State evaluation of relay protection system for state maintenance

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Abstract. Relay protection is the first line of defense for power systems. Its reliable operation is an important guarantee for the safety and stability of power system. At present, Chinese relay protection system has long been implemented with regular planned maintenance and repaired supplemented by after-accident maintenance. This maintenance system has greatly caused the loss and waste of manpower, material resources and financial resources. It is urgently necessary to adopt a reasonable maintenance strategy based on the actual operating state of relay protection. The state maintenance of the relay protection system can formulate the maintenance strategy based on the actual operating state of the relay protection system, which can effectively improve the reliability of the relay protection system. Therefore, this paper studies the state evaluation of the relay protection system for state maintenance. Develop maintenance strategy based on the evaluation results of the current operating state of the protection system. It is of great significance to strengthen the reliability and operation level of the relay protection system and ensure the safe operation of the power grid.

1. Introduction

In recent years, the power grid construction has achieved tremendous development. The pace of construction has been comprehensively accelerated. And the construction and investment scale has exceeded 100 billion. Up to now, the State Grid Corporation's "Eight Crossing and Eight Straight" UHV project has been completed and put into operation. And the "two crosses and three straights" project is under construction [1, 2]. In the big background of the rapid development of the national grid, the power system's operational characteristics have also presented more complex diversity. The relay protection system plays an important role as the first line of defense for the security and stability of the power grid.

At present, Chinese relay protection system has long been implemented with regular planned maintenance and repaired supplemented by after-accident maintenance. This kind of maintenance system only repairs the relay protection at regular time intervals, regardless of the actual situation of the equipment, which inevitably causes the phenomenon of “insufficient maintenance” or “excessive maintenance”, which ultimately results in the loss and waste of effective use time, manpower, material resources and financial resources [3-9]. In the worst case, it may even cause power grid fault. Based on the obvious defects of the above traditional maintenance system, how to adopt a reasonable maintenance strategy according to the actual operating state of relay protection to improve the reliability of equipment operation becomes the key to the development of power equipment maintenance technology.

The state evaluation of relay protection can quantify the state information of relay protection according to the relay protection operating conditions, state detection data, defect information, fault and
accident information, maintenance records and other comprehensive status information. Therefore, the current real state of the evaluation device is judged, and a decision basis is provided for the state maintenance.

Therefore, this paper proposes the state evaluation of relay protection system for state maintenance. Firstly, with the relay protection system with complete protection function as the object, focusing on the actual operating environment of relay protection such as temperature and humidity, the state evaluation index system of relay protection system is constructed. Secondly, establish a review set of the operating state of the relay protection system and determine the membership function of each evaluation factor. Thirdly, determine the weight distribution of evaluation indicators at all levels based on fuzzy analytic hierarchy process. On this basis, carry out fuzzy comprehensive evaluation based on membership function of various evaluation factors and weight distribution and obtain state scores. Finally, the state maintenance strategy is developed based on the evaluation results.

2. Relay protection system status evaluation index system
When analyzing the running state of the equipment, it is not only necessary to evaluate the state of the relay protection according to the equipment operation and maintenance data before the moment, and the familial data of the same type of equipment, but also necessary to evaluate the state of the relay protection according to the current environmental state of the equipment. According to the above analysis, based on the actual influencing factors in the operation of relay protection system and the protection system structure, this paper analyzes the dynamic time-varying environmental influencing factors of the protection system from the protection device, secondary circuit and communication channel, and establishes its state evaluation index system as shown in figure 1.

![Figure 1. State evaluation factor set of protection system](image-url)
3. Establishment of state evaluation model for relay protection system

3.1 Establishment of the comment set and determination of the membership function

In this paper, the operating state of the relay protection system is divided into four levels, namely normal state, attention state, abnormal state and severe state. So a comment set is established $V = \{v_1, v_2, v_3, v_4\}$, in which, $v_1$ represents the normal state, $v_2$ represents the state of attention, $v_3$ represents the abnormal state, $v_4$ represents the serious state [10-13].

According to the evaluation index of protection system, combined with the experience of relevant experts, the fuzzy distribution method is used to establish the membership function of each evaluation index. By analysing the variation rules of the 16 two-level indicators listed in figure 1, the three-level indicators can be divided into three categories to discuss the establishment of their membership functions [14-16].

(1) The first category is the evaluation factor that the evaluation indexes present approximately linear and decreasing regular changes with the equipment operating state. This kind of evaluation factors include environment temperature, relative humidity, infrared temperature of the loop, the corrosion of the cable holder of the terminal block, and the communication status of the fiber channel, the operation of the channel, the check condition of differential current. Here, infrared temperature of the loop refers to the difference between measured temperature and environment temperature, that is, $(\Delta T_{\text{infrared}} = T_{\text{infrared}} - T_{\text{environment}})$. This kind of data can directly establish its evaluation function according to the evaluation index. Based on its linear characteristics, the intermediate trapezoidal distribution or small semi-trapezoidal distribution or large trapezoidal distribution can be used as the distribution function of health degree. It is shown as follows:

Small semi-trapezoidal distribution:

$$A(x) = \begin{cases} 
1 & x \leq a_1 \\
\frac{a_2 - x}{a_2 - a_1} & a_1 < x \leq a_2 \\
0 & x > a_2 
\end{cases}$$ (1)

Large semi-trapezoidal distribution:

$$A(x) = \begin{cases} 
0 & x \leq a_1 \\
\frac{x - a_1}{a_2 - a_1} & a_1 < x \leq a_2 \\
1 & x > a_2 
\end{cases}$$ (2)

Intermediate trapezoidal distribution:

$$A(x) = \begin{cases} 
0 & x \leq a_1 \\
\frac{x - a_1}{a_2 - a_1} & a_1 < x \leq a_2 \\
1 & a_2 < x \leq a_3 \\
\frac{a_4 - x}{a_4 - a_3} & a_3 < x \leq a_4 \\
0 & x > a_4 
\end{cases}$$ (3)

(2) The second type of factors mainly include: temperature rise data, operating life data, and insulation resistance measurement results. These evaluation factors are evaluation factors that need to be properly processed to be applied. It mainly approximates the linear relationship of monotonous decreasing.
a. The temperature rise data including the environment temperature of the device and the external temperature of the secondary circuit is converted as follows:

$$\Delta t = \frac{t_{\text{environment}} - t_0}{t_0}$$

Where \( t_{\text{environment}} \) is the current environment temperature and \( t_0 \) is the intermediate temperature of the normal temperature range.

b. Processing of age data: this type of data includes the operating age of the device and the operating age of the power plug-in. In order to make this kind of data conform to the trend of bathtub curve of power equipment aging rule, the operating age \( Y_{\text{actual}} \) is transformed as follows:

$$Y = \left( \frac{Y_{\text{actual}}}{Y_0} \right)^2$$

Where \( Y_0 \) is the specified age of use.

c. Processing of insulation resistance measurement value: because the insulation resistance measurement value of the circuit is larger than the specified value, the better, so the insulation resistance value shows a monotonically increasing trend with the loop state. In order to make it follow the same distribution as other linear variation evaluation factors, the measurement resistance is transformed as follows:

$$\Delta t = \frac{t_{\text{io}} - t_{\text{measure}}}{t_{\text{i}}_0}$$

Among them, \( t_{\text{measure}} \) is the measured value of the loop insulation resistance, and \( t_{\text{i}}_0 \) is the specified value of the insulation resistance.

After being processed by the above three methods, the second type of factors approximately obey the monotonically decreasing linear distribution law. Therefore, as with the first type of data, an intermediate trapezoidal distribution or a small semi-trapezoidal distribution or a large trapezoidal distribution may be used as the distribution function of health degree.

(3) The third type of data is time-type data. Including the implementation of anti-accident measure of the protection device, the implementation of anti-accident measure of the loop, the loop fault condition, the plugging condition, the rust condition, the inspection overdue period and so on. Since this kind of data show a single point distribution, and there are obvious differences in the influence degree between adjacent two points on the equipment state. Therefore, small normal distribution or large normal distribution or intermediate normal distribution is adopted as the distribution function of such data.

Small normal distribution:

$$A(x) = \begin{cases} 1 & x \leq a \\ e^{-\frac{(x-a)^2}{\sigma}} & x > a \end{cases}$$

Large normal distribution:

$$A(x) = \begin{cases} 0 & x \leq a \\ 1 - e^{-\frac{(x-a)^2}{\sigma}} & x > a \end{cases}$$

Intermediate normal distribution:

$$A(x) = e^{-\frac{(x-a)^2}{\sigma}}$$
Through the above analysis, the membership function of each influencing factor is established. According to the measured values of the indicators of different influencing factors and through processing the data, the fuzzy relation matrix R of the evaluation factors of each level is calculated on the basis of the membership function formula of each factor.

Determine state and experience information by the protection system instructions. The evaluation criteria for the evaluation factors of the protection system are shown in table 1.

**Table 1. Evaluation standard of each protection system evaluation factor**

| First-order evaluation index | Second-order evaluation index | Measurement | Rated state | online | Offline |
|-----------------------------|-------------------------------|-------------|-------------|--------|---------|
| Environment temperature     | Environment temperature T     | $5^\circ C \leq T \leq 40^\circ C$ | $T = 45^\circ C$ | $T = -5^\circ C$ |        |
| Relative humidity           | Relative humidity S           | $0\% \leq S \leq 75\%$ | $S = 95\%$ | $S = 0\%$ |        |
| Insulation condition        | Insulation resistance value R | $R > 10$ | $\infty$ | $R = 1$ |        |
| Implementation of countermeasures | No anti-measurement F | $F = 0$ | $F = 10$ | -- |        |
| Fixed inspection period     | Check the expiration date Y   | $Y = 0$ | $Y = 5$ | -- |        |

| Environment temperature     | Terminal box, terminal block, cable holder | $k \leq 5\%$ | $k \leq 15\%$ | -- |        |
| Corrosion                   | Uncompleted fire               |               |               |        |        |
| Plugging condition          | blocking and fire prevention measures | $n < 1$ | $n = 1$ |        |        |
| Implementation of countermeasures | No anti-measurement F | $F = 0$ | $F = 10$ | -- |        |
### 3.2 Weight assignment based on fuzzy analytic hierarchy process

It can be known from the relay protection state evaluation index system that the state evaluation factors of relay protection are first divided into three parts: protection device body, secondary circuit and communication channel. And the state evaluation factors under each part are established respectively. This classification method can not only realize the comprehensive evaluation of the operation state of the protection system based on dynamic time-varying factors, but also judge the operation state of different links of the protection system based on dynamic time-varying factors, which helps to determine the maintenance scope lays a foundation for maintenance decision.

The influence of each dynamic time-varying factor on the system is different. This paper establishes the weight distribution of each influencing factor based on fuzzy analytic hierarchy process. The steps are as follows:

1. Using the 0.1~0.9 scale method (as shown in table 2), the fuzzy complementary judgment matrix is established through comparing the importance of each evaluation factor by pairwise comparison [1]:

\[
R = \begin{bmatrix}
    r_{11} & r_{12} & L & r_{1n} \\
    r_{21} & r_{22} & L & r_{2n} \\
    L & L & L & L \\
    r_{n1} & r_{n2} & L & r_{nn}
\end{bmatrix}
\]  

(10)
Table 2. Evaluation standard of 0.1~0.9 scaling method

| Scaling | definition | Description |
|---------|------------|-------------|
| 0.5     | Equally important | Comparison of two elements is equally important |
| 0.6     | Slightly important | Comparison of two elements, one is slightly more important than the other |
| 0.7     | More important | Comparison of two elements, one is more important than the other |
| 0.8     | Super important | Comparison of two elements, one is super more important than the other |
| 0.9     | Extremely important | Comparison of two elements, one is extremely more important than the other |
| 0.1, 0.2 | Counter comparison | $a_i$ compares with $a_j$ gets $r_{ij}$, $a_j$ compares with $a_i$ gets $r_{ji} = 1 - r_{ij}$ |
| 0.3, 0.4 | Counter comparison | $a_i$ compares with $a_j$ gets $r_{ij}$, $a_j$ compares with $a_i$ gets $r_{ji} = 1 - r_{ij}$ |

(2) Construct fuzzy consistency matrix

One-sidedness based on human thinking may make the constructed fuzzy complementary judgment matrix not consistent. Therefore, the necessary and sufficient conditions of fuzzy consistency matrix are used for the consistency decision making and adjustment of fuzzy complementary judgment matrix. The adjustment method is: choose the one that is most certain compared to the others, such as the factor $a_i$, then subtract each element of the i-th row in the R matrix from the corresponding element of the other row. For example, the determination of the factor $a_j$. Subtract each element of the i-th row in R from the element corresponding to the j-th row. If the differences are equal, the j-th row elements are consistent, and if they are not equal, the elements in the j-row are adjusted until they are equal.

(3) Obtain the weight of each factor using the fuzzy consistency matrix

The fuzzy consistency matrix has the following relationship with the weight value:

$$w_i = \frac{1}{n} - \frac{1}{2a} + \frac{1}{na} \sum_{k=1}^{a} r_{ik}, i \in \{1, 2, L, n\}$$

In the formula, $w_i$ represents the weight value of factor $a_i$, $n$ is the number of evaluation factors, $a$ is the adjustment parameter, and $a \geq (n-1)/2$. When $a$ is larger, the difference between the weight values is smaller, so $a \geq (n-1)/2$ is taken in this paper.

The weight distribution between the protection device, the secondary circuit and the channel state can be obtained.

$$W = [0.5, 0.3, 0.2]$$

The weight distribution of the influencing factors of the protection device is:

$$W_A = [0.155, 0.18, 0.305, 0.255, 0.105]$$

The weight distribution of the influencing factors of the secondary loop is:

$$W_B = [0.11, 0.13, 0.17, 0.14, 0.12, 0.08, 0.17, 0.08]$$

The weight distribution of the influencing factors of the communication channel is:

$$W_C = [0.333, 0.233, 0.433]$$

3.3 Fuzzy comprehensive evaluation

In this paper, the influencing factors of relay protection are divided into two layers, so a two-level fuzzy evaluation model is formed. Firstly, fuzzy comprehensive evaluation is applied to the second-level influencing factors. In order to fully measure the contribution of each influencing factor to the state of relay protection, the weighted average operator is used for fuzzy calculation.

Taking the evaluation factor set A as an example, A contains five evaluation factors. According to
the analysis in Section 3.2, the weight distribution $W_A$ among the evaluation factors in the evaluation factor set $A$ is determined. And the fuzzy relation matrix $R_A$ is obtained by the membership function established in Section 3.1. Then the first-level comprehensive evaluation result calculated by using the weighted average operator $M(g^+)$ is:

$$B_A = W_A \cdot R_A$$

(16)

In the same way, the first-level comprehensive evaluation results $B_B$ and $B_C$ corresponding to the evaluation factor sets $B$ and $C$ are obtained.

Finally, the second-level comprehensive evaluation result vector $B$ is obtained by the weighted average operator. And the current operating environment state of the relay protection device is judged according to the maximum membership principle.

### 3.4 Acquisition of state scores

Based on the method proposed in this paper, the reliability of the relay protection system is evaluated, and the probability that the relay protection system belongs to each evaluation level can be obtained. According to the maximum membership principle of the fuzzy theory, the corresponding maximum probability value is the current operating state of the relay protection system. The result of relay protection state evaluation based on fuzzy comprehensive evaluation is a probability value. To quantify the result to a score of 0–100, the scoring standard established by analyzing the relationship between the set of evaluation factors and the state score $H$ of the relay protection system is as shown in table 3:

| Status level          | normal status | Attention status | Abnormal state | Severe state |
|-----------------------|---------------|------------------|----------------|--------------|
| Status rating $H$     | $\geq 90$     | $90~76$          | $76~50$        | $\leq 50$    |

According to the classification method of the protection system health state score shown in table 3, the conversion method between the result vector $b_i$ and the state score $H$ of the fuzzy comprehensive evaluation is established:

1. When the fuzzy comprehensive evaluation result is normal:
   $$H = 90 + b_i \times 10$$

2. When the fuzzy comprehensive evaluation result is the attention state or abnormal state:
   $$H = \begin{cases} 
   H_{mi} + b_i \times \frac{(H_{max,i} - H_{min,i})}{2}, & |b_i - b_{i-1}| \geq |b_i - b_{i+1}| \\
   H_{mi} - b_i \times \frac{(H_{max,i} - H_{min,i})}{2}, & |b_i - b_{i-1}| < |b_i - b_{i+1}| 
   \end{cases}$$

(18)

Where $i=2,3$

Here, $i$ represents the state level, 2 is the attention state, 3 is the abnormal state; $H_{mi}$ is the median score of state $i$, $H_{max,i}$ and $H_{min,i}$ respectively represent the upper and lower limits of the state score, and $b_i$ is the fuzzy comprehensive evaluation result.

3. When the fuzzy comprehensive evaluation result is severe:
   $$H = 50 - b_i \times 50$$

(19)

### 4. Maintenance decision making based on state evaluation

Maintenance decision of relay protection system refers to the overall arrangement and maintenance decision optimization of all protection in the network at the whole system level, taking into account the reliability of software and hardware, current operation state and coordination relationship between protection. The emphasis of maintenance decision is to arrange whether the equipment needs
maintenance, the protection maintenance time, the protection maintenance content according to the results of state assessment.

(1) Decision on whether the protection system needs to be repaired

Whether the protection system needs to be repaired is determined by the state of the equipment. The state evaluation result of the protection directly reflects the state of protection. In this paper, the protection state score indicator \( H \) is used as a quantitative evaluation indicator for maintenance decision based on state assessment. According to the different maintenance methods, two maintenance thresholds are set for the protection system state score, which are \( P_{\text{max}} \) and \( P_{\text{min}} \) \( (P_{\text{max}} > P_{\text{min}}) \) respectively. The decision-making method for whether the protection system is repaired is:

- If the protection system state score is \( P > P_{\text{max}} \), the protection system is operating normally. And the system is routinely scheduled for maintenance, no maintenance is required.
- If the protection system status scores \( P_{\text{min}} < P < P_{\text{max}} \), it indicates that the protection system has a large probability of failure. The protection system must be repaired. But it is not very serious. Therefore, the protection is minorly repaired. Some unnecessary maintenance procedures are simplified. Work efficiency is improved and work time is saved.
- If the protection system state score \( P < P_{\text{min}} \), it indicates that the protection system has serious problems. It is necessary to carry out thorough maintenance of the relay protection system, which is called overhaul.

(2) Decision on protection order

The benefit of state maintenance of protection system is reflected in the reduction of failure efficiency of protection system. Therefore, when making maintenance order, the relay protection with low state score should be carried out first, while the relay protection with high state score should be carried out later. So that the maintenance can improve the system reliability the most. Secondly, when the state scores are similar, the higher the failure risk of the protected equipment, the more important the reliability of the protected system is. In order to ensure the stable operation of the power grid to the greatest extent, the higher failure risk of protected equipment should be given priority to repair. Therefore, this paper uses the level of state scoring and the risk of the failure of the protected equipment as the decision variable for the order of protection and maintenance.

5. Case analysis

Based on the evaluation model of the fuzzy comprehensive evaluation method proposed in this paper, combined with the real-time influencing factors of the actual measurement obtained by the power supply company, the weight and membership degree of influence factors are shown in table 4.

| First-order evaluation index | First-order weight | Second-order evaluation | Second-order weight | normal | note | abnormal | serious |
|-----------------------------|-------------------|------------------------|-------------------|--------|------|----------|--------|
| Protective device           | 0.5               | Environment temperature| 0.155             | 0.95   | 0.05 | 0        | 0      |
|                             |                   | Relative humidity      | 0.180             | 0.98   | 0.02 | 0        | 0      |
|                             |                   | Insulation condition   | 0.305             | 0.95   | 0.03 | 0.02     | 0      |
|                             |                   | Implementation of      | 0.255             | 0.90   | 0.07 | 0.03     | 0      |
|                             |                   | countermeasures        |                   |        |      |          |        |
|                             |                   | Overdue period of      | 0.105             | 0.99   | 0.01 | 0        | 0      |
|                             |                   | regular                |                   |        |      |          |        |
Based on the weight of each influencing factor and the membership degree of the second-level influencing factors, the fuzzy comprehensive evaluation method is used to judge the state of the first-level influencing factors.

\[
B_A = \begin{bmatrix} 0.94685 & 0.03940 & 0.01375 & 0.0 \\
\end{bmatrix}, \quad (20)
\]

\[
B_B = \begin{bmatrix} 0.9342 & 0.0507 & 0.0151 & 0.0 \\
\end{bmatrix}, \quad (21)
\]

\[
B_C = \begin{bmatrix} 0.90742 & 0.0716 & 0.01998 & 0.0 \\
\end{bmatrix}, \quad (22)
\]

According to the relay protection device, secondary circuit and communication channel state evaluation result vector \( B_A, B_B, B_C \), combined with the relay protection state level classification of Table 3, it can be known from the principle of maximum membership that the relay protection device body, secondary circuit and communication channels are all in a normal state. As can be seen from Section 3.4, when the device is in a normal state, the health score is obtained as

\[
H = 90 + b \times 10 \quad (23)
\]

Relay protection device, secondary circuit, and communication channel scores can be obtained \( H_A=99.4685, H_B=99.342, \) and \( H_C=99.0742 \) respectively.

Assume that the state maintenance threshold has been determined by historical maintenance record and maintenance inspection, \( P_{\text{min}} = 0.94, P_{\text{max}} = 0.98 \). According to the state evaluation results, the protection system relay protection device, secondary circuit and communication channel are all in normal operation state. No maintenance needs to be arranged.
6. Conclusion
Taking the relay protection system with complete protection function as the object, and considering the
influence of the actual operating environment of relay protection, such as temperature and humidity on
the protection reliability, this paper evaluates the reliable state of relay protection system. The state
assessment method used in this paper can identify the fault that relay protection already exists or is
occurring or potential equipment performance degradation, make judgments on the fault location, fault
severity and fault development trend and determine the best maintenance time. And then maintaining or
restoring the inherent reliability level of the protection system with minimal cost through inspection,
maintenance, repair or renewal of the protection system. This is of great significance for strengthening
the reliability and operation level of the relay protection system and ensuring the safe operation of the
power grid.

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