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A deducing-based reliability optimization for electrical equipment with constant failure rate components duration their mission profile

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ABSTRACT

Recently, with the rapid development of electrical industries, the R&D on electrical equipment has made a massive progress. However, high integration of multiple functions like isolationcircuit breaking, data collection and intelligent control results in low reliabilities. Therefore, a deducing-based reliability optimization for electrical equipment is proposed to enhance the reliability of electrical equipment. The Integrated Isolation Circuit Breaker (IICB), a classical device of power switch, is taken as the object in this research, and the reliability analysis is carried out by building the equipment description model of IICB, bringing forth the deduced method, and taking the constant failure rate components duration their mission profiles as indices for reliability increases. Next, on the basis of the deduced method, the unit to increase the system reliability can be determined. With the guidance of the above method, three kinds of reliability optimization schemes are studied, which are formed in accordance with the topologies of devices, component configurations and redundancy respectively. Finally, the comparing, analyzing and deducing of the three improving schemes are presented respectively. And an example is given to prove that the proposed method is feasible and can effectively improve equipment reliabilities, with valuable guidance for equipment reliability design as well.

1. Introduction

Recently, the rapid development of science and technologies has brought a big revolution of electrical equipment. Meanwhile, the electrical equipment is being improved in directions like high reliabilities [1], large-scale integrations [2], and strong intelligences [3,4]. In power systems, circuit breakers and disconnecting switches are frequently used as electrical equipment [5]. With the non-stop updating and development of electrical equipment, the traditional oil circuit breakers have been replaced by the new integrated switches [6]. So, current equipment reliabilities have been significantly improved, and the average maintenance time can reach more than 15 years [7,8]. However, some devices, e.g. isolation switches, are in a slower development in contrast. Their reliabilities are relatively low, and their average overhaul time is about six years [7]. In general, isolation switches work in exposed environments, and they need maintenances periodically. Not for long, the research on circuit breaker has made a crucial breakthrough by which insulation interface reached to a high level and possessed the capability of isolating switches. In recent years, many states have vigorously promoted the planning of intelligent power grids [9], strongly driving the development of intelligent power equipment as a result. Therefore, it is necessary to improve the electrical equipment's reliabilities [10–12] for the intelligent power grids in substation operations[13,14], in order to reduce operating costs [9], simplify wiring [15], promote construction efficiency, save land resources, and facilitate operations and maintenances[16,17].

However, the multifunction requirements [18] for the electrical equipment make the design quite complex [19–21], and result in the decline in reliability index [22–24]. Therefore, a deducing-based reliability optimization scheme for electrical equipment is suggested. Researchers can use this reliability optimization technology to boost the application of the electrical equipment, and provide guidance for reducing the construction, operation and maintenance costs of a new generation intelligent substation. Recently, a number of research achievements on reliability optimization have been brought forward [25–28], mainly in theoretical fields [29–31]. However, the research for electrical equipment is relatively less. Existing methods are only focused in the improvement and enhancement of product manufacturing means, rather than the theoretical areas. Therefore, equipment reliability improvement is relatively slight.

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Studies of reference [32,33] are the most similar with this paper in content and the newest in the time, which will be discussed in detail next.In reference [32], a method of cost and reliability optimization based on fault tree model is proposed. This method is helpful for system designers to select the technical scheme of basic events. The well-known non dominated sorting genetic algorithm (NSGA-II) is used in the optimization, which has achieved good results in dealing with the leakage problem of subsea oil production system. Although the fault tree model is a popular expression approach, and the optimization ability of NSGA-II is excellent, this paper proposes a reliability optimization method based on deducing. This choice is based on below consideration: 1) the series parallel structure characteristics of the circuit breaker in the research case are obvious, the number of component units is small, and the series parallel modeling is relatively easy to build; using fault tree structure modeling is relatively complex, and it is easy to express inaccuracy or produce modeling errors. 2) The key of circuit breaker optimization is to improve the reliability, so it is more direct and effective to select the inference optimization method; reference [32] solves the leakage problem of subsea oil production system, and pays more attention to the discovery and search of system weak points. 3) Different system objects lead to different models. There are strong couplings between the components of circuit breaker, and the reliability evaluation method can carry out rigorous reasoning; the oil production system needs to find the weak point on the basis of the model, that is, the basic event, and through large-scale calculation to find the probability of the top event. The NSGA-II algorithm is very suitable for the calculation. Therefore, through the comparison, it is found that the two methods have their own suitable applications.

Reference [33] proposed a new analysis method to identify the active failure events of circuit breakers with different orders of accidents. In the method, an active breakerincidence(ABI) matrixwas established to capture the active failure of the circuit breaker which caused the load point fault. Another kind of incidence matrixof the minimal path concatenated the ABI is set up to reflect the information of all failure events. The method mentioned in ref. [33] is effective, and the research object is the circuit breaker, which is same research objection with this paper.It can also provide a usefulguidance for the reliability improvement of system components. However, the method of reference [33] is not fit to solve the reliability improvement problem of electromechanical components. The reasons are as the following: 1) The objectives of the two methods are different. The purpose of reference [33] is to evaluate the reliability indices, butthe aimof this paper is to improve the component reliabilities. 2) The research method is different. Multiple incidence matricesare designed to capture the active failure of breakers and to reflect the information of all failure events in literature ref. [33], while the function deduced and statistical calculation of constant failure rate components is utilized to optimize and increase the component reliability in this paper. 3) The reliability index contentsare different. Reference [33] is used the active failure to evaluate the circuit breaker reliability, butour study is all failures of the IIBC to improve product reliability itself.

Reference [34] gives a feasible methodology to verify the enhanced reliability of interleaved dc-dc converters by redundant component configuration. The Markov model is adapted to calculate the Mean Time to Failure (MTTF) of the equipment. Fuzzy curves for MTTFs of the converters and 3D reliability function are derived first time in this literature [34]. Simulation and experiments are provided to confirm the viability of the redundant-switch configurations in interleaved dc-dc boost converter. To enhance the reliability of the system, ref [34] and this paper all fire a same means of redundant configuration of components. Their applications are different and complementary. The method in reference [34] must have state data and be realized by fuzzy calculation, but the proposed method in this paper needs equipment fault data and statistical calculation.

2. Reliability modeling and analysis

2.1. Notation

R_i	Reliability of system/sub-system i
r_i	Reliability of unit/element i
λ_i	Failure rate of unit i
μ_i	Repair rate of unit i
γ_i	Mean time to repair the fault of unit i
λ_s	Failure rate of a serial system s
μ_s	Repair rate of a serial system s
γ_s	Mean time to repair of a serial system s
λ_p	Failure rate of a parallel system p
μ_p	Failure rate of a parallel system p
γ_p	Failure rate of a parallel system p
X	Reliability variable
X_i	Vector of the ith reliability variables
$F(X)$	Reliability density function
$G(X)$	Reliability change function

2.2. General thought

The research on reliability technology can be traced back to the early 1950s. In order to realize the reliability analysis and design, the system modeling was studied in the early stage. According to the structure of the actual electromechanical system, the system is abstracted into series, parallel, hybrid, tree and network. In recent years, for the reliability problem of large-scale system complexity, people have done a lot of research on reliability configuration optimization, and put forward many good methods, such as fragile component configuration method, topology optimization method, redundancy configuration method and so on. These methods are based on the previous series, parallel, hybrid, tree and network system model structure, and they have their own adapting occasions. It is a very complex problem to choose which optimization method is the most reasonable in the specific application, and the reliability optimization method based on deducing proposed in this paper can effectively solve this problem. The goal of the reliability optimization method based on deducing is to achieve the minimum cost and maximize the reliability improvement. The implementation process of the proposed method is shown in Fig. 1.

2.3. Device function analysis

An intelligent device generally contains a number of function units which work closely together in a task. The failure of any unit may lead to malfunction or shutdown of the system. Therefore, the reliability of any unit is crucial to the performance of the whole system. What relationship would it be among these units? It is determined by the combination structures and the collaboration relationships of the units. It can be a parallel relationship, a series relationship, or other more complex ones.

As an example, a modern electric switch can generally perform functions of control, protection, isolation, measurement, status monitoring and so on. The structure of an Integrated Isolating Circuit Breaker (IICB) is shown in Fig. 2. The equipment is composed of four main function units based on the functional requirements of the modern equipment and the actual situations of the traditional equipment.

(1) Chamber. It consists of an arc extinguishing chamber casing, a static end support, a pressure cylinder assembly, and a movable end bearing. It functions as extinguishing arcs.
(2) Appliance. It includes spring mechanism, mechanism box, split switch coil, etc.which are movement-related or movable parts, being handy for later maintenance.
(3) Sensor. The electronic current transformer is a main structural component. The Rogowski coil, an electronic current transformer, is often adopted for safety protections and data

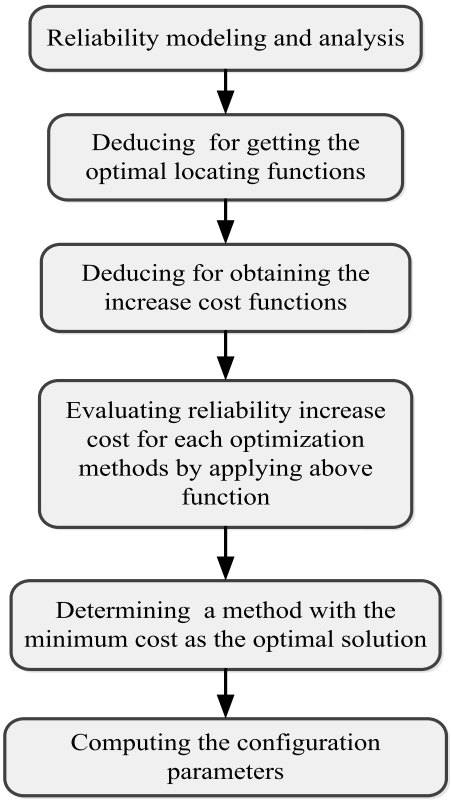

Fig. 1. Flowchart of optimization processes.

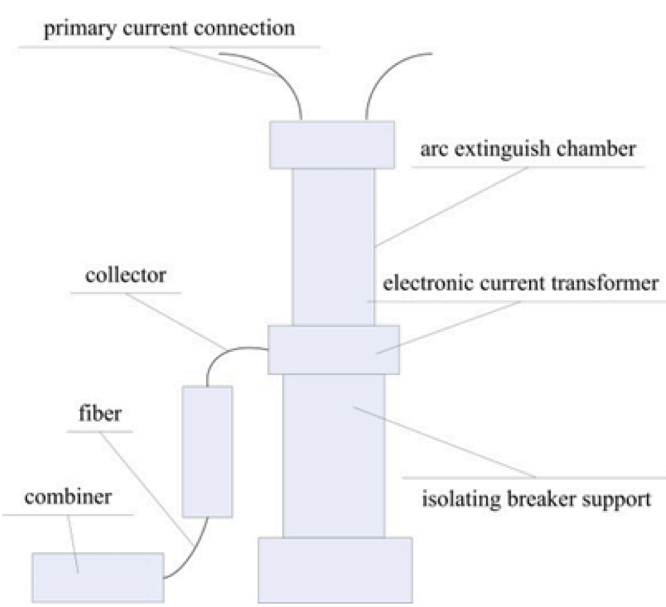

Fig. 2. A structure of electrical equipment.

measurement. The collector is also part of the sensor, and its power supply is the coupling coil or laser power.

(4) Support. It is of a cylindrical shape, which incorporates the isolating breaker inside. It is responsible for offering support for the environment, location and distribution of these components.

Firstly, reliability modeling analysis is carried out for the electrical device. In theory, these four units can be combined in any way to perform their specified functions. For the electronic current transformer, there are varieties of integrated modes. The integrated isolation circuit breaker shown in Fig. 2 is currently the mainstream product in use. The electronic current transformer is in between the isolation circuit breaker and insulator, with protection using the Rogowski coil, and measurement integrating a low power coil.

Only when four components are all in good conditionsimultaneously, can the system work normally. Then, system reliability modelis built and shown in Fig. 3.

2.4. Device reliability modeling analysis

An individual unit can be determined based on the combination of the functional units of the device. The reliability parameters of an individual unit can be obtained with reference to related documents. With the help of the equivalent equipment reliability model, unit relationships become clear, whether series connections or parallel ones. Therefore, the reliability value of the whole equipment can be calculated.

(1) Equivalent reliability model of series systems

In a series system, if any element isin trouble, the whole system will shut down. For a series system with n units, if unit failure rate, repair rate, and the mean time to repair the fault are λ_i, μ_i, and γ_i respectively, then the system can be equivalent to a single element or a system with failure rate, repair rate, the mean time to remove the fault as λ_s, μ_s, γ_s respectively.

Thus, the system failure rate λ_s can be gotten by Eq.(1)as below.

$$\lambda_s = \sum_{i=1}^{n} \lambda_i \tag{1}$$

The mean time to repair γ_s of the system can be obtained by Eq. (2) as below.

$$\gamma_s = \frac{1}{\lambda_s} \sum_{i=1}^{n} \lambda_i \gamma_i \tag{2}$$

Here, the relationship between the repair rate μ_s and the mean time to repair γ_s can be written as Eq. (3) as below.

$$\mu_s = \frac{1}{\gamma_s} \tag{3}$$

(1) Equivalent reliability model of parallel systems

In a parallel system, the whole systemwill shut down when all componentsmalfunction. If any component is restored and stays in good condition, the systemwill run well. For a parallel system with n units, if each unit failure rate, repair rate, and the mean time to repair the fault are λ_i, μ_i, and γ_i respectively, then the system can be equivalent to a single element or a system with failure rate, repair rate, the mean time to remove the faultas λ_p, μ_p, γ_p respectively.

Thus, the repair rate μ_p for the system failures can be obtained by formula (4) as below.

$$\mu_p = \sum_{i=1}^{n} \mu_i \tag{4}$$

The average time to repair$\gamma_p$can be gotten by Eq. (5) as below.

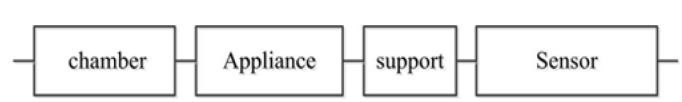

Fig. 3. An electromechanical equipment reliability model.

$$\gamma_p = \frac{1}{\mu_p} = 1 \Big/ \sum_{i=1}^{n} \mu_i \tag{5}$$

Then, the relationshipbetween system repair rate $\mu_p$and failure rate $\lambda_p$is written as Eq. (6) as below.

$$\lambda_p = \prod_{i=1}^{n} \lambda_i \frac{\sum_{i=1}^{n} \mu_i}{\prod_{i=1}^{n} \mu_i} \tag{6}$$

3. Reliability deducing

3.1. Reliability deducing algorithm

For a series system with n elements, assuming the reliability of the i^{th}element isX_i, then, the system reliabilitycan be calculated.

Definition 1. Supposing variable X is the reliability of a series system, then, X_1, X_2, …, X_n represent the sub variables of the series system respectively and they are denoted as X (X_1, X_2, …, X_n).

Defining the discrete density function $F(X)$ as the reliability distribution of the series system, Eq. (7) is written asbelow.

$$F(X) = \prod_{i=1}^{n} X_i \tag{7}$$

Then, we have the differential value of Eq. (7), and consequently Eq. (8) can be yielded as below.

$$G(X) = \frac{\partial F(X)}{\partial X_i} = \prod_{j=1}^{n} X_j = \frac{X}{X_i} \tag{8}$$

In Eq. (8), $G(X)$ represents a reliability change function. Now, in order to improve $G(X)$, Eq. (8) is analyzed as follows.

$$\text{If} \quad \frac{\partial F(X)}{\partial X_i} = \max_{1 \le i \le n} \frac{X}{X_i},$$

$$\text{or} \quad X_j = \min_{1 \le i \le n} X_i,$$

Then, a maximum can be calculated by the differential equation $\frac{\partial F(X)}{\partial X_i}$.

This shows an extremely effective way to improve the system reliability. Namely, $G(X)$ can get a maximum when the j^{th}element's reliability R_j takes a minimum value.

For a parallel system with n elements, assuming the reliability of the i^{th}element is X_i, and then the system reliability can be calculated by the following Eqs. (9) and (10).

Definition 2. Supposing variable X is the reliability of a parallel system, then, X_1, X_2, …, X_n represent the sub variables of the parallel system respectively and they are denoted as X (X_1, X_2, …, X_n).

Defining the discrete density function $F(X)$as the reliability distribution of the parallel system, Eq. (9) is written asfollows.

$$F(X) = 1 - \prod_{i=1}^{n} (1 - X_i) \tag{9}$$

Being the same as the above, we have the differential value of Eq. (9), and Eq. (10) can be yielded as follows as a result.

$$G(X) = \frac{\partial F(X)}{\partial X_i} = 1 - \prod_{j=1}^{n} (1 - X_i) = \frac{1 - F(X)}{1 - X_i} \tag{10}$$

In Eq. (10), $G(X)$ represents a reliability change function. Now, in order to improve $G(X)$, Eq. (10) is analyzed asfollows.

$$\text{If} \quad \frac{1 - F(X)}{1 - X_i} = \max_{1 \le i \le n} \frac{1 - F(X)}{1 - X_i}$$

$$\text{or} \quad X_j = \max_{1 \le i \le n} X_i$$

Then, the maximum can be gotten with the differential equation$\frac{\partial F(X)}{\partial X_i}$.

It is clear that an overwhelmingly effective way to improve the parallel system's reliability R_p is to increase the jth element's reliability R_i to the maximum.

3.2. Optimization and costs

The effective method to improve the reliability of the system, that is, the reasoning optimization method, is described above.This method determines the components of reliability improvement by reasoning, and then realizes the effective improvement of system reliability. This method realizes the qualitative analysis of system reliability growth. Next, the quantitative calculation of reasoning method is studied. In addition, this paper not only studies the optimization design method of system reliability, but also studies the influence of economic factors on system reliability, and reduces the scheme cost as much as possible.

For a series system S, if the reliability of the ith element increases Δ_i, then the system reliability R_S* can be obtained by Eq. (11).

$$R_S^* = \left(\prod_{j=1,\ j \ne i}^{n} R_j \right) (R_i + \Delta_i) = R_s + \Delta_i \prod_{j=1,\ j \ne i}^{n} R_j \tag{11}$$

If R_S* can also be obtained by increasing the reliability of the kth element, then Eq. (12) can be obtained

$$\left(\prod_{j=1,\ j \ne i}^{n} R_j \right) (R_i + \Delta_i) = \left(\prod_{j=1,\ j \ne k}^{n} R_j \right) (R_k + \Delta_k) \tag{12}$$

By sorting out and transforming, formula (13) can be obtained

$$(R_i + \Delta_i) R_k = (R_k + \Delta_k) R_i \tag{13}$$

After organizing and transforming again, we can get formula (14)

$$\Delta_i = \frac{R_i}{R_j} \Delta_j \tag{14}$$

Here, if the cost of increasing reliabilityΔ_i is C_i and Δ_j is C_j, and then Eq. (15) can be obtained.

$$C_i \Delta_i = \frac{C_i R_i}{R_j} \Delta_j = \left(\frac{C_i R_i}{C_j R_j} \right) C_j \Delta_j \tag{15}$$

Therefore, for the series system, in order to improve the reliability with the lowest cost, we should select the component with the smallest $C_i R_i$, that is, the minimum product of degree and unit cost to improve the reliability.

For parallel system P, if the reliability of the ith element is increased by Δ_i, then the system reliability R_p* can be obtained by Eq. (16).

$$R_p^* = 1 - \left[\left(\prod_{j=1,\ j \ne i}^{n} (1 - R_j) \right) (1 - R_i - \Delta_i) \right] \tag{16}$$

After finishing and transforming, formula (17) can be obtained.

$$\Delta_i = \frac{\left(R_p^* + R_p - 1 \right)}{\prod_{j=1,\ j \ne i}^{n} (1 - R_j)} \tag{17}$$

If R_p*can be obtained by increasing R_i to R_i+Δ_i or R_j to R_j+Δ_j, then formula (18) can be obtained.

$$R_p^* = 1 - \left[\left(\prod_{j=1,\ j \ne i}^{n} (1 - R_j) \right) (1 - R_i - \Delta_i) \right] 1 - \left[\left(\prod_{k=1,\ k \ne j}^{n} (1 - R_k) \right) (1 - R_j - \Delta_j) \right] \tag{18}$$

Formula (18) equivalently can be written as a formula (19).

$$(1 - R_j)(1 - R_i - \Delta_i) = (1 - R_i)(1 - R_j - \Delta_j) \tag{19}$$

Eq. (20)and (21) can be deduced.

$$\Delta_i = \left(\frac{1-R_i}{1-R_j}\right)\Delta_j \tag{20}$$

$$C_i\Delta_i = C_i\left(\frac{1-R_i}{1-R_j}\right)\Delta_j = \frac{C_i(1-R_i)}{C_j(1-R_j)}C_j\Delta_j \tag{21}$$

Therefore, for the parallel system, the components satisfying with $\min_{1\le i\le n} C_i(1-R_i)$should be selected to improve the reliability.

4. Reliability analysis

4.1. Failure rate

The development of reliability technology has a history of nearly one hundred years. Up to now, people's interest in the research of product reliability is still increasing. Researchers use modern technical means (electronic information technology, big data technology, etc.) to observe, experiment, verify, discover and reveal the laws of product reliability, and have made a lot of valuable achievements and discoveries.Due to the complexity caused by many factors such as material composition, shape structure and application situation of products, the failure analysis of products has brought considerable challenges.

Failure rate index is often used to measure product failure analysis. Throughout the life cycle of a component, the failure rate can be either constant or variable. In reliability design, the product work should be kept in a low failure rate environment as far as possible. However, the components will still fail, and the life of the product will be reduced even when it is in storage. In order to better analyze the component failure, the following treatment is done.

Definition 3. Supposing failure rate f of component i is defined as a function of time t, denoted as $F_i(t)$, and $f_i(t)$ is the probability density function of component failure, then there are the following situations.

For discrete failure, assuming that the number of failures of component i at time t is n, the calculation method of failure rate of component i is Eq. (22)

$$F_i(t) = \sum_{i=1}^{n} f_i(t) \tag{22}$$

For continuous failure, assuming that component i fails at time t, the calculation method of failure rate of component i is as follows Eq. (23)

$$F_i(t) = \int_0^t f_i(t)dt \tag{23}$$

Based on Eqs. (22) and (23), the calculation method of component reliability $R_i(t)$ can be given, such as Eqs. (24) and (25).

$$R_i(t) = 1 - F_i(t) = 1 - \sum_{i=1}^{n} f_i(t) \tag{24}$$

$$R_i(t) = 1 - F_i(t) = 1 - \int_0^t f_i(t)dt \tag{25}$$

Furthermore, the probability density$f_i(t)$ of product reliability is studied. The object of this study is electromechanical system, which includes mainly mechanical, electronic and other types of components. The reliability distribution of these components is different, and the corresponding expression function and calculation method are also different.

4.2. Failure categories

According to the above situation, the failurerate can be divided into the following three situations for discussion.

1) The component failure rate is constant. This kind of components is most of theseelectronic products of transistors, capacitors, resistors, integrated circuits, etc. They are demanded to work under a wide range of conditions, and are easy vulnerable to failure due to the influence of power intensity, temperature, humidity, dust and other factors. Moreover, they have the characteristics that once a component fails, it will no longer work. In order to achieve a certain function, many components are connected with each other in different ways and form different topologies, including simple series parallel structure and complex network structure. If any component in the system fails, the whole system will no longer work. At present, it is difficult to calculate the reliability of the system with complex network structure.

The distribution of failure rate of electronic products usually follows exponential distribution, and the expression of failure rate density function isEq.(26).

$$f_i(t) = \lambda(t)\exp\left(-\int_0^t \lambda(t)dt\right) \tag{26}$$

The calculation formula of failure rate is Eq. (27).

$$F_i(t) = 1 - \exp\left(-\int_0^t \lambda(t)dt\right) \tag{27}$$

The formula of reliability is Eq. (28).

$$R_i(t) = \exp\left(-\int_0^t \lambda(t)dt\right) \tag{28}$$

During the normal operation of electronic products, the failure rate usually remains constant, then Eq. (23) can be rewritten as Eq. (29).

$$f_i(t) = \lambda e^{-\lambda t} \tag{29}$$

The calculation of failure rate$f_i(t)$ is shown in formula (30).

$$F_i(t) = \int_0^t f_i(t)dt = \int_0^t \lambda e^{-\lambda t}dt = 1 - e^{-\lambda t} \tag{30}$$

The calculation of reliability$R_i(t)$ is shown in formula (31).

$$R_i(t) = 1 - F_i(t) = e^{-\lambda t} \tag{31}$$

1) Multi stage distribution of product failure rate. The failure curve of mechanical products is usually non monotonic and presents the change rule of multi segment curves. The most classic failure distribution curve is called Bathtub Curve, which is divided into three stages: early failure period, accidental failure period and loss failure period, as shown in Fig. 4. below.

The reliability analysis of mechanical products can be divided into two cases. 1. The reliability of static equipment. Most mechanical products of electrical system are static equipment, such as support structure, closed box, etc. The failure rate of static equipment can well obey Weibull distribution. 2. Reliability of dynamic equipment. Dynamic equipment mainly refers to those with reciprocating and rotary motion. Due to the relative motion friction, the distribution of product failure rate completely follows the probability distribution of bathtub curve.

The curve distribution characteristics of mechanical products follow Weibull function, which is expressed as Eq. (32).

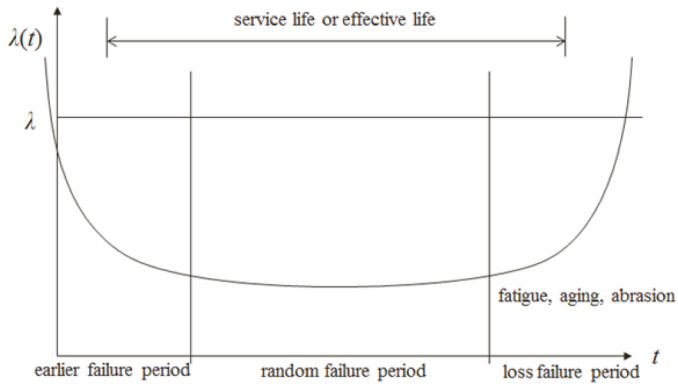

Fig. 4. Bathtub curve.

$$f_i(t) = \alpha\beta(t-\gamma)^{\beta-1}\, e^{-\alpha(t-\gamma)^{\beta}} \qquad (t \geq \gamma,\ \alpha > 0,\ \beta > 0) \tag{32}$$

In Eq. (32), three parameters are used to describe the failure rate density, andthey are scale parameter α, shape parameter β and position parameter γrespectively.

By changingthe β parameter of Weibull function, Weibull function can be transformed into exponential distribution, normal distribution, Rayleigh distribution or other functional forms. This kind of work can be called parameter optimization.

When α and γ remain unchanged and β changes, the curve shape changes with β, as shown in Fig. 5. below. When β is about 3, Weibull distribution is close to normal distribution.

1) Peculiar calculation of reliability. The calculation method is based on the measured data of products, through processing and transformation, to find the relationship with fatigue life of products, so as to accurately calculate the life of products, such as rain flow counting algorithm [35], which simplifies the measured load experience into several load cycles for fatigue life estimation and compilation of fatigue test load spectrum. It is based on the two parameter method, that is, dynamic strength (amplitude) and static strength (mean). The calculation method is in accordance with the inherent characteristics of fatigue load itself.

Another example, the cumulative damage theory, also known as the Mainner's law, is a method for estimating the life of crack formation, which generally adopts the nominal stress method and the local stress-strain method. The nominal stress method calculates the damage degree according to the S-N curve of the component or the S-N curve of the material with the same stress concentration factor as the component. The local stress-strain method firstly analyzes the stress and strain at the root of the notch, and then calculates and accumulates the damage in each cycle according to the curve of the smooth small specimen without notch, and then gives the life.

Suppose that there are k stress levels $\sigma_1, \sigma_2, \ldots\sigma_k$ in a cycle, and the cycle numbers of each stress level are $n_1, n_2, \ldots n_k$ respectively. Let $N_1, N_2, \ldots N_k$ denote the fatigue life under the single action of stress levels at all levels (obtained from S-N curve). According to the cumulative damage theory, the fatigue damage degree can be expressed by the corresponding cycle ratio$\frac{n_1}{N_1}, \frac{n_2}{N_2}, \ldots\frac{n_k}{N_k}$. If t is used to represent the number of cycles, the damage degree caused by each level of stress during the whole working period is $T\frac{n_1}{N_1}, T\frac{n_2}{N_2}, \ldots T\frac{n_k}{N_k}$. When the sum of damage degree is 1 (100%), i.e.$T\sum_{i=1}^{n}\frac{n_i}{N_i} = 1$, the component will be destroyed.

Formula (33) can be used to calculate the reliability of mechanical products.

$$F_i(t) = t * \sum_{i=1}^{n}\sum_{j=1}^{k}\frac{n_{ij}}{N_{ij}} \tag{33}$$

By analyzing the failure distribution function of mechanical products, it is not difficult to find that this kind of calculation is also a kind of parameter optimization, which is an accurate calculation of the scale parameter α of probability distribution.

In formula (32), when β and γ are constant, the shape of Weibull distribution curve is constant. With the decrease of α, the curve extends from the same origin to the right, and the maximum value decreases, as shown in Fig. 6.

Combined with the above optimization idea and the model of electrical system, max[$f_i(t)$] is selected as the optimization object, and the reliability calculation and analysis of system components are shown in Fig. 7.

4.3. Reliability improvement scheme

Based on the above reliability deduction and reliability analysis, the best scheme is selected as the system reliability improvement scheme from topology optimization, component configuration and redundancy configuration.

(1) Topology optimization

According to Fig. 3, the switch is divided into four functional units for the purpose of research. These four units can be combined randomly with differentpositioning, and then multiple switches are formed with different topologies. However, limited by function relationships, only three kinds of topological structures can be produced.

Through the modeling of switches with different topologies, it is clear that their reliability models are almost identical, and the reliability computing resultsare identical. Especially, the sensor of the electronic current transformer, using Rogowski coil, has a low reliability. Therefore, topology optimization is not an effective method to improve the switch's reliability.

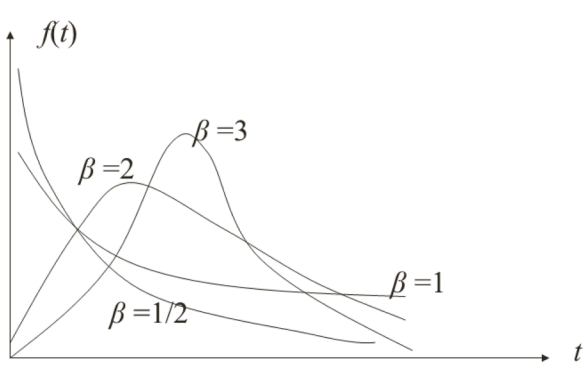

Fig. 5. Distribution curves of different shapes.

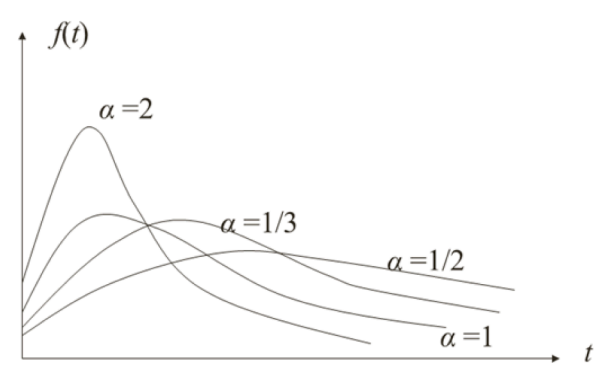

Fig. 6. Distribution curves of different scales.

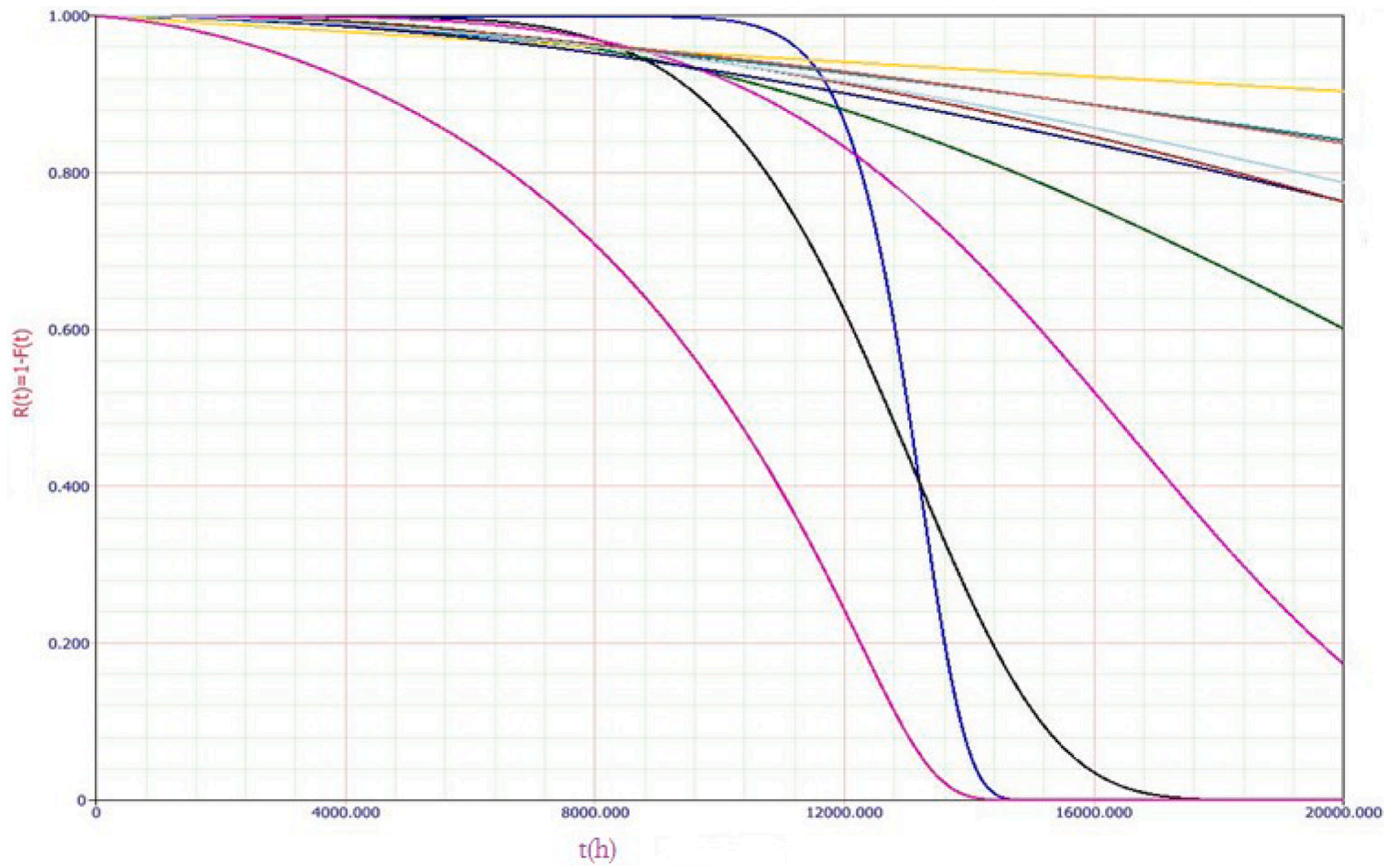

Fig. 7. Component reliability distribution curves.

(1) Component allocation optimization

Component configuration optimization is a method to improve the performance of the whole system by improving the reliability of a component of the system. The goal of configuration is to maximize the reliability of equipment or reduce the failure rate with limited cost. Components have reliability design value in design phase and optimization value in optimization phase. The difference between optimization value and design value is the improvement value of reliability. Optimal configuration is to configure component reliability to optimization value. If there are components with this kind of optimization value in the existing products, or the optimization value can be achieved by adjusting the component failure distribution parameters, this kind of components will be directly selected in the component configuration; if there are no products with this kind of optimization value, they need to be developed. If the product development is complex, the cost is high, or it needs to go through the process of product demonstration and evaluation, the component configuration scheme will not be adopted in this case.

(1) Redundancy optimization

Redundancy optimization is designed to build a backup system for a system or a subsystem, as shown in Fig. 8.

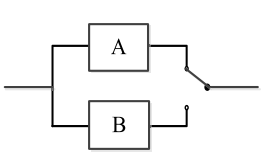

Fig. 8. A redundancy model.

Here A is the main component, and B is the backup element. When the main component A is in failure, the backup element B is immediately put into operation by switching. The system fails only when both A and B fail at the same time, so the backup system can greatly improve the system reliability. Assuming that element A and B are identical, and their failure rate is λ, the system failure probability can be gotten on the basis of Poisson distribution.

The main component reliability can be calculated by Eq. (34) asfollows.

$$F_i(t) = e^{-\lambda t} \tag{34}$$

The 1st redundancy component reliability$F_i^1(t)$can be obtained by Eq. (35) as follows.

$$F_i^1(t) = \lambda t e^{-\lambda t} \tag{35}$$

Thus, the total system reliability$F_a(t)$ is expressed as Eq. (36) as follows.

$$F_a(t) = e^{-\lambda t}(1 + \lambda t) \tag{36}$$

5. Case analysis

Reliability calculation depends on system model. The research needs to model the system first, then carry on the model transformation to judge the parallel connection, series connection or other relationship types of the system, and finally use the reasoning formula mentioned above to calculate the reliability of the system. In the case shown in Fig. 2, the system is divided into four subsystems according to their functions. Then, the four subsystems form a series system. If the sensors in the case are designed according to redundancy optimization, then the system will become a parallel series hybrid system. The following reliability calculation is carried out according to this idea.

5.1. Reliability computation

(1) Reliability parameter calculation

The Reliability Administration Center of National Energy Administration of China published 44,520 Reliability data on electrical devices in 2015.

The corresponding failure and repair rates of each part are obtained in turn by computing, as shown in HYPERLINK \l "tbl0001" Table 1.

Thefailure rate of the arc extinguishing chamber subsystemis calculated and assigned to λ_1, and the failure rate of the circuit breaker subsystem is denoted as λ_2. Their values are λ_1=10^{-4} (time/a) and λ_2=6 × 10^{-4} (time/a) respectively. Consequently, the reliabilities of the two subsystems are $R_1 = e^{-\lambda 1}$ =0.9999 &R_2=$e^{-\lambda 2}$ =0.9994 within a year, and their repair rates are μ_1=19,685.39 (time/a) &μ_2=772.62 (time/a) respectively.

Other parameters are similar as the above, and the calculation results are summed up in Table 2. Consequently, the reliability model parameters of the integrated isolation circuit breaker can be obtained.

(1) Reliability optimization calculation

According to Transmission and Transformation in Trend Analysis Report 2015 released by the Reliability Administration Center of National Energy Administration of China, the forced outage rate of the traditional circuit breaker is 0.108 time/100.year, namely, λ_A=1.08 × 10^{-3}, and the forced outage rate of the isolation switch is 0.009 time/100.year, namely, λ_B=0.09 × 10^{-3}. Thus, the equivalent failure rate of the combination of the traditional circuit breaker and isolation switch is λ=1.17 × 10^{-3}. Therefore, the optimization target of the integrated isolation circuit breaker can be set as λ_t=1.17 × 10^{-3}, and the corresponding target reliability is $R_t(1)$=$e^{-\lambda t}$=0.9988.

Based on the calculation results of the reliability parameters, the failure rate of the integrated isolation circuit breaker is λ_0=1.32 × 10^{-2}. As a result, the range of the failure rate needed to be reduced can be obtained in the light of formulae (16) - (18), and it is $\Delta\lambda$=1.203 × 10^{-2}. And the percentage ofthe reduction is $\Delta\lambda/\lambda_0$=91.1%.

(1) Reliability redundant design

In the light of the processing flowof the proposed deducing method, the redundancy configuration is determined finally as the optimal method, and its configuration model is shown in the Fig. 9.

According to the reducing formulae (7) and (8), the collector/sensor is determined as the part which reliability is to improve.

As a resolution for the redundant design, a backup system is established for the collector. The failure rate of the collector is as follows.

$$\lambda_3 = 1.22 \times 10^{-2}(times / a)$$

The corresponding reliability is as follows.

$$R_3 = e^{-\lambda_3} = 0.9879$$

If 1*st* redundant collector is set up as a backup system, the reliability of the backup systemcan be obtained by formula (35) as below.

$$R_3^1(1) = e^{-\lambda}(1+\lambda) = 0.99993$$

Thus, the equivalent failure rate of the system is asfollows.

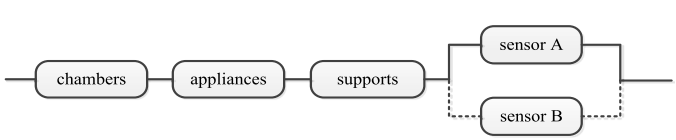

Fig. 9. Redundant configuration model.

$$\lambda_3{}' = 7.38 \times 10^{-5}(times / a)$$

The reliability parameters of the optimized system are shown in Table 3.

Here, the equivalent failure rate of the overall system is as follows.

$$\lambda_a = 1.07 \times 10^{-3}(times / a)$$

After one-year operation, the system reliability is asfollows.

$$R_a^1\ (1) = 0.9989$$

The target failure rate and reliabilitycan be gotten as below respectively.

$$\lambda_t = 1.17 \times 10^{-3}$$

$$R_t = e^{-\lambda_t} = 0.9988$$

5.2. Contribution analysis and comparison

The contribution of the method will be illustrated and confirmed from three aspects: failure rate, reliability, feasibility and economy.

Through the calculation and sorting of the values in Table 1 and the published failure rate boundary values, the standard data values of each component are obtained, as listed in Table 4.

According to the introduction of IICB above, the optimized reliability target can be set as:λ_t= 1.17 × 10^{-3}, $R_t(1) = e^{-\lambda_t}$= 0.9988.

After one year of operation, the comparison of system failure rate, reliability, feasibility and economy of the three optimization schemes is listed in Table 5.

(1) Optimization comparison

From the final optimization results, the topology optimization results are the best. Component configuration optimization is carried out according to the target reliability index, and stops when the overall failure rate of the equipment is lower than the target failure rate. The minimum failure rate of components usually needs some means to obtain,such as component life and reliability test.

For the studied IICB, if the lowest failure rate of all devices in Table 5 is taken, the overall failure rate of the equipment will also be reduced to$\lambda_{2\min} = 1.15 \times 10^{-3}$, which is still higher than topology optimization and redundancy optimization.

If a lower failure rate or higher reliability of the equipment is pursued without changing the reliability of the existing components, a hybrid integration scheme, i.e. a hybrid mode of structure optimization, component configuration and redundant configuration, can be used to improve the system reliability. The optimal optimization results of different schemes are shown in Fig.10.

According to formula (1)–(6), these hybrid reliabilities of topology optimization and component optimization, and component optimization and redundancy optimization can be calculated,$\lambda_{\min}$ = 2.5 × 10^{-4}bytaking the lowest failure rate of the integrated system.

Table 1
Failure and repair rates of elements.

unplanned outage	λ/(10^{-8}/h•p)	μ(time/h)
Breaker	6.671159	0.0882
primary system	2.816712	0.0977
Auxiliary device	1.024259	0.1691
Protect	0.768194	0.2246
Line	0.256065	0.2119
Chamber	1.024259	2.2472
secondary circuit	0.768194	3.1915
Other	0.413297	0.0043

Next, formulae (1)–(6) are applied to resolve the reliability values of equipment/units.

Table 2
Switch device reliability parameters.

	chamber	breaker	sensor	support	entire
$\lambda(10^{-2}$time/a)	0.01	0.06	1.22	0.03	1.32
R	0.9999	0.9994	0.9879	0.9997	0.9869
R importance(%)	0.75	4.55	92.42	2.27	100
μ(time/a)	19685.39	777.62	524.55	912.5	541.75

Table 3
Reliability parameters of backup systems.

	chamber	appliance	sensor	support	entire
$\lambda(10^{-2}$time/a)	0.01	0.06	0.007	0.03	0.107
R(1)	0.9999	0.9994	0.99993	0.9997	0.9989
Rimportance(%)	9.35	56.07	6.54	28.04	100

Table 4
Component reliability allocation parameters.

parts	$\lambda(10^{-2}t/a)$	reliability	low limit (λ)	cost (CNY¥/10^{-3})
appliance	0.06	0.9994	0.01	5476
chamber	0.01	0.9999	0.005	4944
support	0.03	0.9997	0.01	1667
transformer	0.50	0.9950	0.03	7133
A/D	0.56	0.9944	0.03	1220
Opt sender	0.04	0.9996	0.01	118
HFBR	0.12	0.9988	0.02	40

Table 5
Scheme performance comparison.

optimization schema	failure rate (λ)	reliability (R)	Feasibility	economy
topology	10^{-3}	0.9990	Common	middle
part	1.17×10^{-3}	0.9988	Difficult	worst
redundancy	1.07×10^{-3}	0.9989	Easy	best

Fig. 10. Failure rates of different schemas.

(1) Feasibility analysis

Topology optimization is to improve the reliability of the system by changing the connection order or connection mode of IICB components. The scheme is feasible in theory, but it lacks the verification of practical application.

Component optimization is to improve the reliability of components to meet the requirements of system reliability. Although this scheme is feasible in theory, from the component failure rate listed in Table 5, it is known that the reliability of some components needs to be improved more than 90%. Therefore, the feasibility of component optimization in reality is not high.The component reliability improvement is a main direction for equipment reliability improvement. This research is to try to raise the system reliability under maintaining the existing conditions and the system performance.

Redundancy optimization is to improve the reliability of the system by building a reserve system of components. Because the spare parts are completely consistent with the original, the scheme is the most feasible.

(1) Economic analysis

From the above feasibility analysis, we can see that the cost of component configuration optimization is relatively the highest. It needs to study the reliability improvement of components in the system. The cost of topology optimization is higher, it needs to change the way of equipment integration. The cost of redundancy optimization is the lowest. It directly uses the existing components as the backup without additional cost. Therefore, redundancy design optimization is the best of the three schemes.

6. Conclusion

In order to enhance the entire performance of the electrical equipment, a deducing-based reliability optimization for the electrical equipment is proposed. In this method, the weak elements of the system are quickly located by the way of function derivation, the optimization calculation model of reliability improvement is given by the function transformation, and the optimal reliability improvement method is determined by the analysis of optimization scheme. This method can help designers to improve design efficiency, and can be used as a small supplement in the field of reliability research. Suggested method is applied into a real production design with multiple functions and remarkable feasibility and practicability. The reliability deducing method for different structure models is given in this research, which provides a solid basis for the design of electrical equipment. Comparing to the traditional system, reliability calculation functions of three kinds of topological structures are defined, which is a strong support for electrical system reliability design. However, the proposed reliability optimization method is tremendously dependent on data in this research. The data in this paper mainly comes from internet and some references.With the development of technology, the application of the technical systems with magnetic starters and contactors in power equipment becomes more and more prominent. Therefore, in the following work, the verification strategy of reliability data is a valuable study, the research on the magnetic starters and contacts is also a hot issue, as well as it is a study direction that possibility of taking into accounts the operating modes of equipment in the presence of static information.

Declaration of Competing 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.

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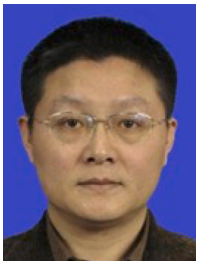

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