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Research on the life assessment of the insulating rod of a fast mechanical switch based on the Weibull distribution and the firefly algorithm

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Abstract

Against the backdrop of increasingly stringent reliability requirements for fast mechanical switches in power systems, the life assessment of the insulating rod, a core component of fast mechanical switches, faces the challenges of insufficient credibility in pure simulation, high costs in pure testing, and limited coverage of operating conditions. To address this, this study proposes a method for predicting the life of insulating rods based on the three-parameter Weibull distribution and the firefly optimization algorithm, enabling reliable assessment of the rod life under multiple driving voltage conditions. First, a multi-physical coupling finite element model of the switch is established, and the validity of the model is verified through actual stress tests. Second, the failure life is calculated by combining the stress-life curve and the linear cumulative damage theory. Subsequently, the three-parameter Weibull distribution is used to fit the data, the parameters are globally optimized via the firefly algorithm, and the statistical characteristic indicators are derived in combination with the gamma function. The experimental verification and simulation expansion methods adopted in this study avoid the drawbacks of pure testing and pure simulation, providing a theoretical and engineering foundation for the reliability design and life assessment of key components of high-end equipment.

Keywords: Fast mechanical switch; Insulating rod; Weibull distribution; Firefly algorithm; Life prediction

1. Introduction

As the core equipment for fault isolation and power quality regulation in the power system, the rapid mechanical switch's millisecond-level opening response speed directly determines the suppression effect of power grid faults [1-3]. The insulating rod, as a key component for transmitting the operating force, is subjected to the coupling action of alternating load and voltage during frequent opening and closing cycles. It is prone to severe faults such as switch refusal and misoperation due to fatigue failure [4]. Engineering statistics show that approximately 35% of switch faults are caused by rod fatigue failure [5-6]. Among them, composite material rods such as glass fiber-reinforced epoxy resin are prone to micro-damage accumulation caused by stress concentration, ultimately leading to interlaminar fracture [7]. Therefore, accurately evaluating the rod's lifespan is of great significance for ensuring the safe and stable operation of the power grid [8].

The core of power equipment life assessment is to establish the mapping relationship between failure data and reliability models [9-11]. The Weibull distribution is widely used because it can flexibly adapt to the fatigue failure characteristics of mechanical components [12-16]. Reference [17] combined the Weibull distribution with the health index theory to construct a discretized time-varying failure rate model considering the equipment deterioration and aging states. The reliability assessment scheme proposed in Reference [18] is supported by a large amount of life test data, and the failure probability is quantified through the Weibull model. Reference [19] combined the Weibull distribution with the accelerated life test to shorten the time for obtaining failure sample data. As a heuristic intelligent optimization algorithm with fast convergence speed and strong global optimization ability, the firefly algorithm has shown good applicability in the field of reliability parameter optimization [20]. Although existing studies have attempted to improve the accuracy of parameter estimation through intelligent algorithms or expand the sample size based on simulation, a closed-loop design that uses experiments to verify simulations, simulations to expand working conditions, and algorithms to optimize models has not been formed, making it difficult to meet the actual engineering requirements [21].

The above traditional methods have significant limitations. On the one hand, the life test cycle of the tie rod is as long as several months, and expensive dedicated equipment is required. In practical engineering, only small - sample failure data can be obtained. On the other hand, the pure simulation model lacks experimental calibration, and the virtual data lacks credibility^[22-23].

In view of this, this paper takes the glass fiber-reinforced epoxy resin insulating rod as the object and constructs a full-process life assessment framework. The simulation model is verified through a small number of actual stress tests to address the problem of the disconnection between pure simulation and engineering. Relying on the verified model to cover multiple voltage conditions can avoid the consumption of a large number of destructive tests. The three-parameter Weibull distribution is used to adapt to the failure characteristics, and combined with the firefly algorithm to break through the bottleneck of parameter optimization for small samples. Through failure mode analysis, test verification, multi-condition simulation, and parameter optimization verification, the accurate prediction of the rod's life is achieved, providing a universal solution for the reliability design and operation and maintenance decision-making of fast mechanical switches, and also offering a reusable idea for the life assessment of similar equipment components.

2. Analysis of the fatigue failure mechanism of insulating rods

2.1. Fatigue failure modes and evolution laws

The test object is a 110kV fast mechanical switch insulation rod composed of glass fiber-reinforced resin. Positioned between the vacuum interrupter and the repulsion mechanism, it serves as a crucial force-transmitting component within the switch transmission system. On-site operation and maintenance monitoring have indicated that the insulation rod is susceptible to fatigue damage due to time-varying multi-axial stress, classifying it as a high-failure-risk component in switch operations. Consequently, research on the fatigue life of this component has been conducted.

The core failure mode of the insulating rod of the fast mechanical switch is the progressive fatigue fracture dominated by cyclic loading. Its essence is the continuous accumulation of damage in the stress concentration area. The complete loss of the bearing function due to damage accumulation can cause problems such as poor switch connection and action jamming.

Fig. 1. shows the diagram of the rod breakage during the simulated opening and the diagram of the actual rod wear and breakage failure at the site, intuitively presenting the macroscopic characteristics of the failure mode.



(a) The damage in the stress concentration area of the insulating rod accumulates until it breaks. (b) On-site picture of tie rod fracture

Fig. 1. shows the simulation of the insulating rod fracture during opening and the on - site failure diagram of the tie rod fracture.

2.2. Theoretical basis of fatigue analysis

The main basis for the fatigue analysis of tie rods is the stress-life curve (S-N curve) of the material. Fig 2 shows the S-N curve of the glass fiber-reinforced resin tie rod material, which establishes a quantitative correspondence between the cyclic stress level and the fatigue life through fatigue tests and clarifies the anti-fatigue ability boundaries of the tie rods under different stresses. Its expression is as follows:

$$e^{\alpha S} N = C_1 \quad (1)$$

Where: N represents the fatigue life under the corresponding stress level S ; α is the attenuation coefficient of stress on life; C_1 is a dimensionless quantity.

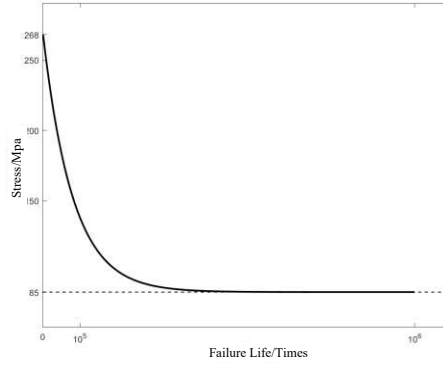


Fig. 2. S-N curve of the insulating rod of the glass fiber-reinforced resin tie rod material

After determining the fatigue life corresponding to each stress level based on the S-N curve, the linear cumulative damage theory (Palmgren - Miner) can be used to quantify the damage accumulation process of progressive fatigue fracture. If the tie rod actually undergoes n_i cyclic loadings under the stress S_i , the damage amount corresponding to this stress is n_i/N_i , where N_i is the fatigue life corresponding to S_i obtained from the S-N curve. The total damage amount D is the sum of the damage amounts under each stress.

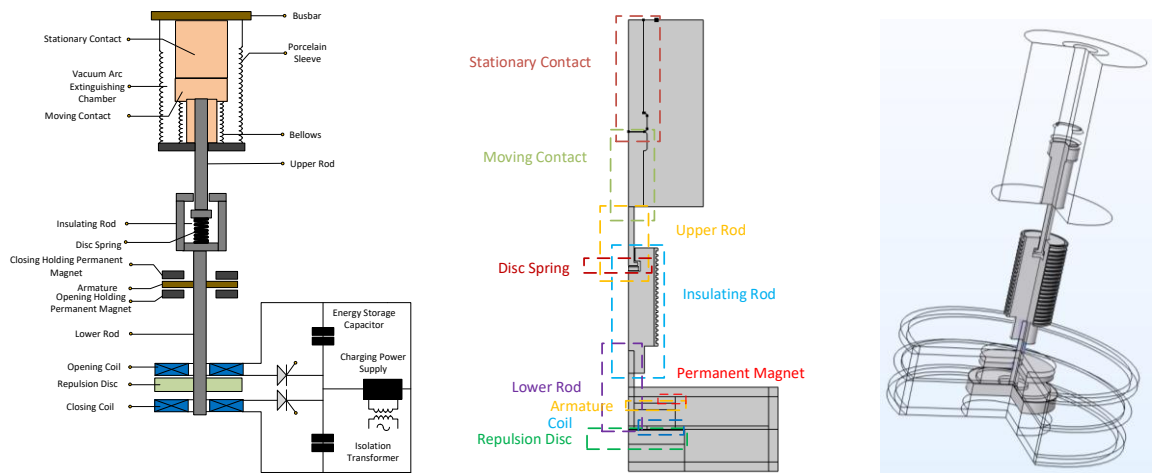
$$D = \sum_{i=1}^n \frac{n_i}{N_i} \quad (2)$$

When the total damage amount $D = 1$, it indicates that the cumulative damage of the tie rod has reached the tolerance limit.

3. Multi - physical field simulation and experimental verification of insulating rods

3.1. Establishment of multi - physical field coupling simulation model

Figure 3 (a) shows the structural diagram of the fast mechanical switch under study, which is composed of components such as a repulsion mechanism, a pull rod, and a vacuum interrupter. A two-dimensional axisymmetric simulation model was established using COMSOL software, as shown in Figure 3 (b) (c).



(a) Structural diagram of the fast mechanical switch (b) Two-dimensional axisymmetric model (c) Three-dimensional view of the model

Fig. 3. Schematic diagram and simulation model of the fast mechanical switch structure

In the initial state, the moving and static contacts are in the closed position, and the disc spring is installed at the connection between the insulator and the upper pull rod. To overcome the spring reaction force and the gravity of moving parts and prevent false opening caused by electrodynamic force or mechanical vibration, the magnetic force generated by

the closing holding permanent magnet and the armature needs to be balanced with the spring reaction force. During opening, the energy storage capacitor is triggered by the thyristor to discharge to the opening coil. The pulse current induces eddy currents in the repulsion disc, forming an induced current opposite to the coil current, and then generating electromagnetic repulsion to drive the pull rod assembly. After the over - travel is completed, the moving contact starts to move, achieving rapid opening. The switch parameters are shown in Table 1.

Table 1 .Switch parameter settings

Project Name	Parameters
Repulsion Disc Dimensions/mm	Diameter 80, Thickness 8
Coil material	Copper
Coil wire diameter	1mm×2.5mm
Number of coil turns	24 turns
Moving armature mass /kg	0.16
Permanent magnet dimensions	90mm×18mm×18mm

The parameters of the insulating rod are shown in Table 2.

Table 2 .Parameters of insulation rods

Project Name	Parameters
Materials	Resin pull rod
Poisson ratio	0.3
Quality /kg	0.7
Density/g/cm ³	1.9
Fatigue Limit Strength/MPa	85
Tensile Modulus of Elasticity/GPa	28

3.2. Design and implementation of actual stress measurement tests

To obtain the benchmark data of the actual maximum stress of the pull rod required for simulation, a targeted test was designed. The fast mechanical switch of the model used in this research was taken as the test object. When the switch is opened, the pull rod mainly transmits axial tension, and the stress concentration area is mainly under uniaxial tension. Therefore, the pasting direction of the strain gauges should be consistent with the axial force direction of the pull rod. Strain gauges were pasted at the vulnerable positions of the insulating pull rod, and the NI - 9923 strain data acquisition system was used to collect the actual strain signals of the pull rod under different voltages. A high - speed camera was used to completely record the entire motion process of the mechanical switch through the movement of the repulsive disc. The layout of the test site is shown in Figure 4.

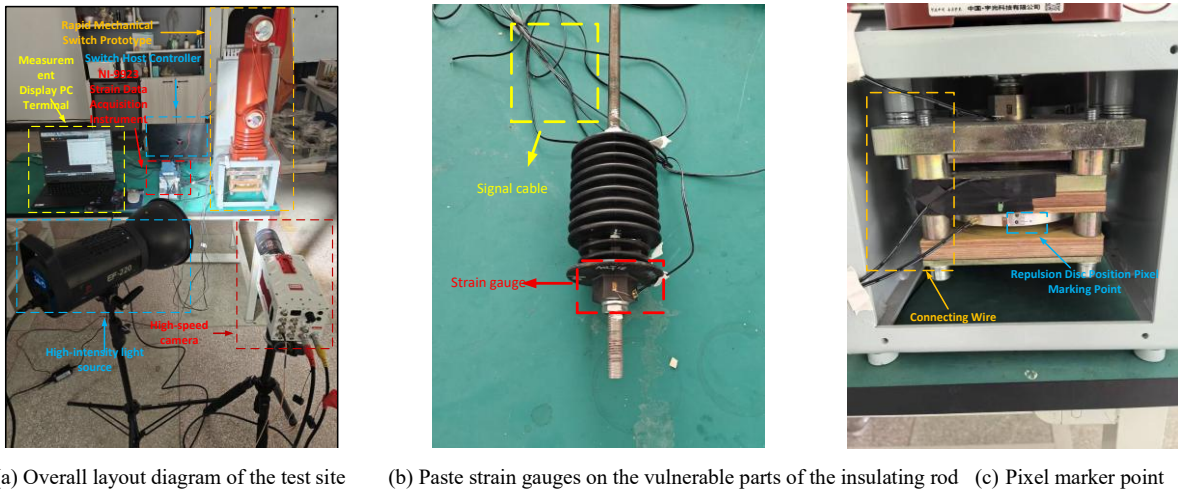


Fig. 4. Layout diagram of the on - site stress measurement test for the rapid mechanical switch prototype

In the experiment, three groups of voltages with capacitor energy storage of 780 V, 820 V, and 867 V were selected, covering the common driving voltage range of the switch repulsion mechanism in engineering practice. Under each group of voltages, the switch was controlled to complete three opening operations, and the deformation data of the strain gauge were synchronously recorded through the NI - 9923 strain data acquisition system. The maximum stress value of the three cycles was taken as the actual maximum stress under this voltage.

3.3. Validation of the simulation model based on experimental data

To verify the correctness of the simulation model in Figure 3, a model test based on experimental data was carried out. The process is as follows:

1) Experimental test implementation: Select the above typical driving voltage conditions, collect strain data through the strain testing system shown in Figure 4, and record the strain change curve during the opening process.

2) Simulation calculation settings: Based on the multi - physical field coupling simulation model in Figure 4, using the same opening drive voltage conditions as those in the experiment, simulate the stress change process during the opening process of the pull rod.

3) Verification results and analysis: When the switch is opening, the pull rod mainly transmits axial tension and is mainly under unidirectional tension. Hooke's law is used to calculate the stress change during the experimental opening process.

$$\sigma(t) = E\varepsilon(t) \quad (3)$$

$\sigma(t)$ represents the instantaneous stress at time t ; E represents the Young's modulus; $\varepsilon(t)$ represents the instantaneous strain measured by the strain gauge at time t .

To enhance the reliability of the signal, targeted pre - processing is performed on the strain signals originally collected from the experiment. First, the local distortion values in the data are removed. Then, through band - pass filtering and local averaging, the strain changes show a smooth trend, effectively improving the signal quality.

Figure 5 shows the force diagram of the insulating rod under the conditions of three-component opening drive voltages of 780V, 820V, and 867V.

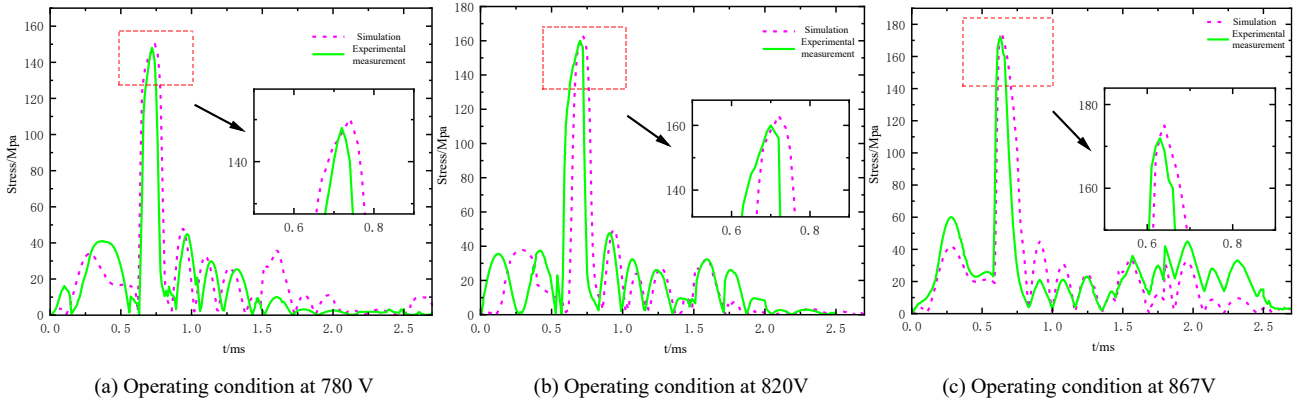


Fig. 5 .Force diagrams of the insulating rod under different voltage conditions

As shown in Figure 5, under the three different opening drive voltage conditions, the maximum stress values measured in the experiment are 147 MPa, 160 MPa, and 172 MPa respectively, and the corresponding maximum stress values calculated by the simulation model are 151 MPa, 163 MPa, and 176 MPa. After calculation, the relative errors between the two sets of data are 2.7%, 2.0%, and 2.3% in sequence. Further comparison of the overall error of the stress data over the entire time period shows that it is less than the 10% error threshold generally recognized in the engineering field.

In terms of the stress variation trend: The waveforms of the stress-time curves obtained from the simulation and the experiment are basically consistent. The stress reaches its peak at 0.75 ms after the opening operation starts at 780 V, 0.68 ms after the opening operation starts at 820 V, and 0.60 ms after the opening operation starts at 870 V. After reaching the peak value, the stress shows a gradually decaying trend, clearly presenting a rule that the higher the voltage, the faster the opening operation starts, and the earlier the stress peak appears.

The experimental verification results show that the relative error of the maximum stress of the established simulation model is less than 5%, and the overall stress error over the entire time period is less than 10%. Moreover, the dynamic stress trend is in good agreement with the actual test results. This model can effectively reflect the actual service conditions of the insulating rod, has sufficient accuracy and credibility, and can be used for subsequent fatigue life assessment.

4. Simulation calculation of the service life of the insulating rod

To comprehensively cover the actual service scenarios of the pull rod, this study selects the voltage range of 775V -

871V, which is the operating voltage range in the actual project of this type of switch, as the simulation voltage interval. Following the principles of typical verification, uniform distribution, and inflection point encryption, 14 groups of simulation voltages are finally determined.

In terms of simulation calculation logic, the key issue to be addressed is the adaptation of the S-N curve to actual working conditions. The S-N curve is essentially an ideal model for a single constant stress loading scenario, which can only provide the fracture life of the pull rod under a specific constant stress. However, during the actual opening process, even under the same voltage condition, the pull rod is subject to the superposition of multiple instantaneously changing stresses due to factors such as electromagnetic repulsion force fluctuations and mechanical shocks. Its stress state fluctuates dynamically over time, making it impossible to directly apply the ideal life data from the S-N curve.

Therefore, this study utilized the fatigue cycle module of COMSOL simulation software. Based on the S-N curve as the input, the dynamic stress history of a single opening cycle of the pull rod under a single voltage condition was restored through simulation, and the fatigue damage amount of a single cycle was accurately quantified. Combined with the Palmgren-Miner linear cumulative damage theory, the single damage amount was converted into the total fatigue life under this voltage condition. When the cumulative damage amount reached the critical value of 1, the pull rod was judged to have failed according to the failure criterion. Figure 6 shows the distribution of single fatigue damage amounts under different voltage conditions.

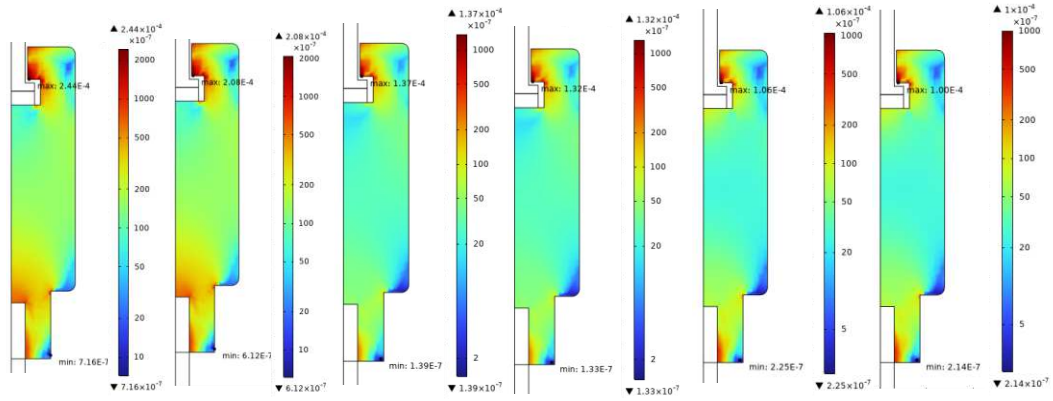


Fig.6. Single fatigue damage amounts under the opening conditions of 871V, 866V, 825V, 820V, 790V and 775V.

Table 3 shows the number of tie rod failures corresponding to 14 sets of simulated voltages.

Table 3. Tension rod failure data under different voltages

Voltage/V	Lifetime/N	Voltage/V	Lifetime/N
775	10000	825	7299
790	9433	830	6905
795	9018	840	6503
800	8608	850	5910
805	8313	856	5302
810	8212	866	4807
820	7575	871	4099

5. Analysis of the goodness-of-fit of the Weibull distribution model

The reliability life of the insulating rod is the core indicator for measuring its quality and service life, and its accurate evaluation relies on a reasonable reliability analysis model. The Weibull distribution is the most widely used in the life analysis of mechanical components. Therefore, the Weibull distribution is selected to construct the reliability life analysis model for the rod.

5.1. Theoretical basis of Weibull distribution

The Weibull distribution takes the cycle-to-failure lifetime data corresponding to product failure modes as the core research object. By establishing a quantitative mapping relationship between the number of cycles and reliability, it can

flexibly adapt to and accurately describe different types of product failure modes, such as early failure, random failure, and wear - out failure. Its four core functions, namely the reliability function, probability density function, cumulative distribution function, and failure rate function, describe the failure characteristics of products from different perspectives. The specific meanings are as follows:

1) The cumulative distribution function (CDF) of failure probability describes the probability that a product fails before reaching a given cycles to failure N , denoted as $F(N)$.

$$F(N) = 1 - R(N) = 1 - \exp\left[-\left(\frac{N - \gamma}{\eta}\right)^\beta\right] \quad (4)$$

$R(N)$: Reliability of the insulating rod after N operating cycles; β : Shape parameter, reflecting the trend of the failure probability changing with the number of operating cycles N . η : Scale parameter, which quantifies the time scale of failure. γ : Location parameter, whose core function is to set a reference origin for the distribution.

2) The probability density function (PDF) describes the instantaneous failure probability density of a product at the number of operating cycles N . It is the derivative of the cumulative distribution function (CDF) and is denoted as $f(N)$.

$$f(N) = \frac{\beta}{\eta} \left(\frac{N - \gamma}{\eta}\right)^{\beta-1} \exp\left[-\left(\frac{N - \gamma}{\eta}\right)^\beta\right] \quad (5)$$

3) The reliability function (RF) describes the probability that a product can still work normally after N operating cycles, denoted as $R(N)$.

$$R(N) = 1 - F(N) = \exp\left[-\left(\frac{N - \gamma}{\eta}\right)^\beta\right] \quad (6)$$

4) The hazard rate function (HRF) describes the probability of a product failing within the subsequent unit cycle given that it has already been in operation for N cycles, denoted as $\lambda(N)$.

$$\lambda(N) = \frac{f(N)}{R(N)} = \frac{\beta}{\eta^\beta} (N - \gamma)^{\beta-1} \quad (7)$$

5.2. Preprocessing of failure data and determination of model adaptability

When determining whether the data follows the Weibull distribution, the Weibull probability paper method is one of the most intuitive discrimination strategies. The core idea is to linearize the cumulative failure probability relationship of the Weibull distribution through mathematical transformation, and then determine the model adaptability based on the transformed data graph. The specific process is as follows:

Mathematical transformation of Equation (4) to achieve linearization yields the following Equation (8).

$$1 - F(N) = \exp\left[-\left(\frac{N - \gamma}{\eta}\right)^\beta\right] \quad (8)$$

Taking the natural logarithm of both sides of Equation (8), we can obtain the following Equation (9).

$$\ln \frac{1}{1 - F(N)} = \left(\frac{N - \gamma}{\eta}\right)^\beta \quad (9)$$

Taking the logarithm of both sides of equation (9) again yields the linearized expression (10).

$$\ln\left(-\ln(1 - F(N))\right) = \beta \ln(N - \gamma) - \beta \ln(\eta) \quad (10)$$

Let

$$y = \ln(-\ln(1 - F(N)))、x = \ln(N - \gamma)、b = -\beta \ln(\eta)、k = \beta$$

Then the linearized expression can be simplified to Equation (11), indicating that y has a linear relationship with x .

$$y = kx + b \quad (11)$$

Substitute the failure data in Table 3 into the Weibull model. By analyzing the model fitting effect and parameter significance, determine whether the data follows the Weibull distribution and the specific type of distribution it conforms to. The specific process is as follows:

Using the minimum sum of squared residuals as the criterion, k and b are calculated through linear regression. The fitting effects of the Weibull model are compared among three cases: the single - parameter case with $k = 1$, the two - parameter case with free k and b , and the three - parameter case with free k , b , and γ .

Slope k :

$$k = \frac{n \sum_{i=1}^n x_i y_i - \left(\sum_{i=1}^n x_i \right) \left(\sum_{i=1}^n y_i \right)}{n \sum_{i=1}^n x_i^2 - \left(\sum_{i=1}^n x_i \right)^2} \quad (12)$$

Intercept b :

$$b = \bar{y} - k \bar{x} \quad (13)$$

Among them: n is the number of data points, $\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i$ is the mean of x , and $\bar{y} = \frac{1}{n} \sum_{i=1}^n y_i$ is the mean of y .

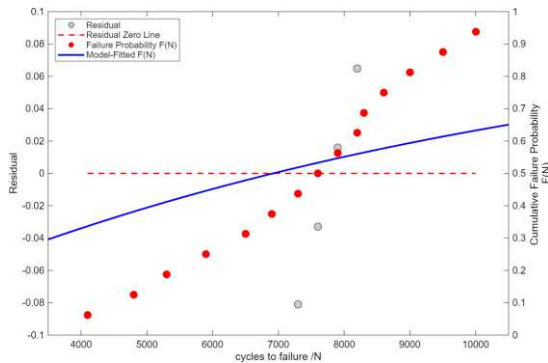
1) Single-parameter Weibull model; Fix k at 1 and calculate the sum of squared residuals.

$$S_1 = \sum_{i=1}^n (y_i - (kx_i + b))^2 \quad (14)$$

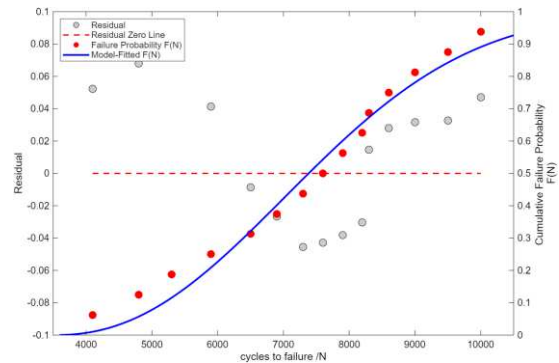
2) Two-parameter Weibull model; k and b are free parameters. The sum of squared residuals S_2 is calculated. The smaller S_2 is, the better the fitting effect.

3) Three-parameter Weibull model; After estimating γ , calculate $x = \ln(t - \gamma)$, then perform linear regression to obtain k and b , and calculate the sum of squared residuals S_3 . The smaller the S_3 , the better the fitting.

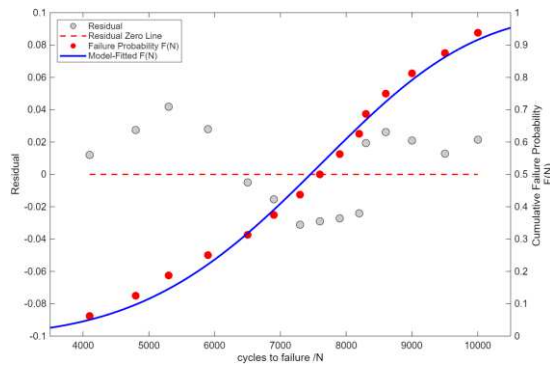
According to the Weibull transformation, the corresponding comparison diagrams of three types of Weibull probabilities and residuals in the coordinate system are obtained, as shown in Figure 7 below.



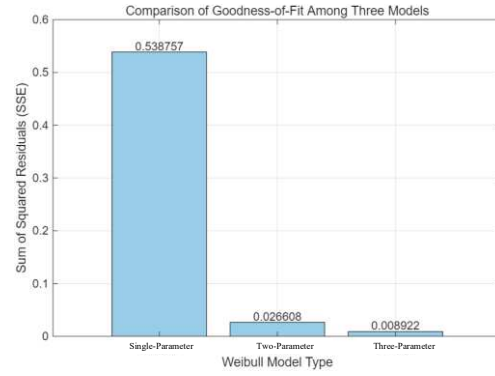
(a) Single-parameter distribution model



(b) Two-parameter distribution model



(c) Three-parameter distribution model



(d) Comparison of residuals of goodness-of-fit for the three models

Fig.7 .Weibull distribution model

To determine the most suitable Weibull type for the data, a comparative analysis should be conducted from three aspects. First, observe the degree of fit between the data points and the fitting lines of different parameter models. Second, calculate and compare the residual values of different parameter models. Third, comprehensively consider the goodness - of - fit of the fitting line and the magnitude of the residuals to determine the optimal model.

The fitting results in Figure 8 show that the data points are generally distributed along the fitting line of the three-parameter model without obvious deviation. Moreover, $S_3 < S_2 < S_1$. Combining the graphical fitting effect and the verification results of the residual values, it indicates that the failure data of the insulating rod best fit the three-parameter Weibull distribution.

6. Parameter estimation of failure distribution model based on firefly algorithm

6.1. Optimization of distribution parameters and generation of reliability curves

After determining that the failure data fit the three-parameter Weibull distribution, the firefly algorithm is used for parameter optimization. The flow chart is shown in Figure 8.

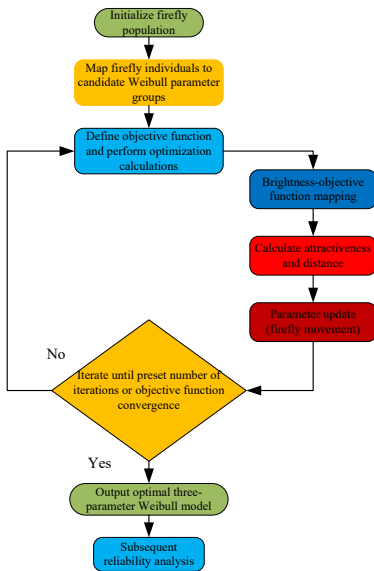


Fig. 8. Flow chart of the optimization of the three-parameter Weibull distribution using the firefly algorithm

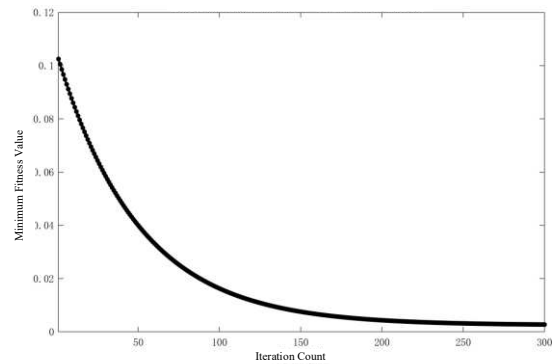


Fig. 10. shows the optimization convergence curve based on the firefly algorithm.

In Figure 8, aiming to minimize the sum of squared residuals between the four core functions of the Weibull distribution and the sample failure data, a four - dimensional weighted objective function is constructed to achieve global optimization of the three parameters of the Weibull distribution. The objective function is defined as follows:

$$\min f(X_k) = w_1 \cdot f_1(X_k) + w_2 \cdot f_2(X_k) + w_3 \cdot f_3(X_k) + w_4 \cdot f_4(X_k) \quad (15)$$

Constraints: $w_1 + w_2 + w_3 + w_4 = 1$, ensuring the normalization of weight distribution.

1) CDF residual sum of squares function

$$f_1(X_k) = \sum_i^n [F_{Weibull}(N_i; X_k) - F_{emp}(N_i)]^2 \quad (16)$$

In the formula: $X_k = [\beta_k, \eta_k, \gamma_k]$ is the candidate parameter group corresponding to the k -th firefly; $F_{Weibull}(N_i; X_k)$ is the CDF; $F_{emp}(N_i) = \frac{i}{n+1}$ is the sample empirical cumulative distribution function calculated based on the mean rank method; i is the serial number of the i -th failed sample after sorting; n is the total sample size. This objective function represents the fitting deviation of the cumulative failure probability, which is the core dimension of the Weibull distribution fitting and has the highest weight.

2) PDF residual sum of squares function

$$f_2(X_k) = \sum_i^n [f_{Weibull}(N_i; X_k) - f_{emp}(N_i)]^2 \quad (17)$$

In the formula: $f_{Weibull}(N_i; X_k)$ represents the PDF; $f_{emp}(N_i) = \begin{cases} \frac{F_{emp}(N_{i+1}) - F_{emp}(N_i)}{N_{i+1} - N_i} & (i = 1, 2, \dots, n-1) \\ f_{emp(n-1)} & (i = n) \end{cases}$ represents

the sample empirical probability density function calculated based on the discrete difference method. This objective function characterizes the fitting deviation of the failure probability density and accurately captures the high - failure intervals.

3) RF residual sum of squares function

$$f_3(X_k) = \sum_i^n [R_{Weibull}(N_i; X_k) - R_{emp}(N_i)]^2 \quad (18)$$

In the formula: $R_{Weibull}(N_i; X_k)$ is RF; $R_{emp}(N_i) = 1 - F_{emp}(N_i)$ is the empirical reliability function of the sample; this objective function represents the fitting deviation of the reliable operation ability of the tie rod.

4) Sum of squared residuals function of HRF

$$f_4(X_k) = \sum_i^n [\lambda_{Weibull}(N_i; X_k) - \lambda_{emp}(N_i)]^2 \quad (19)$$

Where: $\lambda_{Weibull}(N_i; X_k)$; represents the HRF.

$\lambda_{emp}(N_i) = \begin{cases} \frac{F_{emp}(N_{i+1}) - F_{emp}(N_i)}{(N_{i+1} - N_i) \cdot R_{emp}(N_i)} & (i = 1, 2, \dots, 14) \\ \lambda_{emp(14)} & (i = 15) \end{cases}$ is the calculation of the empirical failure rate function; this objective

function represents the fitting deviation of the instantaneous failure rate of the tie rod, reflecting the progressive characteristics of aging failure and the law of damage accumulation.

In this paper, the Analytic Hierarchy Process (AHP) is used to determine the weight distribution of the four - dimensional objective function. The steps are as follows:

1) Construct a hierarchical structure: Set the maximization of the fitting accuracy of Weibull parameters as the target layer, and take the CDF, PDF, RF, and HRF as the criterion layer.

2) Construct the judgment matrix: Based on the engineering characteristics of the insulating rod, the 1 - 9 scaling method is used to construct the judgment matrix, which reflects the weighting logic with CDF and RF as the main factors and PDF and HR as the auxiliary factors.

3) Weight calculation and correction: The initial weights are approximately 0.3333, 0.1667, 0.3333, and 0.1667 through matrix normalization and the row average method. They are fine - tuned to $\omega_1 = 0.35$, $\omega_2 = 0.20$, $\omega_3 = 0.25$, and $\omega_4 = 0.20$ in combination with the engineering operation and maintenance requirements.

4) Consistency check: The calculated consistency ratio $CR < 0.1$, which verifies the rationality of the weight allocation.

The finally constructed four-dimensional objective function is:

$$\min f(X_k) = 0.35 \cdot f_1(X_k) + 0.2 \cdot f_2(X_k) + 0.25 \cdot f_3(X_k) + 0.2 \cdot f_4(X_k) \quad (20)$$

This weight allocation not only ensures the dominant positions of the core fitting dimension CDF and the core index RF, but also enhances the comprehensiveness of the fitting through PDF and HRF. Then, the optimal parameter values are obtained through the iterative optimization of the firefly algorithm $\beta = 1.92$, $\eta = 7689.45$, $\gamma = 3987.21$.

Substitute the optimal parameter values obtained from the optimization into Eqs (4), (5), (6), and (7), and the generated reliability characteristic curves are shown in Fig. 9.

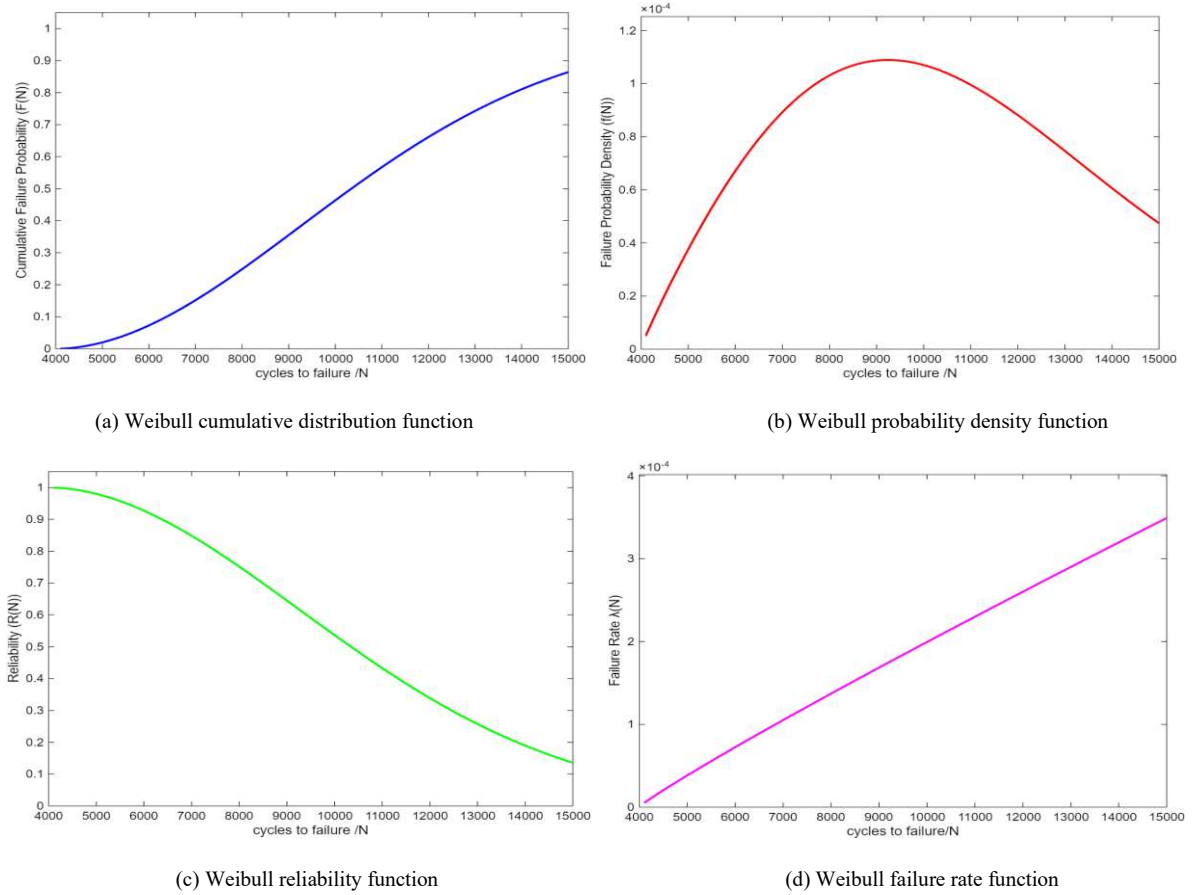


Fig.9. Characteristic curves of the four core functions of the Weibull distribution

1) Analysis from the CDF function curve in Figure 9a: The CDF curve shows an S-shaped progressive growth trend. Combining with the statistical characteristics of the Weibull distribution, it can be known that when the lifespan reaches the median lifespan of 10,344 cycles, the cumulative failure probability is approximately 50%. After the lifespan approaches the characteristic lifespan of 11,676 cycles, the cumulative failure probability approaches 100%.

2) It can be concluded from Figure 9b that the peak of the PDF curve corresponds to the life interval of 7050 - 8525 cycles, which is the dangerous interval with the highest failure probability of the tie rod.

3) As can be seen from Figure 9c, the reliability shows an exponential decline trend with the increase of service times. In the initial stage when the service times are less than 4000, the reliability is close to 100%, and the risk of early failure is extremely low. When the service times reach the median life of 10344, the reliability drops to 50%. When the service times reach 7516, the reliability begins to decline significantly.

4) As can be concluded from Figure 9d, the failure rate continuously increases with the increase in the number of service cycles, and the shape parameter $\beta = 1.92 > 1$, indicating that the failure mode of the tie rod is typical wear - out

failure, which is completely consistent with the progressive damage accumulation mode dominated by cyclic loading.

Meanwhile, the convergence curve of the firefly algorithm for optimization is shown in Figure 10. Figure 10 intuitively demonstrates the iterative process of parameter optimization: as the number of iterations increases, the objective function rapidly decreases and tends to be stable, reaching a convergence state at around 240 iterations, and the final convergence value is close to 0.001. This result indicates that the firefly algorithm has strong global optimization ability and a fast convergence speed, can efficiently jump out of local optimal solutions, and ensures the accuracy and stability of the obtained Weibull distribution parameters.

6.2. Calculation of statistical indicators for the service life of tie rods

Although the qualitative characteristics of the tie rod's lifespan, such as the interval ranges of the median lifespan and characteristic lifespan, can be intuitively observed through the reliability curve, the curve can only reflect the relative trend of the lifespan and cannot provide accurate quantitative indicators. In contrast, various lifespan indicators derived based on the statistical characteristics of the Weibull distribution can offer crucial bases for engineering operation and maintenance decisions, thus avoiding safety risks and cost waste caused by over - maintenance or insufficient maintenance.

The statistical mean time to failure (MTTF) of the three-parameter Weibull distribution is derived based on the definition of the expectation of a random variable, and its mathematical expression is:

$$MTTF = \gamma + \eta \Gamma\left(1 + \frac{1}{\beta}\right) \quad (21)$$

$\Gamma(\cdot)$: The Gamma Function, as an extension of the factorial function in the real - number domain, is defined as follows: when x is a positive integer, $(\Gamma(x) = (x-1)!)$; when x is a half - integer, $(\Gamma(1.5) = \sqrt{\pi}/2)$; for any positive real number, $\Gamma(x+1) = x\Gamma(x)$. Substituting the optimal Weibull parameters obtained through optimization into the average lifespan calculation formula, the average lifespan of the insulating rod is found to be 10,807 times.

The statistical average life in this paper is the statistical expectation of the three-parameter Weibull distribution, rather than the arithmetic mean of the failure data of 14 groups of voltage conditions in Table 3. The reason why its value is slightly higher than the maximum value of the sample is that the location parameter γ of the three-parameter Weibull distribution is 3987.21 and the statistical expectation requires the superposition of the location parameter and the probability expectation derived from characteristic life. This is an inherent statistical characteristic of the Weibull distribution for fitting right-skewed failure data, which is neither contradictory to the actual number of failures under working conditions nor violates the laws of reliability statistics.

Based on the optimization of parameters of the three-parameter Weibull distribution and the derivation of the reliability function RF, the practical engineering life indicators of insulating rods corresponding to different reliability levels are obtained: The service life at a reliability level of 90% is 6820 operations, which means that 90% of the rods can serve safely up to this number of operations, and only 10% may fail. This is suitable for switches in key circuits such as the main grid, meeting high safety requirements; The service life at a reliability level of 80% is 7516 operations, indicating that 80% of the rods can serve safely up to this number, with only a 20% risk of failure. It is recommended as the preventive replacement warning threshold for regular circuits; The service life at a reliability level of 70% is 8050 operations, meaning that 70% of the rods can reach this number of operations, and only 30% may fail. This is applicable to general circuits, balancing safety and operation and maintenance costs; The median life corresponding to a 50% reliability level is 10344 operations. At this point, 50% of the rods will fail before reaching this number, while the other 50% can exceed it. This can be used as the critical threshold for mandatory replacement to avoid a concentrated outbreak of failure risks.

7. Conclusions

To address the core issues of low credibility in pure simulations and high costs along with narrow operating conditions

in pure experiments for the life assessment of insulating rods of fast mechanical switches, this paper establishes a framework of experimental verification, simulation expansion, and algorithm optimization to achieve the predictive assessment of the rod life under multiple operating conditions. The main conclusions are as follows;

1) A verification method for the simulation model based on actual stress testing is proposed. Stress data under typical voltage conditions are obtained through strain gauges, the NI-9923 data acquisition system, and high-speed photography technology. The relative error between the maximum stresses in the simulation and the actual measurement is small, and the dynamic trends are highly consistent, which lays a reliable foundation for multi-condition life simulation.

2) The failure data of the tie rods optimally fit the three-parameter Weibull distribution. The global optimization of parameters is achieved through the firefly algorithm, resulting in the minimum sum of squared fitting residuals and stable convergence. The loss failure mode and failure risk interval of the tie rods are revealed, and the model can accurately capture the loss failure mode of the tie rods.

The experimental verification and simulation expansion methods adopted in this study avoid the drawbacks of pure experiments and pure simulations, providing a theoretical and engineering foundation for the reliability design and life assessment of key components in high-end equipment.

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Data availability

The datasets generated and analysed during the current study are not publicly available due to institutional restrictions, but are available from the corresponding author on reasonable request.

Conflict of Interest

Conflict of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.