An Aging-Degree Evaluation Method for IGBT Bond Wire with Online Multivariate Monitoring

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Abstract: The aging fracture of bonding wire is one of the main reasons for failure of insulated gate bipolar transistor (IGBT). This paper proposes an online monitoring method for IGBT bonding wire aging that does not interfere with the normal operation of the IGBT module. A quantitative analysis of aging degree was first performed, and the results of multivariate and univariate monitoring were compared. Based on the relationship between the monitoring parameters and the aging of the IGBT bonding wire, gradual damage of the IGBT bond wire was implemented to simulate aging failure and obtain the aging data. Moreover, the change of junction temperature was considered to regulate monitoring parameters. Then, the aging degree was evaluated by an artificial neural network (ANN) algorithm. The experimental results showed the effectiveness of the proposed method.

Keywords: IGBT bond wire; aging-degree evaluation; online multivariate monitoring; neural network

1. Introduction

In modern industrial systems, power semiconductor devices have become increasingly indispensable. They are widely used in electric locomotive traction, aerospace, industrial automation, transportation, new energy generation, and so on. Power switching devices as the core components of electronic devices are becoming increasingly important [1–3]. Among them, insulated gate bipolar transistors (IGBTs) are the most widely used power switching devices in the industrial field. As one of the most inefficient devices in power converters [4,5], IGBT failure is mainly caused by the breakage and shedding of bond wires due to aging [6]. In order to improve the reliability of power converters, it is necessary to monitor the state of the IGBT module and study the aging process.

The health management and condition monitoring methods for IGBTs have been widely studied and discussed. The mainstream research can be divided into two categories. The first category is IGBT life assessment technologies. Here, life analysis models, such as the Coffin–Manson model [7], the Norris–Landzberg model [8], and the Bayerer model [9], have been proposed. In addition, physical models of finite element simulation analysis based on different physical properties of materials have also been proposed to more accurately analyze the change in stress [10]. The second category is the IGBT condition monitoring technologies. Gate voltage oscillations are monitored to analyze the relationship between bond wire degradation and high frequency response. The k-nearest neighbor algorithm based on the cycle aging of power is explored to evaluate its health status through power characteristics such as $V_{\text{ce(on)}}$ [11]. Moreover, training data is used to evaluate the weight factor of each feature according to the statistical feature weighting method. The accuracy of the optimized classification is analyzed to estimate the remaining life [12]. In addition, the rupture of the bond wire can be clearly monitored by eddy current pulse thermal imaging, which requires the application of
additional measuring equipment on the IGBT module and may affect the normal operation of the IGBT module [13]. The saturation conduction voltage drop $V_{ce,sat}$ [14–16] and the bond wire equivalent resistance $R_j$ [17] are also often used for the detection of bond wire shedding as well as monitoring of the IGBT turn-off time as a symptom of the latch-up effect [18]. These techniques cannot quantitatively analyze the loss rate of the IGBT bond wire and may affect the normal operation of the IGBT in the application.

In view of the above discussion, an online monitoring and evaluation method based on multivariable IGBT bond wire aging is proposed in this paper. An IGBT aging test bench and monitoring system was built to realize online evaluation of the aging state of IGBT bond wire. First, the failure mechanism of IGBT was analyzed theoretically. Then, the relationship between IGBT’s conduction voltage drop $V_{ce}$, Miller platform voltage $V_{ge}$, Miller platform duration $t_{ge}$, and bond line aging was evaluated. Through the gradual destruction of the IGBT bond wire, the aging failure of the IGBT bond wire was simulated. Meanwhile, $V_{ce}$, $V_{ge}$, and $t_{ge}$ at different degrees of aging were obtained. Then, the relationship between junction temperature and the three parameters was established through experiments. Junction temperature correction was performed after standardizing the three parameters at different temperatures. Finally, an artificial neural network (ANN) algorithm was used to evaluate and monitor the current aging degree of IGBT bond wires.

2. Characteristics Analysis of IGBT Aging Mechanism

2.1. IGBT Failure Mechanism

The key parameter to assess the degree of system performance degradation is reliability, and the life cycle of a power device is determined by the module failure mechanism. Therefore, the power device failure mechanism is the basis of state evaluation [3].

A fully packaged IGBT module is a multilayer structure with different materials packaged together, as shown in Figure 1.

![Figure 1. Diagram of insulated gate bipolar transistor (IGBT) cross-sectional structure.](image)

Each material increases in volume to a certain extent after being heated, also known as thermal expansion. The coefficient characterizing this property is called the coefficient of thermal expansion. Each layer is composed of a different material, and the coefficient of thermal expansion is also different. The difference in thermal expansion coefficient of the aluminum bonding wire and the solder layer is large. In actual work, the on-state loss and switching loss of the IGBT cause the junction temperature of the device to rise. The material of each layer expands, and the device cools to shrink the materials of each layer. Different thermal expansion coefficients lead to different degrees of expansion of different materials during temperature cycling. Therefore, different materials are subjected to different compressive or tensile stresses, so the thermomechanical stress inside the IGBT is generated by the power cycle. These thermal stresses cause repeated impacts on the material joints of the various layers within the IGBT module, especially the bonding of the bond wires to the chip and the solder layer.
In the end, the joints, such as the solder layer, the bonding wires, and the terminal pads, are directly damaged, causing fatigue of the solder layer, cracking, crack growth, and even delamination of the layers, voids, and bonding wires, causing the module to fail [19].

2.2. Influence of Aging of IGBT Bond Wire on Turn-On Voltage

The IGBT module used in this study was Infineon FF225R17ME4. This module is similar to most existing IGBT structures. A diagram of the opened IGBT module is shown below in Figure 2.

The IGBT module comprises a whole IGBT bridge arm and two IGBT submodules. Each submodule has three modules in which one IGBT chip and one diode chip are connected in antiparallel, and each IGBT chip has four bond wires. A direct cutting IGBT bond wire can be used to simulate the aging of IGBT bond wire and ensure an effective simulation of IGBT bond wire failure [20].

The equivalent circuit diagram of IGBT is shown in Figure 3, where \( L_g \) and \( R_g \) are the equivalent inductance and resistance of the bonding wire, respectively; \( L_j \) and \( R_j \) are the gate parasitic inductance and parasitic resistance, respectively; \( C_{ge} \) is the gate-emitter parasitic capacitance; and \( C_{gc} \) is the gate-collective parasitic capacitance, where \( C_{gc} = C_{gdj} + C_{oxd} \).

![Figure 2. The opened IGBT module.](image)

![Figure 3. Equivalent circuit diagram of IGBT.](image)
When the IGBT is fully turned on, the mathematical expression of the turn-on voltage drop $V_{ce}$ is as follows:

$$V_{ce} = V_{pn} + V_{drift} + I_c R_j$$

(1)

The $V_{pn}$ (pn junction voltage drop of the IGBT) and the $V_{drift}$ (conduction voltage drop of the drift region) remain substantially unchanged when the IGBT is fully turned on, and the bond line equivalent resistance $R_j$ gradually becomes larger as the bonding wire ages and breaks. The IGBT turn-on voltage drop rises, with the emitter current $I_c$ not changing.

2.3. Influence of Aging of IGBT Bond Wires on Miller Plateau Voltage and Its Duration

Due to the existence of gate parasitic capacitance, the gate voltage of the IGBT is determined by the charge and gate capacitance, which is given by

$$U = \frac{Q}{C}$$

(2)

When the IGBT is turned on, the change in gate voltage is not linear but rather a multistage process. The changing process of gate voltage $U_{ge}$ during the turn-on process is shown in Figure 4.

Figure 4. The gate voltage $U_{ge}$ changing process.

At point A, $U_{ge}$ rises when the gate capacitance $C_{ge}$ is charged, and $U_{ge}$ rises exponentially, affected by the gate capacitance $C_{ge}$. At point B, $U_{ge}$ reaches the flatband voltage $U_{fb}$, and part of the $C_{ge}$ capacitor, called metal-oxide-semiconductor (MOS) capacitor, no longer affects charging, which is equivalent to the reduction of $C_{ge}$ at this time; the slope of $U_{ge}$ rises faster than the AB segment. Up to point C, the gate voltage exceeds the threshold voltage $U_{ge(to)}$, at which point the IGBT begins to conduct. In the CD segment, the charging process of the gate is affected by $C_{ge}$. During this time, the IGBT starts to conduct, the collector–emitter voltage $U_{ce}$ decreases continuously, the current $I_{ge}$ discharges to the gate through $C_{ge}$, and the discharge current needs the driving current $I_{drive}$ to compensate. At this point, a constant voltage appears at the gate, and this voltage is called the Miller platform voltage. In the DE segment, the drive current charges the gate to point E, and the IGBT is fully turned on to saturation; the turn-on voltage is the saturation voltage $U_{ce-sat}$. Figure 5 shows the gate voltage and the collector–emitter current and the collector–emitter voltage when the IGBT is actually turned on. We can see that the actual voltage change and conduction process are in good agreement with our analysis, which also confirms the correctness of our analysis process.
The expression of the gate equivalent capacitance is as follows:

\[ C = C_{\text{surface of the gate polysilicon and the P well region, including gate polysilicon from the source N^+ region, including gate polysilicon from the source N^+ region, including}} \]

The effect of aging of the IGBT bond wire on the gate equivalent capacitance was analyzed. A concrete diagram of the internal structure of the gate equivalent capacitor \( C_{\text{ge}} \) and the feedback capacitor \( C_{\text{ce}} \) of the IGBT is shown in Figure 6.

Thus, the Miller platform voltage \( V_m \) and the Miller platform duration \( t_m \) are determined by the gate equivalent capacitance \( C_{\text{ge}} \) and the feedback capacitance \( C_{\text{ce}} \) (also called Miller capacitance). The specific mathematical expression of the gate equivalent capacitance \( C_{\text{ge}} \) is usually composed of two parts. One part overlaps the gate polysilicon from the source \( N^+ \) region, including \( C_{\text{oxs}} \) and \( C_s \), and another part overlaps the top surface of the gate polysilicon and the P well region, including \( C_{\text{oxc}} \) and \( C_c \). The specific mathematical expression of the gate equivalent capacitance is as follows:

\[ C_{\text{ge}} = \frac{C_{\text{oxs}} C_s}{C_{\text{oxs}} + C_s} + \frac{C_{\text{oxc}} C_c}{C_{\text{oxc}} + C_c} \]  \hspace{1cm} (3)

with

\[ C_{\text{oxs}} = \varepsilon_0 \varepsilon_{\text{oxs}} \frac{A_{\text{ges}}}{t_{\text{oxge}}} \]  \hspace{1cm} (4)

\[ C_{\text{oxc}} = \varepsilon_0 \varepsilon_{\text{oxc}} \frac{A_{\text{ge}}}{t_{\text{oxc}}} \]  \hspace{1cm} (5)
where \( A_{ges} \) and \( A_{gec} \) represent the area of the gate polysilicon overlapping the source N+ region and the P-well region, respectively; \( t_{oxge} \) is the thickness of the oxide between them; and \( \varepsilon_o \) and \( \varepsilon_{ox} \) are the dielectric constant and conductivity of the oxide, respectively. In the IGBT chip, the breakage caused by the aging of the bond wire leads to the decreasing of \( A_{ges} \) and \( A_{gec} \), and this causes a decrease in \( C_{oxa} \) and \( C_{oxc} \), even leading to a decrease in \( C_{ge} \).

The gate-collector capacitance, that is, the Miller capacitance \( C_{ce} \), is composed of a gate oxide capacitor \( C_{oxd} \) and a depletion layer capacitor \( C_{dep} \) in series. The specific mathematical expression is as follows:

\[
C_{gc} = \frac{C_{oxd}C_{dep}}{C_{oxd} + C_{dep}}
\]

with

\[
C_{oxd} = \varepsilon_o A_{ai}
\]

\[
C_{dep} = \frac{\varepsilon_{ai} A_{ai}}{W}
\]

where \( C_{ox} \) is the oxide capacitance per unit area; \( A_{ai} \) is the area between the cells in the die; and \( W \) is the length of the oxide depletion region. As analyzed previously, the breakage caused by the bonding wire aging causes the \( A_{ai} \) and \( W \) to decrease, which causes the gate oxide capacitance \( C_{oxd} \) to decrease and the depletion layer capacitance \( C_{dep} \) to change, thereby causing the Miller capacitance \( C_{ce} \) to change.

Based on the above analysis, we can find that the gate equivalent capacitance \( C_{ge} \) and the Miller capacitance \( C_{ce} \) change with the IGBT bond wire aging and breakage, therefore affecting the Miller platform voltage \( V_m \) and the Miller platform duration \( t_m \).

3. Accelerated Aging Experiment of IGBT Bonding Wire

3.1. Design Aging Experiment and Parameter Acquisition

An IGBT aging test bench and monitoring system were built. The schematic diagram is shown in Figure 7. The main circuit consisted of a programmable DC power supply, a resistive load, and an IGBT. The drive circuit was composed of a function generator, an IGBT driver board, and a patch cord. The IGBT driver board could only drive the IGBT by setting the driving frequency in the function generator. The monitoring system consisted of a probe, a voltage sensor, a current sensor, a high-precision oscilloscope, and a host computer. The parameters used are shown in Table 1.

Figure 7. Process diagram of monitoring and analysis.
The aging failure in the IGBT operation by gradual damage to the IGBT bond wire (cutting the IGBT bond wire one by one) was simulated. Then, the electrical parameters under the online operation, which included the conduction voltage drop $V_{ce}$, Miller platform voltage $V_m$, Miller platform duration $t_m$, and temperature $T$, were separately recorded in different IGBT aging conditions. The physical diagram is shown in Figure 8.

Nearly 90% of the simulation data for several IGBTs was used to establish the neural network relationship, while the rest was applied for verification of the method. As the actual waveform had voltage fluctuations, the actual voltage value and the average conduction voltage drop $V_{ce}$ and the Miller platform voltage $V_m$ in one cycle was collected into the computer so as to get more reliable experimental data.

Figure 9 shows the effect of breakage of the bond wire, with each broken bond line indicating a 25% increase in bond aging. It can be seen the Miller plateau voltage gradually reduced, and the Miller platform duration also gradually reduced. This is because the bond wire breakage affected the change of the IGBT gate equivalent capacitance. The course changed as the process was affected. The specific structure of an IGBT is complicated, and it is difficult to quantitatively analyze the influence of bonding wire aging on Miller platform voltage value and Miller platform duration. Therefore, in this study, the neural network model was used for subsequent data processing to deal with this relationship.

The average value of $V_m$ in one cycle was taken as the actual value of the IGBT Miller platform voltage in the current state, thereby effectively reducing the measurement error. The IGBT turn-on voltage, the true value of the Miller platform voltage, and the Miller platform duration in the different states are shown in Table 2. It can also be seen from the table that the true value of the Miller platform voltage is the same as our analysis.
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![Waveform Diagrams](https://via.placeholder.com/150)

**Figure 9.** $U_{ge}$, $I_{ce}$, and $V_{ce}$ waveforms with different IGBT bond line losses: (a) bond wire without loss; (b) bond wire after one break; (c) bond wire after two breaks; (d) bond wire after three breaks; (e) comparison of $U_{ge}$ with different IGBT bond line losses.

The above treatment was similarly performed on the turn-on voltage drop $V_{ce}$. Figure 10 shows the change in $V_{ce}$ with the bond wire, while Figure 11 gives a comparison of $V_{ce}$ in different states. The actual value of $V_{ce}$ in one cycle was averaged as the true value of the IGBT turn-on voltage in the current state. It can also be seen from Table 2 that the true value of the turn-on voltage is the same as our analysis.
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The actual value of $V_{ce}$ in one cycle was averaged as the true value of the IGBT turn-on voltage in different states are shown in Table 2. It can also be seen from the table that the true value of the turn-on voltage is the change in $V_{ce}$ with the bond wire, while Figure 11 gives a comparison of $V_{ce}$ at different IGBT bond wire losses: (a) bond wire without loss; (b) bond wire after one break; (c) bond wire after two breaks; (d) bond wire after three breaks.

**Figure 10.** Waveform of $V_{ce}$ at different IGBT bond wire losses: (a) bond wire without loss; (b) bond wire after one break; (c) bond wire after two breaks; (d) bond wire after three breaks.

| Number of Bond Wire Breaks $n$ | 0          | 1          | 2          | 3          |
|-------------------------------|------------|------------|------------|------------|
| Bond wire loss rate $R_l$     | 0          | 25%        | 50%        | 75%        |
| $V_m/V$                       | 10.5191    | 10.4233    | 10.3277    | 10.2074    |
| $t_m/\text{ns}$              | 520        | 490        | 480        | 470        |
| $V_{ce}/V$                    | 2.094117   | 2.165013   | 2.256523   | 2.29834    |

**Figure 11.** Comparison of $V_{ce}$ in different states.

### Table 2. Actual value of $V_m$, $V_{ce}$, and $t_m$ at different IGBT bond wire losses.

3.2. Junction Temperature Conversion Experiment

As the IGBT operates under different working conditions, the internal junction temperature of the IGBT is different, and the change of the temperature causes the internal resistance of the IGBT to change. Therefore, the on-voltage drop $V_{ce}$, the Miller platform voltage $V_m$, and the Miller platform duration $t_m$ of the IGBT vary depending on the junction temperature, which affects predictions. In order to
avoid this effect, the IGBT was placed in an incubator to establish the relationship between the junction temperature of the IGBT at different temperatures and the on-state voltage drop $V_{ce}$, the Miller platform voltage $V_m$, and the Miller platform duration $t_m$. When the data was processed, the $V_{ce}$, $V_m$, and $t_m$ at the current temperature were corrected, and the data obtained at different temperatures were equivalent to the data monitored at the same temperature, thus avoiding the influence of the junction temperature fluctuation on the experimental results.

The change in the IGBT turn-on voltage drop $V_{ce}$ in the same state at different temperatures was measured, as shown in Figure 12. It can be seen that there was a significant change in the conduction voltage drop $V_{ce}$ at different temperatures. In addition, it is obvious that, as the temperature rose, the IGBT turn-on voltage drop $V_{ce}$ gradually increased. However, because there was a certain voltage fluctuation when the IGBT was turned on, preliminary processing was performed on the $V_{ce}$ before fitting the relationship between the conduction voltage drop $V_{ce}$ and the IGBT junction temperature. The actual data was then collected into the computer. The $V_{ce}$ of the on-period was averaged as the actual value of the IGBT turn-on voltage drop at the current temperature. The results are shown in Table 3.

![Vce comparison chart at different temperatures](image)

**Figure 12.** Comparison of $V_{ce}$ at different temperatures.

**Table 3.** Actual value of $V_{ce}$ at different temperatures.

| $T$ (°C) | $V_{ce}$ (V) |
|----------|--------------|
| 20       | 2.078        |
| 30       | 2.1369       |
| 40       | 2.3595       |
| 50       | 2.4195       |
| 60       | 2.4085       |
| 70       | 2.5261       |
| 80       | 2.5132       |
| 90       | 2.6008       |

It can be clearly seen that, as the temperature rose, the IGBT conduction voltage drop also increased. We made a function fit of the junction temperature and the tube pressure drop. Figure 13 is a fitted graph, and the fitting results were as follows:

$$V_{ce} = 0.0072T + 1.9855$$  \(9\)
was basically unchanged with the IGBT junction temperature, which means that $U_{m}$ was made usable for different IGBT monitoring by standardizing $V_{ce}$ at 20 °C at different temperatures. The relationship between the conduction voltage drop and the temperature after the standardization at different temperatures was obtained. Table 4 is the data of the conduction voltage drop $V_{ce}$ after the standardization, and Figure 14 is the fitting map after the standardization. The fitting results were obtained as follows:

$$V_{ce}^* = 0.0035T + 0.9555$$  \hspace{1cm} (10)

| $T$ (°C) | $V_{ce}^*$ |
|-----------|------------|
| 20        | 1          |
| 30        | 1.0605     |
| 40        | 1.0955     |
| 50        | 1.1155     |
| 60        | 1.1655     |
| 70        | 1.2005     |
| 80        | 1.2355     |

Table 4. Comparison of $V_{ce}$ at different temperatures.

![Figure 13](image1.png)

**Figure 13.** A function fitting diagram of $V_{ce}$ and $T$.

Because IGBTs have different conduction voltages $V_{ce}$ at the same temperature, the fitting data was made usable for different IGBT monitoring by standardizing $V_{ce}$ at 20 °C at different temperatures. Meanwhile, the change of gate voltage $U_{ge}$ at different temperatures is illustrated in Figure 15. It is obvious that $U_{ge}$ was basically unchanged with the IGBT junction temperature, which means that $U_{ge}$ was basically unaffected by the change in IGBT junction temperature. The literature [20,21] also shows that the Miller platform voltage is not affected by the IGBT junction temperature. Considering the fact that $V_{m}$ is not affected by the IGBT temperature, taking the average value of $V_{m}$ at different temperatures as the actual value of $V_{m}$, as shown in Table 5, it is clear that $U_{ge}$ has no relationship with junction temperature.
Table 4 shows the correspondence between $V_{ce}$* and $T$ at a partial temperature. Meanwhile, the change of gate voltage $U_{ge}$ at different temperatures is illustrated in Figure 15. It is obvious that $U_{ge}$ was basically unchanged with the IGBT junction temperature, which means that $U_{ge}$ was basically unaffected by the change in IGBT junction temperature. The literature [20,21] also shows that the Miller platform voltage is not affected by the IGBT junction temperature. Considering the fact that $V_m$ is not affected by the IGBT temperature, taking the average value of $V_m$ at different temperatures as the actual value of $V_m$, as shown in Table 5, it is clear that $U_{ge}$ has no relationship with junction temperature.

![Figure 15. Comparison of $U_{ge}$ at different temperatures.](image)

**Table 5. Table of actual values of $V_m$ as a function of temperature.**

| $T$ (°C) | $V_m$ (V)     |
|---------|--------------|
| 30      | 11.08953     |
| 40      | 11.08679     |
| 50      | 11.1175      |
| 60      | 11.07855     |
| 70      | 11.07898     |
| 80      | 11.0616      |

4. The Method of Monitoring IGBT Bond Wire Aging

4.1. Artificial Neural Networks

With the increasing speed of the CPU, more and more neural network structures are used to solve the mapping relationship between parameters. In this study, through theoretical analysis and experimental conclusions, it was found that there is a relationship between the saturation conduction voltage drop $V_{ce}$ of the IGBT, the Miller platform voltage $V_m$, the Miller platform time $t_m$, and the bond line equivalent resistance $R_j$. As mentioned above, the breakage of the bonding wire affects the change of the equivalent capacitance of the IGBT gate, which causes the conduction process to be affected and changed. This law of variation is nonlinear, and it is difficult to quantitatively analyze the influence of bond line aging on Miller platform voltage value and Miller platform duration. It is meaningful to use the ANN structure to establish the corresponding relationship. Therefore, there is a need to fully analyze the specific relationship between the gate voltage $U_{ge}$ and the degree of bond line loss when IGBT is turned on.

As shown in Figure 16, by substituting the test result data after the junction temperature correction and the standardization experiment, the saturation conduction voltage drop $V_{ce}$ of the IGBT, the Miller platform voltage $V_m$, and the Miller platform time $t_m$ were set as the input layer. The bond wire loss rate $R_{loss}$ was set to the output layer, and the ANN correspondence was established by setting a reasonable activation function $f(x)$ in the neural network toolbox. After establishing the neural network
structure, the current IGBT bond wire loss rate could be calculated by inputting the result obtained from online monitoring of the IGBT.

Figure 16. Structural diagram of artificial neural network (ANN).

4.2. Establishment of Multivariate Parameters and Bond Line Aging

Due to the small gap in the actual production of IGBTs, even if the internal equivalent electrical parameters of the same type of IGBT have small gaps, it is necessary to standardize the on-voltage drop $V_{ce}$, Miller platform voltage $V_m$, and Miller platform duration $t_m$ in order to make the neural network widely usable in the monitoring of similar types of IGBTs. The standard value of the standardization was taken as the value when the bonding wire had no loss. Then, using the relationship between the conduction voltage drop and the temperature established in the study, the conduction voltage drop $V_{ce}$ was corrected at the current junction temperature and uniformly converted to a value at a junction temperature of 20 °C. Four IGBT bond wires were used in the study. Using the bond wire loss rate $R_{loss}$ to quantify the current IGBT bond wire loss degree, the loss rate $R_{loss}$ was 0% when the bond wire was intact, 25% when the bond wire broke once, 50% when the bond wire broke twice, and 75% when the bond wire broke three times. Table 6 shows the data before the standardization, and Table 7 shows the data after the standardization. Table 8 gives a comparison of the data before and after the junction temperature conversion.

| IGBT Bond Wire Loss Rate | $T$  | $V_{ce}$ (V) | $V_m$ (V) | $t_m$/ns |
|--------------------------|-----|-----------|---------|--------|
| 0%                       | 20 °C | 1.875     | 10.5     | 510    |
| 25%                      | 20 °C | 2.1125    | 10.375   | 490    |
| 50%                      | 20 °C | 2.1375    | 10.25    | 480    |
| 75%                      | 20 °C | 2.1625    | 10.125   | 470    |

Table 6. Data before standardization.

| IGBT Bond Wire Loss Rate | $T$  | $V_{ce^*}$ | $V_m^*$ | $t_m^*$ |
|--------------------------|-----|-----------|--------|--------|
| 0%                       | 20 °C | 1         | 1      | 1      |
| 25%                      | 20 °C | 1.1266    | 0.98809| 0.96078|
| 50%                      | 20 °C | 1.1412    | 0.97619| 0.94117|
| 75%                      | 20 °C | 1.1533    | 0.96428| 0.92157|

Table 7. Data after standardization.
**Table 8.** Comparison of the data before and after the junction temperature conversion.

| Temperature $T$ (°C) | 40   | 50   | 60   | 70   | 80   |
|----------------------|------|------|------|------|------|
| loss rate $R_{loss}$ | 25%  | 25%  | 25%  | 25%  | 25%  |
| Actual value of $V_{ce}$ (V) | 2.12752 | 2.17454 | 2.20122 | 2.26553 | 2.29866 |
| $V_{ce}$ converted value (V) | 1.91205 | 1.92938 | 1.88864 | 1.87930 | 1.86051 |

Finally, the processed training set data was input to the ANN, and iterative training was performed to establish a corresponding neural network. It can be seen from the results that the accuracy of the neural network correspondence can be verified using a training set.

**4.3. Verification of Results**

In order to verify the effectiveness of the proposed method after establishing the corresponding neural network, the processed verification data was input into the neural network, and the monitored value results and the actual results were output, as shown in Table 9 and Figure 17. From the results, it can be seen that the monitored value results are very close to the theoretical value results, which indicates that the proposed method in this paper is effective.

**Table 9.** Comparison of monitored and actual values.

| $R_{1a}$ (Actual Value of $R_{loss}$) | $R_{1p}$ (Predicted Value of $R_{loss}$) | Prediction Error | $R_{1a}$ (Actual Value of $R_{loss}$) | $R_{1p}$ (Predicted Value of $R_{loss}$) | Prediction Error |
|--------------------------------------|----------------------------------------|-----------------|--------------------------------------|----------------------------------------|-----------------|
| 25%                                  | 26.20%                                 | 1.20%           | 50%                                  | 58.26%                                 | 8.26%           |
| 75%                                  | 73.57%                                 | 1.43%           | 50%                                  | 44.91%                                 | 5.09%           |
| 25%                                  | 27.04%                                 | 2.04%           | 75%                                  | 73.36%                                 | 1.64%           |
| 50%                                  | 47.52%                                 | 2.48%           | 50%                                  | 54.72%                                 | 4.72%           |
| 75%                                  | 75.16%                                 | 0.16%           | 75%                                  | 74.42%                                 | 0.58%           |
| 25%                                  | 26.12%                                 | 1.12%           | 25%                                  | 25.87%                                 | 0.87%           |

**Figure 17.** Diagram comparing the monitored and actual values.

**4.4. Comparison between Univariate Monitoring and Multivariate Monitoring**

A single variable was used to evaluate the aging of IGBT bond wires, and the corresponding results were compared to that of the multivariate monitoring method.
When using the univariate $V_{ce}$ to evaluate the aging degree of the IGBT bond wire, the function fitting method was directly adopted, and Figure 18 shows the corresponding result. The fitting result is as follows:

$$R_{\text{loss}} = 47.1734V_{\text{ce}}^2 - 97.4118V_{\text{ce}} + 50.2347 \quad (11)$$

![Figure 18. Fitted function between the univariate $V_{ce}^*$ and $R_{\text{loss}}$.](image1)

Similarly, the fitted functions between the univariate $V_m$ and the IGBT bond wire loss rate $R_{\text{loss}}$ as well as that between $t_m$ and $R_{\text{loss}}$ were adopted, and the results are presented in Figures 19 and 20, respectively. The fitting results are as follows:

$$R_{\text{loss}} = -17.10514V_m + 17.1346 \quad (12)$$

$$R_{\text{loss}} = -10.79154t_m + 10.6517 \quad (13)$$

![Figure 19. Fitted function between the univariate $V_m^*$ and $R_{\text{loss}}$.](image2)
Implementing the function of Equations (11)–(13), the estimated value of the IGBT bond wire loss rate were calculated and accordingly compared to the actual value. A comparison between the estimated value and the actual value in terms of the IGBT bond wire loss rate is given in Table 10. Additionally, it can be observed from Tables 10–12 that the average monitoring errors were $\Delta e_1 = 17.24\%$, $\Delta e_2 = 7.72\%$, and $\Delta e_3 = 11.52\%$, respectively.

Table 10. Comparison of the estimated and actual values (using the univariate $V_{ce}$).

| $R_{l-a}$ (Actual Value of $R_{loss}$) | $R_{l-p}$ (Predicted Value of $R_{loss}$) | Prediction Error | $R_{l-a}$ (Actual Value of $R_{loss}$) | $R_{l-p}$ (Predicted Value of $R_{loss}$) |
|--------------------------------------|------------------------------------------|-----------------|--------------------------------------|------------------------------------------|
| 25%                                  | 36.38%                                   | 11.38%          | 50%                                  | 47.72%                                   |
| 75%                                  | 63.45%                                   | 38.45%          | 75%                                  | 63.45%                                   |
| 25%                                  | 32.65%                                   | 7.68%           | 25%                                  | 30.56%                                   |
| 50%                                  | 88.13%                                   | 63.13%          | 50%                                  | 52.42%                                   |
| 75%                                  | 59.52%                                   | 34.52%          | 75%                                  | 63.45%                                   |
| 25%                                  | 38.00%                                   | 13.00%          | 25%                                  | 30.40%                                   |

Table 11. Comparison of monitored and actual values (using the univariate $V_{m}$).

| $R_{l-a}$ (Actual Value of $R_{loss}$) | $R_{l-p}$ (Predicted Value of $R_{loss}$) | Prediction Error | $R_{l-a}$ (Actual Value of $R_{loss}$) | $R_{l-p}$ (Predicted Value of $R_{loss}$) | Prediction Error |
|--------------------------------------|------------------------------------------|-----------------|--------------------------------------|------------------------------------------|-----------------|
| 25%                                  | 23.32%                                   | 1.68%           | 50%                                  | 43.68%                                   | 6.32%           |
| 75%                                  | 64.05%                                   | 10.95%          | 75%                                  | 64.05%                                   | 10.95%          |
| 25%                                  | 38.72%                                   | 13.72%          | 25%                                  | 40.43%                                   | 15.43%          |
| 50%                                  | 50.45%                                   | 0.45%           | 50%                                  | 47.10%                                   | 2.90%           |
| 75%                                  | 74.31%                                   | 0.69%           | 75%                                  | 64.05%                                   | 10.95%          |
| 25%                                  | 23.32%                                   | 1.68%           | 25%                                  | 41.97%                                   | 16.97%          |
Table 12. Comparison of monitored and actual values (using the univariate \( t_m \)).

| \( R_{\text{la}} \) (Actual Value of \( R_{\text{loss}} \)) | \( R_{\text{lp}} \) (Predicted Value of \( R_{\text{loss}} \)) | Prediction Error | \( R_{\text{la}} \) (Actual Value of \( R_{\text{loss}} \)) | \( R_{\text{lp}} \) (Predicted Value of \( R_{\text{loss}} \)) | Prediction Error |
|---------------------------------|---------------------------------|----------------|---------------------------------|---------------------------------|----------------|
| 25%                             | 28.34%                          | 3.34%          | 50%                             | 49.51%                          | 0.49%          |
| 75%                             | 49.51%                          | 25.49%         | 75%                             | 70.66%                          | 4.34%          |
| 25%                             | 70.66%                          | 45.66%         | 25%                             | 31.58%                          | 6.58%          |
| 50%                             | 26.19%                          | 23.81%         | 50%                             | 59.87%                          | 9.87%          |
| 75%                             | 72.92%                          | 2.08%          | 75%                             | 70.66%                          | 4.34%          |
| 25%                             | 28.34%                          | 3.34%          | 25%                             | 33.85%                          | 8.85%          |

The average error \( \Delta e \) was 2.47% when multivariable was used to evaluate the aging degree of IGBT bond wires, which is significantly lower than that of the univariate evaluation, indicating that multivariate monitoring was more accurate.

5. Conclusions

On the basis of analyzing the aging of IGBT bond wire in relation to on-voltage \( (V_{\text{ce}}) \), Miller plateau voltage \( (V_{\text{m}}) \), and Miller platform duration \( (t_m) \), an online monitoring method with ANN is proposed in this paper for evaluating the degradation of IGBT bond wires. Before ANN was constructed with \( V_{\text{ce}}, V_{\text{m}}, t_m \), and IGBT bond wire loss rate, \( V_{\text{ce}}, V_{\text{m}}, \) and \( t_m \) were subjected to standardization and junction temperature correction so that the method could be suitable for online monitoring of bond wire aging for different types of IGBTs. The main conclusions of this study are as follows: (1) As the IGBT bond wire aged and broke (the bond wire loss rate increased), its turn-on voltage increased, the Miller plateau voltage decreased, and the Miller platform duration decreased. (2) The monitored value of the IGBT bond wire loss rate obtained by the proposed method was close to the actual value, and the average error was 2.47%, which indicates that the method is feasible and effective. The reliability of an electronic device can be improved by avoiding failure of the entire device due to IGBT failure. This requires pre-identification of the aging degree of IGBT bond wire. In this regard, the method presented in this paper allows replacement of the IGBT module before module failure. When using this method in future works, if the actual aging of the IGBT bond wire is obtained, the result will be more reliable and more realistic. At the same time, monitoring the aging of other locations of the IGBT module is also required. In addition, considering the turn-off voltage and current to evaluate the aging degree of IGBT bond wire is open to further research.

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