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An Anti-Interference Online Monitoring Method for IGBT Bond Wire Aging

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Abstract: Due to the constant changes of the environment and load, the insulated-gate bipolar transistor (IGBT) module is subjected to a large amount of junction temperature (T_j) fluctuations, which often leads to damage to the bond wires. The monitoring parameters of IGBTs are often coupled with T_j , which increases the difficulty of monitoring IGBTs' health status online. In this paper, based on the collector current (I_c) and collector-emitter on-state voltage (V_{ce_on}) online monitoring circuit, an online monitoring method of IGBT bond wire aging against interference is proposed. First, the bond wire aging model is established, and the V_{ce_on} is selected as the monitoring parameter. Secondly, taking a three-phase inverter circuit as an example, the V_{ce_on} and I_c waveforms of the IGBT module are monitored in real time, and the process of online monitoring is introduced accordingly. Finally, the experimental results output by RT-LAB indicate that the method proposed in this paper can accurately identify the aging state of IGBT bond wires under different conditions.

Keywords: IGBT; bond wire aging; junction temperature; collector-emitter on-state voltage; on-line monitoring

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1. Introduction

Compared with other power electronic devices, the insulated-gate bipolar transistor (IGBT) power module has many advantages, such as large input impedance, small driving power, a simple control circuit, small switching loss, and high working frequency, so it has been widely used in power converters [1,2]. In recent years, the application of power converters has been expanding, such as in wind power generation, solar power generation, electric vehicles, and aerospace power systems [3–6], which have harsh operating conditions and strict requirements for IGBT reliability. According to the reliability survey report of the converter system, the power semiconductor device is the component with the highest failure rate in the converter system, accounting for about 34% of failures [7].

Due to the complex and changeable working conditions of the power converter, the IGBT is subjected to a large number of thermal stress, overvoltage, and overcurrent impacts in the process of operation [8,9]. Bond wire aging and solder layer aging are the two most common fatigue failure types of IGBT modules. On account of the different coefficients of thermal expansion (CTE) of the module materials, the thermal stress of the internal structure is uneven under temperature fluctuations, which eventually leads to damage to the bond wires and the solder layer [10–12]. The IGBT module can continue to operate for a period of time before complete failure. Therefore, if potential variations due to aging can be detected before complete failure, catastrophic failure can be avoided. In practical applications, the fatigue failure of IGBT modules is mostly manifested as the bond wires completely lift off [13,14]. IGBT bond wire aging monitoring is very necessary to improve the reliability of the converter, which is also the focus of this paper. Owing to the hindrance of the package structure of the IGBT module, it is difficult to directly monitor the aging process of bond wires. When the bond wire is broken, the equivalent parameters of the emitter area will change so that the external electrical parameters of the IGBT module

will also change accordingly, which provides the possibility for condition monitoring. Therefore, some external electrical parameters with significant variations can be regarded as monitoring parameters for evaluating IGBT aging.

The existing monitoring parameters can be divided into the following categories:

1. Current-based parameter: short-circuit current (I_s). In [15], the authors took the I_s as the monitoring parameter for bond wire aging. When the number of broken bond wires in the IGBT module gradually increases, the I_s will decrease accordingly. However, this method needs to inject current into the IGBT module, which is not suitable for online monitoring application scenarios.
2. Time-based parameter: turn-on time (t_{on}) and turn-off time (t_{off}). The authors in [16,17] calculated t_{on} by measuring the current and voltage waveforms during IGBT turn-on and monitor bond wire failures accordingly. The experimental results show that the t_{on} under the bond wire failure was shorter than that under the healthy state. In [18], the charging time of the gate capacitance was measured by injecting a small current during the IGBT turn-off period to monitor the health status of the bond wires. Since the switching time of the IGBT was in the range of 10–500 ns, the time-based parameters had extremely high requirements for the hardware measurement circuit.
3. Voltage-based parameter: gate voltage (V_g) and collector-emitter on-state voltage (V_{ce_on}). In [19], the V_{ge} was used to monitor the multi-chip parallel IGBT modules' health status. The experimental results showed that this method would not be affected by load current changes or noise caused by switching. However, only when all bond wires of a specific IGBT chip were broken did the V_{ge} change significantly. The application of this method was limited to multi-chip parallel IGBT modules, which are not universal. The authors of [20,21] cut the bond wire to simulate IGBT aging and monitor the IGBT health status by measuring V_{ce_on} online. The results indicated that V_{ce_on} could accurately identify the number of broken bond wires.
4. Temperature-based parameter: junction temperature (T_j) and thermal resistance (R_{th}). In [22], the case temperature (T_c) and junction temperature (T_j) were observed by thermocouples to calculate the R_{th} . When the R_{th} increased by 20%, the IGBT module failed. However, this method needs to invade the IGBT module package for measurement, which is not conducive to online monitoring. In [23], T_j was obtained by measuring the linear relationship between V_{ce_on} and T_j , whereas in [24], T_j was calculated by the turn-off overshoot voltage. It is worth noting that T_j cannot directly reflect the aging state of the IGBT, but it has a close coupling relationship with other parameters, which are called thermosensitive electrical parameters (TSEPs) [25,26]. Almost all the above monitoring parameters for bond wire are TSEPs.

Considering online monitoring capabilities, hardware cost, and measurement accuracy, V_{ce_on} is most suitable for monitoring the aging state of bond wires [27]. Although V_{ce_on} is very suitable as the IGBT monitoring parameter, the voltage between the collector and the emitter can be hundreds of times different when the IGBT is turned on and off at high speed, making it difficult to sample V_{ce_on} online and accurately. In [28], a sampling circuit based on the IGBT, current source, and voltage source is proposed. By modifying the converter's PWM control signal, different currents are injected into the converter during the window period to obtain V_{ce_on} . Although this sampling circuit can realize the online monitoring of the IGBT, it has a significant influence on the converter's working state. In [29], a sampling circuit based on the current source, diode, and MOSFET is proposed which indirectly measures V_{ce_on} by measuring the voltage at the test point. When the IGBT is on, the test point voltage is the sum of the diode conduction voltage drop, the resistance voltage drop, and the V_{ce_on} . When the IGBT is off, the MOSFET is turned on to shield the high voltage between the collector and the emitter. This sampling circuit also needs to inject current into the test circuit and indirectly measure the V_{ce_on} . All in all, the existing V_{ce_on} sampling circuit needs to inject current into the converter or modify the control signal, which will not affect the working state of the converter to varying degrees.

While V_{ce_on} has a strong correlation with bond wire aging, it also has a coupling relationship with T_j . During the operation of the photovoltaic, wind power, and new energy vehicles, T_j of the IGBT module changes all the time, which will interfere with the judgment of the bond wires' aging state. The existing method eliminates the interference of T_j by injecting current into the IGBT module [23,30], which will not be suitable for online monitoring. The authors of [31] calculated the equivalent resistance at the bonding area based on the offline measurement of V_{ce_on} and evaluated the health status of the independent IGBT module accordingly. Although this method considers the influence of T_j , it belongs to the field of IGBT offline reliability evaluation and does not provide a solution for online monitoring under actual working conditions. In general, the existing online monitoring methods are difficult for effectively eliminating the interference of T_j .

Motivated by the analysis described above, based on the voltage and current sampling circuit, this paper proposes an online monitoring method for the IGBT bond wire against T_j interference. The method proposed in this paper can non-intrusively monitor IGBT modules online, which can reduce unnecessary downtime for maintenance. The innovation of the sampling circuit is that it can obtain the full-period waveform of V_{ce_on} varying with the collector current (I_c) during the modulation period. The circuit cleverly utilizes the current flowing through the IGBT and the corresponding turn-on voltage drop during the IGBT working process, and it does not need to inject additional current into the circuit or modify the control signal to collect aging parameters. It obtains the intersection collector current (I_{int}) such that V_{ce_on} is not disturbed by T_j via the IGBT bond wire aging model and datasheet. Then, it compares the real-time sampling waveforms of I_c and V_{ce_on} to obtain the collector-emitter on-state voltage corresponding to I_{int} (V_{ce_int}). Finally, the bond wire aging state can be judged based on V_{ce_int} , which is not interfered with by T_j .

This paper is organized as follows. Section 2 establishes the aging model of the IGBT bond wire and selects the V_{ce_int} value as the aging parameter in combination with the datasheet. Section 3 illustrates the working principle of the sampling circuit and introduces the online monitoring process based on the sampling waveform. Section 4 takes a three-phase inverter as an example for experimental verification and uses the method proposed in this paper to monitor the bond wire aging under the interference of DC voltage and T_j . Section 5 draws the conclusions.

2. IGBT Bond Wire Aging Modeling

2.1. Bond Wire Aging Mechanism

The basic internal structure of the IGBT module is shown in Figure 1a. To meet the rated current requirements and improve the performance, the IGBT module is usually composed of multiple IGBT chips in parallel, in which the emitter and gate of the chip and the corresponding terminals need to be connected via bond wires. Due to the large CTE difference between aluminum and silicon materials, the thermal stress on the chip and the bond wire under the action of the temperature field is inconsistent, causing shear stress at the bonding area of the bond wire and the chip [32], which can be expressed as

$$\varepsilon = L \cdot (\alpha_1 - \alpha_2) \cdot \Delta T \quad (1)$$

where α_1 and α_2 are the CTE of the bond wire and the silicon chip, ΔT represents the temperature fluctuation, and L is the length of the bonding area between the bond wire and the silicon chip.

In the actual working process of the IGBT, the continuous thermal stress impact makes the bonding area age, and the specific manifestation is the bond wire's lift-off. As long as one of the bond wires in the IGBT module breaks first, the current passing through the remaining bond wires will increase and bear greater thermal stress impact, which will accelerate the failure of the IGBT device. Therefore, bond wire lift-off is one of the main modes of IGBT failure in practical engineering applications.

Figure 1. (a) The structure of the IGBT (insulated-gate bipolar transistor) module. (b) Equivalent model of the IGBT bond wires.

2.2. Bond Wire Aging Model

Since the V_{ce_on} of the IGBT module is affected by both aging and T_j , it is necessary to exclude the influence of T_j on the V_{ce_on} to accurately reflect the bond wire aging. In the actual operation of converters, it is difficult to accurately control and measure the internal T_j of the IGBT module, which makes it harder to determine whether the variation in the V_{ce_on} is caused by T_j or aging.

Taking the FF50R12RT4 half-bridge module as an example, the IGBT in the module contain six bond wires, as shown in Figure 1b. V_{ce_on} is affected by T_j and I_c in a healthy state [28], as shown in Equation (2):

$$V_{ce_on} = V_0 - k_1 \cdot (T_j - T_{j0}) + [R_0 + k_2 \cdot (T_j - T_{j0})] \cdot I_c \quad (2)$$

where V_0 and R_0 are the on-state voltage and on-state resistance of the IGBT at the reference junction temperature T_{j0} , respectively, and k_1 and k_2 are the temperature coefficients of V_0 and R_0 , respectively.

When the IGBT bond wires are broken due to thermal stress impact, R_0 will change, which will affect V_{ce_on} . The equation of V_{ce_on} under the bond wire aging is as follows:

$$V_{ce_on} = V_0 - k_1 \cdot (T_j - T_{j0}) + [R_0 + \Delta R + k_2 \cdot (T_j - T_{j0})] \cdot I_c \quad (3)$$

where ΔR represents the variation in the on-state resistance of the IGBT caused by the broken bond wire and $k_1 \cdot (T_j - T_{j0})$ is inversely proportional to $(T_j - T_{j0})$, whereas $[R_0 + \Delta R + k_2 \cdot (T_j - T_{j0})] \cdot I_c$ is directly proportional to $(T_j - T_{j0})$. The contribution of the former is negative, while the contribution of the latter is positive. There is a value I_{int} , where V_{ce_on} is not affected by the T_j . When $I_c = I_{int}$, V_{ce_on} at this time is called V_{ce_int} , as shown in Equation (4), where $k_1 \cdot (T_j - T_{j0})$ and $k_2 \cdot (T_j - T_{j0}) \cdot I_c$ cancel each other out and V_{ce_int} is only affected by $(R_0 + \Delta R) \cdot I_c$:

$$V_{ce_int} = V_0 - k_1 \cdot (T_j - T_{j0}) + (R_0 + \Delta R) \cdot I_c + k_2 \cdot (T_j - T_{j0}) \cdot I_c \quad (4)$$

Therefore, V_{ce_int} can accurately reflect the voltage drop change caused by the bond wire aging and is not affected by T_j , which can be regarded as the monitoring parameter of bond wire aging.

Referring to the datasheet of the FF50R12RT4 IGBT module, the typical values of I_{int} and V_{ce_int} can be obtained according to their output characteristic curves, as shown in Figure 2. When T_j is 25 °C, 125 °C or 150 °C, the output characteristic curve of the IGBT

module will have an intersection where $I_{\text{int}} = 12$ A. When $I_c = I_{\text{int}}$, $V_{\text{ce_int}}$ is not affected by T_j , which is consistent with the previous discussion.

Figure 2. IGBT output characteristic curve.

3. Online Monitoring of IGBT Bond Wire Aging

In this paper, a three-phase inverter is taken as an example to illustrate the working principle of the proposed anti-interference online monitoring method for bond wire aging. It will be explained in two parts: the sampling circuit and online monitoring.

3.1. Sampling Circuit

Although $V_{\text{ce_on}}$ is very suitable as an IGBT aging parameter, the voltage between the collector and the emitter can be hundreds of times different when the IGBT is turned on and off at a high speed, making it difficult to sample $V_{\text{ce_on}}$ online and accurately. The $V_{\text{ce_on}}$ sampling circuit utilized in this paper was implemented in three steps: clamping, filtering, and amplifying, as presented in Figure 3. Clamping refers to the high-voltage shielding between the collector and emitter during the turn-off period of the IGBT via the switching of two MOSFETs (M_1 and M_2). Take the U-phase upper leg IGBT (S1) as an example to explain the working principle. When S1 is turned on, M_1 is turned on so that the voltage sampling channel is turned on, thereby sampling $V_{\text{ce_on}}$. When S1 is turned off, M_2 is turned on, so the voltage sampling channel is clamped to the ground potential, thereby shielding the high voltage between collector and emitter. The specific control diagram is shown in Table 1.

Table 1. Voltage sampling circuit drive signal.

Switch	M_1	M_2	M_3	M_4
S1 on	1	0	0	0
S1 off	0	1	0	0
S2 on	0	0	1	0
S2 off	0	0	0	1

Figure 3. Working principle of the voltage and current sampling circuit.

Filtering is related to eliminating the noise contained in the waveform obtained after clamping by a second-order RC circuit, but it also produces a certain degree of attenuation. Amplification refers to the use of an operational amplifier to compensate for the waveform attenuation caused by the filter part, which ensures the accuracy of the sampled waveform. As for the current sampling part, Hall current sensors are used for synchronous sampling. The voltage and current waveforms obtained by the sampling circuit are presented in Figure 3. By comparing the waveforms, I_{int} and V_{int} can be further collected to prepare for condition monitoring.

3.2. Online Monitoring

Based on the above sampling circuit, this paper proposes an online monitoring method for IGBT bond wire aging, as illustrated in Figure 4. First, the voltage and current sampling circuits are used to collect the V_{ce_on} and I_c waveforms of the three-phase inverter system in real time. Second, considering the impact of fluctuations on the DC side or the load side on I_c , the amplitude of I_c is compared with that of I_{int} . Only when the amplitude of I_c is greater than I_{int} is the corresponding V_{ce_int} sampling performed. Then, V_{ce_int} is compared with the aging threshold to judge the aging state of the bond wires. Finally, when the aging state reaches the failure threshold set in advance, a failure warning is triggered to the control system. The measurement of the aging threshold will be described in detail in the next section.

Figure 4. Voltage and current sampling circuit.

4. Experiment and Result Analysis

In order to verify the effectiveness of the method proposed in this paper, an experimental platform for aging monitoring was built as presented in Figure 5, which included the DC power supply, three-phase inverter circuit, sampling circuit, thermostat, IR thermal imager, and control unit. The experimental parameter settings are listed in Table 2. It is worth noting that the voltage and current signals collected in this paper were input into RT-LAB for high-precision A/D conversion.

Table 2. Experimental platform parameter settings.

Parameters	Values
Switching frequency (f_{sw})	20 kHz
Output frequency (f)	50 Hz
IGBT module type	FF50R12RT4
IR type	Testo 865
Thermostat type	JF-966
Junction temperature (T_j)	25–75 °C
Number of broken bond wires	0–4
Resolution of ADC	16-bit
Gain band width of amplifier	4 MHz

Figure 5. Aging monitoring platform.

4.1. Sampling under DC Voltage Fluctuations

In the actual working process of the inverter, it will be subjected to electrical disturbances on the load or DC voltage side, which will cause I_c fluctuations. In order to prove that the sampling circuit could still maintain excellent working performance under this disturbance, this paper carried out relevant sampling under the condition of DC voltage fluctuation, as shown in Figure 6. It could be found that the V_{ce_on} waveform could follow the fluctuation of I_c , which indicates that the sampling circuit had good anti-interference performance. The red dotted line marks I_{int} and its corresponding V_{int} , which are the basis for subsequent condition monitoring.

In the case of $T_j = 25^\circ\text{C}$, V_{ce_int} was selected when the IGBT was fully healthy (V_{ce_int0}) as the healthy reference value. When 1–4 bond wires were broken (see Figure 7), the corresponding V_{ce_int} was sampled, and Equation (5) was used to calculate the deviation percentage of each aging stage (ΔV_{ce_int}), which was regarded as the aging indicator, as listed in Table 2. For subsequent comparison, this paper also measured the V_{ce_on} amplitude voltage (V_{ce_f0}) in the healthy state and calculated the deviation percentage of each aging stage (ΔV_{ce_f}) according to Equation (6), as listed in Table 3. The two dashed lines marked in Figure 7 are the health reference values. After measurement, V_{ce_int0} and V_{ce_f0} could be obtained as 1.05 V and 1.32 V, respectively:

$$\Delta V_{ce_int} = (V_{ce_int} - V_{ce_int0}) / V_{ce_int0} \quad (5)$$

$$\Delta V_{ce_f} = (V_{ce_f} - V_{ce_f0}) / V_{ce_f0} \quad (6)$$

Table 3. Aging threshold.

Number of Broken Bond Wires	Aging Threshold for V_{ce_int}	Aging Threshold for V_{ce_f}	Aging States
0	<0.57%	<0.68%	I
1	0.58–1.25%	0.69–1.14%	II
2	1.26–2.68%	1.15–2.58%	III
3	2.69–4.89%	2.59–4.86%	VI
4	>4.90%	>4.86%	V

Figure 6. (a) The waveform of I_c . (b) The waveform of V_{ce_on} .

Figure 7. Online monitoring results with different broken bond wires in the case of $T_j = 25^\circ\text{C}$.

4.2. Junction Temperature Interference

Taking three bond wires' lift-off as an example to illustrate the interference of T_j , the T_j of S1 was stabilized at 50 °C and 75 °C by adjusting the thermostat to simulate T_j fluctuations. In the above four cases, the V_{ce_on} waveform is shown in Figure 8. It can be found that the waveform near V_{ce_int} was not affected by T_j . V_{ce_int} did not deviate with the increase in T_j , which could accurately reflect the aging state of the bond wires. In addition, the waveform near V_{ce_f} was most disturbed by T_j . V_{ce_f} had a significant deviation as V_{ce_f} increased, and the maximum deviation reached 60 mV. In summary, selecting V_{ce} as the aging indicator could achieve resistance to the interference of T_j .

Figure 8. Online monitoring results with different junction temperatures.

4.3. Aging Monitoring Results

In order to show that the monitoring method proposed in this paper could eliminate the interference of T_j , in the case of $T_j = 75$ °C, the sampling circuit was used to measure V_{ce_on} under different bond wire aging stages, as shown in Figure 9. Using Equations (5) and (6), the aging index of each aging stage was calculated. The aging indicators with the previously determined aging threshold (see Table 3) were compared to judge the current aging state, as shown in Table 4.

Figure 9. Online monitoring results with different broken bond wires in the case of $T_j = 75\text{ }^{\circ}\text{C}$.

Table 4. Aging monitoring results in the case of $T_j = 75\text{ }^{\circ}\text{C}$.

Number of Broken Bond Wires	V_{ce_int} (V)	ΔV_{ce_int}	V_{ce_f} (V)	ΔV_{ce_f}
0	1.052	0.19%, I	1.397	5.83%, V
1	1.059	0.86%, II	1.402	6.21%, V
2	1.068	1.71%, III	1.412	6.97%, V
3	1.085	3.33%, IV	1.429	8.26%, V
4	1.111	5.81%, V	1.462	10.76%, V

When T_j rose from $25\text{ }^{\circ}\text{C}$ to $75\text{ }^{\circ}\text{C}$, V_{ce_int} had a slight deviation compared with V_{ce_int0} , but ΔV_{ce_int} could still accurately reflect the current aging state. On the contrary, V_{ce_f} had a large deviation compared with V_{ce_f0} , and ΔV_{ce_f} was far away from the current aging state. For example, when the IGBT was in aging stage II, ΔV_{ce_int} was 0.86%, which was judged as aging state I according to the aging thresholds. However, ΔV_{ce_f} was 6.21%, which was misjudged as aging stage V.

In order to compare the aging monitoring results more intuitively, different color blocks in Figure 10 are used to indicate the different aging stages. It can be clearly seen that the monitoring results based on ΔV_{ce_int} could accurately distinguish each aging stage, while the monitoring results based on ΔV_{ce_f} deviated far from the actual situation. In general, V_{ce_int} had good resistance to the interference of T_j . For this three-phase inverter system, when the monitoring circuit detected that the aging indicator exceeded 4.90%, the aging state of the IGBT bond wire was judged as stage V. At this time, a shutdown maintenance signal was triggered in the control system.

Figure 10. Comparison of aging monitoring results.

5. Conclusions

The aging parameter V_{ce_int} , which is not affected by T_j , is obtained by combining the IGBT aging model and the datasheet. Moreover, V_{ce_int} is collected in real time to judge the aging state of the IGBT bond wire by comparing the I_c and V_{ce_on} waveforms. Different from the existing method, this method cleverly utilizes the current flowing through the IGBT and the corresponding turn-on voltage drop during the IGBT working process, and it does not need to inject additional current into the circuit or modify the control signal to collect the aging parameters. In addition, the anti-interference online monitoring method proposed in this paper can reduce downtime for maintenance.

The experimental results output by RT-LAB prove that the method proposed in this paper can judge the aging state of the IGBT bond wire in the three-phase inverter under the condition of DC voltage disturbance and junction temperature disturbance. It is worth noting that this paper only introduced this method's application in a three-phase inverter system, and it also applies to other power electronic converters.

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