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RESEARCH ARTICLE

Reliability Assessment Method for Power Grid Security and Stability Control Devices Based on Weibull Fault Rate Fitting

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ABSTRACT The stability control device is an important part of the safety and stability control system of the power system. The stability control devices cooperate through certain control logic, so that the stability control system can realize the functions of prevention control, emergency control, and recovery control, to guarantee the safe and stable operation of the power system. The existing reliability assessment methods of the stability control devices mainly rely on the analysis of the failure principle of the devices and the statistics of the historical operation data, which cannot make an effective prediction of the changing trend of the failure rate of the stability control devices. In this paper, we propose a Weibull fault rate fitting-based reliability assessment method for power grid control devices, which is based on a function fitting method to fit the parameters of the fault rate function of the control devices and use the obtained parameters to calculate the reliability evaluation index of the control devices. The method has important engineering significance for the production and deployment of stabilization control devices and the design improvement of grid stabilization control systems.

INDEX TERMS Stability control device, parameter fitting, Weibull distribution, reliability assessment.

I. INTRODUCTION

With the rapid development of social and economic development, the pace of China's power grid construction is increasingly accelerated. In the first decade of this century, the 1 000 kV Chang-South-Jing AC project and the ±800 kV Fufeng DC project have been put into operation, marking China's entry into a new era of high-capacity ultra-high voltage AC and DC interconnection of regional power grids, with unprecedented requirements for safe and stable operation of power grids [1]. As a huge system with wide geographical distribution, the power system is characterized by many components, complex structure, and fast dynamic response [2]. Especially in the "strong direct and weak AC" grid structure [3], a DC fault will cause a huge impact on the grid. Therefore, to ensure the safe and stable operation of the grid, not only the existing grid structure should be strengthened, but also a robust and reliable defense system with fast fault response characteristics should be deployed [4].

In China, the grid security and stability control system (referred to as the stability control system) is an important facility to ensure the safe and stable operation of the grid as the second line of defense [5]. During the transition period of the "strong direct and weak AC" grid, China has carried out several engineering practices of UHV AC and DC grid stability control, such as frequency emergency coordination control system for multi-DC feeder grid [6] and system protection for hydropower convergence multi-DC weak feeder grid [7], [8] and other partitioned grid stability control systems. At present, the stability control system shows the development trend of large-scale, wide-area, and complex. When the power grid is hit by a serious fault, the

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reliable and timely action of the stability control system is an important prerequisite to ensure the safety and stability of the power grid, the reliability of the stability control system to reduce mis-operation, rejection will bring unbearable secondary shock to the power grid. Stabilization control devices through a certain control logic with each other, so that the stabilization control system can achieve preventive control, emergency control and recovery control, and other functions. However, there is a risk of failure of the safety and stability control device during operation due to hidden problems such as irregular operation, the mismatch between the setting of the fixed value and the actual power grid, and aging of the equipment over a long time [9]. The failure rate function tends to show a "bathtub curve" of "first falling, then flattening, then rising". The failure of the stabilization device leads to the rejection or mis-operation of the stabilization system, which may cause large-scale grid security and stability problems. Historically, there are few grid accidents related to the failure of the stabilization system [10], [11], e.g., the "7.1" blackout in Central China in 2006 [12], the "9.8" blackout in the United States in 2011 [13], and the "3.21" blackout in Brazil in 2018. In Brazil, the "3.21" blackout [14], improper calibration, system logic design without reasonable consideration of extreme events, and hardware and software failures were the main causes of the blackout. Therefore, the failure risk analysis and reliability assessment of stabilization and control devices are of great significance to ensure the resilience of power systems against grid failures.

The reliability of a stability control system refers to its ability to complete the specified functions according to the scheduled time and scheduled working conditions [15]. At present, the reliability study of the stability control system is still in its initial stage, mainly for the reliability of single components, device hardware, single-station systems, or small systems [16], [17], with a single analysis and research method, and lacking a general method to adapt to the reliability study of large stability control systems. The reliability assessment of equipment mainly relies on the statistics of the historical operation data of faulty equipment and the calculation of the probability of failure of equipment using statistical methods. The existing reliability assessment of power systems mainly includes fault tree and Markov methods [18]. The fault tree method decomposes the whole power system into multiple subsystems and bottom components, and obtains the failure distribution of the top-level system by calculating the failure distribution of the bottom-level components, together with the logical relationship between each subsystem within the system [19]. Markov method analyzes the reasons and probability of transferring a device or system to a failure state by establishing a state transfer model of the device or system and combining the importance of different components to the device [20]. However, the above method has high requirements for the size of the sample capacity. The exponential growth of the number of states due to complex influence mechanisms and high coupling within the system also makes the corresponding computational complexity exponentially higher. Parameter-fitting-based equipment reliability assessment with small data requirements and simple computation is starting to come into view.

The reliability assessment of equipment based on parameter fitting is mainly done by fitting a function to the collected data to determine the failure rate function that conforms to the operation law of the equipment and then calculating reliability evaluation indexes such as reliability function and compound failure probability. Literature [20] proposed the failure rate model of relay protection devices was constructed using the great likelihood estimation and the Tonglen algorithm. Literature [21] proposed the reliability parameters of relay protection devices were estimated using the gray-three-parameter Weibull distribution, which solved the problem of insufficient accuracy of reliability evaluation methods under small sample conditions and improved the computational speed at the same time. The literature [19] used the Markov method to predict the action behavior of relay protection devices and proposed a strategy to call emergency protection devices and put them into operation in an emergency. However, there are few studies on the parameter fitting of stabilization devices. The reliability assessment methods for primary equipment and relay protection are difficult to be applied to the stability control devices because of the differences in constituent components, operation principles, and functions.

The operation of intelligent substations has effectively improved the reliability of relay protection and stability control devices. The limited fault data makes the on-site operation data of relay protection and stability control devices have small sample and truncation characteristics, which increases the difficulty of reliability evaluation of relay protection and stability control devices. Therefore, constant failure rate (assuming that it obeys exponential distribution) is widely used to evaluate the reliability of relay protection stability control devices. Representative methods include Markov state model [22], Goal Oriented method [23], fault tree method [24], etc. However, in terms of accuracy, the reliability evaluation results based on a constant failure rate have lower accuracy [25]. Compared with constant fault rate, time-varying fault rate is more flexible in data fitting and can effectively simulate the change of fault rate over time, especially the time-varying fault rate model that follows Weibull distribution. It is widely used in reliability evaluation and analysis of relay protection devices [26], [27]. The mainstream method currently used is the least squares method based on the two-parameter Weibull distribution, considering the truncation characteristics of the observed samples, and combining the average rank method to estimate the parameters of the Weibull distribution model [28], [29], [30], [31]. However, the disadvantage of the least squares method is its poor robustness, especially under the condition of small samples, it is vulnerable to the influence of outlier such as gross error and noise to reduce the estimation accuracy.

At the beginning of the commissioning period, the stabilization device has been well commissioned and usually maintains operation for a while with a low failure rate. As time goes by, the failure rate starts to rise due to the aging of components and the mismatch between the operation mode and the grid, and the stabilization device enters the wear and tear period. However, the current research on the reliability assessment of stabilization devices is only limited to the analysis of the failure mechanism and the statistics of the failure rate. The literature [20] took the SCS-500E safety and stability control device as an example, which is a new generation of safety and stability control device developed to meet the stable operation requirements of ultra-high voltage interconnected power grids, combined the fault tree method with the Markov state space method, and analyzed the composition and inner cooperation relationship of the hardware system of the stability control device; the literature [9] used Markov state space method and Monte Carlo method to evaluate the reliability calculation of the typical engineering application cases of the stability control system respectively and compared the applicability of the two methods in the small stability control The applicability of the two methods in the reliability analysis of small-scale stability control systems was compared. However, no reliability assessment based on the fitting of the failure rate of the stability control device from a quantitative perspective has been seen.

In this paper, a reliability assessment method for grid stabilization devices based on Weibull failure rate fitting is proposed. Firstly, the components of the stability control device that may fail and the failure principle are analyzed. Then, the fitting model and fitting method are proposed to calculate the failure rate of the stability control device based on the operating characteristics of the stability control device. Then, the calculation models of reliability assessment parameters such as reliability function, compound failure probability, and availability are established by relying on the functions and parameters obtained from the failure rate fitting. Finally, the relevant device data will be cited for arithmetic analysis to prove the rationality of the method in this paper.

II. FAILURE ANALYSIS OF STABILIZATION CONTROL DEVICE

The operating states of the stability control device include the fully normal operating state, the implicit mis-operation state, the implicit rejection state, and the shutdown state. When the safety and stability control device is in normal operation if a component fails and is not detected, the device enters the implicit fault state (implicit rejection state or implicit mis-operation state); if a component failure is detected, the device enters the shutdown state. When the hidden fault of the device is triggered by an external fault, it will cause the device to malfunction or refuse to move, and the device will enter the shutdown state accordingly.

The main control unit, I/O unit, and communication unit are mainly composed of the main control unit, and each unit contains different stability control modules. The main control unit contains a power supply module, interface management module, central decision module, export module, etc. The I/O unit contains an AC head module, a filter module, an open-in module, etc. The communication unit contains a communication main control board and communication interface board. The stability control module is composed of a large number of electronic components. The failure of most components requires consideration of basic failure rate, environmental factor, temperature stress factor, quality factor, maturity factor, etc., while some components also require consideration of their unique properties, such as voltage stress factor of transistors, capacitor capacity factor, circuit complexity of integrated circuits, etc [9].

Due to the complex mechanism and close coupling inside the stabilization and control device, when a single module fails, the unit in which it is located is a failure, which also means the failure of the device. Because the overall failure rate of the device is a weighted average based on the failure rate and importance of the modules, after the initial decline in failure rate and a long period of low failure rate operation, the failure rate of the stability control device will rise rapidly with time due to component aging and other reasons, and the overall trend of the ‘‘bathtub curve’’. The failure rate of most of the stabilizers is in line with the direction of the ‘‘bathtub curve’’. However, the detailed parameters of the failure rate curve vary from model to model. To accurately evaluate the reliability of different operating environments, different manufacturers, and different functions of stabilizers, a parameter fitting method can be used to build a failure rate model of stabilizers.

III. FAULT RATE FITTING PRINCIPLE OF THE STABILIZATION CONTROL DEVICE

Fitting the parameters of the failure rate function of the stability control device is the basis for achieving reliability evaluation. Data fitting is to connect a series of discrete data points on a plane with a smooth curve to reflect the changing pattern of the target data at a certain time. For the same set of stability control device failure data, there exist countless possible curves. For different structures and functions of the stability control device, although they all conform to the direction of the ‘‘bathtub curve’’, the specific curve parameters of different devices are different. Therefore, according to the source of the data background to choose the appropriate function model to fit, can accurately and flexibly solve the stability control device failure rate.

The function model is the key to the accuracy of the device failure rate. Due to the complex and changing operating environment and functions of the stability control device, most of the function models cannot accurately describe the ‘‘bathtub curve’’ trend of the failure rate. Therefore, the widely used Weibull distribution model is used as the function model for failure rate fitting. The Weibull distribution is a continuous probability distribution. Because of its shape parameter, it can flexibly change its curve shape in the face of different devices and different operating environments and has the advantages of generalizability, simple parameter acquisition, and an adjustable curve.

According to the probability density function of the Weibull distribution, the goal of fitting based on the Weibull distribution is to solve the shape parameters and scale parameters of the distribution function and achieve an accurate description of the changing pattern of the target data. The specific values of the target parameters can be obtained successfully with a sufficient number of samples, and the accuracy of the fitting results can be evaluated. However, the reliability of the stability control device is relatively high, and its reliability assessment is faced with small sample conditions. Therefore, the three-parameter Weibull distribution is introduced into the reliability analysis of the stability control device. The three-parameter Weibull distribution adds the threshold parameter to the scale parameter and shape parameter that the two-parameter Weibull distribution has. Stabilization devices usually do not fail during the initial period of operation, making their failure data nonlinear after the Weibull transformation. The threshold parameter enables the three-parameter Weibull distribution to reflect this phenomenon, and the time point when the device enters the wear and tear period can be obtained, which substantially improves the accuracy of device reliability assessment under small sample conditions [18].

Using the Weibull distribution parameters obtained by parameter fitting, a function fit of the reliability of the stability control device can be achieved. The failure rate values of individual devices can be applied to the solution of the associated failure probability and availability, and the reliability assessment of the stability control device can be realized using these reliability evaluation indexes.

IV. FITTING MODEL FOR THE FAILURE RATE OF THE STABILITY CONTROL DEVICE

A. ESTABLISHMENT OF THE GENERALIZED PROPORTIONAL FAILURE RATE MODEL

The existing failure rate models are generally time-based models and equipment condition-based models. The former failure distribution is generally two-parameter Weibull distribution and exponential distribution, but the Weibull distribution only focuses on the influence of the operating age of the equipment on the failure rate, ignoring the influence of some external factors such as equipment maintenance on the equipment failure rate. The latter model only focuses on the influence of the current state of the equipment on the failure rate, and when the equipment has a serious failure, the failure rate may be greater than or equal to 1, which is contrary to the actual operation.

To consider the influence of the historical state, internal structure, and service age on the failure rate of the stabilization device, the generalized proportional failure rate model (GPHM) based on the full range of condition monitoring quantities and failure data is chosen as the failure rate fitting model for the stabilization device. The GPHM uses the Weibull distribution as the reference function, combined with the covariate vector to reflect the state of the device in real time, and can be written as follows:

$$\lambda\left(t|Z\right)=\lambda 0\left(t\right)\psi\left(Z\left(t\right)\right) \tag{1}$$

where the $\lambda_0\left(t\right)$ is the baseline failure rate, which is related to the service age $\psi\left(Z\left(t\right)\right)$ is the connection function, reflecting the effect of being in different states $Z\left(t\right)$ on the failure rate;$Z\left(t\right)$ is the vector of covariates, characterizing the effect of the operating environment, equipment service age, manufacturer and other factors on the equipment failure rate, and the set of all covariates forms the set of covariates as follows:

$$Z=\left[Z1\left(t\right),Z2\left(t\right)\ldots Zn\left(t\right)\right] \tag{2}$$

The expression of the concatenation function is:

$$\psi\left(Z\left(t\right)\right)=\exp\left(\gamma 1Z1\left(t\right)+\gamma 2Z2\left(t\right)+\ldots.+\gamma nZn\left(t\right)\right) \tag{3}$$

where $\gamma=\left(\gamma 1,\gamma 2\ldots\gamma n\right)$ is the regression coefficient corresponding to each covariate.

Therefore, the failure rate expression is:

$$\begin{aligned}\lambda\left(t|Z\right)=\lambda 0\left(t\right)\exp(&\gamma 1Z1\left(t\right)\\&+\gamma 2Z2\left(t\right)+\ldots.+\gamma nZn\left(t\right))\end{aligned} \tag{4}$$

To ensure the accuracy of the model construction, the following principles need to be followed when establishing the failure rate expression: the failure interval of the stability control equipment is relatively long relative to the maintenance time, so the maintenance time is neglected; the influence of the covariates on the equipment failure rate is constant and does not vary with time; the benchmark failure rate function obeys a two-parameter Weibull distribution, i.e.

$$\lambda 0\left(t\right)=\frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \tag{5}$$

where β is the shape parameter;η is the scale parameter.

B. SELECTION OF COVARIATES

Covariates are the key to the GPHM model. Accurate covariate values can play a good role in correcting the failure rate curve of the stability control device. In this paper, the age, operating environment, health, and manufacturer of the equipment are used as covariates.

The equipment health (HI) reflects the overall health level of the stability control equipment itself and is closely related to the equipment failure rate. HI is divided into five levels: normal, attention, abnormal, serious, and failure, and the corresponding values in the expression are 0, 0.1, 0.3, 0.6, and 1. After the equipment enters the wear and tear period, the failure rate satisfies the Weibull distribution, which is a function of time, i.e., the failure rate and the equipment. The failure rate is a function of time, i.e., the failure rate is related to the service life of the equipment, so the service life of the equipment is taken as the covariate. The failure rate of the stabilization device is also affected by the different degrees of hardware wear and tear under different climatic conditions (high temperature, high humidity, etc.). Considering the characteristics of the wide-area operation of the stability control device, the operating environment of the device is chosen as a covariate. The manufacturer is chosen as a covariate because different manufacturers may have different familial defects, which affect the historical data of the device.

The two types of data, manufacturer, and equipment operating environment, are fixed during the operation of the stability control device. For the covariates of the operating environment, the value is 1 when the equipment is operating in the urban area and 2 when the equipment is operating in the mountainous area. The corresponding covariate values are different: 1 for the equipment from Nanrui Relay, 2 for the equipment from Beijing Sifang, 3 for the equipment from Changyuan Shenrui, 4 for the equipment from Guodian Nanzhi, and 5 for the equipment from Xuji Electric.

Based on the two-parameter Weibull distribution of the benchmark function and the choice of covariates, the expression of the generalized proportional failure rate model is:

$$\lambda\left(t|Z\right)=\frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}+\exp\left(\begin{array}{l}\gamma ageZage\left(t\right)+\gamma envZenv\left(t\right)\\ +\gamma HIZHI\left(t\right)+\gamma mauZmau\left(t\right)\end{array}\right) \tag{6}$$

where $Zage, Zenv, ZHI, Zmau$ is the age of the equipment, the environment in which the equipment is located, the health of the equipment, and the manufacturer of the equipment, respectively.

C. FITTING OF PARAMETERS FOR THE FAILURE RATE OF THE STABILIZATION CONTROL DEVICE

From Eq. (6), to determine the failure rate function of the stability control device, the parameters β and η, and the regression coefficients γi need to be estimated. Therefore, this paper extracts the covariates based on the operating environment and historical statistics of the stabilization device and fits the function based on the Weibull distribution and generalized proportional failure rate model to characterize the change in the failure rate of the stabilization device in the operating cycle by adjusting the parameters.

By using the cftool in MATLAB which comes with the Weibull distribution model, we can realize the fitting of failure rate parameters based on the Weibull distribution. We organize the collected discrete failure rate data in time order, set the "time" set as the X-axis and the "failure rate" set as the Y-axis, select the Weibull distribution as the fitting model, and set the corresponding fitting parameters. The expected curve of the failure rate function of the stability control device after fitting is shown in Figure 1.

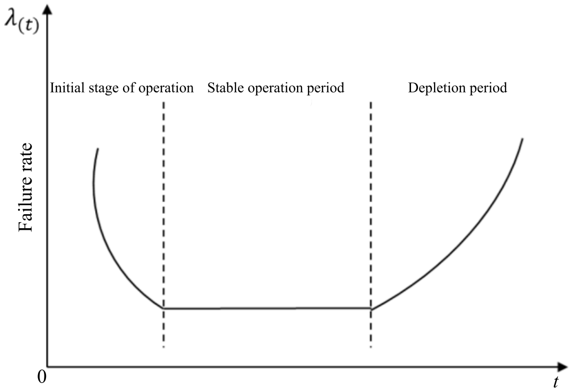

FIGURE 1. **The expected curve of the failure rate function of the stability control device.**

To verify the reliability and accuracy of the model, residual tests and correlation tests can be adopted to evaluate the fitting results. The residual test is the calculation of the absolute and relative error between the series consisting of the original failure data $X^{(0)}$ and the series consisting of the fitted results $\hat{X}^{(0)}$. The smaller the error value, the higher the accuracy of the fit. The absolute error can be written as:

$$\Delta^{(0)}\left(k\right)=\left|X^{(0)}\left(k\right)-\hat{X}^{(0)}\left(k\right)\right|, k=1,2\ldots n \tag{7}$$

The relative errors are:

$$\Phi\left(k\right)=\frac{\Delta^{(0)}\left(k\right)}{X^{(0)}\left(k\right)}\times 100\%, k=1,2\ldots n \tag{8}$$

The correlation test verifies the correlation between the original series $X^{(0)}$ and the fitted series $\hat{X}^{(0)}$ by calculating the correlation coefficient and the correlation degree between them. The correlation coefficient can be written as:

$$\eta\left(j\right)=\frac{\min\left\{\Delta\left(j\right)\right\}+\rho\max\left\{\Delta\left(j\right)\right\}}{\Delta\left(j\right)+\rho\max\left\{\Delta\left(j\right)\right\}} \tag{9}$$

where $\Delta\left(j\right)$ is the absolute error, max/min corresponds to the maximum/minimum value of the absolute error; ρ is the resolution, generally taking the value of 0.5.

The degree of correlation can be written as:

$$r=\frac{1}{n}\sum_{j=1}^{n}\eta\left(j\right) \tag{10}$$

When the correlation degree $r>0.55$is reached, the model can be considered to pass the test [32].

V. RELIABILITY ASSESSMENT METHODS FOR STABILIZATION AND CONTROL DEVICES

After the parameter fitting of the failure rate function of the stability control device is completed, the Weibull distribution parameters (shape parameter β, scale parameterη) in the benchmark function can be used in the parameter fitting of the reliability function represented by Eqs. (11) and (12). The failure probability of a single stabilizer can be involved in the calculation of the associated failure probability and availability to realize the reliability assessment of the stabilizer.

A. RELIABILITY FITTING OF THE STABILITY CONTROL DEVICE

Weibull distribution is a continuous probability distribution proposed by Swedish scientist Walodi-Weibull.

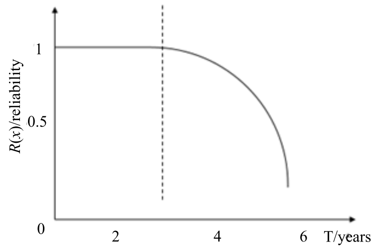

FIGURE 2. **The expected curve of reliability function of the stability control device.**

The two-parameter Weibull distribution is widely used for instrument reliability analysis, but in actual working conditions, the initial failure probability is very low. After the transformation of the two-parameter Weibull distribution, a small amount of fault data is nonlinear. Therefore, the article introduces a three parameter Weibull distribution to analyze the reliability of relay protection devices. Only after determining the three parameters of scale, shape, and position can the distribution model be used to calculate various reliability indicators.

The cumulative distribution function of the three-parameter Weibull distribution is:

$$F\left(x\right)=\begin{cases}1-\exp\left[-\left(\dfrac{x-\gamma}{\eta}\right)^{\beta}\right] & x\geq\gamma\\ 0 & x<\gamma\end{cases}\tag{11}$$

Its reliability function is.

$$R\left(x\right)=\exp\left[-\left(\frac{x-\gamma}{\eta}\right)^{\beta}\right]x\geq\gamma\tag{12}$$

where,$\eta > 0$ is the scale parameter, which is a special parameter in the probability distribution, the larger the scale parameter, the more dispersed the distribution. $\beta > 0$ when $\beta < 1$, the failure rate function decreases, which corresponds to the initial operation of the stabilization device; when $\beta = 1$, the failure rate function is exponentially distributed, and the failure rate tends to be stable, which corresponds to the stable operation period of the stabilization device; when $\beta > 1$, the failure rate function increases and the reliability of the stabilization device decrease and starts to enter the attrition period;γ is the threshold parameter, which characterizes the time point when the stabilization device enters the attrition period.

By analyzing the failure rate data of commercially available stabilization devices and combining the general operating rules of stabilization devices, the direction of the reliability function of stabilization devices can be predicted, and the expected curve of the reliability function is shown in Figure 2.

B. PROBABILITY OF COMPOUND FAILURE OF THE STABILITY CONTROL DEVICE

Stabilization systems rely on different types of stabilization devices to cooperate to achieve complex stabilization functions, and the high degree of coupling makes the failure rate of stabilization devices not only determined by the internal structure of the device, but also by the influence of other stabilization devices associated with it. This failure rate affected by other devices is called the compound failure rate of the stabilizer:

$$P_i\left(t\right)=\begin{cases}\lambda_i\left(t\right) & k=1\\ \mathrm{U}_i\left(t\right) & k\neq 1\end{cases}\tag{13}$$

where $P_i(t)$ is the compound failure rate of the ith stabilizer, $k = 1$ means the failed stabilizer has no associated device; $k \neq 1$ means the failed stabilizer has an associated device; $\mathrm{U}_i(t)$ is the associated failure rate of the i^{th} stabilizer as:

$$\mathrm{U}_i\left(t\right)=\left[1-\prod_{i=1}^{M}\left(1-\lambda_i\left(t\right)\right)\right]\tag{14}$$

where M is the total number of stabilization devices contained in the association set where the device in fault state is located [33].

C. STABILITY CONTROL DEVICE AVAILABILITY

Availability is an indicator that describes the reliability of a repairable system and indicates the long-term state probability (also called steady-state probability) that the system is in a normal operating condition. The availability of a stability control device can be written as:

$$A=\frac{\mu}{\lambda+\mu}=\frac{T_F}{T_F+T_R}\tag{15}$$

where μ is the repair rate;T_F is the average failure-free duration;T_R is the average repair time; In the actual calculation, the availability can be solved based on the failure rate function of the stability control device, assuming that the repair rate of the same class of devices is constant [34].

VI. ANALYSIS OF CALCULATION CASES

The relay protection device was put into operation and maintained continuously for 70 128 hours under the same working conditions and operating levels. The fault time of each device was recorded, and the operation record data of the relay protection device was obtained [35]. The operation records of the relay protection device are shown in Table 1.

A. SELECTION OF SAMPLE DATA FOR THE FAILURE RATE FUNCTION

The data sources for the generalized proportional failure rate model for Weibull parameter fitting mainly include device historical operation data, device maintenance records, device online operation monitoring data, similar device operation experience data, and device operation manuals, etc. The above data form the failure samples of the stabilization control device. Using these data, the discrete data points of the failure rate of the stability control device can be obtained for a while from the start of commissioning. In this paper, a safety and stability control device manufactured by a company is

TABLE 1. **Relay protection device operation record.**

Fault sequence	Running time/h	Exit mode	Notes
1	25 560	Fault exit	--
2	31 848	Fault exit	--
3	36 648	Fault exit	--
4	43 104	Fault exit	--
5	46 872	Fault exit	--
6	49 656	Fault exit	--
7	51 864	Fault exit	--
8	55 608	Fault exit	--
9	60 624	Fault exit	--
10~30	70 128	Normal exit	Total 21

selected as a sample for reliability assessment. The device is deployed in a town area and has been in operational service for 6 years, during which time it has been regularly serviced 3 times and repaired once for failures. According to the principle of covariates, the age of the device can be directly used as the value of the corresponding covariate; because it works in a town, the covariate of the operating environment is 1; according to the historical maintenance records of the device, the health of the device is in the ''abnormal'' state, and the covariate is 0.3; considering the possible existence of family defects of the manufacturer, the corresponding covariate is 0.3. Finally, the covariate values of the equipment are shown in Table 2.

TABLE 2. **Stabilizer covariates.**

Covariates	Numerical value
Equipment service life	6
Operating Environment	1
Healthiness	0.3
Manufacturers	3

After the device is put into operation, the operation and maintenance personnel according to the background operation data of the device, with the fault maintenance records of the maintenance personnel, can be calculated for each year of the operation failure rate of the device and then can get the discrete failure rate data of the stability control device as shown in Figure 3.

B. FITTING AND EVALUATION OF FAILURE RATE FUNCTION PARAMETERS

The cftool in MATLAB is selected as the environment for the failure rate fitting of the stability control device. By adjusting the fitting parameters in the fitting tool, different baseline failure rate functions and the corresponding Weibull distribution parameters can be obtained. Among them, the baseline failure rate function that makes the residual test and correlation test optimal is:

$$\lambda 0\,(t) = \frac{0.704}{1.664}\left(\frac{t}{1.664}\right)^{-0.296} \tag{16}$$

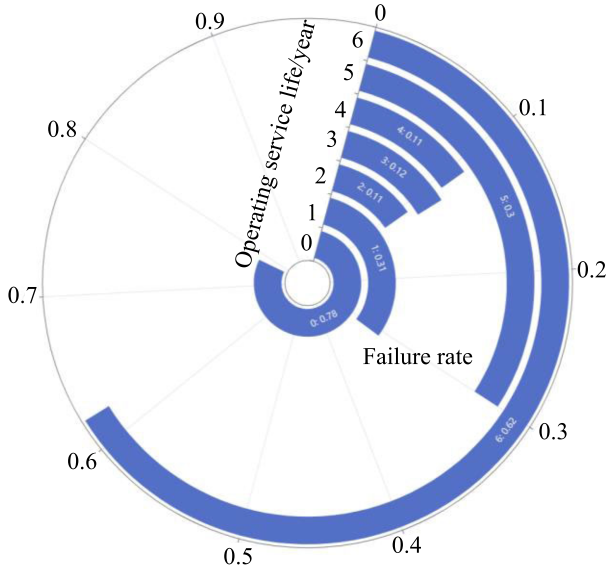

FIGURE 3. **Distribution of failure rate of a stability control device.**

The corresponding Weibull distribution parameters can be involved in the subsequent reliability assessment.

According to Eq. (6), to reflect the influence of non-device structural factors on the failure rate, the covariates in Table 2 are introduced based on the benchmark failure rate function, and factors such as operating environment and maintenance are included in the consideration of the failure rate calculation of the stabilization control device, and the optimal failure rate function of the stabilization control device can be obtained by adjusting the benchmark failure rate through the covariates as shown in Figure 4.

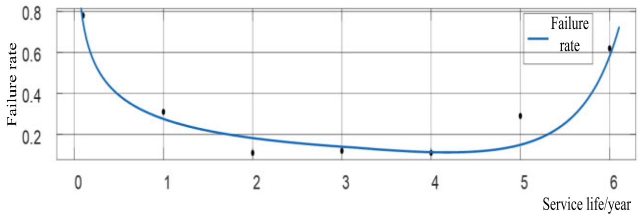

FIGURE 4. **The fitting curve of the failure rate function of the stability control device.**

As shown in Figure 4, the failure rate of the device has a clear decreasing trend at the beginning of the operation, and after a long period of low failure rate operation, the device enters the attrition period, and the failure rate increases rapidly with time, which is in line with the prediction result of the ''bathtub curve'' of the failure rate of the stabilization control device. According to the cftool, the corresponding Weibull shape parameter of this function is 0.704 and the scale parameter is 1.664.

As shown in Figure 4, the fitted failure rate function of the stabilization device has errors with the actual failure rate values at each discrete point, and the accuracy of the fitted

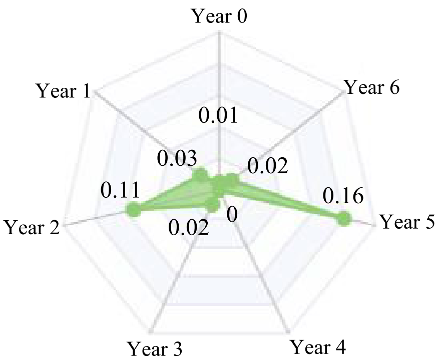

FIGURE 5. Absolute errors.

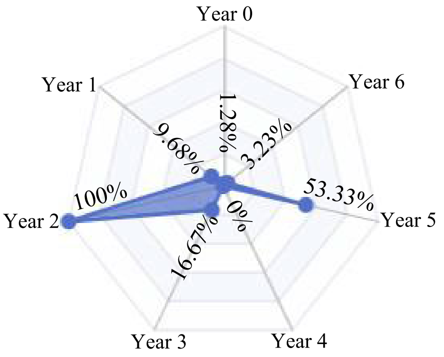

FIGURE 6. Relative errors.

failure rate curve is characterized by calculating the absolute and relative errors according to Eqs. (7) and (8). The absolute and relative errors are shown in Figures 5 and 6.

1) RESIDUAL TEST

To verify the correlation between the failure rate fitting results and the actual failure rate variation, the values of the absolute errors are substituted into Eqs. (9) and (10), and the correlation between the fitted curves and the actual values are judged by the results of the correlation test. The correlation coefficients are shown in Figure 7.

2) CORRELATION TEST

According to Eq. (10), the correlation of the failure rate function of the stabilization device can be obtained: 0.71. Since the correlation of this failure rate function to the failure sample $r > 0.55$, it proves that the failure rate fitting method in this paper has a high confidence level.

C. *RELIABILITY EVALUATION INDEX OF THE STABILIZATION CONTROL DEVICE*

1) RELIABILITY

Using the failure rate function curve of the stability control device, the time point when the device enters the attrition period can be obtained, and the threshold parameter in the reliability function can be inferred from it $\gamma = 1.32$. Based on the threshold parameter, together with the Weibull parameter in the failure rate function, the reliability function of the device can be obtained according to Eq. (12) as:

$$R(x) = \exp\left[-\left(\frac{x-1.32}{1.664}\right)^{0.704}\right] x \geq 1.32 \tag{17}$$

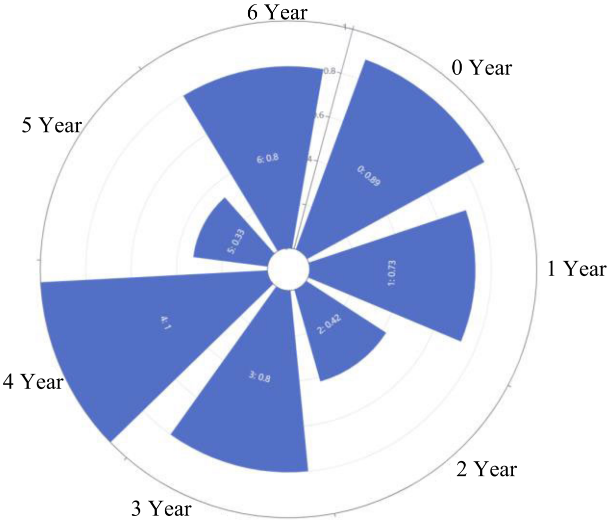

FIGURE 7. Correlation coefficients.

As shown in Figure 8, at the early stage of commissioning, the failure rate of the well-commissioned stabilization and control device decreases rapidly and its reliability is maintained at a high level; after entering the attrition period, the failure rate of the device gradually increases with time while its reliability decreases accordingly. Since the image of the function is in good agreement with the expected curve shown in Figure 2, it shows that the reliability function model proposed in this paper is in line with the actual operation of the device.

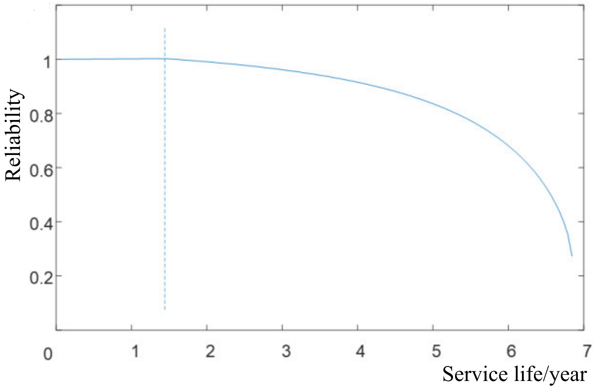

FIGURE 8. Reliability function curve of the stabilization control device.

2) COMPOUND FAILURE PROBABILITY

The generalized proportional failure rate model shown in Eq. (6) is used in the failure rate calculation of other

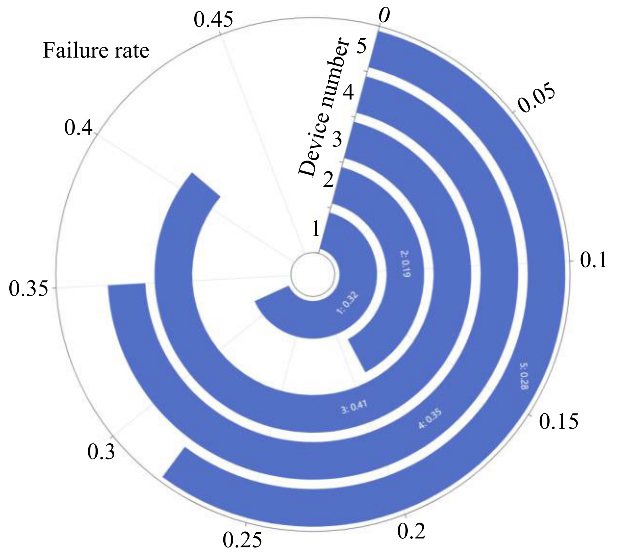

FIGURE 9. Distribution of failure rate of associated devices.

stabilization devices that are associated with the sample device. As shown in Figure 9, the time node when the device enters the attrition period ($\gamma = 1.32$) is selected as the sampling point for the failure rate calculation, and the covariates of each device are adjusted by substituting the baseline failure rate function to obtain the failure rates of other devices at this moment as:

According to Eq. (14), in the system in which the sample device is located, the probability value of associated failure of the device at this time: 0.88. From Eq. (13), the probability of compound failure at this time is:

$$P_i(1.32) = \begin{cases} 0.22 & k = 1 \\ 0.88 & k \neq 1 \end{cases} \tag{18}$$

As can be seen, the failure rate of the stabilization control device is highly susceptible to the state of the associated device. Therefore, by evaluating the reliability of the stabilization and control device and finding ways to improve the reliability of the device operation, the normal operation of the entire stabilization and control system can be effectively ensured.

3) AVAILABILITY

According to the historical operation data, maintenance records, and equipment manual of the sample device, we can get a repair rate value μ =0.89; an average fault-free duration value T_F =3.85; an average repair time value T_R =0.26. For the same device, the above three parameters can be regarded as constants, so according to Eq. (15), the availability of the sample device is 0.937. Thus, it can be seen that a well-commissioned stability control device can maintain better operation after commissioning, which is the basis to ensure the stable operation of the power grid.

TABLE 3. Comparison of estimation results.

Method	η	β	γ	Correlation coefficient
Text method	1.5421	83224.21	17087.884	0.99224
LSM	3.059	83324.68	-	0.9221

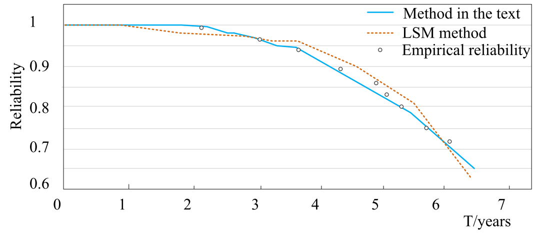

FIGURE 10. Reliability comparison.

TABLE 4. Comparison of estimation results.

Method	Grey estimation method	Probability weighted method	Maximum likelihood method
η	1.542 1	-13.7824	5.2301
β	83 224.21	-64266.38	53315.40
γ	17 087.844	10816.528	2842.613
K-S test value	0.1988	0.2566	0.211
Correlation coefficient	0.9922	0.8572	0.985

D. COMPARATIVE ANALYSIS

In the commonly used two parameter Weibull distribution, the least squares method (LSM) is chosen to compare with the method in the article [36]. The comparison results are shown in Table 3.

According to the data in Table 3, the reliability time curve is plotted based on the reliability function as shown in Figure 10.

From Table 3 and Figure 10, it can be seen that:

(1) If the shape parameter η is greater than 1, the failure rate increases and the device is in a loss period;

(2) The least squares correlation coefficient is smaller than the algorithm in the text, so the parameter calculation in the text is more accurate;

(3) Compared to the other two parameter methods, the algorithm in this paper does not require iteration and training of samples. More convenient to operate; The position parameters obtained by the algorithm in the article, namely the time from operation to power loss of the relay protection device, are very important for on-site maintenance. Currently, the most common three parameter Weibull model parameter estimation methods are grey estimation method, probability weighted moment method, and maximum likelihood method. These three methods are used to analyze the original operating time data of relay protection devices in Table 1.

Compare and analyze the above methods using K-S test values (smaller parameter estimation is more accurate) and correlation coefficients (closer to 1 parameter estimation is more accurate), and the results are shown in Table 4.

The K-S test values and correlation coefficients indicate that the grey estimation method has significant advantages in the accuracy of the three parameter Weibull distribution with small samples.

VII. CONCLUSION

The stability control device is an important part of the second line of defense of the power system, which plays an indispensable role in ensuring the safe and stable operation of the power system. For the current situation that the parameter fitting of the stability control device is less studied, this paper first analyzes the common faults of the stability control device and their principles, proposes the GPHM based on the whole state monitoring quantity and fault data as the failure rate fitting model of the stability control device, and uses the cftool of MATLAB to realize the parameter fitting of the failure rate of the stability control device. Based on the obtained failure rate function, this paper proposes a model and method to calculate reliability indexes such as reliability, compound failure probability, and availability of the stability control device and realizes the reliability assessment of the stability control device. Based on the calculation of the failure probability and reliability assessment of the stabilization control device, effective prediction of the state change of the stabilization control device can be realized, which is of great significance for improving the design and production, deployment strategy, and maintenance plan of the stabilization control device, improving the fault handling capability of the stabilization control system, and ensuring the safe and stable operation of the power grid.

In this paper, the evaluation of the reliability of the stability control system focuses only on the impact of device failure rate and repair rate on system availability. It is worthwhile to further investigate the action discrimination logic of the devices and the coordination and reliability of the logical cooperation among the devices. In addition, in future research on the reliability of the stability control system, we should also focus on collecting and organizing the basic data of system, device, and component failures to provide a reference basis for the subsequent in-depth work on the reliability of the stability control system.

INSTITUTIONAL REVIEW BOARD STATEMENT

Not applicable.

INFORMED CONSENT STATEMENT

Not applicable.

DATA AVAILABILITY STATEMENT

All data generated or analyzed during this study are included in this published article.

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CONFLICTS 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.

REFERENCES

[1] L. Mingjie, "Characteristic analysis and operational control of large-scale hybrid UHV AC/DC power grids," *Power Syst. Technol.*, vol. 40, no. 4, pp. 985–991, 2016.

[2] J. Xu, "Analysis and research on complex power system cascading failures considering hidden failure of protection," China Electr. Power Res. Inst., Beijing, China, Tech. Rep., 2011.

[3] T. Zhang and Y. Gong, "Research on transmission technologies and operational performance of UHV AC/DC power grid in China," *Smart Power*, vol. 46, no. 2, pp. 87–92, 2018.

[4] G. Song, X. Cai, S. Gao, J. Suonan, and G. Li, "Novel current differential protection principle of VSC-HVDC considering frequency-dependent characteristic of cable line," *Proc. CSEE*, vol. 31, no. 22, pp. 105–111, 2011.

[5] X. Dong, H. Li, and X. Li, "Influence of shunt reactor on power system security and stability control equipment trip criterion & fixed value setting," *Shanxi Electr. Power*, vol. 44, no. 3, pp. 68–70, and 84, 2016.

[6] T. Xu, G. Li, Z. Yu, J. Zhang, L. Wang, Y. Li, Y. Zhang, K. Zhuang, J. Luo, and D. Li, "Design and application of emergency coordination control system for multi-infeed HVDC receiving-end system coping with frequency stability problem," *Automat. Electr. Power Syst.*, vol. 41, no. 8, pp. 98–104, 2017.

[7] H. Shen, Y. Yao, N. Du, T. Li, W. Chen, X. Zhang, and G. Zou, "A method of emergency frequency control based on multi-resources coordination," in *Proc. Int. Conf. Green Buildings Environ. Manag.*, Qingdao, China, 2018, pp. 1–8.

[8] W. Zhuang, D. Li, Z. Yu, H. Li, T. Liu, and Z. Li, "Security and stability control system coping with simultaneous multi-UHVDC commutation failure," *Power Syst. Technol.*, vol. 40, no. 11, pp. 3420–3426, 2016.

[9] *General Administration for Quality Supervision, Inspection and Quarantine of the People's Republic of China, Standardization Administration, Technical Guide for Electric Power System Security and Stability Control*, Standard GB/T 26399-2011, 2011.

[10] W. Lin, H. Sun, Y. Tang, G. Bu, and Y. Yin, "Analysis and lessons of the blackout in Brazil power grid," *Automat. Electr. Power Syst.*, vol. 34, no. 7, pp. 1–5, 2010.

[11] D. He, "The successive ponderation (layers-built analysis) over U.S. WSCC two outages in 1996," *Electr. Power*, vol. 31, no. 5, pp. 37–40, 1998.

[12] X. Qin, T. Bi, and Q. Yang, "WAMS based power system disturbance identification and location approach," *Power Syst. Technol.*, vol. 33, no. 12, pp. 35–41, 2009.

[13] Y. Fang, "Lessons from September 8, 2011 Southwest America blackout for prevention and control of cascading outages," *Automat. Electr. Power Syst.*, vol. 36, no. 15, pp. 1–7, 2012.

[14] J. Yi, G. Bu, Q. Guo, G. Xi, J. Y. Zhang, and J. Z. Tu, "Analysis on blackout in Brazilian power grid on March 21 2018 and its enlightenment to power grid in China," *Automat. Electr. Power Syst.*, vol. 43, no. 2, pp. 1–6, 2019.

[15] Y. Guo, *Power System Reliability Analysis*. Beijing, China: Tsinghua Univ. Press, 2003.

[16] J. Luo, X. Dong, X. Cui, D. S. Li, H. J. Li, and X. Li, "Discussion on reliability of large scale security and stability control system," *Power Syst. Protection Control*, vol. 46, no. 8, pp. 65–72, 2018.

[17] R.-Y. Zhang, L. Zhou, G.-L. Dong, W.-H. Liu, and C. Zhang, "Reliability analysis of stability control system in single plant station," *Power Syst. Protection Control*, vol. 38, no. 19, pp. 61–64, 2010.

[18] H. G. Kang, S. H. Lee, S. J. Lee, T.-L. Chu, A. Varuttamaseni, M. Yue, S. Yang, H. S. Eom, J. Cho, and M. Li, "Development of a Bayesian belief network model for software reliability quantification of digital protection systems in nuclear power plants," *Ann. Nucl. Energy*, vol. 120, pp. 62–73, Oct. 2018.

[19] J. Zhang, "Research on hidden failures related issues of relay protection system," Hefei Univ. Technol., Hefei, China, Tech. Rep., 2012.

[20] L. Zhao, X. Li, M. Ni, and C. Y. Cheng, "Review and prospect of research on hidden failures of protection system and security and stability control system," *Automat. Electr. Power Syst.*, no. 22, pp. 128–135, 2014.

[21] Z. Li, X. Gao, Y. L. Li, Y. Hu, and X. G. Jiang, "The development of risk assessment technology related to a hidden failure of protection system," *Proc. CSEE*, vol. 36, no. S1, pp. 29–35, 2016.

[22] A. Xue, L. Luo, and S. Huang, "Research on Markov model based risk assessment of protective relaying for high voltage transmission line," *Power Syst. Technol.*, vol. 38, no. 7, pp. 1995–2000, 2014.

[23] Y. Ye, Z. Liu, and Z. Zhao, "Research on the reliability analysis method of condition-based maintenance of relay protection equipment in substation," *Power Syst. Protection Control*, vol. 49, no. 10, pp. 170–177, 2021.

[24] Z. Dai and Z. Wang, "Protection dynamic reliability analysis system based on 3RF technique," *IEEE Trans. Power Syst.*, vol. 26, no. 3, pp. 1137–1144, Aug. 2011.

[25] H. Li, X. Lin, K. Yu, and H. Zhao, "Based on continuous time Markov chain prediction model of action behavior of relay protection device," *Proc. CSEE*, vol. 38, no. 1, pp. 121–128, 2018.

[26] J. Wang and H. Yin, "Failure rate prediction model of substation equipment based on Weibull distribution and time series analysis," *IEEE Access*, vol. 7, pp. 85298–85309, 2019.

[27] P. Zhou et al., "Research of risk assessment reliability of relay protection based on three-parameter Weibull distribution," *Ind. Mine Automat.*, no. 8, pp. 60–65, 2016.

[28] T. Li, W. D. Griffiths, and J. Chen, "Weibull modulus estimated by the non-linear least squares method: A solution to deviation occurring in traditional Weibull estimation," *Metall. Mater. Trans. A*, vol. 48, no. 11, pp. 5516–5528, Nov. 2017.

[29] I. J. Davies, "Confidence limits for Weibull parameters estimated using linear least squares analysis," *J. Eur. Ceram. Soc.*, vol. 37, no. 15, pp. 5057–5064, Dec. 2017.

[30] Z. Lu, L. Dong, and J. Zhou, "Nonlinear least squares estimation for parameters of mixed Weibull distributions by using particle swarm optimization," *IEEE Access*, vol. 7, pp. 60545–60554, 2019.

[31] X. Jia, G. Xi, and S. Nadarajah, "Correction factor for unbiased estimation of Weibull modulus by the linear least squares method," *Metall. Mater. Trans. A*, vol. 50, no. 6, pp. 2991–3001, Jun. 2019.

[32] X. Han, X. Yin, and Z. Zhang, "Application of fault tree analysis method in the reliability analysis of substation communication system," *Power Grid Technol.*, no. 1, pp. 56–59, 2004.

[33] J. Zhu, "Study and processing of sampled value in intelligent substation grid security and stability control device," *Nanjing Univ. Posts Telecommun.*, 2013.

[34] X. Wu, J. Zhang, L. Wu, and Z. Huang, "Method of operational risk assessment on transmission system cascading failure," *Proc. CSEE*, vol. 32, no. 34, pp. 74–82 and 12, 2012.

[35] J. Wang, Y. Xu, and Y. Ye, "Estimation of reliability parameters of protective relays based on grey-three-parameter Weibull distribution model," *Power Syst. Technol.*, vol. 43, no. 4, pp. 1354–1360, 2019.

[36] F. Chengli, F. Qiang, L. Guangzheng, and X. Qinghua, "Hybrid artificial bee colony algorithm with variable neighborhood search and memory mechanism," *J. Syst. Eng. Electron.*, vol. 29, no. 2, pp. 405–414, Apr. 2018.

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