Relay Protection State Evaluation of Smart Substation Based on Fuzzy Comprehensive Evaluation and Improved D-S Theory

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To make an accurate evaluation for relay protection state of smart substation under more and more operation information, a twice modeling evaluation method is presented about relay protection state. Characteristic indexes system of relay protection device is built and expected values of various characteristic indexes and state classification of device are given by this method. Considering fuzziness of various factors for evaluation result, fuzzy comprehensive evaluation is utilized to established elementary evaluation model by studying membership functions and determination methods of weighting factors of different type data. By introducing improved D-S theory, the framework of information fusion evaluation about relay protection is studied, elementary evaluation results are further fused and evaluation model is once again built. Case study shows that this method can significantly distinguish the different states of relay protection, obtain specific evaluation conclusion, overcome evaluation result invalidations of traditional D-S theory under evidence conflict and avoid evaluation result uncertainties of different fuzzy comprehensive evaluation methods because of the lack of information.

Keywords: Smart Substation, Relay Protection, State Evaluation, Fuzzy Comprehensive Evaluation, Improved D-S Theory, Information fusion

1. Introduction

Owing to late development of smart substation in our country, study of relay protection state evaluation mostly focuses on traditional substation and appears a lot of evaluation methods, for example, fault tree analysis, Markova state-space method and fuzzy synthetic evaluation, et al [1-3]. So it is urgent tasks to make an accurate assessment for operating state of smart substation relay protection and timely find hidden dangers which can influence safe operation of whole substation. Reference [4] builds dynamic reliability model of repairable
redundant digital protection system based on dynamic fault tree and monte carlo simulation but this model can meet actual project application through a large number of systemic accumulation, analysis and excavation for reliably basic data of protection system. Reference [5] set up the relay protection state evaluation model based on the fuzzy comprehensive evaluation thoughts and carries out quantitative assessment based on online monitoring and record information of relay protection device but selective information is less and selects simpler fuzzy membership function which influences the accuracy of evaluation result.

In virtue of more and more operation information of smart substation and fuzziness of various factors for evaluation result, relay protection state is more difficult evaluated by single method so multi-information and Multi-evaluation methods are given in this paper. Under building assessment system of relay protection, fuzzy comprehensive evaluation that has advantages to quantize fuzzy information and D-S theory that has advantages to effectively dispose uncertain information are combing. Relay protection state is primarily evaluated by fuzzy comprehensive evaluation. In order to acquire more complete information, build decision-making evaluation and enhance precision of evaluation result, primarily evaluation result of relay protection is fused by improving D-S theory.

2. State Evaluation Index System of Relay Protection about Smart Substation

In order to roundly reflect real-time operation state of smart substation relay protection, real-time data and historical data of relay protection are classified as evaluation indexes in this paper and built evaluation system in figure 1.

Environmental temperature and humidity are collected through temperature and humidity controller of protection cell in figure 1 and remaining real-time data are collected through monitoring and analytical unit of reference [5]. All historical data are received through before and after operation. Considering expert opinions and operating experiences, relay protection states are divided into normality, attention and abnormity in this paper. Expectations of real-time data and historical data A are shown in table 1 and 2 [5,6] and memberships of historical data B are gained through fuzzy statistical method and expert investigation [7].
State evaluation indexes of relay protection

- Real-time data
- Historical data
  - A
  - B
  - Human error
  - Abnormal alarm events
  - Correct operating rate
  - Display screen luminance
  - Operation time
  - Channel condition
  - Perioidic inspection
  - Device defect condition
  - Power source voltage
  - Power source temperature
  - Environmental temperature
  - Environmental humidity
  - Power source voltage

Figure 1. The evaluation index system of relay protection based on smart substation.

Table 1. Expected value of real time data.

<table>
<thead>
<tr>
<th>State parameters</th>
<th>Assessment contents</th>
<th>Unit</th>
<th>Low limit</th>
<th>Good</th>
<th>Upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power source voltage</td>
<td>Monitoring value at a certain time</td>
<td>V</td>
<td>4.9</td>
<td>5</td>
<td>5.1</td>
</tr>
<tr>
<td>Power source temperature</td>
<td></td>
<td>℃</td>
<td>20</td>
<td>35</td>
<td>70</td>
</tr>
<tr>
<td>Environmental temperature</td>
<td></td>
<td>RH%</td>
<td>5</td>
<td>50</td>
<td>95</td>
</tr>
<tr>
<td>Environmental humidity</td>
<td></td>
<td>℃</td>
<td>-10</td>
<td>20</td>
<td>55</td>
</tr>
<tr>
<td>CPU temperature</td>
<td></td>
<td>℃</td>
<td>Determined by the specific model</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Light module intensity</td>
<td></td>
<td>dBm</td>
<td>-10</td>
<td>-20</td>
<td>-30</td>
</tr>
<tr>
<td>Display screen luminance</td>
<td></td>
<td>cd/m²</td>
<td>150</td>
<td>200</td>
<td>250</td>
</tr>
</tbody>
</table>

Table 2. Expected value of historical data A.

<table>
<thead>
<tr>
<th>State parameter</th>
<th>Assessment contents</th>
<th>Unit</th>
<th>Low limit</th>
<th>Good</th>
<th>Upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Periodical inspection</td>
<td>From the last scheduled inspection</td>
<td>Times per year</td>
<td>2</td>
<td>2.5</td>
<td>3</td>
</tr>
<tr>
<td>Channel condition</td>
<td>Alarm times</td>
<td>Times per year</td>
<td>0</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Operation time</td>
<td>Operation time</td>
<td>year</td>
<td>5</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>Put into operation and test</td>
<td>Missing category</td>
<td>Category</td>
<td>1</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Device defect condition</td>
<td>Defect times</td>
<td>Times per year</td>
<td>1</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>
3. State Evaluation Model based on Fuzzy Comprehensive Evaluation

3.1 Confirmation of Membership Functions

According to evaluation index system that is built in this paper, all kinds of indexes those reflect operation states of devices component factor assemblage \( u = \{u_i, u_2, \ldots, u_n\} \) and form comment \( v = \{v_1, v_2, v_3\} = \{\text{normality, attention, abnormality}\} \). Factor \( u_i \) is evaluated and membership of \( v_j (j = 1, 2, 3) \) is \( r_{ij} \) that is obtained through membership function so single factor evaluation assemblage of \( u_i \) is \( r_i = (r_{i1}, r_{i2}, r_{i3}) \) that is fuzzy sub aggregate of \( v \).

Membership functions usually has trapezoidal distribution, triangular distribution and normal distribution and so on [8]. Triangular membership function has simple form and obtains lesser distinction with other complicated membership functions so triangular function and semi-trapezoid function are combined in this paper to confirm memberships of each factor about real-time data. Membership of historical data \( A \) is confirmed through fuzzy normal distribution of reference [6].

Relative deterioration rate can reflect relative degree of virtual condition and fault condition so distribution function of corresponding triangular and semi-trapezoid and fuzzy boundary interval of various states are built through expert experiences in this paper which is shown in figure 2.

![Figure 2. Computational mode of membership about fuzzy triangle and semi-trapezoid.](image)

Membership of every factor is obtained through method of relative deterioration rate that is confirmed in reference [5].

3.2 Confirmation of Evaluation Factor Weight

Analytic hierarchy process is multi-objective decision method of identification and quantification and has the advantages to qualify non-quantitative incidents
[9] so judgment matrix \( N \) of every factor is established through this method in this paper. Through computing, eigenvector of matrix \( N \) maximum eigenvalue is \( a = (a_1, a_2, \cdots, a_n) \) \( \sum_i a_i = 1 \) that is the weight of every evaluation factor.

3.3 Establishment of Evaluation Model

Assuming membership assemblage of factor \( u_i \) is \( r = \{r_1, r_2, r_3\} \), membership assemblages of all factors are \( R = \{r_1, r_2, \cdots, r_n\} \). In order to hold all useful information, fuzzy compositional operation of weighted average is selected so fuzzy comprehensive evaluation model is obtained through \( R \) and \( a \) in formula (1).

\[
b = a \odot R = \{b_1, b_2, b_3\}
\]  

\( \odot \) is broad sense fuzzy operational symbol.

4. D-S Theory and Its Improvement

Dempster-Shafer theory that is called D-S evidence theory which has the advantages of random process and epistemic uncertainty so D-S theory is increasingly valued by experts and scholars [10, 11].

4.1 Basic Definition

Definition 1: Supposing \( \Theta \) is frame of Discernment and \( 2^\Theta \) is power set of \( \Theta \). If function \( m \) accord with \( 2^\Theta \to [0, 1] \), \( m(\emptyset) = 0 \) and \( \sum_{A \subseteq \Theta} m(A) = 1 \) \( m \) is called basic credit assignment of \( \Theta \). Supposing \( \forall A \subseteq \Theta \) and \( m(A) > 0 \), \( m(A) \) is basic reliability value of \( A \) that is focal element of evidence and is expresses levels of trust for \( A \).

Definition 2: If \( m \) is basic credit assignment of \( \Theta \) function \( Bel \) is defined through \( Bel(A) = \sum_{B \subseteq A} m(B) \) \( \forall A \subseteq \Theta \) and \( 2^\Theta \to [0, 1] \) is credit function of \( \Theta \).

4.2 Composition Rule of Dempster about D-S

Supposing \( Bel, Bel, \cdots, Bel \) those correspond to basic credit assignment \( m_1, m_2, \cdots, m_n \) are credits functions of independent evidences about \( \Theta \) and relevant focal elements are \( A_{11}, A_{12}, \cdots, A_{ij} (i = 1, 2, \cdots, n; j = 1, 2, \cdots, m) \) so final credit assignment is shown in formula (2).
4.3 Improved D-S Theory

Dempster composition rule can obtain better fusion effect for lesser confliction of all evidences but traditional D-S theory can appear fusion failure because of seriously conflicting evidences [12]. Considering evidence confliction and differently important degree in the process of evidence composition, weight coefficient that is described important degree of evidence is introduced in this paper to composite various data.

Supposing frame of discernment is $\Theta = \{A_1, A_2, \ldots, A_n\}$ and basic credit assignment matrix of relevant evidence is shown in formula (3):

$$
Y = \begin{bmatrix}
m_1(A_1) & m_1(A_2) & \cdots & m_1(A_n) \\
m_2(A_1) & m_2(A_2) & \cdots & m_2(A_n) \\
\vdots & \vdots & \ddots & \vdots \\
m_n(A_1) & m_n(A_2) & \cdots & m_n(A_n)
\end{bmatrix}
$$

Basic credit assignment average value $\overline{y}_i$ and standard deviation $s_i$ of each evidence in matrix $Y$ are obtained through formula (4) and (5).

$$
\overline{y}_i = \frac{1}{n} \sum_{j=1}^{n} m_j(A_i)
$$

$$
s_i = \sqrt{\frac{1}{n} \sum_{j=1}^{n} (m_j(A_i) - \overline{y}_i)^2}
$$

Because index weight can be confirm by variation degree of evaluated object index based on variation coefficient method that can realize dynamic weighting of evaluated object index $W_i$ is computed by average value and standard deviation in formula (6).
The weight of number 1 evidence is 

\[ \beta_i = \frac{W_i}{\sum_{i=1}^{n} W_i} \]

(6)

that is obtained through coefficient \( W_i \) so weight vector of all evidences is \( \beta = [\beta_1, \beta_2, \ldots, \beta_n] \) and number 1 basic credit assignment function of \( A_j \) is \( \beta_i m_i(A_j) \). If evidence of maximum credit is believed the first evidence that is 1 about weight and evidence weight of other evidence is \( \alpha_i \), that is compared with the first evidence. Supposing number x evidence is the first evidence so evidence elementary probability assignment of number j subordinate evidence is computed in formula (7):

\[
\begin{align*}
    m'_i(A_j) &= \alpha_i m_i(A_j) \\
    m'_i(\Theta) &= \alpha_i m_i(\Theta) + (1 - \alpha_i) \quad i \neq x
\end{align*}
\]

(7)

\( m_i() \) and \( m'_i() \) are probability distribution of before and after conversion.

Every evidence has equal evidence weight through before and after conversion so final fusion is obtained by D-S theory.

5. Evaluation Framework of Information Fusion based on Fuzzy Comprehensive Evaluation and Improved D-S Theory

Owing to changeability of relay protection index information and advantages of D-S theory, improved D-S theory is adopted in this paper to fuse and reevaluate fuzzy comprehensive evaluation results of different index data to take full advantage of the advantages of different methods, overcome roundedness of single method, select state of most elementary probability as final evaluation result and realize exact evaluation of relay protection. Whole evaluation framework of information fusion is shown in figure 3.

![Figure 3. Evaluation framework of information fusion about relay protection.](image_url)
6. Instance Analysis

Operational relay protection devices of smart substation are selected and evaluated through above-methods in this paper. Owing to length of this paper, data of 2 devices are shown in table 3.

<table>
<thead>
<tr>
<th>Information classification</th>
<th>Name of factors</th>
<th>Unit</th>
<th>Actual values of device 1</th>
<th>Actual values of device 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real-time data</td>
<td>Power source voltage</td>
<td>V</td>
<td>4.95</td>
<td>4.971</td>
</tr>
<tr>
<td></td>
<td>Power source temperature</td>
<td>℃</td>
<td>60</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Environmental temperature</td>
<td>RHP%</td>
<td>63%</td>
<td>55%</td>
</tr>
<tr>
<td></td>
<td>Environmental humidity</td>
<td>℃</td>
<td>32</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>CPU temperature</td>
<td>℃</td>
<td>68</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>Light module intensity</td>
<td>dBm</td>
<td>-18.6</td>
<td>-23.5</td>
</tr>
<tr>
<td></td>
<td>Display screen luminance</td>
<td>cd/m2</td>
<td>185</td>
<td>210</td>
</tr>
<tr>
<td>Historical data A</td>
<td>Periodical inspection</td>
<td>Times per year</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Channel condition</td>
<td>Times per year</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Operation time</td>
<td>Year</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Put into operation and test</td>
<td>Category</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Device defect condition</td>
<td>Times per year</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Historical data B</td>
<td>Correct operating rate</td>
<td></td>
<td>93%</td>
<td>89%</td>
</tr>
<tr>
<td></td>
<td>Abnormal alarm events</td>
<td>Times per year</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Human errors</td>
<td>Class</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Hidden failures</td>
<td>Class</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Firstly, feature vectors of data maximum eigenvalue of device 1 are calculated in table 3 and each factor weight is normalized those are \( a_1=(0.219,0.092,0.047,0.047,0.129,0.338,0.12), a_2=(0.088,0.330,0.171,0.318,0.093), a_3=(0.520,0.251,0.114,0.115) \) so each factor weight of device 2 can be acquire by above-method.

Secondly, \( a_1, a_2 \) and \( a_3 \) are fuzzily computed with membership values of real-time data, historical data A and historical data B of table 3 through fuzzy comprehensive evaluation and final evaluation result that is shown in table 4 is obtained through normalizing operation results.
Table 4. Computation results of fuzzy comprehensive judgment.

<table>
<thead>
<tr>
<th>Data classification</th>
<th>Membership confirmation method</th>
<th>Device 1 membership</th>
<th>Device 2 membership</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Normality</td>
<td>Attention</td>
</tr>
<tr>
<td>Real-time data</td>
<td>Fuzzy trapezoidal and triangle distribution</td>
<td>0.68</td>
<td>0.228</td>
</tr>
<tr>
<td>Historical data A</td>
<td>Fuzzy normal distribution</td>
<td>0.296</td>
<td>0.581</td>
</tr>
<tr>
<td>Historical data B</td>
<td>Fuzzy experimental approach</td>
<td>0.536</td>
<td>0.414</td>
</tr>
</tbody>
</table>

Finally, membership values of table 4 are fused through traditional D-S theory and its improved method and state of maximal evaluation value is confirmed as final evaluation result which is shown in table 5.

Table 5. Traditional D-S theory and its improved evaluation results.

<table>
<thead>
<tr>
<th>Name</th>
<th>Traditional D-S theory</th>
<th>Improved D-S theory</th>
<th>Final evaluation results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normality</td>
<td>Attention</td>
<td>Abnormality</td>
</tr>
<tr>
<td>Device 1</td>
<td>0.661</td>
<td>0.336</td>
<td>0.003</td>
</tr>
<tr>
<td>Device 2</td>
<td>0.20818</td>
<td>0.38963</td>
<td>0.40219</td>
</tr>
</tbody>
</table>

According to table 5, improved D-S theory can remarkably evaluate and distinguish state of device and enhance identification ability for evaluation results, especially when evidence conflicts in device 2. At the same time, limitation of inconsistent results that is caused by different evaluation methods in table 4 is overcome by improved D-S theory because of imperfect information. Evaluation results of the rest devices those correspond to actual conditions are obtained through the same method.

7. Conclusions

Case study shows that the method which is raised in this paper can significantly distinguish the different states of relay protection, obtain specific evaluation conclusion, and overcome evaluation result invalidations of traditional D-S theory under evidence conflict.

This method can avoid evaluation result uncertainties of different fuzzy comprehensive evaluation methods because of the lack of information.
New ideas are provided to exactly evaluate relay protection state through utilizing advantages of different evaluation methods and conditions of conflicting evidences.

The evaluation result can give guidance to master state of every protection device, reasonably formulate repair schedules and realize condition-based maintenance for operation maintenance personnel.

References


