Reliability Evaluation of Inverter Based on Accelerated Degradation Test

Xinghui Qiu and Jianwei Yang

Abstract In order to evaluate the reliability of the inverter, this paper adopted sequence and stress accelerated degradation test of a certain type of inverter. Take the voltage as the accelerated stress, setting 0.8 as the linear growth proportion coefficient of stress levels, through the detection of the inverter IGBT collector emitter voltage state and diode voltage to judge the wear condition of the inverter. The accelerated model is obtained through analyzing the test data, and the model parameters are estimated by the least square method. At the same time, the reliability of the inverter is evaluated, and the reliability curve is obtained. Finally, the reliability at the normal stress level is solved through accelerate model. In order to evaluate the effectiveness of Bayes reliability analysis of inverter, the Monte Carlo simulation about accelerated test is done, simulation results and evaluation results are similar. It shows that the accelerated degradation testing data is valid. The evaluation method can be used to evaluate the reliability of other power electronic devices in the rail transit vehicle.

Keywords Accelerated degradation test · Inverter · Inverse power law model Bayes reliability

1 Introduction

Urbanization is the inevitable trend of development in China, railway transit vehicle carrying an important historical mission as the key equipment on the road of urbanization. As a power electronic device, traction inverter is an important part of the traction system. To ensure the stable operation of the train, it is necessary to evaluate the reliability of traction inverter in advance. The electronic device in the

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railway transit railway has a long life, it is difficult to obtain enough data. Thus, the accelerated degradation test is adopted to research this problem.

Many researches [1–5] analyzed the reliability and the wear-out failure of electronic device in the railway transit vehicle. Xiao et al. [6–8] used accelerated degradation test to evaluate the reliability of some products, through managing the environment temperature and reliability change with time, more accurate results were obtained. In the Bayes reliability field, Zhu and Jia [9, 10] evaluated the reliability of bearing and other parts under the circumstance of extremely small sample and minimal failure data. Trabelsi [11] analyzed the fault diagnosis of the IGBT modules in the voltage source inverter, a new control system can increase the efficiency of the inverter has been found. Czerny et al. [12–14] conclude that the longer the time of temperature swing is, the smaller the failure cycling number is. And a new method to evaluate the reliability of inverter has been presented.

This article put forward a method of evaluating the reliability of inverter using the accelerated degradation test. Meantime, the Bayes method is adopted to estimate the failure rate. In order to analysis the effectiveness of the reliability evaluating of the inverter, the Monte Carlo simulation about the accelerated degradation test of inverter is operated.

2 Accelerated Degradation Test

Figure 1 shows the layout of accelerated degradation test with inverter, it consist of three parts, the first part is the power system with 220 V alternating current and the load converter, it provides the needed voltage that input to the test inverter, also monitoring the IGBT collector emitter voltage and the forward voltage of the diode to decide the inverter is failure or not. The second part is the control system. It consists of the PC et al. It can achieve the object that improve the voltage
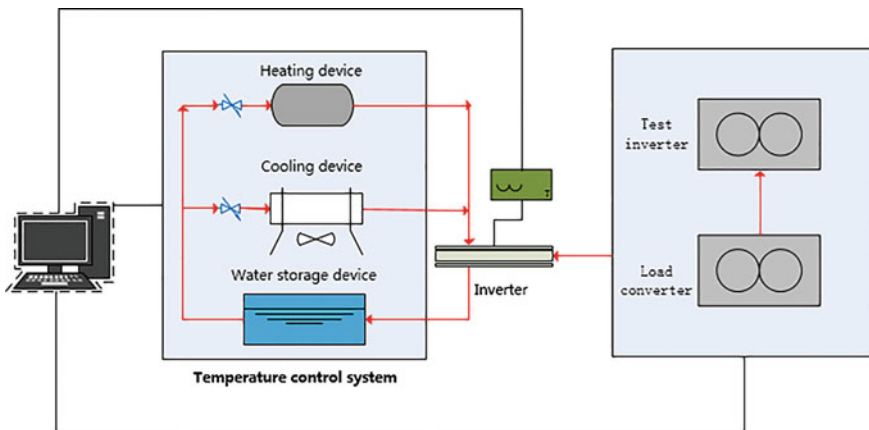

Fig. 1 The layout of accelerated degradation test system

accordingly and control the environment temperature. The third part is the water cooling system, it can keep the environment temperature relatively constant, and it can simulate the reality situation closely.

2.1 Testing Program

The object of the accelerated degradation test is a kind of inverter, the plate size of the inverter is 15.2*10.2 cm, the rated input voltage of the inverter is 32 V. The main reason that caused the failure of the traction inverter is the wear-out of the switch components, mainly marked by the short circuit and the broken circuit of the IGBT power switches. Taking the overall level of the test into account, voltage is chosen as the acceleration stress of the test, set from scratch, and the scale coefficient of the linear growth stress level is 0.8. To control the cost of the accelerated degradation test and meet the statistical requirements, the test inverter sample is set as 4. In the test, the change of the IGBT collector emitter voltage and the forward voltage is taken as the degradation parameter, and the failure threshold is the change of the IGBT collector emitter voltage is up to 3 V. The censored time of each sub test is set as: [72 205 252 277 300 324 348 372 374].

2.2 Testing Circuit

To simulate the working circuit of the traction inverter closely, the test circuit is designed as Fig. 2. The unit is the dashed box above is the test inverter, and the unit in the dashed box below is the load converter. The load converter provides the needed voltage to test inverter, this two are connected with the electric fuse, it protects the whole system from abnormal heavy current. The IGBT collector emitter voltage is monitored by the online testing circuit that can tell the inverter is failure or not. The test inverter and the load converter are both controlled by the control board, the control board is consists of DSP and PC terminal. The water cooling system makes the whole system a temperature stable state.

2.3 Test Data Processing

The data processing of the accelerated degradation test is shown as Fig. 3. It shows the voltage variation trend of 4 samples, as time goes on, the value of the voltage variation is continuous increase. It fits the purpose of the accelerated degradation test that the test can accelerate the wear-out of the inverter, and the priori information can be obtained from the test results. According to the results of the accelerated degradation test, the fault type of inverter can be diagnosed as wear-out type failure.
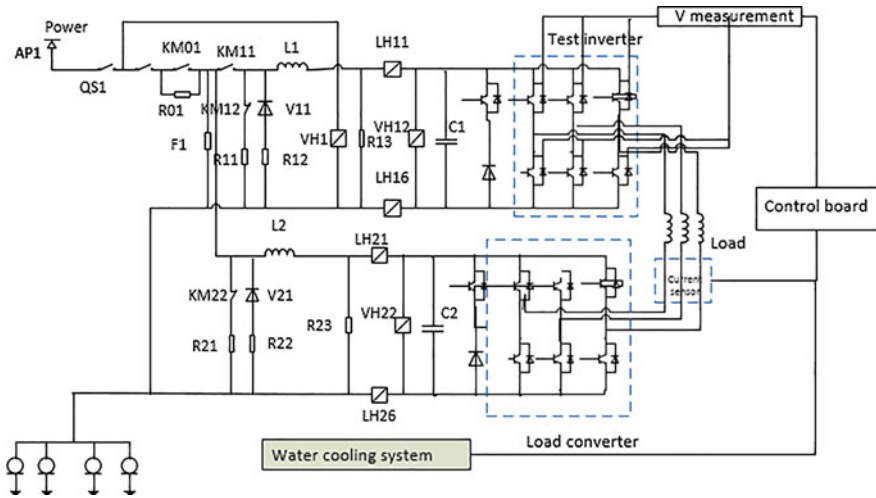
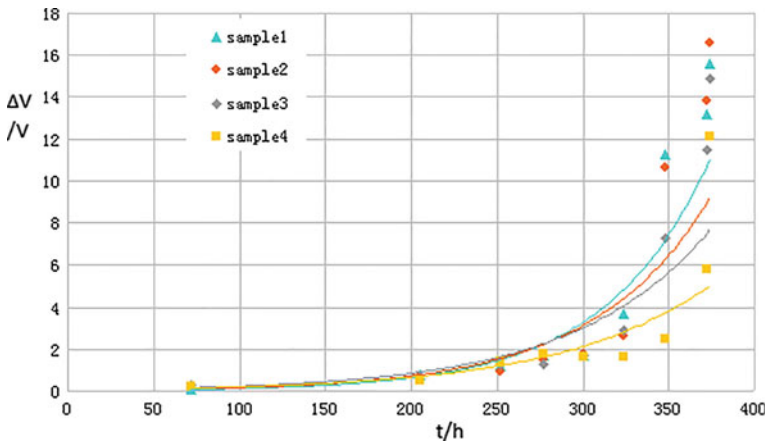**Fig. 2** The circuit of the accelerated degradation test of inverter

Fig. 3 The data of the accelerated degradation test of inverter

3 Analysis of the Acceleration Model

In the accelerated degradation test with electronic equipment, inverse power law model is often adopted to describe the relation between product life and the added stress:

$$\eta(V) = 1/[dV^{\wedge}C\ ] \tag{1}$$

where, V is the stress, $\eta(V)$ is the scale parameter, parameter to be estimated c and d is irrelative to stress V. Log on Eq. (1):

$$\ln[\eta(V)] = b_0 + b[\phi(V)] \tag{2}$$

where, $b_0 = -\ln(d), b = -c, \phi(V) = \ln(V)$.

In the test, the failure mechanism of inverter is high voltage, the voltage that far greater than the rated voltage caused the high temperature of inverter, accelerated the damage of the IGBT module, thus, the fault type of inverter can be also diagnosed as wear-out type failure. It assumed that the life distribution of inverter is two-parameter Weibull distribution $wei(\theta, \beta)$, θ is scale parameter, β is the shape parameter. Thus, on the condition of order stress $V(t) = Kt$, the cumulative failure probability is:

$$F^*(t) = \exp\left[-\frac{d^m K^{mc}}{c+1} t^{m(c+1)}\right] = 1 - \exp\left[-\left(\frac{t}{\theta}\right)^{\beta}\right] = G\left[\frac{\ln t - \mu}{\sigma}\right] \tag{3}$$

where, $G(x) = 1 = \exp[-\exp(x)]$ is the distribution function of standard extreme value distribution, and:

$$\begin{cases} \beta = \frac{1}{\sigma} = m(1+c) \\ \mu = \ln\theta = A + B\ln K \end{cases} \tag{4}$$

where, $\begin{cases} A = \frac{-m\ln d + \ln(1 + c)}{m(1+c)} \\ B = -\frac{c}{1+c} \end{cases}$

There is a set of stress levels: $k_1 < k_2 < \cdots < k_p (p \geq 2)$, owing to $\mu_i - \mu_j = B(\ln k_i - k_j), 1 \leq i < j \leq p$, there is $\theta_i = e^{\mu_i}, i = 1, 2, \ldots, p$. And:

$$\theta_p < \theta_{p-1} < \cdots < \theta_1 < \theta_2 k_{2,1} < \cdots < \theta_p k_{p,1} \tag{5}$$

where, $k_{i,j} = k_i/k_j, i, j = 1, 2, \ldots, p$.

4 Parameter Estimation

There are n_i products in the accelerated degradation test, the ordered stress is $V_i(t) = k_i t$. The failure time of the products is $0 < t_{i1} < t_{i2} < \cdots < t_{ir_i} < \tau_{i0}, r_i < n_i, i = 1, 2, \ldots p$. τ_{i0} is the censored time. r_i is the number of failed products before the censored time.

Assumed that $r = \sum_{i=1}^{p} r_i, V = \prod_{i=1}^{P} \prod_{j=1}^{r_i} t_{ij}, \tau = (n_i, r_i, t_{ij}, j = 1, 2, \ldots, p)$, and

$$\tau_i(\beta) = \sum_{j=1}^{r_i} t^{\beta} + ij(n_i - r_i)\tau_{i0}^{\beta}.$$

From the analysis above, the likelihood function is:

$$L(\beta, \theta | \tau) = \beta^r V^{\beta-1} \prod_{i=1}^{p} \frac{1}{\theta_i^\beta r_i} \exp\left[-\frac{\tau_i(\beta)}{\theta_i^\beta}\right] \tag{6}$$

According to the Bayes method about the prior distribution [15], it assumed that the prior distribution of θ_j^β is the inverse Γ distribution $IG(a_j, b_j)$, from the prior information, it concludes that $a_j > 0, b_j > 0$, thus, the prior distribution is:

$$\pi(\theta_j | \beta) = \frac{\beta b_j^{\alpha_j}}{\Gamma(\alpha_j)} \theta_j^{-(1+\beta\alpha_j)} \exp\left(-\frac{b_j}{\theta_j^\beta}\right) \tag{7}$$

When $\beta \in (0, 1)$, the prior distribution of β is beta distribution:

$$\pi_1(\beta) = \frac{1}{B(\alpha_1, \beta_1)} \beta^{\alpha_1-1} (1-\beta)^{\beta_1-1}, 0 \leq \beta \leq 1 \tag{8}$$

When $\beta \in (1, \infty)$, the prior distribution of $\beta - 1$ is Γ distribution $\Gamma(\alpha_2, \beta_2)$:

$$\pi_2(\beta) = \frac{\beta_2^{\alpha_2}}{B(\alpha_1, \beta_1)} (\beta-1)^{\alpha_2-1} e^{-\beta_2(\beta-1)}, \beta > 1 \tag{9}$$

From the prior distribution, it can be affirmed that $\alpha_1 > 1, \beta_1 > 1, \alpha_2 \geq 1, \beta_2 > 0$. And:

$$\frac{\partial^2 \pi_1(\beta)}{\partial \beta^2} = -\frac{\alpha_1 - 1}{\beta^2} - \frac{\beta_1 - 1}{(\beta-1)^2} < 0$$

$$\frac{\partial^2 \pi_2(\beta)}{\partial \beta^2} = -\frac{\alpha_2 - 1}{\beta^2} < 0$$

From the equation above, the prior distribution about β is both logarithmic convex function. Where, B is the value space of β, and H_p is the value space of θ, where $H_P = \{(\theta_1, \ldots, \theta_p) | \theta_p < \theta_{p-1} < \cdots < \theta_1 < \theta_2 k_{2,1} < \cdots < \theta_p k_{p,1}\}$, it assumed that the prior distribution of β is $\pi(\beta)$. According to the Bayes equation, the posterior distribution of $\beta, \overrightarrow{\theta}$ is:

$$g(\beta, \theta | \tau) \propto \pi(\beta) \beta^{r+p} V^{\beta-1} \prod_{i=1}^{p} \frac{1}{\theta_i^{1+\beta(\alpha_i+r_i)}} \exp\left[-\frac{\tau_i(\beta)+b_i}{\theta_i^\beta}\right] \beta \in B, \theta \in H_p \tag{10}$$

It is difficult to solve the equation through traditional method, in this article, the Gibbs sampling is used to solve the equation above. The foundation of the Gibbs sampling is the complete posterior distribution that can be sampled.

$\bar{\theta}_{-j} = \{\theta_i, i \neq j, i = 1, 2 \ldots p\}$, according to Eq. (10), the complete posterior distribution of θ_j is:

$$\pi(\theta_j | \beta, \theta_{(-j)}, \tau) = \frac{\beta(b_j + \tau_j(\beta))^{\alpha_j + r_j}}{\Gamma(a_j + r_j)} \frac{1}{\theta_j^{1 + \beta(a_j + r_j)}} \exp\left(-\frac{b_j + \tau_j(\beta)}{\theta_j^\beta}\right) \quad (11)$$

That is: $(\theta_j | \beta, \theta_{(-j)}, \tau) \sim IG(a_j + r_j, b_j + \tau_j(\beta))\, j = 1, 2, \cdots, p, \theta_j \in G_j$, and

$$G_1 = \{\theta_1 : \theta_2 < \theta_1 < \theta_2 k_{2,1}\}$$
$$G_p = \{\theta_p : \theta_{p-1} k_{p-1,p} < \theta_p < \theta_{p-1}\}$$
$$G_i = \{\theta_i : \theta_{i+1} < \theta_i < \theta_{i-1}, \theta_{i-1} k_{i-1,i} < \theta_i < k_{i+1,i} \theta_{i+1}\}$$
$$= \{\theta_i : \max(\theta_{i+1}, \theta_{i-1} k_{i-1,i}) < \theta_i < \min(\theta_{i-1}, k_{i+1,i} \theta_{i+1})\}$$

The complete posterior distribution of β is:

$$\begin{aligned}\pi(\beta | \overrightarrow{\theta}, \overrightarrow{\tau}) \\ \propto \pi(\beta) \beta^{r+P} V^{\beta-1} \prod_{i=1}^{P} \frac{1}{\theta_i^{1 + \beta(a_i + r_i)}} \exp\left[-\frac{\tau_i(\beta) + b_i}{\theta_i^\beta}\right], \beta \in B\end{aligned} \quad (12)$$

Make $\ln \pi(\beta | \overrightarrow{\theta}, \tau) = h(\beta)$, there is:

$$\begin{aligned}\frac{\partial^2 h(\beta)}{\partial \beta^2} = \frac{\partial^2 \ln \pi(\beta)}{\partial \beta^2} - \frac{r+p}{\beta^2} \\ - \sum_{i=1}^{p} \left\{ \sum_{k=1}^{r_i} \left(\frac{t_{ik}}{\theta_i}\right)^\beta \left[\ln \frac{t_{ik}}{\theta_i}\right]^2 + (n_i - r_i)\left(\frac{\tau_{i0}}{\theta_i}\right)^\beta \left[\ln \frac{\tau_{i0}}{\theta_i}\right]^2 \right\} \\ - \sum_{i=1}^{p} \frac{b_i}{\theta_i^\beta} [\ln(\theta_i)]^2\end{aligned}$$

From the analysis above, it can be concluded that $b_i > 0, i = 1, 2, \ldots, p, \tau_{i0} > 0, t_{ik} > 0, k = 1, 2, \ldots, r_i, i = 1, 2, \ldots, p$, the concavity of β complete posterior distribution depends on the concavity of $\pi(\beta)$, that is the logarithmic convex. The sampling method is as follows:

It assumed that $(\theta_{k,1}, \theta_{k,2}, \ldots, \theta_{k,p}, \beta_k, k = 1, 2, \ldots, M_1, M_1 + 1)$ is a sample of parameter $(\theta_1, \ldots, \theta_p, \beta)$, M_1 is the abandoned sample capacity. Thus, the estimated value of θ_j, β can be obtained as follows:

$$\hat{\theta}_j = \frac{1}{M - M_1} \sum_{k=M_1+1}^{M} \theta_{k,j}, j = 1, 2, \ldots, p, \quad (13)$$

$$\hat{\beta} = \frac{1}{M - M_1} \sum_{k=M_1+1}^{M} \beta_k \tag{14}$$

According to Eqs. (4), (13), (14) and the Markov theorem, the estimation value of m, c and d can be obtained as follows:

$$\hat{m} = \hat{\beta}(1 + \hat{\beta}),$$

$$\hat{c} = -\frac{\hat{B}}{1 + \hat{B}},$$

$$\hat{a} = -\ln(\hat{d}) = \ln(1 + \hat{B}) + \frac{\hat{A}}{1 + \hat{B}},$$

where, $\hat{A} = \frac{GH - IM}{EG - I^2}$, $\hat{B} = \frac{EM - IH}{EG - I^2}$, $I = \sum_{i=1}^{p} A_{r_i, n_i}^{-1} \ln(k_i)$,

$G = \sum_{i=1}^{p} A_{r_i, n_i}^{-1} \ln^2(k_i)$, $H = \sum_{i=1}^{p} \hat{\mu}_l$, $M = \sum_{i=1}^{p} A_{r_i, n_i}^{-1} \hat{\mu}_l \ln(k_i)$,

$E = \sum_{i=1}^{p} A_{r_i, n_i}^{-1}$, $\hat{\mu}_l = \ln \hat{\theta}_l$, A_{r_i, n_i}^{-1} is the coefficient of variation. Supposed that the estimation of A and B is the normal least square estimation so that the value of the coefficient of variation is 1. Refer to the [16], the acceleration model, the coefficient of the acceleration model and the reliability of inverter under the normal voltage can be obtained as follow:

$$\ln \hat{\eta}_V = -\ln(\hat{d}) - \hat{c} \ln(V),$$

$$\hat{\tau}_p = \left(\frac{V}{V_0}\right)^{\hat{c}}, \tag{15}$$

$$\hat{R}_{V(t)} = \exp\{-(\hat{d} V^{\hat{c}} t)^{\hat{m}}\}, t > 0$$

5   Reliability Evaluation of Inverter

From the hypothesis above, the life distribution of inverter is two-parameter Weibull distribution, and the scale parameter and the added stress meet the inverse power law model. From the test data in the second part of this article and the expertise experience, the value of β is larger than 1, according to Eq. (9), the prior distribution of $\beta - 1$ is $\Gamma(12, 2)$, the prior distribution of $\theta_1^\beta, \theta_2^\beta, \theta_3^\beta, \theta_4^\beta$ is $IG(10, 9 \times 10^{10}), IG(8, 5 \times 10^{10}), IG(5, 8 \times 10^9), IG(3, 4 \times 10^6)$. In the Gibbs sampling, the iterations are $M = 1000$, the initial value is $\beta = 4.6, \theta_1 = 80, \theta_2 = 30, \theta_3 = 10, \theta_4 = 5$, after the sampling, the results is $\hat{\beta} = 6.0206, \hat{\theta}_1 = 54.3507, \hat{\theta}_2 = 41.3841, \hat{\theta}_3 = 29.9559, \hat{\theta}_4 = 11.4457$, according

to Eq. (15), the estimation value of m, c, a can be obtained as follows: $\hat{m} = 0.2385, \hat{c} = 24.2384, \hat{a} = 111.6332$. And the acceleration model is as follows:

$$\ln \hat{\eta}_v = 111.6332 - 24.2387 \ln V$$

When the inverter works under the rated voltage 32 V, the reliability of inverter at any work time can be described as follows:

$$\hat{R}_V(t) = \exp\{-(111.6332 \times 32^{24.2387} t)^{0.2385}\}$$

The reliability curve of inverter is showed as Fig. 4.

To checkout the evaluation results of the inverter based on the Bayes reliability, the simulation of the accelerated degradation test based on Monte Carlo is thought to be done. The detailed procedure is as follow:

1. Generate the candidate point $x_{(0)}$.
2. Given the proposal distribution $q(x_{(k)}, x_{(k-1)})$, this distribution refers to the probability of the value of $x_{(k)}$ transfer to the value of $x_{(k-1)}$. This probability is also called alternative probability. Based on the current value $x_{(k-1)}$, extract the x^* from the distribution $q(x_{(k)}, x_{(k-1)})$.
3. Compute the accept probability α_{accept}.

$$\alpha_{accept} = \min[1, \frac{p(x^*)q(x^*, x()k-1)}{p(x(k-1)q(x()k-1), x^*)}]$$
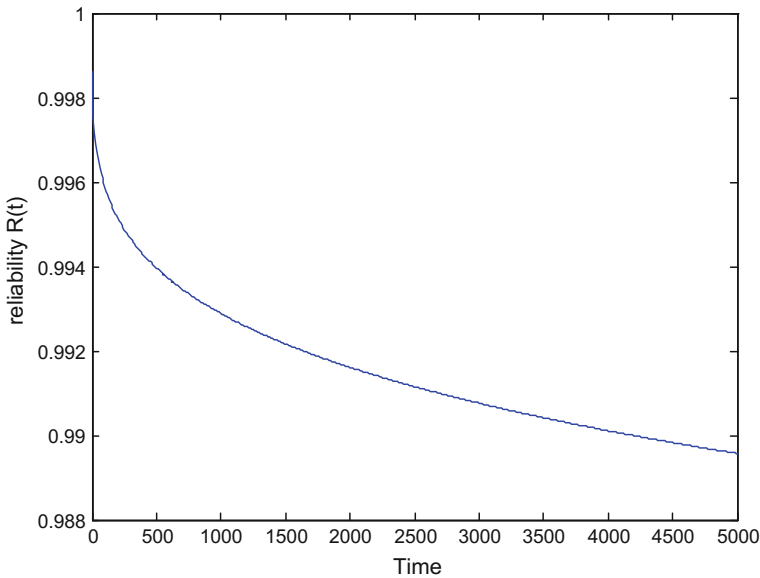

Fig. 4 The reliability curve of inverter

4. Extract the value of α' from [0, 1], if $\alpha' < \alpha^{accept}$, then the x^* is accepted. If not, x^* is rejected, that is $x_{(k)} = x_{(k-1)}$.
5. Repeat the previous step, until the sampling is down.

The simulation of accelerated degradation with inverter is done, the life distribution of inverter is two-parameter Weibull distribution, and the acceleration model is inverse power law model, the simulation scheme is as follows:

The normal stress of the inverter is 32 V, set the scale coefficient as 0.8, the accelerated stress is growing as time goes, the initial value is $\beta = 4.6$, $\theta_1 = 80, \theta_2 = 30, \theta_3 = 10, \theta_4 = 5$, the times of the Monte Carlo simulation is 2000. The simulation results are as Fig. 5.
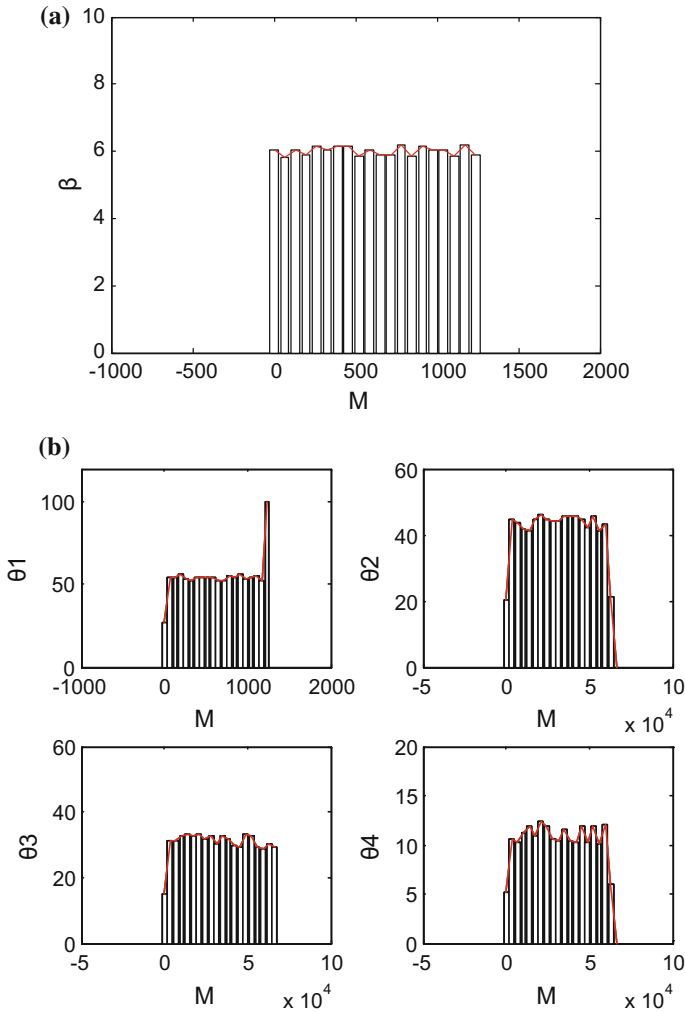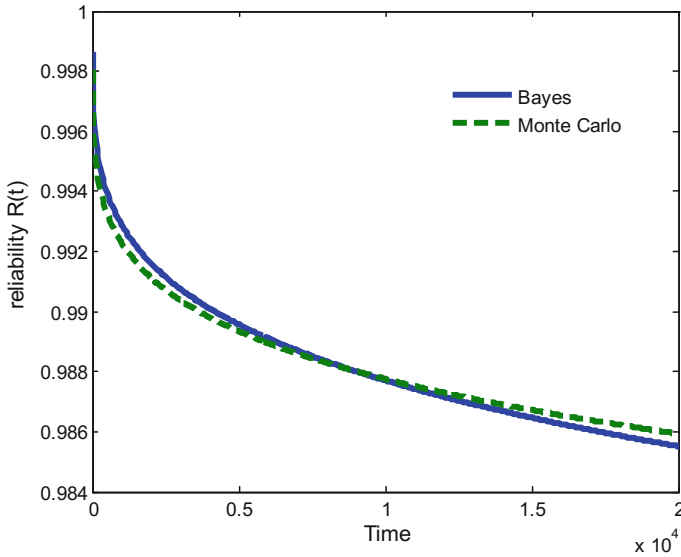

Fig. 5 Monte Carlo simulation results of parameter β, θ

Fig. 6 The comparison of reliability curve based on Bayes and Monte Carlo method

According to the results of simulation, the average value of β, θ can be obtained as $\bar{\beta} = 5.3128, \bar{\theta}_1 = 59.3527, \bar{\theta}_2 = 39.2596, \bar{\theta}_3 = 31.4867, \bar{\theta}_4 = 13.1694$, put these value into equation of $\hat{m}, \hat{c}, \hat{a}$ and Eq. (15), the acceleration model is:

$$\ln \hat{\eta}_v = 125.5483 - 23.2571 \ln V$$

As shown above, the reliability of inverter under the normal working voltage 32 V is:

$$\hat{R}_V(t) = \exp\{-(125.5483 \times 32^{23.2571}t)^{0.2015}\}$$

Figure 6 shows the comparison of two reliability curve under the Bayes method and the Monte Carlo simulation. From the curve, it is obviously that the two curves are extremely close. It validates the accuracy of the evaluation method of inverter's reliability.

Several conclusions can be drawn from this article:

1. In the accelerated degradation test, the water cooling system is adopted to maintain the test temperature relatively stable, thus, the failure mechanism of inverter can consistent with practice, during the test, the fault type of inverter can be diagnosed as wear-out type failure. It assumed that the life distribution of inverter is two-parameter Weibull distribution.

2. Combined with Weibull distribution, the acceleration model is analyzed, using the Bayes method, the evaluation method of inverter is obtained, and the reliability curve of inverter is solved through the accelerated degradation test.
3. To checkout the evaluation results of the inverter based on the Bayes reliability, the simulation of the accelerated degradation test based on Monte Carlo is operated. The evaluate results and the simulation results are extremely close. It validates the accuracy of the evaluation method of inverter's reliability. This method can used to evaluate the other electronic equipments' reliability.

References

1. Minwu C (2011) The reliability assessment of traction substation of high speed railway by the GO methodology. Power Syst Protect Control 39(18):56–61 (in Chinese)
2. Jiankang Z, Xiaohua L, Xia Y (2015) Discussion on protection configuration and setting calculation for 750 kV transformer. Power Syst Protect Control 43(9):89–94 (in Chinese)
3. Kaiyi Z, Yifa S, Yongsheng L (2016) Research on transient characteristics of passing neutral section in CRH2 trains traction motor. Res Develop 4:38–41
4. Chenxi D, Zhigang L, Song G (2016) Fault diagnosis for traction transformer of high speed railway on the integration of model-based diagnosis and fuzzy petri nets. Power Syst Protect Control 44(11):26–32 (in Chinese)
5. Gaofu D, Dan Z, Pengfeng L, Chunchun Z (2016) Study of control strategy for active power filter based on modular multilevel converter. Power Syst Protect Control 43(8):74–80 (in Chinese)
6. Yashun W, Chunhua Z, Xun C, Yongqiang M (2009) Simulation-based optimal design for accelerated degradation tests with mixed-effects model. J Mech Eng 45(12):108–114 (in Chinese)
7. Kun X, Xiaohui G, Chen P (2014) Reliability evaluation of the O-type rubber sealing ring for fuse based on constant stress accelerated degradation testing. J Mech Eng 50(16):62–69 (in Chinese)
8. Yongqiang M (2008) Investigation in lifetime assessment of electron multiplier based on double-stress accelerated degradation test. National University of Defense Technology (in Chinese)
9. Xiang J, Xiaolin W, Bo G (2016) Reliability assessment for very few failure data and zero-failure data. J Mech Eng 52(2):182–188 (in Chinese)
10. Dexin Z, Hongzhao L (2013) Reliability evaluation of high-speed train bearing with minimum sample. J Central South Univ 44(3):963–969 (in Chinese)
11. Trabelsi M, Boussak M, Benbouzid M (2016) Multiple criteria for high performance real-time diagnostic of single and multiple open-switch faults in ac-motor drives: application to IGBT-based voltage source inverter. Electr Power Syst Res 144:136–149
12. Xiaoping D, Yangang W, Yibo W, Haihui L, Guoyou L, Daohui L, Steve J (2016) Reliability design of direct liquid cooled power semiconductor module for hybrid and electric vehicles. Microelectron Reliab (in Chinese)

13. Czerny B, Khatibi G (2016) Interface reliability and lifetime prediction of heavy aluminum wire bonds. Microelectron Reliab 58:65–72
14. Choi UM, Blaabjerg F, Jorgensen S, Lannuzzo F, Wang H, Uhrenfeldt C, Munk-Nielsen S (2016) Power cycling test and failure analysis of molded intelligent power IGBT module under different temperature swing duration. Microelectron Reliab
15. Hamada MS, Wilson AG, Shane Reese C, Martz HF (2008) Bayesian Reliability. Springer, pp 51–60
16. China Electronics Standardization Institute (1987) Reliability Test Table. National Defend Industry Press, Beijing (in Chinese)