurately calculate the temperature field of the IGBT module, but it requires detailed equipment material properties and a large amount of calculation time. It is also a difficult point to accurately calculate the loss when dealing with operating conditions and control strategies. So far, there is no universal solution in the field of junction temperature online detection, and related scholars are still in-depth research to determine a suitable online junction temperature detection technology for IGBT modules.

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