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Multi-Chip IGBT Module Failure Monitoring Based on Module Transconductance with Temperature Calibration

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Abstract: The Insulated Gate Bipolar Transistor (IGBT) is the component with the highest failure rate in power converters, and its reliability is a critical issue in power electronics. IGBT module failure is largely caused by solder layer fatigue or bond wires fall-off. This paper proposes a multi-chip IGBT module failure monitoring method based on the module transconductance, which can accurately monitor IGBT module chip failures and bond wire failures. The paper first introduces the failure mechanism and module structure of the multi-chip IGBT module; then, it proposes a reliability model based on the module transconductance and analyzes the relationship between chip failure, bond wire failure, and the transmission characteristic curve of the IGBT module. Finally, the module transconductance under chip failure and bond wire failure is measured and calculated through simulation, and the temperature is calibrated, which can eliminate the influence of temperature on health monitoring. The results show that the method has a high sensitivity to chip failures and bond wire failures, can realize the failure monitoring of multi-chip IGBT modules, and is of great significance for improving the reliability of power converters.

Keywords: multi-chip IGBT module; bond wire; module transconductance; temperature calibration; failure monitoring; reliability

1. Introduction

The Insulated Gate Bipolar Transistor (IGBT) module is a power electronic integrated module composed of multiple IGBT chips, diode chips, solder layers, bond wires, ceramic copper-clad substrates, heat dissipation base plates, and power terminals. IGBT modules are mainly used in inverters, frequency converters, uninterruptible power supplies, wind power, and solar power generation. They are the core components of power converters and have one of highest failure rates out of all the power converters [1]. To reduce the failure rate and improve the reliability of the power converter, it is of great significance to monitor the failure status of the IGBT module [2].

At present, many scholars at home and abroad are committed to the reliability research of IGBT modules, most of which focus on the online measurement of IGBT health-sensitive parameters (HSPs) or thermosensitive electrical parameters (TSEPs). Researchers measure the collector, gate, emitter, and appropriate Kelvin terminals of the IGBT module to obtain the external electrical parameters of the IGBT module, and realize the health monitoring of the IGBT module through the fault characteristic parameters [3–5]. Reference [6,7] proposed measuring IGBT saturation voltage drop $V_{CE(sat)}$ during the operation of the power converter. This method must ensure that the measured current is constant during operation, but it is difficult to achieve in practice. Reference [8–10] proposes using the on-state voltage drop $V_{CE(ON)}{}^{a}$ under load current to monitor the shedding of IGBT bond wires in real time. Still, this parameter has a weak anti-interference ability. In reference [11], the on-state voltage drop $V_{CE(on)}{}^{B}$ at the inflection point is used to monitor the aging and shedding of bond wires, which has strong resistance to junction temperature interference. However, the measurement of the on-state voltage drop $V_{CE(ON)}$ needs to consider the high-voltage isolation problem, and the measurement is from thousands of volts in the off phase to a few volts in the on phase. The measurement range is broad, and the measurement circuit must consider a large V_{CE} voltage swing. There are certain difficulties in practical applications. Reference [12] uses on-state resistance $R_{CE(ON)}$ to monitor the aging degree of the IGBT module package online. Although it has high sensitivity, its resistance to junction temperature interference is low, and the first bond wire lift-off in the IGBT module cannot be detected. Reference [13–15] uses the peak gate current I_{GPeak} to monitor the shedding of the bond wire in the parallel IGBT module. Although this parameter has a strong resistance to changes in junction temperature, detecting the peak gate current value is difficult in practical applications. In addition, the gate current is relatively small, and the measurement is performed on the side close to the IGBT module. The detection circuit also needs to deal with the challenge of electromagnetic interference. In reference [16], the grid emitter voltage variation dV_{CE}/dt was used to detect the drop of the bond wire during the process of turning the circuit on and off. This method could not identify the first bond wire lift-off. Reference [17] proposes using the gate-emitter pre-threshold voltage $V_{GE(pre\text{-}th)}$ to monitor IGBT chip failures in multi-chip IGBT modules. This method can only monitor chip failures and cannot monitor a small number of bond wire fall-off failures. Most of the above research methods can only monitor one of the failures of the IGBT bond wire lift-off or the IGBT chip failure, and it cannot be monitored at the same time. Temperature-sensitive electrical parameters need to be considered when used as fault characteristic parameters. However, in the above studies, temperature-sensitive electrical parameters have not been normalized to eliminate the impact of temperature on failure monitoring.

Aiming at the shortcomings of the existing research methods, this paper proposes using the IGBT module transconductance as the characteristic quantity to identify both the chip failure and the bond wire failure in the multi-chip IGBT module and realize the failure monitoring of the IGBT module. The paper first analyzes the failure mechanism and module structure of the multi-chip IGBT module; then, it proposes a reliability model based on the module transconductance and analyzes the relationship between chip failure, bond wire failure, and the IGBT module transmission characteristic curve (i_C-u_{GE}) Finally, the quantitative relationship between chip failure and bond wire failure and module transconductance is measured and calculated through simulation. Furthermore, the temperature is normalized, which can eliminate the influence of temperature on failure monitoring. The results show that the method has good sensitivity to chip failures and bond wire failures, can realize the failure monitoring of multi-chip IGBT modules, and is of great significance for improving the reliability of power converters.

The sections of this article are arranged as follows. In Section 2, the failure mechanism and module structure of the multi-chip IGBT module are introduced in detail. In Section 3, a reliability model based on the module transconductance is constructed. Section 4 is based on the reliability model to monitor the chip failure and bond wire failure status of the DIM800NSM33-F IGBT module. The results are discussed and analyzed in Section 5.

2. Multi-Chip IGBT Module Failure Mechanism and Structure

The failure of the solder layer and the falling off of the bond wires are the main aging failure mechanisms of IGBT modules. The bond wire is mainly used to connect the chip (IGBT chip or diode chip) and the terminal (gate or emitter). The main reason for the bond wire to fall off is the inconsistent coefficient of thermal expansion (CTE) of each layer of the semiconductor device. Figure 1 shows the IGBT module packaging structure and the coefficient of thermal expansion of each layer of material. The IGBT chip and the diode chip are electrically connected by bond wires, as are the chip and the copper substrate. During the normal operation of the IGBT, the heat generated by the power loss of the semiconductor chip will pass through the multi-layer structure to the heat sink to produce a junction temperature fluctuation ΔT, which causes the bond wire to generate shear stress at its welding point, and the changing stress produces cracks, which leads to the bond wires fall-off [18,19]. Initially, cracks are generated at both ends of the bond wire; then, they are gradually extended to the middle until the bond wire completely falls off. Once a bond wire in the module falls off, the current passing through the remaining bond wires will increase immediately, thereby accelerating the fall-off process of the remaining bond wires [20]. The deformation ε_t of the IGBT due to the fluctuation of the junction temperature can be expressed by Equation (1):

$$\varepsilon_t = L(\alpha_{Al} - \alpha_{Si}) \cdot \Delta T \quad (1)$$

where α_{Al} and α_{Si} are the CTEs of aluminum and silicon, L is the length of the aluminum bond wire; ΔT is the junction temperature fluctuation.

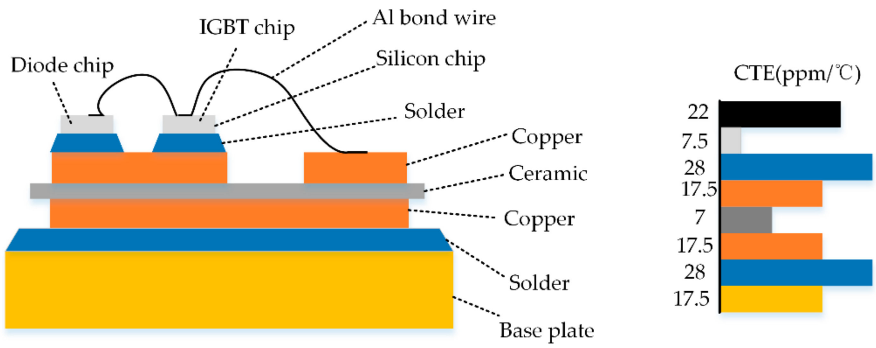


Figure 1. Insulated Gate Bipolar Transistor (IGBT) module structure and material coefficient of thermal expansion (CTEs).

For multi-chip IGBT modules, in addition to the parasitic parameters of the cell chip, stray parameters such as the substrate, board lining, solder layer, and bond wire in the module packaging process need to be considered [21]. Among the stray parameter changes caused by IGBT failure, the bond wire fall-off is the most typical. Therefore, the chip fault and bond wire fault studied in this paper are caused by the bond wire fall-off. If the bond wires of a certain unit IGBT chip are all falling off, the number of effective IGBT chips connected in parallel in the IGBT module will be reduced, and the fault type is chip failure at this time. If the bond wire of a certain unit IGBT chip falls off, the number of effective bond wires on the chip will be reduced, and the fault type is bond wire failure at this time. The reliability of multi-chip IGBT modules depends on the health of all parallel IGBT chips and bond wires. Therefore, it is very important to evaluate the overall health of the multi-chip IGBT module by monitoring IGBT chip failure and bond wire failure [22].

Figure 2 shows the equivalent diagram of the internal structure of the multi-chip IGBT module. There are n IGBT chips in parallel. This article takes the DIM800NSM33-F IGBT module as the research object. This module is a commercial module. The physical map and the internal equivalent circuit of a single chip in the module are shown in Figure 3. The module is a 16-unit IGBT module. Each chip has eight emitter bond wires, and there are 128 emitter bond wires in total. Refer to the data sheet for the basic parameters of the module, as shown in Table 1. The acceptable number of chip losses for IGBT modules depends on the working environment and working requirements. Generally, 10% chip losses in IGBT modules and 70% bond wire lift-off on the chip are considered acceptable [23]. Therefore, for the DIM800NSM33-F IGBT module, the detection of two chip failures in 16 chips is set as the safety margin. The failure simulation is the situation of the first two chips that failed; the first chip that failed is called “Chip 1”, the second chip that failed is called “Chip 2”.

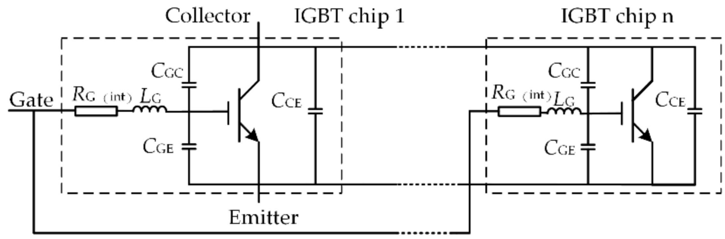
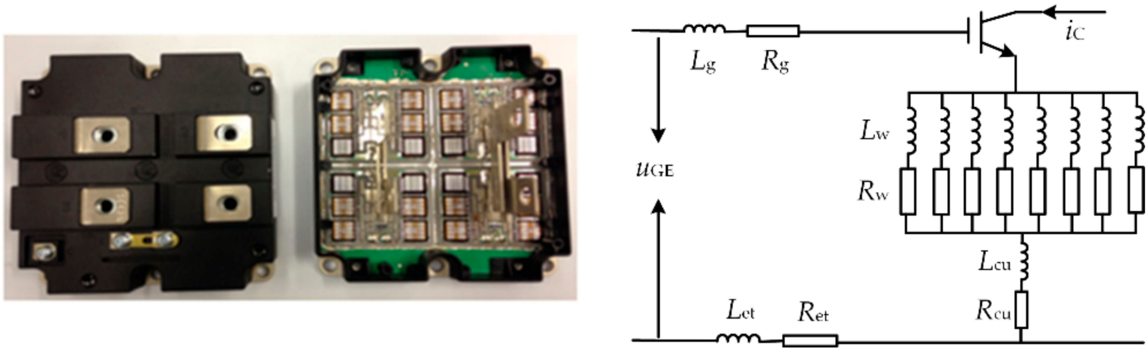


Figure 2. Internal structure diagram of multi-chip IGBT module.



(**a**) (**b**)

Figure 3. The physical diagram of the IGBT module and the internal equivalent circuit diagram of a single chip: (**a**) physical diagram; (**b**) equivalent circuit diagram.

Table 1. Basic parameters of IGBT module.

Gate Voltage Source V_{GG}	Internal Gate Resistance $R_{G(int)}$	Gate-Emitter Capacitance C_{GE}	Gate-Collector Capacitance C_{GC}	Gate Inductance L_G
±15 V	2.16 mΩ	8.8625 nF	0.1375 nF	12 nH

3. Reliability Model Based on Module Transconductance

The transmission characteristic curve of the IGBT module usually adopts Auto Curve Tracer to test, the horizontal axis is the gate-emitter voltage u_{GE}, and the vertical axis is the collector current i_C, which is affected by temperature. The general definition of transconductance refers to the slope of the transmission characteristic curve of the IGBT chip, which is the characteristic parameter of the IGBT chip itself. For the entire IGBT module, its module transconductance is affected by IGBT chip fatigue and bond wire failure. The transmission characteristic of IGBT refers to the response function of i_C to u_{GE} changes at different temperatures. The gradient of the transmission characteristic at a given temperature is called the transconductance of the device at that temperature. IGBT is a device that uses input voltage to control output current. The ratio of output current to input voltage is represented by transconductance, which also reflects the gain of IGBT. The chip transconductance g_{mc} reflects the sensitivity of i_c to u_{GE}, and the module transconductance g_m reflects the sensitivity of i_c to u_i. This article mainly focuses on the failure research of the IGBT module chip and bond wire, which belongs to module package level failure: a slow and gradual process.

The relationship between IGBT chip fatigue, bond wire lift-off, and module transconductance is analyzed in detail below. According to the working principle of the IGBT chip, when the IGBT chip operates in the active area, the governing equation of the collector current i_c is shown in Equation (2) [24]:

$$i_c = \frac{\mu_{ni} C_{OX} Z}{2L(1-\alpha_{pnp})}(u_G - U_{GE(th)})^2 = A(u_{GE} - U_{GE(th)})^2 \tag{2}$$

where μ_{ni} is the electron migration speed, C_{OX} is the oxide layer capacitance, Z and L are the length and width between the gate-emitter of the MOSFET, α_{pnp} is the current gain of the PNP transistor,

$U_{GE(th)}$ is the threshold voltage of the IGBT chip; the above parameters are all determined by the chip structure and material, but they are all affected by the junction temperature T_j of the chip.

For simplification, the parameter A is used to characterize the parameters related to the physical size and structure of the chip in Equation (2), and the chip transconductance g_{mc} is the sensitivity of i_c to u_{GE} as shown in Equation (3):

$$g_{mc} = \frac{di_c}{du_{GE}} = 2A(u_{GE} - U_{GE(th)}). \tag{3}$$

From Figure 3b, we can see that for a single IGBT branch, the circuit equation during the switching transient device is Equation (4):

$$u_G = u_i - i_C R_w - L_G \frac{di_G}{dt} - i_G R_G - (L_{cu} + L_{et}) \frac{d(i_G + i_C)}{dt} - (i_G + i_C)(R_{cu} + R_{et}) \tag{4}$$

where R_w is the equivalent parasitic resistance of bond wires; R_{cu} and L_{cu} are the equivalent parasitic resistance and inductance of the copper layer; u_i is the gate drive voltage of the IGBT module; and i_G is the gate current of the IGBT module. L_{et} is the equivalent stray inductance of the IGBT emitter lead, and R_{et} is the equivalent stray resistance of the IGBT emitter lead.

The parasitic resistance of the IGBT is about 40 μΩ, the parasitic inductance is about 30 nH, and the bonding wire resistance is about 50 mΩ. The parasitic resistance and all parasitic inductances are relatively small compared to the bonding wire resistance. In practical applications, di_c/dt is about 3000 A/μs, and di_g/dt is about 0.2 A/μs. When the IGBT works in the safe active region, the collector current i_c and the gate current i_g remain almost constant. Considering that the measurement of the transconductance g_m of the detection parameter module in this paper is when the IGBT is working in the safe active area, Equation (4) can be simplified to Equation (5):

$$u_G = u_i - i_c R_w. \tag{5}$$

When u_i is equal to $U_{GE(th)}$, the current flowing through the IGBT is zero. In order to study the influence of IGBT module transconductance and bond wire resistance R_W on the module transconductance, we substitute Equation (5) into Equation (1) and perform appropriate transformations to obtain the relationship between i_c and u_i as Equation (6):

$$i_c = \frac{2AR_w\left(u_i - U_{GE(th)}\right) + 1 - \sqrt{4AR_w\left(u_i - U_{GE(th)}\right) + 1}}{2AR_w{}^2}. \tag{6}$$

The module transconductance g_m of the IGBT module reflects the sensitivity of i_c to u_i, which can be derived as Equation (7):

$$g_m = \frac{di_c}{du_i} = \frac{1}{R_w}\left(1 - \frac{1}{\sqrt{4AR_w\left(u_i - U_{GE(th)}\right) + 1}}\right). \tag{7}$$

Comparing Equations (2) and (6), we can see that the relationship between chip transconductance g_{mc} and module transconductance g_m is as shown in Equation (8):

$$g_m = \frac{1}{R_w + 1/g_{mc}}. \tag{8}$$

The transconductance of the IGBT module is not only related to the transconductance of the IGBT chip itself but also to the health of the parallel chip and the bond wires. The module transconductance will decrease as R_w increases during the aging failure process. From Equation (2), we can get Equation (9):

$$u_i - U_{GE(th)} = \frac{Ri_c\sqrt{A} + \sqrt{i_c}}{\sqrt{A}}. \tag{9}$$

Then, we put Equation (9) into Equation (7) to get the module transconductance, as shown in Equation (10). The transconductance expression of this module has nothing to do with the threshold voltage affected by the gate oxide layer.

$$g_m = \frac{1}{R_w}\left(1 - \frac{1}{\sqrt{4Ai_c{R_w}^2 + 4\sqrt{Ai_c}R_w + 1}}\right) \tag{10}$$

Among the failure modes of power devices, package-related failures are the most common and are generally considered to be the main factors affecting the life of IGBTs. It can be seen from Equation (10) that the module transconductance is a function of parameter R_w, parameter A, and collector current i_c. Parameter A characterizes the physical size and structural parameters of the chip, and it is generally believed that these parameters will not change with aging. In this case, the bond wire lift-off is the only aging factor that affects the module transconductance change. For multi-chip IGBT modules, the chip characteristics and bond wire resistance on each branch may not be consistent, and the gate oxide degradation of each chip may also be different. For simplicity, it is assumed that the chip branches are consistent, and the aging process is also consistent, so as to eliminate the influence of the threshold voltage $U_{GE(th)}$.

The junction temperature will affect the electrical characteristics of the IGBT. The dependence of the physical material parameters of the silicon-based semiconductor on temperature determines the temperature dependence of its operating characteristics. The lifetime of carriers increases with the decrease of temperature and mobility, and the charge storage in the drift region decreases with the increase of temperature, so the IGBT switching process is affected by temperature. In the IGBT module, both the parameter R_w and the parameter A are affected by the junction temperature, and the transconductance of the module under the same collector current can be expressed as Equation (11):

$$g_m = f(R_w, T). \tag{11}$$

In actual engineering, with the aging of the IGBT module, the equivalent resistance of the module will change accordingly. At the same time, the junction temperature T_j will also fluctuate during the normal operation of the power converter [25,26]. The influence of fluctuation on the transconductance of the module can be expressed by Equation (12):

$$\begin{cases} \Delta g_{mi\_T} = f(T_i, R_{w0}) - f(T_0, R_{w0}) \\ \Delta g_{mi\_Rw} = f(T_0, R_{wi}) - f(T_0, R_{w0}) \end{cases} \tag{12}$$

where T_0 is the selected reference temperature; R_{w0} is the equivalent resistance of bonding wire in the healthy state of the IGBT module; T_i is the temperature after change; and R_{wi} is the bond wire equivalent resistance after module aging failure.

Figure 4 shows the transmission characteristic curve before and after the IGBT module bonding wire lift-off. As the bond wires fall off, the collector current gradually decreases in the active area. At the same collector current i_C measurement point, the gate-emitter voltage after the bond wire falling off increases from u_{GE1} to u_{GE2}, and the power loss of the IGBT module will also increase, which will lead to an increase in junction temperature and failure of the bond wire. The resulting junction temperature difference is $T_2 - T_1$. Therefore, when the module transconductance is used to monitor the health of a multi-chip parallel IGBT module, it is necessary to eliminate the effect of junction temperature. The extraction of module transconductance requires the chip to work in the active area, and it is also necessary to consider that the IGBT module is located in the safe operating area (SOA).

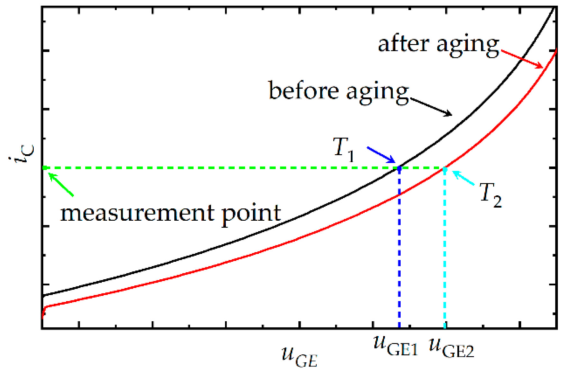
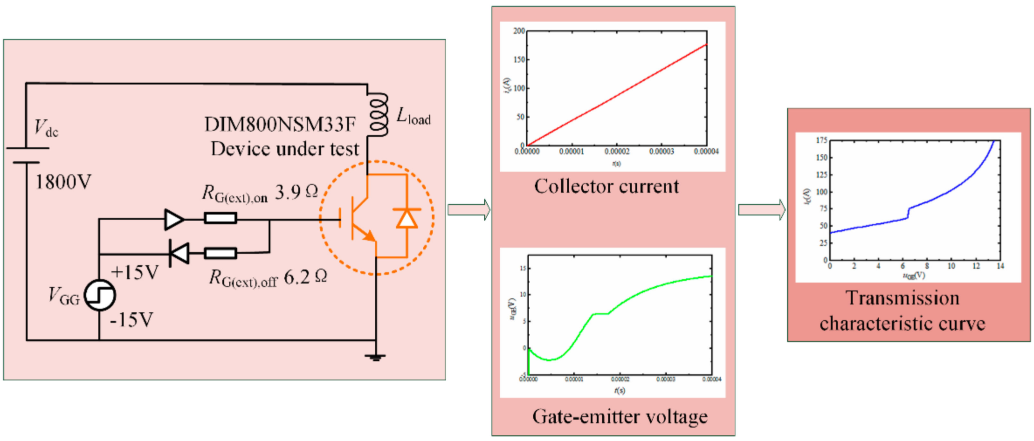


Figure 4. Transmission characteristic curve of the IGBT module before and after aging.

4. Model and Test

Figure 5 shows the schematic diagram of multi-chip IGBT module failure monitoring based on module transconductance. According to the test circuit, the collector current and gate emitter voltage are measured to obtain the transmission characteristic curve, and then the transconductance of the module is calculated according to the transmission characteristic curve. The DC bus power supply voltage of the test circuit is 1800 V, and the load is an inductive load of 400 µH. The tested IGBT module is driven by the gate driver with a voltage pulse of approximately −15 to +15 V. Between the ideal pulse voltage power supply and the IGBT gate terminal, 3.9 Ω turn-on gate resistance $R_{G(ext),on}$ and 6.2 Ω turn-off gate resistance $R_{G(ext),off}$ are used. In this paper, the test of the transmission characteristic curve under the condition of chip failure and bonding wire failure is completed in Matlab/Simulink.



(**a**) (**b**) (**c**)

Figure 5. Schematic diagram of failure monitoring: (**a**) Test circuit; (**b**) Measurement i_C and u_{GE}; (**c**) Acquisition of transmission characteristic curve.

4.1. IGBT Chip Failure

The type of chip failure studied in this paper is that all bond wires on a chip fall off or the IGBT chip is completely fatigued due to the optimus effect caused by overcurrent, overvoltage, overheating, or beyond the shutdown safe working area. The research object DIM800NSM33-F IGBT module of this paper is a multi-chip parallel IGBT module. All parallel chip branches are regarded as the same, and chip failure is simulated by changing the number of parallel chip branches. Considering the safety margin of the module under study—two chip failures, the chip position has a relatively small influence, so the influence of the chip failure position is not considered for the time being. Select the reference temperature T_0 = 2 °C, and consider the safety margin of the selected IGBT module. In the above model, the IGBT module is tested under three different health conditions: "health", "one chip failure", and "two chip failure". The transmission characteristic curve of the IGBT module under different chip fault conditions is shown in Figure 6. With the increase of the number of chip failures, under the same collector current i_C, the gate-emitter voltage u_{GE} gradually increases; under the same gate-emitter voltage u_{GE}, the collector current i_C gradually decreases. The slope of the transmission characteristic curve of the IGBT module also decreases gradually. That is, the transconductance of the IGBT module decreases gradually. When the gate voltage u_{GE} is less than the threshold voltage $V_{GE(th)}$, the IGBT is in the off state. In most of the collector current range after the IGBT is turned on, i_C and u_{GE} have a good positive correlation. Considering that the IGBT works in the active area and is located in the safe working area, and the transmission characteristic curves have obvious differences under different fault conditions, the u_{GE} value is selected as 12 V to calculate the transconductance value of the module. According to the transmission characteristic curve, the transconductance value of the IGBT module under different chip fault states is calculated, as shown in Table 2. It can be seen that the transconductance of the module gradually decreases with the increase of IGBT failure chips, and the transconductance of the module decreases by about 6.2% when an IGBT chip fails. When two IGBT chips in the module fail, the transconductance of the module is reduced by 12.472%. At this time, the health status of the module has exceeded the safety margin, and the module is close to failure. It should be repaired or replaced in time to improve the reliability of the power converter.

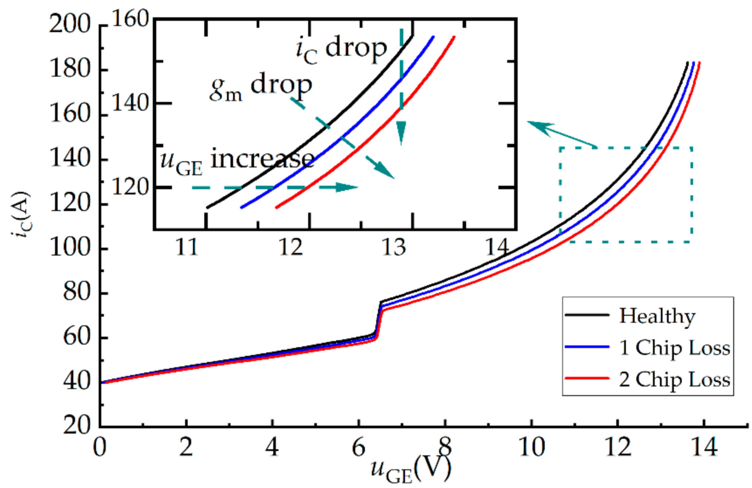


Figure 6. Transmission characteristic curves of IGBT modules under chip failure states.

Table 2. Transconductance of IGBT modules under chip failure states.

Number of IGBT Chip Failures	IGBT Module Transconductance g_m (A/V)	Percentage Change (%)
0	19.1843	0
1	17.9982	−6.243
2	16.8176	−12.472

When the IGBT is aging and failing, it will cause changes in parameters such as the thermal resistance and heat capacity, which will change the junction temperature of the IGBT, which will affect the transconductance parameters of the IGBT module. This article attributes the effect of aging failure to the effect of temperature on the transconductance, so it is necessary to exclude the effect of temperature on the module transconductance. When the IGBT module was in a healthy state, that is, when there was no chip failure and no bond wire fall-off, we measured and calculated the transconductance of the IGBT module at 25, 50, 75, 100, and 125 °C, as shown in Table 3. When the module is in a healthy state, as the temperature increases, the transconductance of the IGBT module gradually decreases. Figure 7 shows the relationship between the IGBT module transconductance and temperature. It can be seen from the figure that the module transconductance and temperature show a very good linear relationship, so the linear fitting can be used to obtain the module transconductance and temperature. The relationship, as shown in Equation (13), has a linear fit of up to 0.998. In order to eliminate the influence of temperature, the module transconductance at different temperatures can be calibrated to 25 °C according to Equation (13). At this time, the module transconductance is only related to the module's health status.

$$g_{\mathrm{mT,j\_25\,°C}} = g_{\mathrm{mT,j}} + 0.00664\,(T - 25) \tag{13}$$

where T is the temperature, j is the module's different health states, $g_{\mathrm{mT,j}}$ is the transconductance at different temperatures and different health states, and $g_{\mathrm{mT,j\_25\,°C}}$ is the module's transconductance calibrated to 25 °C.

Table 3. Transconductance of the IGBT module in a healthy state at different temperatures.

Temperature (°C)	IGBT Module Transconductance g_m (A/V)
25	19.1843
50	19.0316
75	18.8554
100	18.6828
125	18.5292

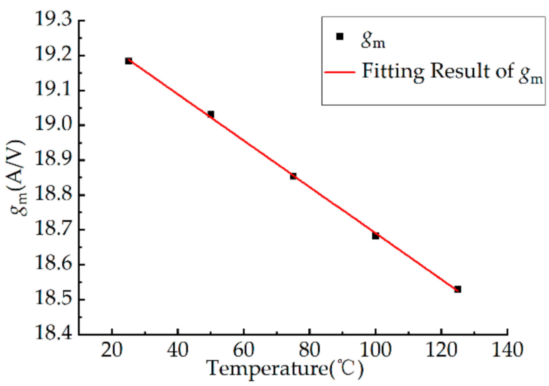


Figure 7. The relationship between IGBT module transconductance and temperature.

We tested different IGBT chip fault types at 25, 50, 75, 100, and 125 °C and calculated the IGBT module transconductance, as shown in Table 4. It can be seen that the module transconductance decreases as the number of IGBT chips increases, and it decreases as the temperature increases. Figure 8a shows the module transconductance under different temperatures and health conditions. Within a certain temperature range, the module transconductance can be used to determine the number of IGBT module chip failures and realize the health status monitoring of the IGBT module.

Table 4. Transconductance of IGBT modules under different temperatures and healthy states.

Number of IGBT Chip Failures	IGBT Module Transconductance g_m (A/V)				
	T = 25 °C	T = 50 °C	T = 75 °C	T = 100 °C	T = 125 °C
0	19.1843	19.0212	18.8554	18.6937	18.5268
1	17.9982	17.8328	17.6823	17.5135	17.3416
2	16.8176	16.6553	16.4876	16.3231	16.1587

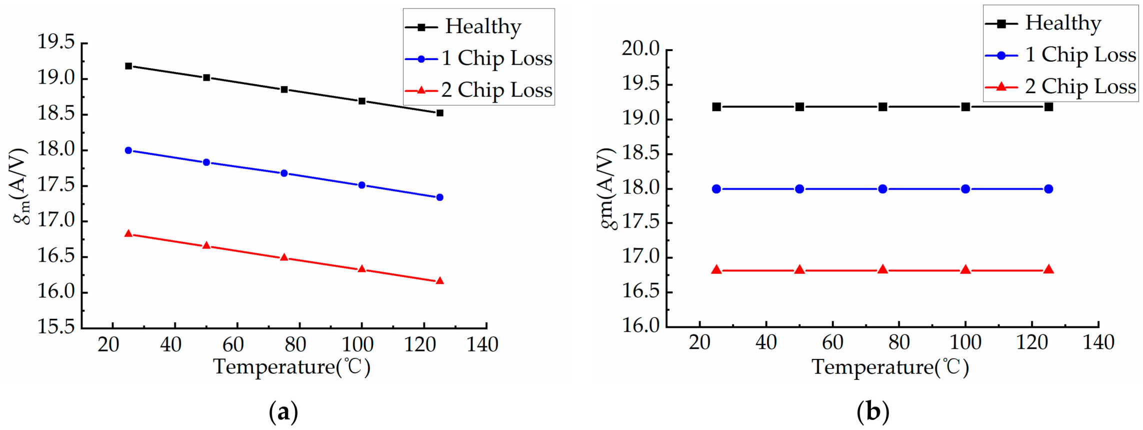


Figure 8. Transconductance of the IGBT module with chip failure: (**a**) before temperature calibration (**b**) after temperature calibration.

In order to monitor the health status of the IGBT module more accurately and eliminate the influence of temperature, the module transconductance at different temperatures is calibrated to the reference temperature T = 25 °C according to Equation (13). Figure 8b shows the module transconductance after temperature calibration. Compared with the module transconductance that has not undergone temperature correction, g_m after temperature calibration is only related to the module's health status. The latter can more intuitively and clearly judge the type of chip failure and more accurately assess the health of the IGBT module status.

4.2. Bond Wire Failure

The bond wire failure studied in this paper is caused by the bond wire lift-off. The DIM800NSM33-F IGBT module has eight bond wires on each IGBT chip. Considering the maximum safety margin of the IGBT module, the following will test and analyze different types of bond wire faults on Chip 1 and Chip 2.

For Chip 1, the state of the bond wire is i (i = 0, 1, 2, ... , 8) bond wire lift-off. When the reference temperature T_C = 25 °C, the transmission characteristic curve of the measurement of Chip 1 under different bond wire failure states is shown in Figure 9. After the eighth bond wire lift-off, the transmission characteristic curve is completely separated from other curves, and Chip 1 is completely invalid at this time. This is because all the bond wires fall off so that the chip is completely faulty and invalid, and the electrical characteristics of the IGBT module have changed significantly, making the transmission characteristic curve clearly separated. According to the transmission characteristic curve, the module transconductance corresponding to the number of bond wire shedding is calculated, as shown in Table 5. It can be seen from Table 5 that the module transconductance gradually decreases with the increase in the number of bond wires falling off. Each time a bond wire lifts off, the module transconductance decreases about 0.753% on average. When the last bond wire falls off, the transconductance of the module changes significantly.

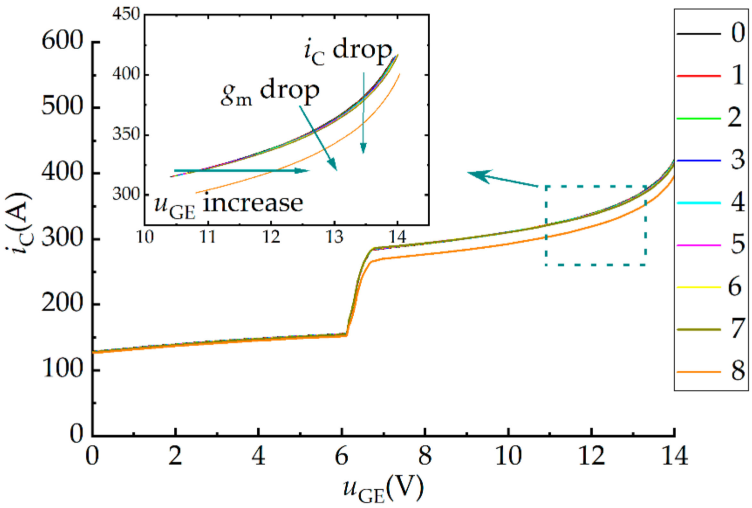


Figure 9. Transmission characteristic curves of Chip 1 under bond wire failure states.

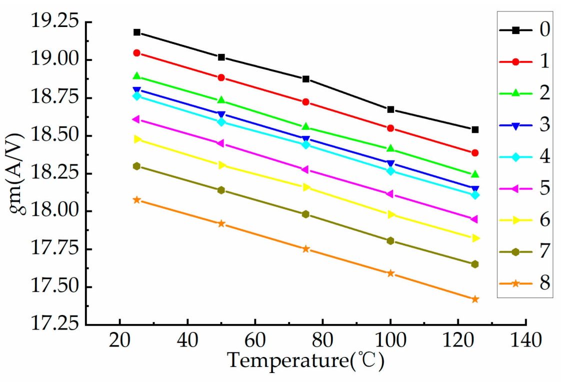
Table 5. Module transconductance under bond wire failure states of Chip 1.

Number of Chip 1 Bond Wires Lift-Off	IGBT Module Transconductance g_m (A/V)	Percentage Change (%)
0	19.1843	0
1	19.0469	−0.723
2	18.8914	−1.542
3	18.8065	−1.988
4	18.7641	−2.211
5	18.6086	−3.030
6	18.4774	−3.721
7	18.3015	−4.646
8	18.0772	−5.827

The same measurements and calculations are done for different bond wire fault states of Chip 1 at different temperatures, and the module transconductance is obtained, as shown in Table 6. It can be seen from Figure 10a that under the same bond wire state, the temperature is different, the module transconductance value is also different, and the temperature has a great influence on the type of bond wire failure of the monitoring of Chip 1, and it is impossible to accurately determine the number of Chip 1 bond wires falling off. For example, when Chip 1 is in a healthy state, the decrease of the module transconductance caused by the temperature increase may be misjudged as a bond wire failure state.

Table 6. Module transconductance of Chip 1 in bond wire fault states at different temperatures.

Number of Bond Wires Lift-Off	IGBT Module Transconductance g_m(A/V)				
	T = 25 °C	T = 50 °C	T = 75 °C	T = 100 °C	T = 125 °C
i = 0	19.1843	19.0187	18.8754	18.6753	18.5412
i = 1	19.0469	18.8852	18.7231	18.5498	18.3864
i = 2	18.8914	18.7316	18.5576	18.4135	18.2418
i = 3	18.8065	18.6451	18.4832	18.3218	18.1517
i = 4	18.7641	18.5935	18.4426	18.2687	18.1102
i = 5	18.6086	18.4506	18.2775	18.1174	17.9483
i = 6	18.4774	18.3079	18.1621	17.9789	17.8235
i = 7	18.3015	18.1427	17.9812	17.8056	17.6518
i = 8	18.0772	17.9185	17.7509	17.5903	17.4186



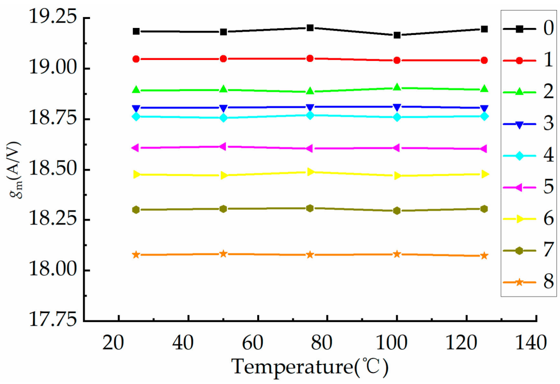


Figure 10. Transconductance of Chip 1 bonding wire fault module: (**a**) before temperature calibration and (**b**) after temperature calibration.

In order to reduce the error rate of bond wire fault monitoring and improve the accuracy of IGBT module health monitoring, it is necessary to eliminate the influence of temperature. Therefore, Equation (13) can be used to calibrate the module transconductance at different temperatures to the reference temperature T_C = 25 °C, as shown in Table 7; then, the temperature calibrated module transconductance can be used to achieve IGBT module health condition monitoring. The module transconductance interval is different under different bond wire failure states; that is, the module transconductance difference is different, and the percentage of change is different. When the last bond wire falls off, the module transconductance interval is the largest, and the module transconductance change is the largest. The module transconductance and junction temperature show a good linear relationship under the bonding wire failure state. Figure 10b shows the transconductance of the IGBT module after temperature correction. It can be seen from the figure that the calibrated module transconductance can accurately distinguish the chip bonding wire off at any temperature, and it is basically not affected by temperature changes. It can accurately monitor the health status of the IGBT module.

Table 7. Module transconductance of Chip 1 bond wire fault state after temperature calibration.

Number of Bond Wires Lift-Off	IGBT Module Transconductance g_m (A/V)				
	T = 25 °C	T = 50 °C	T = 75 °C	T = 100 °C	T = 125 °C
i = 0	19.1843	19.1824	19.2028	19.1664	19.1960
i = 1	19.0469	19.0489	19.0505	19.0409	19.0412
i = 2	18.8914	18.8953	18.885	18.9046	18.8966
i = 3	18.8065	18.8088	18.8106	18.8129	18.8065
i = 4	18.7641	18.7572	18.7700	18.7598	18.7650
i = 5	18.6086	18.6143	18.6049	18.6085	18.6031
i = 6	18.4774	18.4716	18.4895	18.4700	18.4783
i = 7	18.3015	18.3064	18.3086	18.2967	18.3066
i = 8	18.0772	18.0822	18.0783	18.0814	18.0734

Similarly, in order to monitor the health status of the bond wires of Chip 2, when the temperature is 25 °C, the transmission characteristic curves of different bond wires of Chip 2 under fault conditions are measured, as shown in Figure 11. The change rule of the transmission characteristic curve is the same. According to the calculation of the transmission characteristic curve, the module transconductance corresponding to the number of bond wires lift-off is shown in Table 8. It can be seen from Table 8 that the module transconductance gradually decreases with the increase in the number of bond wires lift-off. For each bond wire lift-off, the module transconductance decreases by about 0.812% on average. The change rule is basically the same as that of the Chip 1 bond wire failure state.

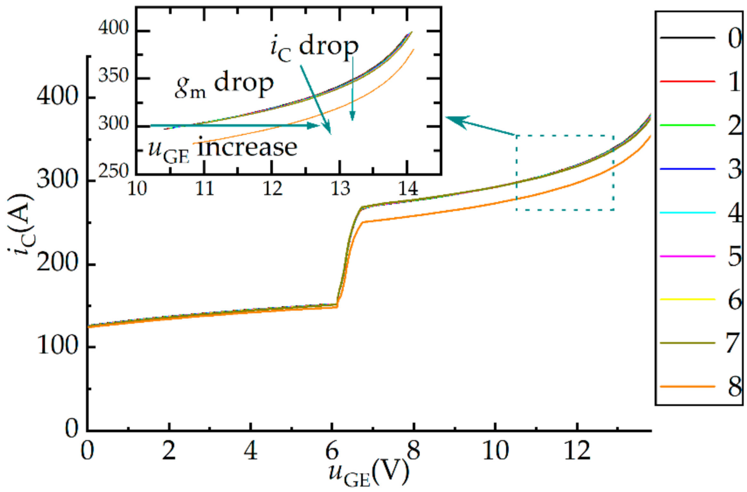


Figure 11. The transmission characteristic curve of Chip 2 under bond wire failure states.

Table 8. Module transconductance of Chip 2 under bond wire failure states.

Number of Bond Wires Lift-Off	IGBT Module Transconductance g_m (A/V)	Percentage Change (%)
0	18.0147	−6.156
1	17.9369	−6.565
2	17.8167	−7.198
3	17.7036	−7.793
4	17.6258	−8.203
5	17.4279	−9.244
6	17.2299	−10.286
7	17.0743	−11.105
8	16.9188	−11.924

In order to study the influence of temperature on the monitoring of the fault state of the bond wire of Chip 2, the transmission characteristic curves of different bond wire fault states are measured at temperatures of 25, 50, 75, 100, and 125 °C, and the IGBT is obtained by calculation. The module transconductance is shown in Table 9. It can be seen from Figure 12a that with the increase of temperature, the module transconductance decreases gradually, which is consistent with the change of the number of bond wires lift-off. The increase of IGBT module transconductance caused by temperature rise is easy to be misjudged as the falling off of bond wire, so the influence of temperature change will interfere with the monitoring of the failure state of bond wires.

Table 9. Module transconductance of Chip 2 with bond wire failure at different temperatures.

Number of Bond Wire Lift-Off	IGBT Module Transconductance g_m (A/V)				
	T = 25 °C	T = 50 °C	T = 75 °C	T = 100 °C	T = 125 °C
i = 0	18.0147	17.8479	17.6754	17.5316	17.3618
i = 1	17.9369	17.7682	17.5897	17.4429	17.2865
i = 2	17.8167	17.6581	17.4962	17.3315	17.1589
i = 3	17.7036	17.5454	17.3705	17.2183	17.0535
i = 4	17.6258	17.4651	17.3326	17.1287	16.9842
i = 5	17.4279	17.2645	17.0898	16.9465	16.7706
i = 6	17.2299	17.0731	16.8956	16.7498	16.5802
i = 7	17.0743	16.9305	16.7510	16.5345	16.4832
i = 8	16.9188	16.7554	16.6031	16.4010	16.2972

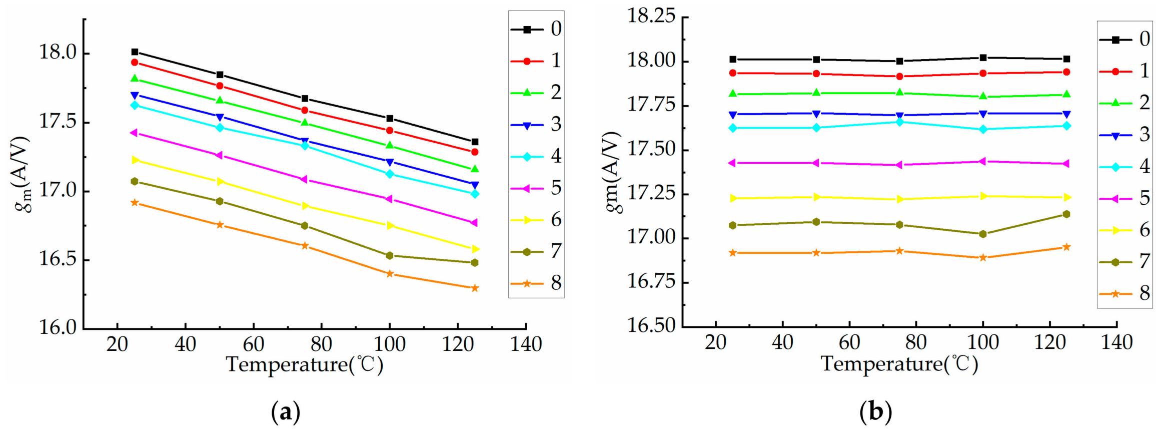


Figure 12. Module transconductance of Chip 2 with bond wire failure: (**a**) before temperature calibration and (**b**) after temperature calibration.

In order to eliminate the interference of temperature factors on health status monitoring, Equation (13) is used to normalize the module transconductance at different temperatures to the reference temperature T_c = 25 °C, as shown in Table 10. Then, the module transconductance after temperature calibration is used to monitor the health status of the IGBT module. Figure 12b shows the transconductance of the IGBT module after temperature correction. It can be seen from the figure that the calibrated module transconductance can accurately distinguish the chip bond wire lift-off condition at any temperature and monitor the health status of the IGBT module.

Table 10. Module transconductance of Chip 2 with bond wire failure after temperature normalization.

Number of Bond Wires Lift-Off	IGBT Module Transconductance g_m (A/V)				
	T = 25 °C	T = 50 °C	T = 75 °C	T = 100 °C	T = 125 °C
i = 0	18.0147	18.0116	18.0028	18.0227	18.0166
i = 1	17.9369	17.9319	17.9171	17.9340	17.9413
i = 2	17.8167	17.8218	17.8236	17.80226	17.8137
i = 3	17.7036	17.7091	17.6979	17.7094	17.7083
i = 4	17.6258	17.6288	17.6600	17.6198	17.6390
i = 5	17.4279	17.4282	17.4172	17.4376	17.4254
i = 6	17.2299	17.2368	17.2230	17.2409	17.2350
i = 7	17.0743	17.0942	17.0784	17.0256	17.1380
i = 8	16.9188	16.9191	16.9305	16.8921	16.9520

4.3. Result Verification

In the reference [27] "Research on Accelerated Aging and Aging Characteristic Parameters of IGBT Modules", the author chooses multi-chip parallel IGBT modules as the research object and uses the method of artificial wire cutting to simulate the falling off of the IGBT module bonding wires. Among them, the experimental test results of Chip 1 falling off zero, one, two, three, and four bonding wires are shown in Table 11. The simulation results of this article are also recorded in Table 11 for comparison.

It can be seen from Table 11 that the transconductance g_m of the two modules are similar, and with the increase in the number of bond wires falling off, the change trend and rate of change of the transconductance g_m of the module are also very close; that is, the parallel IGBT module experiment result is similar to the parallel IGBT module simulation. The results are basically the same, with only slight differences, and the number of bond wires falling off can be judged by the percentage of transconductance change. Therefore, based on the experimental data, this paper can preliminarily show that the theoretical method and simulation results are correct and effective.

Table 11. Verification of simulation results.

Number of Bond Wires Lift-Off	Transconductance g_{m1} Experiment Results (A/V)	g_{m1} Percentage Change (%)	Transconductance g_{m2} Simulation Results (A/V)	g_{m1} Percentage Change (%)
0	22.528	0	19.184	0
1	22.326	−0.90	19.047	−0.723
2	22.259	−1.20	18.891	−1.542
3	21.998	−2.35	18.807	−1.988
4	21.730	−3.54	18.764	−2.211

5. Result Analysis

According to the above theoretical analysis and test results, it can be known that the chip failure and bond wire failure in the multi-chip IGBT module will cause the module transmission characteristic curve u_{GE}-i_C to change, and the module transconductance value calculated from the transmission characteristic curve can be used as characteristic parameters for health monitoring of the IGBT module. Since the temperature dependence of the module transconductance can conceal its fault characteristics or reduce its ability to monitor bond wire or chip faults, temperature calibration processing is required to eliminate temperature effects. The temperature-corrected module transconductance can effectively monitor chip failures and bond wire failures in IGBT modules.

For the IGBT module selected in this article, when one IGBT chip fails, the value of the module transconductance decreases by 6.243%. When two IGBT chips fail, the value of the module transconductance decreases by 12.472%. At this time, it can be basically determined that the IGBT module is in an aging failure state. It means that system failure will occur at any time, and the IGBT module should be repaired or replaced in time. If 70% of the bond wires on one IGBT chip fall off, it can be determined that the chip is close to aging failure [28]. When six bond wires in Chip 1 lift off, the value of the module transconductance is reduced by 3.721%, which means that Chip 1 is about to fail; when six bond wires lift off in Chip 2, the value of the module transconductance decreases by 10.286%, which means that the system is at risk of failure, Chip 2 is about to age and fail, and the module should be degraded or repaired.

Table 12 compares different state monitoring methods. Under the same test object and condition, the pre-threshold voltage $V_{GE(pre\text{-}th)}$ during the gate-emitter turn-on transient, collector-emitter voltage change rate dV_{CE}/dt, and gate peak current $I_{G(peak)}$ have high sensitivity, but the three fault characteristic parameters are affected by temperature, and $V_{GE(pre\text{-}th)}$ and dV_{CE}/dt cannot be used to monitor bond wire faults. dV_{CE}/dt has a weak anti-interference ability. The $I_{G(peak)}$ measurement circuit needs to consider electromagnetic interference. The advantages of the method proposed in this article are as follows. (1) It can monitor chip faults and bonding wire faults at the same time, and it has good sensitivity. (2) This method has low sampling signal frequency and short measurement time, and it can ignore external heat sources and other electrical signals. It has a strong anti-interference ability such as the influence of external noise. (3) The parameter module mentioned in this article has a good linear relationship between the transconductance and temperature. This method is added to the temperature calibration process, which can be more accurately achieved under different junction temperatures IGBT module fault status monitoring. The method proposed in this paper can be used for in situ monitoring of the fault status of multi-chip parallel IGBT modules. It can be used to perform in situ monitoring when the converter is shut down (such as when the fan cuts off the wind speed, when the electric vehicle is stopped, etc.). Limitations and challenges include the stability of in situ monitoring devices, the lack of a standardized analysis of fault diagnosis, and condition assessment technology. However, this method cannot locate the specific location of chip faults and bond wire faults in the IGBT module and will continue to study the real-time online location and monitoring of IGBT module faults in the future.

Table 12. Comparison of IGBT module chip fault monitoring methods.

Method	1 Chip Failure	70% of the Bonding Wires Fall Off	Affected by Temperature	Anti-Interference Ability
$V_{GE(pre\text{-}th)}$	485 mV (8.182%)	-	yes	strong
dV_{CE}/dt	113.175 V/μs (7.545%)	-	yes	weak
$I_{G(peak)}$	0.1734 A (−9.372%)	0.04135 A (−2.235%)	yes	strong
This article	1.1861 A/V (−6.243%)	0.7069 A/V (−3.721%)	no	strong

6. Conclusions

This paper presents a method for monitoring the health of a multi-chip IGBT module based on module transconductance. According to the reliability model based on the module transconductance, the transmission characteristic curve of the selected IGBT module is measured in the test circuit, and its module transconductance value is calculated. The results show that the method can accurately identify the type of chip failure and the type of bond wire failure, and after temperature calibration, it can identify the aging failure process of the IGBT module without the influence of temperature. The method proposed in this article can simultaneously monitor the chip failure and the bond wire failure in the multi-chip IGBT module, and it is not affected by temperature. Compared with the existing monitoring method, it has better comprehensive characteristics, can realize the failure monitoring of the IGBT module, and improve the power inverter reliability.

Author Contributions: Conceptualization, methodology, software, validation, formal analysis, investigation, resources, C.W. (Chenyuan Wang) and Y.H.; data curation, writing—original draft preparation, C.W. (Chuankun Wang); writing—review and editing, X.W.; visualization, L.L. All authors have read and agreed to the published version of the manuscript.

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References

1. Schulze, H.; Niedernostheide, F.; Pfirsch, F.; Baburske, R. Limiting Factors of the Safe Operating Area for Power Devices. *IEEE Trans. Electron Devices* **2013**, *60*, 551–562. [CrossRef]
2. Ghimire, P.; de Vega, A.R.; Beczkowski, S.; Rannestad, B.; Munk-Nielsen, S.; Thogersen, P. Improving power converter reliability: Online monitoring of high-power IGBT modules. *IEEE Ind. Electron. Mag.* **2014**, *8*, 40–50. [CrossRef]
3. Wang, Z.; Qiao, W. An Online Frequency-domain Junction Temperature Estimation Method for IGBT Modules. *IEEE Trans. Power Electron.* **2015**, *30*, 4633–4637. [CrossRef]
4. Bruckner, T.; Bernet, S. Estimation and Measurement of Junction Temperatures in a Three-level Voltage Source Converter. *IEEE Trans. Power Electron.* **2007**, *22*, 3–12.
5. Eleffendi, M.A.; Johnson, C.M. Application of Kalman Filter to Estimate Junction Temperature in IGBT Power Modules. *IEEE Trans. Power Electron.* **2016**, *31*, 1576–1587.
6. Choi, U.; Blaabjerg, F.; Jørgensen, S.; Munk-Nielsen, S.; Rannestad, B. Reliability Improvement of Power Converters by Means of Condition Monitoring of IGBT Modules. *IEEE Trans. Power Electron.* **2017**, *32*, 7990–7997.
7. Beczkowski, S.; Ghimre, P.; de Vega, A.R.; Munk-Nielsen, S.; Rannestad, B.; Thogersen, P. Online Vce Measurement Method for Wear-out Monitoring of High Power IGBT Modules. In Proceedings of the 15th European Conference on Power Electronics and Applications (EPE), Lille, France, 2–6 September 2013; pp. 1–7.

8. Smet, V.; Forest, F.; Huselstein, J.; Rashed, A.; Richardeau, F. Evaluation of Vce Monitoring as a Real-time Method to Estimate Aging of Bond wire-IGBT Modules Stressed by Power Cycling. *IEEE Trans. Ind. Electron.* **2013**, *60*, 2760–2770.
9. Ji, B.; Pickert, V.; Cao, W.; Zahawi, B. In Situ Diagnostics and Prognostics of Wire Bonding Faults in IGBT Modules for Electric Vehicle Drives. *IEEE Trans. Power Electron.* **2013**, *28*, 5568–5577.
10. Oh, H.; Han, B.; Mccluskey, P.; Han, C.; Youn, B.D. Physics-of-failure, Condition Monitoring, and Prognostics of Insulated Gate Bipolar Transistor Modules: A review. *IEEE Trans. Power Electron.* **2015**, *30*, 2413–2426.
11. Singh, A.; Anurag, A.; Anand, S. Evaluation of Vce at Inflection Point for Monitoring Bond Wire Degradation in Discrete Packaged IGBTs. *IEEE Trans. Power Electron.* **2017**, *32*, 2481–2484.
12. Eleffendi, M.A.; Johnson, C.M. In-service Diagnostics for Wire-bond Lift-off and Solder Fatigue of Power Semi-conductor Packages. *IEEE Trans. Power Electron.* **2017**, *32*, 7187–7198.
13. Baker, N.; Dupont, L.; Munk-Nielsen, S.; Iannuzzo, F.; Liserre, M. IR Camera Calidation of IGBT Junction Temperature Measurement via Peak Gate Current. *IEEE Trans. Power Electron.* **2017**, *32*, 3099–3111.
14. Baker, N.; Munk-Nielsen, S.; Iannuzzo, F.; Liserre, M. IGBT Junction Temperature Measurement via Peak Gate Current. *IEEE Trans. Power Electron.* **2016**, *31*, 3784–3793. [CrossRef]
15. Mandeya, R.; Chen, C.; Pickert, V.; Naayagi, R.T. Prethreshold Voltage as A Low-component Count Temperature Sensitive Electrical Parameter without Self-heating. *IEEE Trans. Power Electron.* **2018**, *33*, 2787–2791. [CrossRef]
16. Kexin, W.; Mingxing, D.; Linlin, X.; Jian, L. Study of bonding wire failure effects on external measurable signals of IGBT module. *IEEE Trans. Device Mater. Reliab.* **2014**, *14*, 83–89. [CrossRef]
17. Mandeya, R.; Chen, C.; Pickert, V.; Naayagi, R.T.; Ji, B. Gate-Emitter Pre-threshold Voltage as a Health-Sensitive Parameter for IGBT Chip Failure Monitoring in High-Voltage Multichip IGBT Power Modules. *IEEE Trans. Power Electron.* **2019**, *35*, 9158–9169. [CrossRef]
18. Du, M.; Kong, Q.; Ouyang, Z.; Wei, K.; Hurley, W.G. Strategy for Diagnosing the Aging of an IGBT Module by ON-State Voltage Separation. *IEEE Trans. Electron. Devices* **2019**, *66*, 4858–4864. [CrossRef]
19. Musallam, M.; Johnson, C.M. Real-time Compact Thermal Models for Health Management of Power Electronics. *IEEE Trans. Power Electron.* **2010**, *25*, 1416–1425. [CrossRef]
20. Hui, H.; Mawby, P.A. A Lifetime Estimation Technique for Voltage Source Inverters. *IEEE Trans. Power Electron.* **2013**, *28*, 4113–4119.
21. Luo, H.; Chen, Y.; Sun, P.; Li, W.; He, X. Junction Temperature Extraction Approach with Turn-Off Delay Time for High-Voltage High-Power IGBT Modules. *IEEE Trans. Power Electron.* **2016**, *31*, 5122–5132. [CrossRef]
22. Sun, P.; Gong, C.; Du, X.; Peng, Y.; Wang, B.; Zhou, L. Condition Monitoring IGBT Module Bond Wires Fatigue Using Short-Circuit Current Identification. *IEEE Trans. Power Electron.* **2017**, *32*, 3777–3786. [CrossRef]
23. Chen, C.; Pickert, V.; Al-Greer, M.; Jia, C.; Ng, C. Localization and Detection of Bond Wire Faults in Multichip IGBT Power Modules. *IEEE Trans. Power Electron.* **2020**, *35*, 7804–7815. [CrossRef]
24. Wang, K.; Zhou, L.; Sun, P.; Du, X. Monitoring Bond Wires Defects of IGBT Module Using Module Transconductance. *IEEE J. Emerg. Sel. Top. Power Electron.* **2020**, in press. [CrossRef]
25. Gao, B.; Yang, F.; Chen, M.; Ran, L.; Ullah, I.; Xu, S.; Mawby, P.A. Temperature Gradient-Based Potential Defects Identification Method for IGBT Module. *IEEE Trans. Power Electron.* **2017**, *32*, 2227–2242. [CrossRef]
26. Hu, K.; Liu, Z.; Du, H.; Ceccarelli, L.; Iannuzzo, F.; Blaabjerg, F.; Tasiu, I.A. Cost-Effective Prognostics of IGBT Bond Wires with Consideration of Temperature Swing. *IEEE Trans. Power Electron.* **2020**, *35*, 6773–6784. [CrossRef]
27. Li, Y. Research on Accelerated Aging and Aging Characteristic Parameters of IGBT Modules. Ph.D. Thesis, Chongqing University, Chongqing, China, 2018.
28. Reigosa, P.D.; Wang, H.; Yang, Y.; Blaabjerg, F. Prediction of Bond Wire Fatigue of IGBTs in a PV Inverter Under a Long-Term Operation. *IEEE Trans. Power Electron.* **2016**, *31*, 7171–7182.