Accelerated Aging Experiment of IGBT under Pulsed Power and Reliability Studies

Yinhao Mao\(^{1,*}\), Zhaolong Sun\(^{1}\), Zhifang Yuan\(^{1}\) and Xiaochen Pan\(^{1}\)

\(^{1}\)Naval University of Engineering, Wuhan, Hubei Province, 430033, China

*Corresponding author’s e-mail: wangfb@ahjzu.edu.cn

Abstract. Pulsed power technology gives full play to the characteristics of high pulses in the form of short pulses, and gradually occupies a certain position in industrial applications. It needs to ensure stability and durability while ensuring that the working parameters are met, the switching performance is particularly important. Therefore, the reliability study of IGBT power module becomes an inevitable requirement for reliability evaluation in engineering. This article mainly introduces the experimental method of the accelerated aging experiment of IGBT under pulsed power conditions. The electro-thermal simulation is carried out through PLECS and the low-power experimental platform is built to obtain experimental data. Finally, the experimental data is analyzed, and the change rule of the failure characteristic parameters with the aging process under the pulse power condition and the IGBT failure standard different from the typical operating condition are obtained.

1. Introduction

Pulsed power technology has a wide range of applications in the field of national defense scientific research and civil industry due to its ability to generate strong current pulses. Therefore, improving the stability, reliability and repeatability of pulsed power sources is one of the main tasks of pulsed power technology. In the pulsed power system, its overall performance is mostly determined by the switching element [1], so the reliability of the pulsed power system depends on the reliability of the switching element to a great extent.

At present, most of the papers on IGBT reliability focus on the typical working conditions of IGBT operating in the safe working area. Literature [2] summarizes and analyzes the failure mechanism and failure representation modes of IGBT under stable working conditions and the accelerated aging methods. The power cycle accelerated aging method and failure precursor parameters are summarized, and the general steps of accelerated aging test are proposed. Literature [3-5] introduced the change trend of IGBT saturation voltage drop with the accelerated aging test process, and concluded that the saturation voltage drop gradually increased with the aging process of the device, but did not fully consider the effect of junction temperature and other factors on the saturation voltage drop influences. Literature [6] summarized and analyzed the common failure representation modes of high-power devices. However, IGBT reliability studies under the special condition of pulsed power are not common.

This article mainly elaborates the accelerated aging experiment of IGBT under pulsed power, builds a low-power experiment platform, introduces the equivalence of the experiment topology, the choice of control strategy, and the determination and measurement of aging characteristic quantities. Finally, the experimental data is analyzed and compared with the failure criterion obtained under normal operating conditions.
2. Theoretical analysis

2.1. Accelerated aging test topology determination

It can be seen from the working principle of the electromagnetic launching system that the instantaneous pulse of the electromagnetic launching device is extremely large. The inverter device in the energy storage system is very important to the realization of pulsed power. The essence of the energy storage system inverter device is a variable-frequency transformer. The variable frequency device with speed regulation function can drive or brake the energy storage motor with a smaller power. It adopts a modular design scheme of large-capacity multilevel power electronic converter, the circuit topology is shown in Figure 1 [7].

![Figure 1](image.png)

Figure 1. Energy storage system contravariant circuit topology

For the above diode-clamped H-bridge cascaded hybrid nine-level topology, in order to make the IGBT module on the accelerated aging test platform consistent with the actual working conditions as much as possible, the platform will choose the AC accelerated aging scheme. The power level of the IGBT in the application is relatively high. If the actual working condition of the IGBT is simulated in the experiment, it is not appropriate from the economic level or the safety level. Therefore, the derating is performed according to the principle of consistent packaging and reduced power.

Considering that poor current sharing will cause unnecessary interference to the aging results of the module, the strategy of multiple IGBT modules in redundant parallel connection will not be used. This simplification has no effect on the aging research at the device level. The basic module of the cascaded multilevel topology is a diode-clamped three-level circuit, the electrical and thermal stresses of each group of modules are similar. Considering more realistic working conditions, a diode-clamped three-level circuit can be used to build an aging platform. According to the calculation, the maximum value of the variable voltage and variable frequency output voltage in the three-level topology is greater than 450V in this article, but the DC power supply stand-alone voltage output value is 450V or less, and the procurement cost of power supply series and parallel connection is too high. Based on engineering considerations, the three-level topology cannot be selected without derating the platform, therefore, the traditional H-bridge inverter shown in Figure 2 was used for the experiment.

![Figure 2](image.png)
In order to ensure the same failure mechanism, the method adopted in this paper is to ensure the same stress on the device level, that is, the voltage and current stress on the IGBTs in the two topologies are the same. Since there are four IGBTs at the same time for the nine-level to bear the bus voltage, and only one IGBT for the two-level bears the bus voltage, the voltage stress to the nine-level is four times that of the two-level, and the current stress is the same.

2.2. Control Strategy

Two-level inverter mainly includes DC side buffer capacitor, H-bridge topology, LC filter and RL load. The inverter chooses the SPWM modulation method. Like ordinary inverters, SPWM modulation is divided into unipolar modulation and bipolar modulation. Compared with unipolar modulation and bipolar modulation, the former is selected after research. The reason is that the bus current of bipolar modulation will change in the same magnitude and reverse direction every time the switch changes. Because of the parasitic inductance in the bus line, during the IGBT commutation process, the parasitic inductance current of the busbar will be forced to commutate, and the parasitic inductance will generate a high parasitic voltage and the busbar voltage will be superimposed on the IGBT to form an overshoot voltage, which may cause overvoltage breakdown of the IGBT. One of the ways to reduce the overshoot voltage is to change the modulation method to reduce the rate of change of the busbar current. Among them, the unipolar frequency doubling modulation method can reduce the bus current change rate by one time.

2.3. Selection and measurement of aging characteristics

How to choose the characteristic parameters that can identify the device failure and accurately measure it is very important. The aging characteristic quantity refers to the characteristic quantity that the measured parameter changes with the upcoming failure [8]. Through the monitoring and identification of the characteristic parameter, the influence of prediction and corresponding measures can be taken to reduce its influence [9].

Taking packaging reliability as the research object, the failure of IGBT is mainly due to the mismatch of thermal expansion coefficients of different materials in the multilayer vertical structure, fatigue aging and plastic deformation of the material caused by repeated temperature fluctuations and impacts. The main manifestations are the peeling and fracture of the bonding line and the cracks, cavities, metallization reconstruction of the material layer [10].

2.3.1. Failure of aluminum bonding wire

The essence of the bonding wire is actually the current-carrying conductor inside the IGBT module. When the bonding wire decays, it is mainly manifested as the key foot cracking, the bonding wire falling off, etc. The most obvious parameter is the saturation voltage drop of the IGBT chip [11-13]. Therefore, this article takes IGBT saturation voltage drop as one of the characteristic quantities to evaluate the IGBT state. The IGBT saturation voltage drop measurement circuit uses a measurement circuit that can isolate the high voltage of the DC bus, as shown in Figure 3.

![H-bridge topology](image-url)
Figure 3. IGBT saturation voltage drop measurement circuit

Its working principle is as follows:

1. When the IGBT is turned off, the high withstand voltage fast recovery diode is reversely blocked to isolate the DC bus side voltage to protect the $V_{ce}$ acquisition circuit;

2. When the IGBT is turned on, the output voltage of the operational amplifier is:

$$V_{out1} = V_{ce1}$$

$$V_{out2} = -V_{ce2}$$

Considering that the IGBT collector-emitter saturation voltage drop is temperature sensitive, it is not only related to the aging state, but also to the junction temperature, so it is necessary to keep the junction temperature the same each time when measuring the saturation voltage drop.

When the IGBT flows through a specific small current (such as 100mA), the collector-emitter saturation voltage drop has a very good linear relationship with the junction temperature [14,15]. When this method is used to measure the junction temperature, it is necessary to pass a small current, the experiment sequence diagram is shown in Figure 4.

![Experimental sequence diagram](image)

Figure 4. Experimental sequence diagram

The accelerated aging experiment is carried out on the IGBT module, which is divided into an aging stage and a measurement stage, in which heating current is passed through the aging stage, and a small current is passed through the measurement stage. The aging stage takes "a group of contravariant" as
the working unit, after 50 sets of contravariant are continuously carried out and the heat is dissipated to the reference temperature, the aging stage is ended, and the small current junction temperature is measured in the measurement stage to ensure that the collector-emitter saturation voltage drop is the same measured at junction temperature.

2.3.2. Solder layer failure
Solder layer fatigue is also the main failure mechanism of IGBT devices[16-19]. It is most likely to occur in the solder layer between the substrate and the bottom plate, because the thermal expansion coefficient difference of the interface material is the largest here. If there is a bubble defect in the solder layer between the chip and the substrate, it is also easy to occur cracking of the solder layer.

The solder layer is located below the IGBT chip and above the package substrate. When the solder layer cracks or appears voids, since the thermal resistance of the air is much greater than the solder layer, the thermal conduction between the IGBT chip and the IGBT module substrate will be blocked to different degrees. The junction-case thermal resistance of IGBT can effectively reflect the degradation of this thermal circuit, so the junction-case thermal resistance of IGBT is used as the second characteristic quantity to evaluate the IGBT state.

The junction-to-case thermal resistance measurement of the IGBT module will be followed by the saturation voltage drop measurement.

The measurement scheme of the junction-to-case thermal resistance of the IGBT module is as follows: First, heat the IGBT module and the heat sink according to the control strategy shown in Figure 5.

\[
T_{j\_\text{meas}}^n(i) = \frac{\sum_{j=1}^{n} T_{j\_\text{meas}}(j)}{n}
\]

In this process, the junction temperature and the case temperature of the module are continuously measured similar to the measurement of the saturation voltage drop. Equation 3 calculates the standard deviation of the historical shell temperature.

\[
T_{\text{STDDEV}} = \sqrt{\frac{\sum_{i=1}^{n} T_{j\_\text{meas}}^2(i) - \left(\frac{\sum_{j=1}^{n} T_{j\_\text{meas}}(j)}{n}\right)^2}{n}}
\]  

(3)

According to JESD51 standard, When the standard deviation is less than \(K_{\text{TCrit}} = 0.042\), the system is considered to be in thermal steady state. After entering the thermal steady state, the IGBT module, heat sink and environment form a thermal network as shown in Figure 6.
Collect $V_{ce}$ and the heating current $I_h$ to calculate the heating power $P_H = V_{ce} \times I_h$, and calculate the junction-to-case thermal resistance of the IGBT module according to the thermal resistance definition equation 4. The junction temperature $T_j$ and case temperature $T_c$ are measured by the measurement circuit.

$$R_{th \_jc} = \frac{T_j - T_c}{P_H} \approx \frac{T_j - T_{hsx}}{P_H} \tag{4}$$

2.4. Failure criterion

The selection of the aging characteristics of IGBT modules is diverse. Most of the researches are based on the saturation voltage drop of the collector-emitter and the junction-case thermal resistance. However, the failure standards of the aging characteristics in the existing research have not been unified, and the commonly used failure standards as shown in the table 1[20].

| Aging characteristics          | symbol | Failure criterion |
|--------------------------------|--------|------------------|
| saturation Voltage drop        | $V_{ce}$ | 5%               |
| junction-case thermal resistance | $R_{th \_jc}$ | 20%             |

3. Simulation and experiment

3.1. Simulation and conclusion

In order to guide the systematic design of the experimental platform better, it is necessary to perform basic electrical and thermal stress analysis on the AC aging experimental platform to help to locate the weaker IGBT modules in the topology for subsequent targeted analysis. In this paper, with the help of the power electronics simulation software PLECS, the system-level electric and heating co-simulation of the entire inverter system is carried out.

Based on the device manual, the conduction loss, switching loss and thermal circuit of the IGBT module were modeled, and the model was imported into PLECS for analysis. The junction temperature data of the IGBT with the greatest temperature stress is shown in Figure 7.
The following conclusions can be obtained through simulation in Figure 8: the IGBT module has a significant temperature rise in the low frequency band of the output, and the temperature rise is large (above 50 degrees Celsius), which is the main factor affecting the life of the IGBT. The upper tube is more stressed than the lower tube in the same bridge arm.

Analysis of experimental results, after the platform was built, the IGBT module was subjected to aging test, and the aging characteristic quantity test data is shown in Figure 9,10. On the whole, the number of module failure cycles is about 6000 (each aging cycle contains 50 groups of contravariant), which are relatively similar and the aging characteristics of the module have obvious changes during the life cycle. The overall degradation process of the upper tube is far more obvious than that of the lower tube, which is consistent with the conclusion of the simulation analysis.

Figure 7. Junction temperature waveform

Figure 8. Comparison of losses IGBT in same bridge arm

Figure 9. Saturation voltage drop degradation data
Analyzing Figure 10, it is found that the saturation voltage drop rises slowly in the first and middle stages of aging, showing a linear law, while in the later stage of aging, the saturation voltage drop immediately fails after a sudden rise. This is because the IGBT single tube is composed of two chips "paralleled". The aging causes the bonding wires on the chip to fall off one by one, and the saturation voltage drop increases. When all the bonding wires on a chip fall off, it is equivalent to some if the chip is no longer flowing, the currents of the two IGBT chips converge on one chip, causing the saturation voltage drop to rise sharply. Obviously, after this happens, the bonding wire on the only remaining IGBT chip will quickly fall off (or burn out) due to the inability to withstand the high current stress and cause the IGBT to fail.

Table 2. Change of IGBT characteristic quantity

| Aging characteristics | \( V_{ce} \) Starting value | \( R_{\text{in}, \text{jc}} \) Starting value | \( V_{ce} \) Final value | \( R_{\text{in}, \text{jc}} \) Final value | Variation | Variation |
|-----------------------|-----------------------------|---------------------------------|------------------------|------------------------|-----------|-----------|
| Upper IGBT            | 1.421V                      | 0.432K/W                        | 1.478V                 | 0.517K/W               | 3.99%     | 19.44%    |
| Lower IGBT            | 1.417V                      | 0.449K/W                        | 1.434V                 | 0.469K/W               | 1.23%     | 4.32%     |

Analyzing experimental data in Table 2 found that for the saturation voltage drop, there is an increase of about 3%-4% during the aging cycle; for the thermal resistance of the junction case, there is an increase of about 19% during the aging cycle. The saturation voltage drop and the rate of change of the junction-case thermal resistance at the time of failure did not meet the commonly used failure standards. This may be due to the temporary decrease of the internal insulation performance of the IGBT module under the high stress cycle of the pulse power special working condition.

4. Conclusions
This article proposes a reliability evaluation method for the reliability of IGBTs under special conditions of pulse power. The reliability of IGBTs is evaluated by using the aging characteristic parameters in the process of module degradation, and the conclusion that the common failure criteria are not applicable under this special condition is obtained. Secondly, a low-power experimental platform was built to provide an effective means for the next step of life prediction.

References
[1] Jiang W. Repetition rate pulsed power technology and its applications:(vi) Typical applications[J]. Qiangjiguang Yu Lizishu/High Power Laser and Particle Beams, 2014, 26(3).
[2] LI Yaping, ZHOU Luowei, SUN Pengju. Review of Accelerated Aging Methods for IGBT Power Modules[J]. Journal of Power Supply, 2016: 122-135.
[3] V. A. Sankaran, C. Chen, C. S. Avnat, X. Xu. Power cycling reliability of IGBT power modules[C]. IEEE Industry Application Society Annual Meeting, pp: 1222-1227.

[4] M. Held, P. Jacob, G. Nicoletti, P. Scacco, M. H. Poeh. Fast power cycling test for IGBT modules in traction applications[C]. International Conference on Power Electronics and Drive Systems, 1997, vol.1, pp: 425-430.

[5] A. Ouakour, B. Tala-Ighil, B. Poudereux, M. Tounsi, M. Bouarroudj-Berkani, S. Lefebvre, B. Boudart. Ageing defect detection on IGBT power modules by artificial training methods based on pattern recognition[J]. Microelectronics Reliability, 51(2011): 386-391.

[6] J. Urresti-Ibáñez, A Castellazzi, M Piton, et al. Robustness test and failure analysis of IGBT modules during turn-off[J]. Microelectronics Reliability, 2007, 47(9): 1725-1729.

[7] Weiming M, Fei X, Shixiong N. Applications and development of power electronics in electromagnetic launch system[J]. Transactions of China Electrotechnical Society, 2016, 31(19): 1-10.

[8] Vichare N M, Pecht M G. Prognostics and health management of electronics [J]. Components and Packaging Technologies, IEEE Transactions on, 2006, 29(1): 222-229.

[9] Patil N, Das D, Goebel K, et al. Identification of failure precursor parameters for insulated gate bipolar transistors (IGBTs) [C]. Prognostics and Health Management, 2008, PHM 2008, International Conference on, IEEE, 2008: 1-5.

[10] Hua Y, Lin M, Basaran C. Failure modes and FEM analysis of power electronic packaging [J]. Finite Elements in Analysis & Design, 2002, 38(7): 601-612.

[11] Ciappa M. Selected failure mechanisms of modern power modules[J]. Microelectronics & Reliability, 2002, 42(4/5):653-667.

[12] Morozumi A, Yamada K, Miyasaka T, et al. Reliability of power cycling for IGBT power semiconductor modules[J]. IEEE Transactions on Industry Applications, 2003, 39(3):665-671.

[13] Hamidi A, Kaufmann S, Herr E. Increased lifetime of wire bonding connections for IGBT power modules[C]// APEC 2001. Sixteenth Annual IEEE Applied Power Electronics Conference and Exposition (Cat. No.01CH37181). IEEE, 2001.

[14] Coquery G, Lallemand R. Failure criteria for long term Accelerated Power Cycling Test linked to electrical turn off SOA on IGBT module. A 4000 hours test on 1200A–3300V module with AlSiC base plate[J]. Microelectronics Reliability, 2000, 40(8-10):1665-1670.

[15] Cova P, Fantini F. On the effect of power cycling stress on IGBT modules[J]. Microelectronics Reliability, 1998, 38(6-8):1347-1352.

[16] Herr E, Froy T, Schlegel R, et al. Substrate-to-base solder joint reliability in high power IGBT modules[J]. Microelectronics Reliability, 1997, 37(10-11):1719-1722.

[17] Katsis D C, Wyk J D V. Void-induced thermal impedance in power semiconductor modules: some transient temperature effects[J]. IEEE Transactions on Industry Applications, 2003, 39(5):1239-1246.

[18] Katsis, D. C, van Wyk, etc. A Thermal, Mechanical, and Electrical Study of Voiding in the Solder Die-Attach of Power MOSFETs.[J]. IEEE Transactions on Components & Packaging Technologies, 2006.

[19] A Study on Packaging Thermal Stress of IGBT Modules[J]. Power Electronics, 2000.

[20] Hamidi A, Beck N, Thomas K. Reliability and lifetime evaluation of different wire bonding technologies for high power IGBT modules[J]. Microelectronics Reliability, 1999, 39(6/7):1153-1158.