Remaining Useful Life Prediction of an IGBT Module in Electric Vehicles Statistical Analysis

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Abstract: The whole life cycle of an insulated gate bipolar transistor (IGBT) is a kind of asymmetry process, while the whole life cycles of a set of IGBTs can be regarded as a symmetry process. Modelling these symmetry characteristics of the IGBT life cycles enables the improvement of the remaining useful life (RUL) prediction performance. For this purpose, based on the key failure mechanism of IGBT in electric vehicles, a new method for estimating the RUL of an IGBT module is proposed based on the two-stress acceleration synthesis environment of junction temperature and vibration. The maximum likelihood estimation (MLE) was employed to estimate the logarithmic standard deviation and covariance matrix. The Shapiro–Wilk (S–W) test was performed to investigate the satisfaction degree of the RUL of the IGBT module to the lognormal distribution. The accelerated life test datasets of the IGBT module were analyzed using the Weibull++ software. The analysis results demonstrate that the IGBT lifetime is confirmed to lognormal distribution, and the accelerated model accords with the generalized Eyring acceleration model. The proposed method can estimate IGBT RUL in a short time, which provides a certain technical reference for the reliability analysis of the IGBT module.

Keywords: IGBT; remaining useful life; failure mechanism; reliability analysis; prognostics

1. Introduction

Insulated gate bipolar transistor (IGBT) is the most widely used full-control voltage-driven power semiconductor device [1]. The IGBT has been used in various types of electrical energy conversion devices, switching power supply, new energy generation, electric vehicles, etc. [2–4]. IGBT has the advantages of simple drive, low switching loss, good thermal stability, high carrier current density and low on-state voltage drop [5–8]. With the rapid development of materials, welding, packaging and control technologies, the reliability of the IGBT module is also increasing. However, according to recent investigation [9], the IGBT module is one of the most frequent failure devices in power electronic equipment. In order to improve the reliability of power electronic equipment, it is necessary to monitor the reliability of the IGBT modules in a timely manner. Ideally, the life cycle of an IGBT can be symmetrical to any other IGBTs; however, due to differences in actual manufacturing quality and operating conditions, the life cycle of an IGBT is often asymmetrical to another one, which poses great

difficulty in predicting the remaining useful life (RUL) of the IGBTs. The methods for IGBT reliability analysis can be divided into two categories: one is based on statistical methods [10,11] and the other one is based on the accelerated life test [12–14]. The statistics models aim to analyze the reliability of the IGBT modules through collected field data. However, field data of IGBT failure samples are always difficult to collect; so it is very difficult to perform statistical analysis for the IGBT reliability. The other one based on the accelerated life test can obtain sufficient failure data; as a result, subsequent analysis has been very popular with an astounding degree of success. Zhao et al. [15] put forward a method to predict the life of bonding lead based on shell temperature. This method can determine the service life of bonding lead according to the easily measured shell temperature, so as to reduce the failure rate and improve the reliability of IGBT modules. Lai et al. [16] used the IGBT module aging test to analyze the IGBT aging mechanism. The test results showed that the failure of the welding layer was the main failure mode due to alternating temperature. In the process of failure, the thermal resistance of the characteristic parameter satisfied the parameter degradation model, and the junction temperature difference is the key factor to IGBT failure. Lu et al. [17] proposed a multistep Bayesian method to estimate the RUL of IGBT modules under power cycle. The estimation results showed that the RUL distribution of the IGBT modules approximately conformed to the Weibull distribution. Luo et al. [18] made use of an advanced gate driver of a switchable grid resistor network to analyze the temperature wobble of the AC load current related junction in the IGBT modules. The simulation and experiment results showed that the advanced gate driver could change the switching power loss according to the amplitude of the AC current and effectively reduce the junction temperature wobble associated with the maximum junction and AC load current. Hence, the service life of the equipment can be improved. Fang et al. [19] used the junction temperature tester to study the junction temperature of the IGBT module. The infrared imager was used to record the surface heat distribution of the IGBT module, and the thermal distribution field of the IGBT module was simulated and modeled by ANSYS and MATLAB. The simulation and experimental results showed that the highest temperature appeared at the chip and the connection between the chip and the lead in the temperature distribution diagram of the device. It was confirmed that the main factors affecting the reliability of the IGBT module were in the stripping and breaking of the lead caused by the overheating of the device. Choi et al. [20] used an advanced power cycle test to study the effect of the IGBT module junction temperature variation duration on its lifetime. The results showed that this effect had a significant impact on lifetime. Although much excellent work has been done to address the IGBT reliability analysis, there is still a long way to go to completely solve the IGBT reliability problem. For example, the joint analysis of the life distribution and reliability of the IGBT modules remains a challenge.

In this paper, the life distribution and reliability of the IGBT module were studied systematically. The logarithmic normal function was used to describe the life distribution of the IGBT module. Six sets of double stress accelerated life test data were analyzed by Weibull and maximum likelihood estimation (MLE). The reliability analysis shows favorable results, which provides a simple and practical method for IGBT reliability analysis.

The remainder of this paper is as follows. The fault mechanism analysis of the IGBT Module is presented in Section 2. Section 3 presents the RUL prediction model. Section 4 demonstrates the specific steps for the Shapiro–Wilk hypothesis test. Section 5 illustrates examples to perform qualitative analysis using Weibull++ software for six sets of IGBT life test data and the RUL estimation using the MLE covariance matrix. Finally, conclusions and discussions are given in Section 6.

2. IGBT Fault Mechanism Analysis

2.1. Structure of IGBT Module

The IGBT module has a multi-layer structure, each of which uses different materials and different coefficients of thermal expansion. The layering structure diagram is shown in Figure 1. It can be seen from the diagram that the IGBT module is mainly composed of an aluminum lead, a direct copper

bonded (DCB) copper layer, a DCB ceramic layer, a pair of silicon chips and substrate, which are welded by a specific solder between the layers. The material, thickness, thermal conductivity, expansion coefficient, thermal resistance value, and heat capacity of each layer are all different. The material properties of the IGBT module of type GD50HFL120C1S 1200V/50A are shown in Table 1.

Figure 1. The hierarchical structure of the IGBT module.

Table 1. Material properties of each layer of an insulated gate bipolar transistor (IGBT) module.

Hierarchies	Material	Thickness/ μm	Expansion Coefficient/ 10^{-6} K	Thermal Conductivity/ $\text{W} \cdot (\text{m} \cdot \text{K})^{-1}$	Thermal Resistance/ $\text{K} \cdot \text{W}^{-1}$	Heat Capacity/ $\text{J} \cdot \text{K}^{-1}$
IGBT chip	Si	320	3.0	80~150	0.05	0.05
Solder layer (between chip and copper layer)	SnAgCu	80	25.0	35	0.02	0.01
Copper layer on DBC	Cu	300	16.8	390	0.031	0.03
DBC ceramic layer	Al_2O_3	700	4.0	140~170	0.02	1.19
Copper layer below DBC	Cu	300	16.8	390	0.031	0.03
Solder layer (between copper layer and substrate)	$\text{Sn}_{63}\text{Pb}_{37}$	100	25.0	35	0.005	0.24
Copper substrate	Cu	3000	16.8	390	0.003	32.33

2.2. Failure Mechanism of IGBT Module

With the miniaturization of module encapsulation and the increase in switching frequency and current, the temperature of the actual working node increases day by day; while the performance and lifetime of the power device are closely related to the actual working node temperature. When the high node temperature passes through the module, the thermal stress is produced because of the different expansion coefficient of the material. When the module works under the thermal cycle impact for a long time, it will lead to the material fatigue and aging, which eventually leads to the module failure such as the welding layer fracture or shedding. The main heat source of the IGBT module is from the silicon chip. From Table 1 of the GD50HFL120C1S module, it can be seen that the node temperature T_j of the module is $-40 \sim 150^\circ\text{C}$. However, the thermal expansion coefficient of the welding layer between the silicon chip and its connected aluminum lead is quite different. The thermal expansion coefficient of aluminum lead is $22 \times 10^{-6} \text{ K}$, the difference of the thermal expansion coefficient between the silicon chip and aluminum lead is $19 \times 10^{-6} \text{ K}$, and the difference between the silicon chip and welding layer is $22 \times 10^{-6} \text{ K}$. Subject to the high difference of the thermal expansion coefficient, the main failure modes of the IGBT modules are aluminum bonding lead shedding and the welding layer fatigue.

2.2.1. Aluminum Bonding Lead Shedding

The bonding lead is welded to the silicon chip and DBC copper layer through the bonding place, which is one of the weakest links in the IGBT module [21]. The failure of the aluminum bonding is caused by thermal overstress, mechanical stress and cracks in the interface between the bonding lead and the silicon chip [22]. Due to constant impact of large current and the different thermal expansion coefficients of different materials at the bonding site, the thermal stress is constantly

changing and continues with the power cycle. With the continuous accumulation of the peeling effect of different thermal stresses on the bonding site, if it exceeds the bearing capacity of the bonding lead, the bonding lead wire will be stripped off or melted. Therefore, in order to improve the reliability of the electrical connection, each chip in the power module is connected in parallel through multiple lead wires. In actual operation, the shedding of one lead wire will cause the imbalance of the current, thus accelerating the shedding of other leads and resulting in the IGBT failures.

2.2.2. Welding Layer Fatigue

As can be seen from Figure 1, the solder layer is the key link between the silicon chip and the DBC copper layer, DBC and substrate, electrical terminal and the DBC. In [23] it pointed out that the structure of solder layer material is one of the important factors affecting IGBT reliability. The time-varying mechanical parameters, such as mechanical hardening of materials, will increase the thermal stress and accelerate the cracks in the solder layer. The improper contact between physical layers will reduce the thermal conductivity of the module and overheat the chip, which will lead to stress increase and cracks. As the crack grows, the device eventually fails. As pointed out in [24], the thermal resistance of the chip will increase due to delamination of the solder layer, cracks and voids, which will lead to the increase in the junction temperature and the non-emission of the heat accumulation.

3. Life Prediction Model of IGBT Module

3.1. Basic Assumption

Statistical analysis of the accelerated life test data of the IGBT module is carried out on the premise of the following four hypotheses.

Hypothesis A: under the normal stress level combination $(0, 0)$ and the accelerated stress level combination (i, j) , the lifetime of the IGBT module is followed by the lognormal distribution, and t is the random variable for the lifetime of the IGBT. So its failure distribution function is expressed as:

$$F_{T_{ij}}(t) = \Phi\left(\frac{\ln t - \mu_{ij}}{\sigma_{ij}}\right) = \int_{-\infty}^{(\ln t - \mu_{ij})/\sigma_{ij}} \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{x^2}{2}\right] dx \quad (1)$$

where $\Phi(\bullet)$ is the distribution function of the standard normal distribution $N(0, 1)$, μ_{ij} is logarithmic mean, and σ_{ij} is logarithmic standard deviation.

Hypothesis B: under the normal stress level combination $(0, 0)$ and the accelerated stress level combination (i, j) , the failure mechanism of the IGBT module is unchanged, and the relational expression can be defined as:

$$\sigma_{00} = \sigma_{11} = \sigma_{21} = \sigma_{22} = \cdots = \sigma_{l_1 l_2} = \sigma \quad (2)$$

Hypothesis C: for the IGBT module, the acceleration equation satisfies between the mean value μ_{ij} and the stress level S_{ij} , as defined by:

$$\begin{aligned} \mu_{ij} &= A_0 + A_1 \phi_1(S_{1i}) + A_2 \phi_2(S_{2j}) \\ i &= 0, 1, 2, \cdots, l_1; j = 0, 1, 2, \cdots, l_2 \end{aligned} \quad (3)$$

where A_0, A_1, A_2 are the estimated parameters; $\phi_1(S_1)$ or $\phi_2(S_2)$ is a known function of the stress levels S_1 or S_2 .

Hypothesis D: the failure probability is consistent with Nelson's theorem, which defines that the residual life of the sample is only related to the accumulated failure part and the current stress level, but is not related to the accumulation mode.

3.2. Establishment of IGBT Module Life Acceleration Model

According to the main failure modes of the IGBT module, such as aluminum wire bonding lead shedding and welding layer fatigue, and based on the actual running condition of pure electric vehicle, the influence of the vibration on the IGBT module is not small because of the complicated driving condition and the variable speed of the running vehicle. The vibration stress can accelerate the formation of cracks at the interface between the aluminum lead and the chip and strip or warp of the aluminum lead during the process of aluminum wire bonding lead shedding. During the fatigue process of the welding layer, the vibration stress accelerates the cracking of the solder layer. Therefore, in order to further shorten the test time to an acceptable level and to simulate the actual working conditions more accurately, this paper proposes that in the accelerated life test the vibration stress should be taken into account in order to carry out double accelerated stress accelerated life test. The obtained accelerated life test data of the IGBT modules are assumed to be close to the real-life data.

According to the performance degradation trajectory curve, an appropriate degradation trajectory model is selected to model the degradation trajectory. The degradation model of the i -th IGBT module at the m stress level can be expressed as:

$$y_i = f(t, B_{1mi}, B_{2mi}, \dots, B_{lmi}) \quad (4)$$

where $m = 1, 2, 3, 4, 5, 6, i = 1, 2, \dots, 8$; $B_{1mi}, B_{2mi}, \dots, B_{lmi}$ are the model parameters.

Using the least square method, the degradation equation of the IGBT module at different accelerated degradation stress levels is obtained as follows:

$$y_i = f\left(t, \hat{B}_{1mi}, \hat{B}_{2mi}, \dots, \hat{B}_{lmi}\right) \quad (5)$$

where $\hat{B}_{1mi}, \hat{B}_{2mi}, \dots, \hat{B}_{lmi}$ are the degradation model parameters.

Through the accelerated life data of the IGBT module at each stress level and the degradation trajectory equation, the life acceleration model is obtained. The Eyring model can be used to describe the damage mechanism caused by thermal and non-thermal variables. When the temperature range is relatively large, the Eyring model can be extended to a generalized Eyring model. The accelerated stress level is a double stress level consisting of a temperature stress level and a vibration stress level, the temperature stress is caused by the thermal variable, while the vibration stress is caused by the non-thermal variable. Then, the generalized Eyring acceleration model can be used to model the double stress level [25]. The generalized Eyring acceleration model is shown in Equation (6).

$$t = \alpha_0 \exp\left(\frac{\alpha_1}{T}\right) (V^{-\alpha_2}) \quad (6)$$

where α_0, α_1 and α_2 are model parameter; T is temperature stress (K); V is vibration stress (Hz).

$\ln t = \ln \alpha_0 + \frac{\alpha_1}{T} - \alpha_2 \ln V$ can be obtained from Equation (6), $A_0 = \ln \alpha_0, A_1 = \alpha_1, A_2 = \alpha_2$ are assumed. A_0, A_1 and A_2 are model parameters.

The lifetime of IGBT is assumed to obey the lognormal distribution, and the stresses only affect the location parameter of the distribution. Thus, the accelerated life model is obtained as:

$$t \sim \text{Lognormal}\left(\exp\left(A_0 + \frac{A_1}{T} + A_2 \ln V\right), \sigma\right) \quad (7)$$

4. Shapiro–Wilk Hypothesis Testing Principle

The Shapiro–Wilk (S–W) test [26–28] is based on the regression of order statistics to their expected values. It is a test of the ANOVA form of a complete sample. The test statistic is the ratio of the square of the linear combination of sample order statistics to the usual variance estimator [29–31].

Hypothesis 1 (H1). *sample overall obeys normal distribution.*

Hypothesis 2 (H2). *sample overall does not obey normal distribution.*

This hypothesis is based on the order observation value, and the test sample value is arranged in ascending order first:

$$x_1 \leq x_2 \leq \cdots \leq x_n \quad (8)$$

and then S is calculated as

$$S = \sum a_k [x_{n+1-k} - x_k] \quad (9)$$

The value of subscript k here takes $1, 2, \dots, \frac{n}{2}$ (n is an even number) or $1, 2, \dots, \frac{(n-1)}{2}$ (n is an odd number) according to the parity of n . The coefficient a_k has a specific value when the sample size is n . S-W test statistic W :

$$W = \frac{S^2}{nm_2} \quad (10)$$

Here

$$nm_2 = \sum (x_i - \bar{x})^2 \quad (11)$$

Under the significant level of $\alpha = p$, if the value of statistic W is less than its p quantile ($p = \alpha$), then the original hypothesis is rejected; otherwise, the original hypothesis is accepted. By looking up the statistical parameter table, one can get the quantile p under different significance levels. The logarithm of the original data is tested by normal test. If the test results conform to the normal distribution, the original data is followed by lognormal distribution.

5. Data Processing and Result Analysis

5.1. Data Analysis of Accelerated Life Experiment

From the research of Liu et al. [32], it can be seen that the rated working current of the IGBT module of GD50HFL120C1S 1200V/50A is 50A, and the conduction current should not exceed 110 A under the condition that the acceleration effect is maximum and the failure mechanism is invariable. According to the vibration test requirements of the motor [33–35] and its controller in QC/T 413-2002 “Basic specifications for automotive equipment” of GB/T 18488.1-2006 “Electric motors and their controllers for electric vehicles-part1: technical requirements”, the vibration stress should be within 250 Hz. Therefore, in this paper, the temperature stress is selected as 70 K and 100 K, the vibration stress is selected as 150 Hz and 200 Hz, and six groups of double stress IGBT module accelerated life test data are obtained, as shown in Table 2.

Table 2. The accelerated life test data of the IGBT module.

Temperature Stress/(K)	Vibration Stress/(Hz)	Time Failed/ (h)							
70	150	6500	6433	6563	6519	6533	6467	6459	6477
	200	4875	4825	4922	4889	4900	4850	4844	4858
90	150	2520	2535	2563	2537	2460	2503	2474	2500
	200	1890	1901	1922	1903	1845	1878	1856	1875
100	150	1320	1360	1335	1383	1307	1300	1285	1265
	200	990	1020	1001	1037	980	975	964	949

5.1.1. Qualitative Test Analysis

The data in Table 2 were analyzed using Weibull++ software. The results are shown in the following Figures 2–4. It can be seen that the data points at each stress level are approximately a straight line within the bilateral confidence level 95%, illustrating that the lifetime of the IGBT module is followed by the lognormal distribution. The approximate parallelism of six straight lines also fully shows that the failure mechanism of the IGBT module under double stress levels is the same as that under normal stress level.

(a) Vibration stress 150 Hz

(b) Vibration stress 200 Hz

Figure 2. Data under accelerated stress of 70 K.

(a) Vibration stress 150 Hz

(b) Vibration stress 200 Hz

Figure 3. Data under accelerated stress of 90 K.

Figure 4. Data under accelerated stress of 100 K.

5.1.2. Quantitative Test Analysis

Under the normal stress level combination (0, 0) and the accelerated stress level combination (i, j), the IGBT lifetime is assumed to obey the Weibull distribution, and t is the random variable for the lifetime of the IGBT. Its distribution function is given by Equation (12):

$$F_{T_{ij}}(t) = 1 - \exp\left[\left(-\frac{t}{\eta_{ij}}\right)^{m_{ij}}\right], t \geq 0, m_{ij}, \eta_{ij} > 0 \quad (12)$$

where m_{ij} is shape parameter, and η_{ij} is characteristic life.

The shape parameter m_{ij} and characteristic life η_{ij} of the Weibull distribution function are estimated by the maximum likelihood estimation method.

The Weibull distribution function and related parameters were calculated according to the data in Table 2. Table 3 shows the shape parameters and related data under each stress level, where r is the correlation coefficient and a is the slope. Figures 5–7 show the straight lines obtained from the fitting data at each stress level.

Table 3. Shape parameters and related data under the Weibull distribution.

Temperature Stress (K)	Vibration Stress (Hz)	m	r	$a/10^{-3}$
70	150	588.2	0.9866	3.14
	200	373.7	0.9858	3.26
90	150	196.4	0.9857	2.36
	200	162.3	0.9860	2.67
100	150	115.9	0.9856	2.64
	200	89.2	0.9858	2.86

Figure 5. Data under accelerated stress of 70 K.

Figure 6. Data under accelerated stress of 90 K.

Figure 7. Data under accelerated stress of 100 K.

The correlation coefficient of each stress level obtained from Table 3 is close to 1 and the straight lines obtained from the fitting data in Figures 5–7 indicate that the life of the IGBT module may follow the Weibull distribution. However, the slopes of the fitted straight line at each stress level are not equal to each other and the fitted straight lines are not parallel to each other, indicating that the shape parameters of the Weibull distribution function are varied. The shape parameter values obtained from Table 3 also prove that the failure mechanisms of the IGBT modules are different at each stress level. This contradicts the fact that the IGBT module's accelerated life data is obtained when the failure mechanism remains unchanged (otherwise the obtained data is invalid). Thus, it can be concluded that the IGBT module life is actually not subject to the Weibull distribution [36,37].

The base e logarithm was taken for the six groups of the accelerated life test data in Table 2 before the Shapiro–Wilk test. Then the logarithmic data under the six stress levels were tested by Shapiro–Wilk test. Table 4 shows the S–W test results. Take into account that the sample size $n = 8$, and the significant level $\alpha = p = 0.05$. From the Shapiro–Wilk test statistic W parameter table, the p quantile is 0.818 when $n = 8$ and $\alpha = p = 0.05$. Because the calculated $W_i (i = 1, 2, \dots, 6)$ is larger than this value, the original assumption H_0 is accepted. Then one can conclude that the life of the IGBT module is followed by the lognormal distribution.

Table 4. Shapiro–Wilk (S–W) test of IGBT module life.

Temperature Stress (K)	Vibration Stress (Hz)	W
70	150	0.981
	200	0.980
90	150	0.974
	200	0.975
100	150	0.983
	200	0.981

5.2. MLE Double Accelerated Life Estimation

The parameters A_0, A_1, A_2 and the logarithmic standard difference σ in Equation (7) were estimated by the global maximum likelihood estimation to obtain the estimated value $\hat{A}_0, \hat{A}_1, \hat{A}_2, \hat{\sigma}$ and covariance matrix Σ . The global maximum likelihood function is:

$$L(A_0, A_1, A_2, \sigma) = \prod_{i=1}^k \prod_{j=1}^m \left\{ \sigma t_{ij}^{\sigma-1} \exp \left[-\sigma \left(A_0 + \frac{A_1}{T} + A_2 \ln V \right) \right] \right\} \cdot \exp \left\{ -t_{ij}^{\sigma} \exp \left[-\sigma \left(A_0 + \frac{A_1}{T} + A_2 \ln V \right) \right] \right\} \quad (13)$$

where, t_{ij} is the life data value of the j ($j = 1, 2, \dots, 8$) IGBT module under the accelerated stress level S_i ($i = 1, 2, 3, 4, 5, 6$).

The maximum likelihood estimators for $\hat{A}_0, \hat{A}_1, \hat{A}_2, \hat{\sigma}$ were obtained by letting $\frac{\partial \ln L}{\partial A_0} = 0, \frac{\partial \ln L}{\partial A_1} = 0, \frac{\partial \ln L}{\partial A_2} = 0, \frac{\partial \ln L}{\partial \sigma} = 0$.

The covariance matrix Σ of parameters A_0, A_1, A_2, σ is as follows:

$$\Sigma = \begin{bmatrix} \frac{\partial^2 \ln L}{\partial A_0^2} & \frac{\partial^2 \ln L}{\partial A_0 \partial A_1} & \frac{\partial^2 \ln L}{\partial A_0 \partial A_2} & \frac{\partial^2 \ln L}{\partial A_0 \partial \sigma} \\ \frac{\partial^2 \ln L}{\partial A_0 \partial A_1} & \frac{\partial^2 \ln L}{\partial A_1^2} & \frac{\partial^2 \ln L}{\partial A_1 \partial A_2} & \frac{\partial^2 \ln L}{\partial A_1 \partial \sigma} \\ \frac{\partial^2 \ln L}{\partial A_0 \partial A_2} & \frac{\partial^2 \ln L}{\partial A_1 \partial A_2} & \frac{\partial^2 \ln L}{\partial A_2^2} & \frac{\partial^2 \ln L}{\partial A_2 \partial \sigma} \\ \frac{\partial^2 \ln L}{\partial A_0 \partial \sigma} & \frac{\partial^2 \ln L}{\partial A_1 \partial \sigma} & \frac{\partial^2 \ln L}{\partial A_2 \partial \sigma} & \frac{\partial^2 \ln L}{\partial \sigma^2} \end{bmatrix}$$

Using the data in Table 2, the global maximum likelihood estimation of the parameters in the accelerated life model was carried out to obtain $\hat{A}_0, \hat{A}_1, \hat{A}_2, \hat{\sigma}$ and the covariance matrix Σ as shown in Table 5.

Table 5. Maximum likelihood estimation (MLE) and covariance matrix.

Parameter	MLE	Covariance Matrix			
		A_0	A_1	A_2	σ
A_0	0.5738	123.2535	−4653	0.0562	−0.0256
A_1	1516.8	−4653	15	−5324	12.3542
A_2	−2.5462	0.0562	−5324	0.4563	0.0025
σ	5.1532×10^{-5}	−0.0256	12.3542	0.0025	0.0132

The logarithmic lifetime of the IGBT module under normal operating temperature T , vibration V and the reliability of R is estimated as follows:

$$\ln t_R = A_0 + \frac{A_1}{T_k} + A_2 \ln V + \frac{1}{\sigma} \ln[\ln(1/R)] \quad (14)$$

The minimum sample size corresponding to different reliability R and confidence γ is shown in Table 6, where the failure number m has two values: 0 and 1.

Table 6. The minimum sample size.

m		0			1		
R	γ	0.7	0.8	0.9	0.7	0.8	0.9
	0.85	7	10	14	10	15	22
	0.9	12	15	22	24	29	38
	0.95	24	32	45	49	59	77

According to the sample size n , it can be seen from Table 6 that the corresponding minimum reliability R is 0.85 and the confidence degree is 0.7. Therefore, the average service life of the IGBT module is 12.56 years under different environmental conditions (30 K + 80 Hz).

6. Conclusions

In this paper, the Shapiro–Wilk test, Weibull and MLE were used to analyze the accelerated life test data of the IGBT modules. The main conclusions are drawn as follows:

- The graph analysis method based on Weibull++ software has fast computation speed, high precision, and good visualization; and the overall performance is better than the traditional computational sketch plotting method.
- The lifetime of the IGBT module is followed by the lognormal distribution, and its acceleration model conforms to the generalized Eyring acceleration model.
- The IGBT RUL can be estimated effectively by the proposed MLE method based on the accelerated life test data.
- This method can provide a certain technical reference for the reliability research of high reliability and long life power electronic devices.

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