Research on reliability evaluation method of protection system based on Kaplan-Meier and GO method

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Abstract. In the reliability analysis of the traditional substation protection system, methods such as minimum path set method, fault tree method and Markov method are mostly used. These three methods have disadvantages such as large amount of calculation and strong subjectivity in the application process. Based on the shortcomings of traditional reliability analysis methods, this paper proposes a protection system reliability evaluation method based on survival analysis plus GO method. In view of the problem of timing truncation of the failure data of the protection system and the different time of operation of the protection device, the survival analysis (Kaplan-Meier) method is used to estimate the reliability of the equipment in different time periods, and the GO method is combined to obtain the GO graph of the protection system and GO operation, and then get the reliability of the entire protection system. The results show that the method can quantitatively calculate the reliability of the relay protection system, has the advantages of simplicity, intuitiveness, and easy computer programming. It can be used to analyse the reliability of the relay protection system and guide the design, operation and maintenance of the substation.

1. Introduction
Since its establishment in the 1950s, reliability theory has received extensive attention from researchers all over the world, and has been successfully applied in many industries (especially aerospace, military equipment, nuclear power and other fields with high reliability requirements). One of the important steps of reliability analysis is to select an appropriate analysis method according to the structure of the system to be analyzed and establish a reliability analysis model. Common reliability analysis methods include minimum path set method, fault tree method, Markov method and so on. The minimum path set method needs to find all the minimum paths between the first and last nodes, and then calculate the reliability of each path separately and then perform parallel processing; The fault tree method needs to analyze all the possibility of failure, establish a fault tree diagram, and find the minimum cut set of the failure; The Markov method is mainly used for the reliability analysis of repairable systems. It is necessary to establish a Markov space model and use the state transition equation for calculation. Literature [1] describes the reliability analysis of the relay protection system based on the Markov model method. This method requires a lot of data and information, the structure is more complex, and it is closer to reality, but because the transfer matrix is difficult to solve and the fault of the self-check system Probability and maintenance related data are not available, etc. This
method is difficult to apply to actual work. Literature [2] uses the fault tree analysis method to quantify the reliability index of the system, and uses the probability model to estimate the system component failure rate, repair time and other availability indexes, thereby calculating the reliability of the IEC61850 system. At present, in the reliability analysis of the traditional substation protection system, the aforementioned three methods are mostly used. These three methods have disadvantages such as large amount of calculation and strong analysis subjectivity in the application process. Among them, the fault tree method needs to list all paths or failure causes when analyzing the system model, and omissions or missing phenomena are easy to occur, leading to the analysis results There is an error. In view of the shortcomings of the above methods, the Goal Oriented (GO) method is compared with the traditional analytical method. The GO method is based on the system structure diagram, which can specifically reflect the functional relationship and logical relationship between the system and components, focusing on the system's Simulation and simulation, so it is more suitable for the system structure is clear, the relationship between components is clear, especially the system analysis of specific logistics [3-4]. In the Literature [5], a new quantitative calculation method was explored for the complex problem of state probability reliability evaluation Calculation Company caused by shared signals, and a new reliability analysis method—GO method was introduced into the field of power system. The application of this method in the reliability analysis of relay protection system is presented. Literature [6] uses the extended GO probability method to evaluate the reliability of the HVDC transmission line protection system, so that the state cumulative probability formula containing the common signal can be directly used in the reliability calculation of the multi-state system, but the modeling is not fully considered existing common signal problems.

Based on the shortcomings of traditional reliability analysis methods, this paper aims at the problem of timing censoring of the failure data of the protection system and the different time of operation of the protection device. The survival analysis (Kaplan-Meier) method is used to estimate the reliability of the equipment in different time periods. To a certain extent, the logic relationship and operation sequence of the protection system can be obtained through the GO method, which can obtain the reliability of the entire protection system. The results show that this method can quantitatively calculate the reliability of the relay protection system, and has the advantages of simplicity, intuitiveness, and easy computer programming. Therefore, it can be used to guide the analysis, design, operation and maintenance of the relay protection system.

2. Basic data for reliability evaluation of relay protection

2.1. Basic data collection of relay protection reliability

The collection of basic data on the reliability of relay protection is an important aspect of the research on the reliability of relay protection. In this way, users who have no knowledge about the data source can also use the data in the data source to evaluate the reliability of relay protection. Provide reference for verifying the reliability evaluation model of relay protection. The scope of data collection should be the entire life cycle of the equipment. The complete basic data of relay protection reliability mainly includes:

1. Original data (nameplate parameters, factory test report, installation and commissioning records, acceptance and handover records, etc.);
2. Operation data (operation record information, defect record, operation analysis record of the relay protection device in the event of a fault within or outside the area, live detection record, etc.);
3. Maintenance test data (maintenance report, patrol inspection record, implementation of countermeasures, elimination record, major defect analysis);
4. Other data (family defects and failure records of equipment of the same manufacturer and model, implementation of relevant countermeasures, etc).

The above basic data are distributed in different data sources. Among them, the original data mainly refers to the basic equipment files and test data generated before the equipment is officially put into service, which can be obtained from the equipment ledger and test records. The basic types
mainly include: the total number of protection devices, protection models, protection delivery time, protection commissioning Time, protection of manufacturers, etc. The operating data is the core data for studying the reliability of relay protection. It mainly refers to the fault data and maintenance data generated during the operation of the equipment, which can be obtained from the fault information system, dispatch center operation report, fault recorder and maintenance report. Operating data mainly includes: faulty equipment model, fault start time, fault duration, fault type, faulty module, repair method, repair time, etc. The maintenance test data mainly comes from maintenance reports and inspection records. The basic types mainly include: maintenance start time, maintenance methods, defect records, etc., and other data such as family defects and failure records of equipment of the same manufacturer and model in recent years. It can be obtained through statistical analysis of protection action.

2.2. Common indicators of relay protection reliability

Convert the collected basic data into common indicators for evaluating protection reliability as follows:

1. Operation failure rate: \( P_0 = \frac{\lambda}{T_0} \), where \( \lambda \) is the number of failures, and \( T_0 \) represents the accumulation of operating time;

2. The failure rate of the protection device found in the self-inspection is \( \lambda_s = \frac{n_s}{T_0} \), where \( n_s \) is the number of times that the protection device is in operation until the current moment of failure and is detected by the self-inspection. For details, please refer to the self-inspection report of the protection device. \( T_0 \) is the protection Time accumulation during device operation;

3. The fault repair rate of the protection device detected by the self-inspection is \( \mu_s = \frac{1}{T_{MTT0}} \), where \( T_{MTT0} \) is the average repair time, which is calculated from the cumulative maintenance time and the total number of repairs for all faults detected in the self-inspection since the protection device was put into operation;

4. Periodic maintenance cycle \( R \): The data is obtained from the relevant departments of the power system, and it can also be set as the best maintenance cycle value;

5. The failure rate of the protection device that is not detected by the self-inspection is \( \lambda_u = \frac{n_u}{T_0} \), where \( n_u \) is the number of times that the protection device is in operation until the current moment of failure but not detected by the self-inspection;

6. Failure rate of regular maintenance \( \lambda_r \): The number of regular maintenance in a unit time. Since the period of regular maintenance is \( R \), then \( \lambda_r = \frac{1}{R} \);

7. Comprehensive failure rate: use the sum of the cumulative time (including \( T_0 \), periodical maintenance time \( T_{rm} \), and failure stop time \( T_{dr} \)) from the time the protection is put into operation to the current moment, and the number of failures found during regular maintenance, \( n_{rm} \). The calculation formula of the comprehensive failure rate is as follows:

\[
P_\Sigma = \frac{(\lambda + n_{rm})}{(T_0 + T_{rm} + T_{dr})}\]

In fact, when collecting reliability data for relay protection, due to the large difference in the operating time of the protection device and the difference in on-site operation, the measured data is always incomplete. Therefore, the reliability data of relay protection also has the problem of data truncation. Data truncation mainly includes timing truncation and left truncation.

1. Timing truncation

Due to the limitation of the observation time, only part of the relay protection devices fail during the observation period, or only the failure data of the protection devices within a period of time can be obtained, and the failure data of all the protection devices cannot be obtained, which is called timing truncation.

2. Left truncation

The failure data of the newly put into operation protection device is relatively complete, while the early failure data of the earlier put into operation protection device is often not recorded. As a result, the collected data starts at a certain time, and the data before this time cannot be obtained. This is called left truncation.
The reliability calculation of the relay protection device requires complete equipment failure data. However, the complete equipment failure data includes all the failure times of all equipment. When the number of observed equipment is small and the observation time is longer, it is possible to obtain complete invalidation data. The problem of data truncation is common in engineering reliability data. When directly performing reliability analysis on the collected basic data, the approximate median rank and other formulas are often used in engineering to obtain the empirical distribution function, and then the seven indicators listed above to measure the reliability of the relay protection device are calculated. However, formulas such as approximate median rank do not consider the problem of data truncation, and other formulas are often used in engineering to obtain the empirical distribution function, and then the number of observed equipment is small and the observation time is longer, it is possible to obtain complete invalidation data. The problem of data truncation is common in engineering reliability data.

3. Reliability calculation of protection system based on Kaplan-Meier method

Aiming at the problems of timing censoring of the failure data of the protection system and the inconsistency of the time when the protection device is put into operation, this paper uses the method of Kaplan-Meier to estimate the reliability of the device. The meaning of equipment reliability refers to the probability that a certain equipment will not fail at the current running time. The following uses survival analysis method to analyze the reliability of the equipment.

First of all, according to the respective starting time \( t_{\text{begin}} \) of the equipment in the basic data and the failure time \( t_{\text{fail}} \), the failure time interval \( t \) of the protection device can be obtained, and the failure time interval \( t_j \) of the \( j \)-th device should be the failure time \( t_{j, \text{fail}} \) minus the time of operation \( t_{j, \text{begin}} \), namely \( t_j = t_{j, \text{fail}} - t_{j, \text{begin}} \).

Let \( T \) denote the survival time, \( R(t) = P(T > t) \) denote the survival function of \( T \), which is the reliability of the device, which means the probability that the device will survive (or run) longer than the time \( t \). Survival function is the most basic metric in survival analysis. In order to effectively estimate \( R(t) \), consider the RSS Kaplan-Meier under the random censored model. Let \( t_1, t_2, t_3, \ldots, t_n \) be a simple random sample drawn from \( T \), and let \( t_{(1)} \leq t_{(2)} \leq t_{(3)} \leq \ldots \leq t_{(n)} \) be the order value of \( t_1, t_2, t_3, \ldots, t_n \) from small to large. In order to estimate \( R(t) \), the Kaplan-Meier method is used [7]. The survival analysis method of the equipment reliability function in this paper is shown in Equation (2).

\[
R(t) = \begin{cases} 
1 & t \in \left[0, t_{(1)}\right) \\
\prod_{i=1}^{j} \left( \frac{n-i}{n-i+1} \right)^{\delta(i)} & t \in \left[t_{(j)}, t_{(j+1)}\right), j = 1, \ldots, n-1 \\
0 & t \in \left[t_{(n)}, \infty\right)
\end{cases}
\]

(2)

If \( t \) is the survival operation time of the protection device, then \( R(t) \) is the probability that the protection device is still operating normally at \( t \), that is, the probability that the operation time is longer than \( t \). The minimum failure time of the protection device is \( t_1 \), which means that the operation time of all protection devices exceeds \( t_1 \), so the equipment reliability \( R(t) = 1 \) in the range of \( t \in [0, t_1) \). The maximum operating time of the protection device is \( t_n \), which means that the operating time of all the protection devices does not exceed \( t_n \), so the equipment reliability of the protection device in the range of \( t \in [t_n, +\infty) \) is \( R(t) = 0 \). In Formula (2), if \( t_{(j)} \) is truncated data, set \( \delta(j) = 0 \); if \( t_{(j)} \) is invalid data, set \( \delta(j) = 1 \). Obviously, the truncation information is contained in \( \delta(j) \). When \( t \in [t_{(j)}, t_{(j+1)}) \), \( R(t) \) is obtained by multiplying the reliability of \( i \) from 1 to \( j \). Because \( t_{(j)} \) is the \( j \)-th duration arranged from small to large, there is a device whose working time is exactly in the interval \( [t_{(j)}, t_{(j+1)}) \), and the working time is less than \( t_{(j)} \) are shared \( j-1 \) pcs. The equipment reliability \( R(t) \) in this time interval is obtained by multiplying the probability that the equipment will not fail in this interval \( (n-j)(n-j+1) \) and the reliability \( R_{j-1}(t) (t \in [t_{(j)}, t_{(j+1)})) \). For example, when \( t \in [t_{(3)}, t_{(4)}) \), \( t_{(4)} \) is truncated data, \( \delta(1) = \delta(2) = \delta(3) = 1 \); \( t_{(4)} \) is truncated data, \( \delta(4) = 0 \), the equipment reliability \( R(t) \) in this time period is as follows:
Where $n$ is the total number of data of this type of equipment.

In order to use Formula (2) to estimate the reliability of equipment, it is necessary to collect basic data on the reliability of relay protection. The calculation process is as follows.

1. Collect the commissioning time $t_{\text{begin}}$ and the failure exit time $t_{\text{fail}}$ of $n$ devices of this type of relay protection device, and calculate the survival and service time of each device $t = t_{\text{fail}} - t_{\text{begin}}$, where the survival time of the $j$th device is expressed as $t_j = t_{j, \text{fail}} - t_{j, \text{begin}}$.

2. Arrange the survival and service durations $t_1, t_2, t_3, \ldots, t_n$ of $n$ pieces of equipment in ascending order to obtain the duration sequence $t(1), t(2), t(3), \ldots, t(n)$.

3. Use Formula (2) to calculate the equipment reliability of $t \in [t(j), t(j+1)]$. Among them, if $t_j$ is censored data, let $\delta(t_j) = 0$; if $t_j$ is invalid data, let $\delta(t_j) = 1$.

Take the protection device as an example for calculation and description. Select 31 relay protection devices of the same model, record their respective operating time and failure time under the same operating level and the same working conditions, and arrange them in order of running time from smallest to largest, and the specific data as shown in Table 1.

| Put into operation time (year-month-day) | Failure time (year-month-day) | Deadline (year-month-day) | Running time/h | Exit mode | Remarks |
|------------------------------------------|-------------------------------|---------------------------|---------------|-----------|---------|
| 2000-2-1                                 | 2003-1-1                      | 2008-2-1                  | 25560         | Failure exit | -------- |
| 2000-2-1                                 | 2003-9-20                    | 2008-2-1                  | 31848         | Failure exit | -------- |
| 2000-2-1                                 | 2004-4-7                     | 2008-2-1                  | 36648         | Failure exit | -------- |
| 2000-2-1                                 | 2005-1-1                     | 2008-2-1                  | 43104         | Failure exit | -------- |
| 2000-2-1                                 | 2005-6-7                     | 2008-2-1                  | 46872         | Failure exit | -------- |
| 2000-2-1                                 | 2005-10-1                    | 2008-2-1                  | 49656         | Failure exit | -------- |
| 2000-2-1                                 | 2006-1-1                     | 2008-2-1                  | 51864         | Failure exit | -------- |
| 2000-2-1                                 | 2006-6-6                     | 2008-2-1                  | 55608         | Failure exit | -------- |
| 2000-2-1                                 | 2007-1-1                     | 2008-2-1                  | 60624         | Failure exit | -------- |
| 2000-2-1                                 | 2008-2-1                     | 2008-2-1                  | 70128         | Exit normally | 22 in total |

The data in Table 1 includes the data of 9 protection devices that have exited operation due to failure and 22 protection devices that have normally exited operation. Use Formula (2) to process the data in the table, where $n=31$ and the calculation process is as follows:

When $j=0$, $[0,t_1) = [0,25560h)$ All equipment is operating normally, and the equipment reliability in this time interval is $R(t)_{0} = 100\%$.

When $j=1$, $[t_1,t_2) = [25560h,31848h)$, and only a device with a running time of $t_1$ exits operation due to a failure during this time interval, the reliability of the device in $[t_1,t_2)$ as follows:

$$R_1(t) = \left( \frac{n-1}{n} \right) \delta(t_1) \cdot \left( \frac{n-2}{n-1} \right) \delta(t_2) \cdot \left( \frac{n-3}{n-2} \right) \delta(t_3) \cdot \left( \frac{n-4}{n-3} \right) \delta(t_4) \cdot \left( \frac{n-5}{n-4} \right) \delta(t_5) \cdot \left( \frac{n-6}{n-5} \right) \delta(t_6) \cdot \left( \frac{n-7}{n-6} \right) \delta(t_7) \cdot \left( \frac{n-8}{n-7} \right) \delta(t_8) \cdot \left( \frac{n-9}{n-8} \right) \delta(t_9) = 0.96774$$

When $j=2$, $[t_2,t_3) = [31848h,36648h)$, and the two devices with operating durations of $t_1$ and $t_2$ fail to exit operation within this time interval, then the reliability of the equipment within $[t_2,t_3)$ as follows:
When \( j = 3 \), \([t_3, t_4) = [36648h, 43104h)\), in this time interval, the three devices with operating durations of \( t_1 \), \( t_2 \) and \( t_3 \) fail to exit operation, then the devices in \([t_1, t_4)\) The reliability is as follows:

\[
R_c(t) = 0.90322
\]

When \( j = 4, 5, 6, 7, 8 \), the calculation process is the same as the above process.

When \( j = 9 \), \([t_9, t_{10}) = [60624h, 70128h)\), in this time interval, the nine devices running within the range of \( t_1 \sim t_9 \) fail and exit. Only the last 22 devices can operate reliably, then The reliability of the equipment in \([t_9, t_{10})\) is as follows:

\[
R_e(t) = 0.70968
\]

When \( j = 10 \), \([t_{10}, \infty) = [70128h, \infty)\), all equipment has exited operation, and the equipment reliability is

\[
R_0(t) = 0
\]

The equipment reliability of this type of relay protection device in each of the above time periods is sorted into the form of Table 2, and it can be found that the equipment reliability \( R(t) \) of the device in each time period decreases as the running time becomes longer.

|  |  |  |  |
|---|---|---|---|
| \( j \) | \( t_j \) | \([t_j, t_{j+1})\) | \( R(t) \) |
| 1 | 25560h | [25560h, 31848h) | 0.96774 |
| 2 | 31848h | [31848h, 36648h) | 0.93548 |
| 3 | 36648h | [36648h, 43104h) | 0.90322 |
| 4 | 43104h | [43104h, 46872h) | 0.87097 |
| 5 | 46872h | [46872h, 49656h) | 0.83871 |
| 6 | 49656h | [49656h, 51864h) | 0.80645 |
| 7 | 51864h | [51864h, 55608h) | 0.77419 |
| 8 | 55608h | [55608h, 60624h) | 0.74194 |
| 9 | 60624h | [60624h, 70128h) | 0.70968 |
| 10 | 70128h | [70128h, \( \infty \)) | 0 |

The Kaplan-Meier method can be used to obtain the reliability of the relay protection device. If the reliability of the entire protection system is to be obtained, it is necessary to use the GO method to obtain the logical relationship and operation sequence of the protection system. The following analyzes how to use the GO method to obtain indicators to measure the reliability of the entire protection system.

### 4. Reliability evaluation of relay protection system based on GO method

GO method is a success-oriented system reliability probability analysis theory. Its basic idea is to directly translate system schematic diagrams, flowcharts or engineering diagrams into GO diagrams composed of two major elements: operators and signal flow. Where the operator represents a specific component or logical relationship, the signal flow represents a specific logistics; the signal flow connects the operators, and then calculates according to the operation steps of the operators. Therefore, the main steps of GO method can be summarized as the establishment of GO graph and GO operation.

#### 4.1. Establishment of GO diagram for reliability of relay protection system

Operators represent the logical relationship between unit functions and unit input and output signals, including three attributes: type, data, and operation rules. The type reflects the unit functions and characteristics represented by the operator. The GO method defines standard operators of types 1 to 17, as shown in Figure 1, where 2, 10, and 11 are logical operators. The subordinate types have specified
data and operation rules, the specified data represents the state probability of the unit, and the specified operation rules represent the characteristics of the unit [8].

![GO diagram](image)

**Figure 1.** Establishment of GO diagram for reliability of relay protection system.

The signal flow represents the input and output of the system unit and the association between the units, including two attributes: state value and state probability. The state value \(0 \sim N\) is used to indicate the multi-state of the signal flow, the state value 0 represents an advanced state, the state value 1, 2, \(\cdots\), N-1 indicates multiple successful states, and the largest state value N indicates the failure state. The state value has a corresponding state probability. For a system with time sequence, the \(0 \sim N\) state value can be called the time point to represent a series of given specific time values.

Take the HVDC line protection system of a converter station of an UHVDC project as an example to establish a converter station relay protection system structure model, as shown in Figure 2. The protection device of the HVDC line protection system consists of three sets of protection.

![HVDC line protection system structure](image)

**Figure 2.** HVDC line protection system structure.

The relay protection system is a repairable system, so only two states of normal operation and fault repair are considered for the originals in the loop. The output of the secondary side of TA/TV is the input of the protection system and the output of the system when the circuit breaker is tripped or
signaled. Based on the model in Figure 2, the GO model of relay protection is established. The two-state unit represents the protection system 1, the protection system 2, the protection system 3, and the circuit breaker. A single signal generator represents CT/PT and optical fiber. The type 11 operator represents the judging device. The type 10 operator represents the logical relationship of CT/PT at both ends of the line. By the above mapping method, the system can be translated into the GO graph shown in Figure 3.

![Figure 3. HVDC line protection system GO diagram.](image)

Given the success probability of each unit, the correct working probability of the entire system can be calculated. Using Kaplan-Meier method to calculate the reliability of some components, the type of each operator, the name of the representative unit and the reliability are shown in Table 3. The reliability here is the reliability when the equipment is running for a short time. In practice, the reliability of this period of time is selected for calculation according to the equipment running time.

| Numbering | Types | Unit name     | Reliability $R_i$ |
|-----------|-------|---------------|-------------------|
| 1         | 5     | CT            | 0.9988            |
| 2         | 5     | PT            | 0.9988            |
| 3         | 10    | AND gate      | ×                 |
| 4         | 1     | Protection System 1 | 0.9990 |
| 5         | 1     | Protection System 2 | 0.9970 |
| 6         | 1     | Protection System 3 | 0.9990 |
| 7         | 11    | M K gate      | ×                 |
| 8         | 1     | CB            | 0.9991            |

4.2. GO calculation of reliability of relay protection system
There are usually two GO method operations after the GO graph is established, the state combination algorithm and the probability formula algorithm. Among them, the state combination algorithm needs to enumerate the combination of all operator states, which requires a lot of work and is only suitable for simple system analysis. The probability formula algorithm can be directly calculated by the operator formula, without the need to analyze the GO graph, and the workload and analysis subjectivity are far less than the state combination algorithm. Therefore, the probability formula algorithm will be used to calculate the reliability of the relay protection system by the GO method.

The probability formula algorithm will introduce the "state cumulative probability", which is defined as: $A(i)$ represents the sum of all probabilities of the signal flow state value from 0 to i.

$$A(i) = \sum_{j=0}^{i} P(j), \quad i = 0, 1, ..., N$$

(3)

Where: $i$ represents the possible state of the system; $P(j)$ represents the probability that the signal flow state value is $j$.

The signal flow represents the input and output of the system unit and the association between the units, including two attributes: state value and state probability. The state value 0–N is used to
represent the multi-state of the signal flow, the state value 0 represents an advanced state, the state value 1, 2, •••, N-1 represents multiple successful states, and the largest state value N represents the fault state. The state value has a corresponding state probability. For a system with time sequence, the 0-N state value can be called the time point to represent a series of given specific time values.

In a system with N+1 states, the general state 0 indicates the advanced state, the states 1 to N-1 indicate multiple success states, and the state N indicates the failure state. Some systems do not have an advance state, the value of is 1 to N, a total of N states. The state cumulative probability has the following characteristics.

\[ A(N) = 1 \] (4)

After introducing the cumulative probability of the state of the signal flow, the formula for calculating the state probability of the output signal from the state probability of the input signal and the operator can be derived according to the operating rules of the operator. When performing quantitative calculations, you can directly apply the calculation formula of the operator to calculate the state probability of each signal flow of the system. In actual calculations, multiple signal streams may contain the same common signal. In this case, probability correction is required. The general method is to expand the state probability product expression according to the common signal flow probability, and then modify the high-order terms of all common signal state probabilities in the expression with one term replacement.

The following is an example of the operation of the GO graph model in Figure 3, where all operators are 2-state operators, 1 is the normal state, and 2 is the fault state. According to Formula (3), \( A(1) = P(1) \) and \( A(2) = 1 \).

Let \( A_i(j) \) denote the sum of all the probabilities of the state value of the signal flow numbered \( i \) from 0 to \( j \); \( PS_i(j) \) denote the probability that the state value of the operator numbered is \( j \). For the above operators, \( PS_i(j) \) represents the success status of the operator numbered \( i \), which is equal to the reliability of the operator numbered, that is, \( PS_i(j) = R_i \). Using the probability formula algorithm, the expression of the success probability of each signal flow of the system is directly obtained as follows.

**Input operator:**

\[
A_1(1) = P_{51}(1) = R_1 = 0.9988 \\
A_2(1) = P_{52}(1) = R_2 = 0.9988
\] (5)

The output of AND gate 3:

\[
A_3(1) = A_1(1)A_2(1) = R_1R_2 = 0.9988 \times 0.9988 = 0.9976
\] (7)

**Signal flow 4:**

\[
A_4(1) = A_5(1)P_{34}(1) = R_1R_2R_4 = 0.9976 \times 0.9990 = 0.9966
\] (8)

**Signal flow 5:**

\[
A_5(1) = A_3(1)P_{55}(1) = R_1R_2R_5 = 0.9976 \times 0.9970 = 0.9946
\] (9)

**Signal flow 6:**

\[
A_6(1) = A_3(1)P_{56}(1) = R_1R_2R_6 = 0.9976 \times 0.9990 = 0.9966
\] (10)

M takes the output of K gate 7: The state probability involves the processing of the shared signal \( A_7(1) \). When there is no common signal processing, the state probability expression is as follows.

\[
A_7(1) = A_4(1)A_5(1) + A_4(1)A_6(1) + A_5(1)A_6(1) - 2A_4(1)A_5(1)A_6(1)
\] (11)

\[= A_2^1(1)R_4R_5 + A_3^1(1)R_4R_6 + A_4^1(1)R_5R_6 - 2A_4^1(1)R_4R_5R_6 \]

The common signal should be considered in the calculation, and the higher-order term of \( A_7(1) \) should be changed to a one-time term. The state probability of operator 7 after the correction of the common signal is as follows.

\[
A_7(1) = A_2(1)(R_4R_5 + R_4R_6 + R_5R_6 - 2R_4R_5R_6) \\
= R_1R_2(R_4R_5 + R_4R_6 + R_5R_6 - 2R_4R_5R_6)
\] (12)

\[= 0.9982 \]
Signal flow 8:

\[ A_8(1) = A_7(1) P_{88}(1) = R_4 R_5 (R_4 R_5 + R_4 R_6 + R_5 R_6 - 2 R_4 R_5 R_6) \]

\[ = 0.9982 \times 0.9991 = 0.9973 \]  

(13)

In summary, the success probability of signal stream 1 to signal stream 8 is listed in Table 4.

| Signal flow number | Reliability \( A_i(1) \) | Failure Rate 1- \( A_i(1) \) |
|--------------------|---------------------|---------------------|
| 1                  | \( A_1(1) = 0.9988 \) | 0.0012              |
| 2                  | \( A_2(1) = 0.9988 \) | 0.0012              |
| 3                  | \( A_3(1) = 0.9976 \) | 0.0024              |
| 4                  | \( A_4(1) = 0.9966 \) | 0.0034              |
| 5                  | \( A_5(1) = 0.9946 \) | 0.0054              |
| 6                  | \( A_6(1) = 0.9966 \) | 0.0034              |
| 7                  | \( A_7(1) = 0.9982 \) | 0.0018              |
| 8                  | \( A_8(1) = 0.9973 \) | 0.0027              |

5. Conclusions

This paper proposes a protection system reliability evaluation method based on survival analysis plus GO method. In view of the problem of timing truncation of the failure data of the protection system and the different time of operation of the protection device, the survival analysis (Kaplan-Meier) method is used to estimate the reliability of the equipment in different time periods, and the GO method is combined to obtain the GO graph of the protection system and GO operation, and then get the reliability of the entire protection system. The actual calculation example shows that the GO method can quantitatively calculate the reliability of the relay protection system. It has the advantages of simple, intuitive and easy computer programming, so it can be used to guide the analysis and design of the relay protection system.

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