Improved IGBT Dynamic Model and Electro-Thermal-Mechanical Multi-Field Coupling Failure Analysis

Jianbo Zhou 1*, Yigang He 1, Jiacheng Liu 1, Huadong Ni 1, Zhangsheng Peng 1

1 School of Electrical Engineering and Automation, HeFei University of Technology, HeFei, Anhui, 230000, China

*Corresponding author’s e-mail: 977846734@qq.com

Abstract. Failure of insulated gate bipolar transistors (IGBTs) can make a serious impact on the entire rectification or inverter system. IGBTs are used in different practical applications, causing a large difference in the form of failure of its solder layer. Therefore, it is necessary to study the aging failure law of IGBT solder layer. Firstly, the improved IGBT dynamic model is used to build a three-phase rectifier circuit and correct its circuit power consumption error. Then constructing three-dimensional finite element model of IGBT and analyzing its chip temperature and solder layer stress distribution under electro-thermal-force multiphysics coupling. Finally, the randomly generated solder layer defects are used to investigate the effects of voids, cracks, etc. on solder layer failure, and the aging failure mechanism of the solder layer is obtained. The simulation results show that after the solder layer defect area ratio is higher than 15%, solder layer voids, cracks and shedding have a significant effect on chip junction temperature and solder layer stress. Among them, shedding and cracks have a greater influence on the stress of the solder layer.

1. Introduction
Insulated Gate Bipolar Transistors (IGBTs) combine the advantages of MOSFETs and BJTs, which is widely used in new energy, high-speed rail, military industry, etc [1-3]. In these occasions, the application environment of the device should be harsh, and the device is required to have high reliability[4]. At present, there is a large error in the IGBT dynamic model[5]. The IGBT physical analysis is closely related to the environmental stress field of the actual application scenario, so specific modeling analysis is required for different applications. IGBT power consumption is the main cause of its chip heating[6]. The calculation accuracy of power consumption directly determines the accuracy of IGBT junction temperature and stress field distribution[7]. At present, the calculation of power consumption is mainly based on mathematical modeling. The simulation of chip temperature mainly includes Foster model, Cauer model and 3D finite element thermal simulation. The IGBT module consists of seven layers[8]. Due to the different thermal expansion coefficients between the layers, under the action of the thermal cycle emitted by the device chip, the fragile parts such as the solder layer and the bonding wire are detached, plastically strained[9], resulting in a gradual failure. Studies have shown that the development of solder layer cracks starts from the corners and gradually spreads toward the center of the solder layer[10-11].

At first, using the dynamic IGBT model to simulate the working process of a real IGBT device by extracting the datasheet of the 6MBI300V-120-50 IGBT. The solder layer voids and cracks were then studied under the premise of studying normal thermal stress. The results show that the improved
dynamic model has a significant improvement in the prediction of IGBT switching losses. Electro-thermal-mechanical simulations using improved models are also more accurate.

2. Correction of IGBT Dynamic Model

2.1. IGBT dynamic model

The IGBT dynamic model considers both the static and dynamic characteristics of the device. Compared with the traditional model that only considers the static characteristics, the simulation results of the dynamic model are more accurate and reliable. The IGBT dynamic model built using the device data sheet is shown in Figure 1:

![Figure 1. correction curve of dynamic switching process.](image)

IGBT dynamic model consists of three parts: IGBT electrical model, oscillation cancellation circuit, and the reverse diode electrical model. The values of the resistors, inductors and capacitors in the circuit are available in the data sheet. In the model, the saturation voltage drop of the FET is \( V_{sat} \):

\[
I_{sat} = \frac{K}{2} (V_{GS} - V_P)^{N_{\text{FET}}}
\]  

Where: \( K \) is the transistor temperature and \( N_{\text{FET}} \) is the transfer characteristic index of the FET. Normally, the current \( I_D \) can characterize the current of the FET under different states, and the \( I_D \) can be used for the calculation of the collector current.

When the device is in the linear region, the FET’s continuous leakage current is:

\[
I_D = I_{sat} (1 + V_{DS} \cdot KML)(2 - \frac{V_{DS}}{V_{sat}}) \frac{V_{DS}}{V_{sat}}
\]  

(2.2)

When the device is in the saturation region, the FET’s continuous leakage current is:

\[
I_D = I_{sat} (1 + V_{DS} \cdot KML)
\]  

(2.3)

Where: \( I_{sat} \) is the FET drain current, \( V_{DS} \) is the drain voltage of the FET, and \( KML \) is the channel length modulation factor of the FET.

The IGBT collector current \( I_C \) is the key to power dissipation. Its direction is shown by the arrow in Figure 1, and its value can be obtained by formula (2.4). \( I_B \) is the FET reference current and is typically taken as \( I_B = I_D \). \( I_B \) can also be obtained by equation (2.5):

\[
I_C = I_B BN
\]  

(2.4)

\[
I_B = I_{sat} \left[ \frac{V_{GE}}{e^{(V_{GS} - V_{Bsat})/RT}} - 1 \right]
\]  

(2.5)
Where: BN is the gain of BJT at the rated temperature, VT is the turn-on voltage at the rated temperature, and M_BJT is the BJT ideal factor at the rated temperature.

The behavioral region of the IGBT dynamic model is differentiated. If the difference between the voltage drift portion and the junction voltage is equal to zero, there is a dynamic process, this process can be expressed by equation (2.6):

\[
SHIFT \cdot V_{DIFF} = V_{JNCT}' = 0
\]  

Where: SHIFT is the voltage drift factor, VDIFF is the diffusion voltage, and VJNCT is the junction voltage.

In order to suppress abnormal oscillations that may occur in the circuit, a damping resistor is introduced, which is calculated as:

\[
R_{DAMP} = DAMPING \sqrt{\frac{L}{C(V)}}
\]  

Where: DAMPING is the damping coefficient, which is related to DAMPING_R and DAMPING_C, DAMPING_C is the capacitance damping factor, and DAMPING_R is the resistance damping factor. L is the parasitic inductance of the oscillation circuit, and C(V) is the internal capacitance of the oscillation circuit.

2.2. Improve IGBT dynamic model

Since the measurement of power determines the accuracy of the electro-thermal-mechanical simulation, it is necessary to correct the IGBT dynamic model. The main cause of IGBT power consumption error is the dynamic partial offset of the turn-on and turn-off voltage and current. By studying its dynamic model, the main factors affecting the switching characteristics of the IGBT switching characteristics are the driving resistance and the parasitic capacitance inside the device. This paper corrects its current and voltage.

\[
\begin{align*}
I_c & = BN \cdot I_B + \frac{\alpha \cdot C_{be} \cdot t^2 + \beta \cdot R_g \cdot t + m}{t^2 + q \cdot t + p} \quad , \quad t < t_0 \quad \text{or} \quad t > t_1 \\
I_c & = BN \cdot I_B \quad , \quad \text{others}
\end{align*}
\]  

\[
\begin{align*}
V_{ce}' & = V_{ce} + \frac{\gamma \cdot C_{ge} \cdot t^2 + \eta \cdot C_{ge} \cdot t + n}{t^2 + q \cdot t + p} \quad , \quad t < t_0 \quad \text{or} \quad t > t_1 \\
V_{ce}' & = V_{ce} \quad , \quad \text{others}
\end{align*}
\]  

Dynamic correction of the turn-on and turn-off voltage values of the IGBT by Equations (2.8) and (2.9), t0, t1 is the start time of the dynamic process \(\alpha, \beta, \gamma, \eta\) are respectively correction factors, which are obtained by extracting and fitting the opening waveform parameters. Cge is the drive circuit capacitor, Rg is the collector drive resistor, and q, p are the matching coefficients in the correction.

Figure 2. Experimental test platform.

Figure 3. Comparison of experimental results.
Figure 2 shows the dynamic process of turn-on and turn-off of IGBT voltage and current. Figure 3 is the experimental test platform. $I_{c\_sim}$ is the traditional dynamic model current simulation waveform, $I_{c\_test}$ is the measurement value of datasheet, $I_{c\_improve}$ is the improved simulation waveform. The improved dynamic model greatly reduces its dynamic error in the dynamic process of the power module. Under the test conditions of module 200V/400A, the error of the traditional model reaches more than 10%. The improved dynamic model is within 5%, and the improved model has better accuracy.

3. Finite Element Model

Device stress analysis experiments under actual working conditions are often difficult, and the use of three-dimensional finite element simulation can solve the problem of device stress analysis. When the IGBT is working, the power consumption of the chip will cause the device to heat up. Due to the different coefficients of thermal expansion between the layers of the IGBT, thermal stresses are generated between the layers of the device under the action of the temperature field.

The package structure of the IGBT in Fig. 4 is composed of a plurality of layers of materials. From top to bottom are: IGBT chip and diode chip, solder layer, upper layer copper, aluminum oxide, underlying copper, solder layer and copper substrate. The 6MBI300V-120-50 IGBT module contains 6 IGBT chips and 6 diode chips. Among them, T1~T6 are IGBT chips, and D1~D6 are diode chips. The package size determines the range of simulation boundary conditions and multiphysics coupling, and the size parameters can be obtained from the data sheet. and the IGBT size parameters are shown in Table 1 [10].

![Figure 4. Structure of IGBT package.](image)

Table 1. Material properties.

| IGBT struct       | Size (mm) | IGBT struct       | Size (mm) |
|-------------------|-----------|-------------------|-----------|
| Chip of IGBT      | 11×11×0.10| Upper Cu          | 45×35×0.38|
| IGBT layer        | 11×11×0.08| Al₂O₃             | 45×35×0.30|
| Chip of Diode     | 9×9×0.10  | Lower copper      | 45×35×0.37|
| Diode layer       | 9×9×0.08  | Solder layer      | 45×35×0.23|
| Cu Base           | 120×50×2.9|                   |           |

The chip heat flux is obtained by equation (3.1):

$$H = \frac{P_L}{V}$$

(3.1)

Where: $H$ is the heat flux, $P_L$ is the power consumption, and $V$ is the chip area. The total power consumption $P_L$ is composed of the on-power consumption $P_{on}$, the off-power consumption $P_{off}$, and the on-state loss $P_{oth}$. In order to simulate the working process of the device, it is also necessary to consider the thermal insulation of the device housing. In order to simulate the working process of the device, it
is also necessary to consider the thermal insulation of the device housing. The length, width, and height (i.e., IGBT casing package size) of the three-dimensional finite element simulation boundary are set to 120 mm, 50 mm, and 14 mm, respectively. A fixed constraint is applied to the four corners of the copper substrate, and the periphery of the substrate is set to the Z-direction constraint, that is, the displacement \( u_z = 0 \). The ambient temperature is set to 25 °C, the forced convection coefficient of the bottom surface of the copper substrate is set to \( 4000 \text{W/m}^2 \cdot \text{K} \), and the forced convection coefficient of the four sides of the copper substrate is set to \( 20 \text{W/m}^2 \cdot \text{K} \), and the other side of the device is set to thermal insulation to simulate the heat dissipation between the device and the air.

4. Simulation Experiment and Result Analysis

In order to analyze the failure law in the practical application of IGBT, the IGBT dynamic model is applied to the rectifier circuit. The three-phase rectification system is composed of main circuit, communication module and control module. Among them, the main circuit is built in Simpler, the control module is built in Simulink, and the communication module in Simpler realizes the communication between the main circuit and the control circuit. The parameters of the main circuit components are shown in Table 2:

| Component       | Value       | Component       | Value   |
|-----------------|-------------|-----------------|---------|
| Power supply voltage | 400V        | DC voltage      | 1200V   |
| Power resistance | 0.0068Ω     | Load resistance | 30Ω     |
| Power Inductor  | 0.0023H     | Bus Capacitance | 3mF     |

The power simulation results are shown in Figure 5. Figure 5 (a) shows the phase waveform of the rectifier circuit A. The phase A voltage amplitude is 400V and the current amplitude is 156A. At the beginning of the simulation, the capacitor charging causes the DC bus voltage to rise. After the bus voltage value increases to 1280V, it begins to drop and finally stabilizes at 1200V. Figure 5 (b) shows the IGBT turn-off process. The current fluctuation is large during the IGBT turn-off dynamic process, and the integral of the current and voltage product is the IGBT turn-off power consumption. Figure 5 (c) shows the device turn-on voltage and current. During the turn-on process, the voltage fluctuates greatly. The integral of the product of voltage and current is its turn-on power consumption. Figure 5 (d) shows the total power consumption of the IGBT and the diode. The peak power consumption of the IGBT is 300W. The capacitor charging effect causes the peak power consumption at the beginning of the simulation to be much larger than other times, which will cause a large thermal shock to the device in actual work. The diode consumes a peak power of 150W. The average power consumption of the IGBT and the diode can be obtained by integrating the instantaneous power consumption: 108.8W and 88.5W, respectively. The heat flux per unit volume of the IGBT chip and the diode chip obtained by the formula (3.1) is 9.36 W/mm³ and 11.5 W/mm³, respectively.

(a) Voltage and current of phase A and voltage of DC bus. (b) IGBT turn-off waveform.
5. IGBT Stress Distribution

In this paper, transient thermo dynamic analysis is selected. The simulation results are shown in Figure 6 and 7.

- Figure 6. Total deformation of IGBT.
- Figure 7. Chip solder layer stress distribution.

The total deformation of the IGBT is obtained by simulation as shown in Figure 6. The deformation of the device is elliptical, and the elliptical center has the largest deformation, which is 12.49μm. The edge deformation of the copper substrate is the smallest, close to 0μm. When the IGBT is subjected to a large temperature impact, the ceramic substrate may be broken due to deformation. As can be seen from the figure 7, the stress gradually decreases from the outside to the inside, the maximum stress of the solder layer is distributed at the edge of the solder layer, and the minimum point is distributed at the center of the solder layer.

6. Conclusion

This paper is mainly based on the modified dynamic model, analysis of IGBT electric-thermal-mechanical multi-physics coupling failure analysis based on dynamic model. It can be concluded as follow: 1) Comparing the simulation results, it can be seen that the improved dynamic model can significantly reduce the power consumption solution error, and the accuracy of the thermal resistance solved by the modified power consumption is significantly improved. 2) The solder layer shedding has the greatest effect on the chip temperature. There is an intersection point between the influence of crack and cavity on the temperature of the chip. Before the intersection, the effect of the cavity on the temperature of the chip is greater. After the intersection, the influence of the cavity on the temperature of the chip increases rapidly. Solder layer cracks and shedding should be taken into account in practical use compared to solder layer voids. 3) Solder layer cracks and shedding usually occur at the edge of the solder layer. Under the same proportion of defects, the solder layer falling off has the greatest influence on the solder layer stress, and the stress increase caused by the aging cracking of the solder layer is more serious than the solder layer void.
Acknowledgements
This work was supported by the National Natural Science Foundation of China under Grant No. 51577046, the State Key Program of National Natural Science Foundation of China under Grant No. 51637004, the national key research and development plan "important scientific instruments and equipment development" Grant No.2016YFF0102200, Equipment research project in advance Grant No.41402040301.

References
[1] Wang LJ, Xu JY, Wang G, et al. (2018) Lifetime estimation of IGBT modules for MMC-HVDC application, Microelectronics Reliability, 82: 90-99.
[2] Wu Zhihong, Su Xiezu, Zhu Yuan. (2018) IGBT junction and coolant temperature estimation by thermal model, Microelectronics Reliability, 87: 168-182.
[3] Wei Lai, Minyou Chen, Li Ran, et al. (2017) Experimental Investigation on the Effects of Narrow Junction Temperature Cycles on Die Attach Solder Layer in an IGBT Module, IEEE Transactions on Power Electronics, 32(2): 431-1441.
[4] Tanya Kirilova Gachovska, Bo Tian, Jerry L. Hudgins A, et al. (2015) Real-Time Thermal Model for Monitoring of Power Semiconductor Devices, IEEE Transactions On Industry Applications, 51(4): 3361-3367.
[5] Rui Wu, Huai Wang, Kristian Bonderup Pedersen, et al. (2015) A Temperature-Dependent Thermal Model of IGBT Modules Suitable for Circuit-Level Simulations, IEEE Transactions On Industry Applications, 52(4): 3304-3314.
[6] Ze Wang, Wei Qiao. (2016) A Physics-Based Improved Cauer-Type Thermal Equivalent Circuit for IGBT Modules, IEEE Transactions On Power Electronics, 31(10): 6781-6786.
[7] Ze Wang, Bo Tian, Wei Qiao. (2016) Real-Time Aging Monitoring for IGBT Modules Using Case Temperature, IEEE Transactions On Industrial Electronics, 63(2): 1168-1178.
[8] Vladimir Székely, Mártia Rencz. (2015) Thermal Dynamics and the Time Constant Domain, IEEE Transactions On Components Packaging And Manufacturing Technology, 23(3): 587-594.
[9] Bin Du, Jerry L. Hudgins, Enrico Santi, et al. (2010) Transient Electro-thermal Simulation of Power Semiconductor Devices. IEEE Transactions On Power Electronics, 25(1): 237-248.
[10] Angus Bryant, Nii-Adotei Parker-Allotey, et al. (2012) A Fast Loss and Temperature Simulation Method for Power Converters, Part I: Electrothermal Modeling and Validation, IEEE Transactions On Power Electronics, 21(1): 248-257.
[11] CHRISTOPHE Batard, NICOLAS Ginot, JOE Antonios. (2018) Lumped Dynamic Electrothermal Model of IGBT Module of Inverters, IEEE Transactions On Components Packaging And Manufacturing Technology, 5(3): 355-364.