Bidirectional Weighing Fuzzy State Assessment on the Fusion Pole-Mounted Switch of Primary and Secondary

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Abstract. Cyber physical fusion enhances the coupling effect and influence of primary and secondary equipment in distribution network. In order to reflect the overall operating state of pole-mounted switch, this paper proposes the secondary equipment state indexes and other indexes, based on the current on-line monitoring index system. Then with fuzzy comprehensive evaluation and bidirectional weighing method, the result of condition assessment can be obtained. When determining weight, the deterioration of data taken from a certain single equipment in a certain period of time is analyzed by the entropy weight method, which highlights the index with obvious deterioration of specific equipment at specific stages. Moreover, the data deterioration weights are combined with the index importance weights. Finally, the accuracy of the condition assessment method is verified in the calculation of a specific example.

Introduction

The pole-mounted switch is an essential equipment in power distribution automation system, whose intelligence level directly relates to that of distribution network[11]. However, its secondary equipment is separated from primary switch, which restricts the development of power distribution automation. Recently, the energy internet[2] based on cyber physical fusion[3,4] has contributed to the integration of distribution equipment. For the improvement of pole-mounted switch in safety, intelligence and interconnection, many institutions are carrying out the research on its primary and secondary fusion.

Each parts of the traditional pole-mounted switch, such as switch itself, controller and some other, are relatively independent. Then, the lack of means to monitor its controller state makes it difficult to carry out its state evaluation. So mostly existing state evaluation researchers focus on the switch itself without consideration of the controller's state, like literature [5]. With the development of smart grid, its physical system and cyber system turn to fusion, promoting the integration of secondary device into primary switch[6,7], making their interaction stronger and stronger. However, the existing state evaluation methods can’t evaluate the state of pole-mounted switch thoroughly, which, therefore, is necessary.

As for assessment methods, many studies, such as literature [8, 9], determine the index weights based on the failure rate. If in the case of insufficient data, this way is of little significance. Even if the amount of data is large enough, the weights obtained are universal, which cannot highlight the abnormal state indicators of certain equipment in a certain period. Therefore, there is a problem of low sensitivity to deterioration of indexes with low failure rate. To solve it, variable weight based on entropy weight method can dynamically adjust the index weights with the increase of the running time of the equipment.

In view of this, this paper expands the existing pole-mounted switch index system. Then, based on the fuzzy mathematics theory and bidirectional weighing method, puts forward bidirectional weighing fuzzy state assessment on the fusion pole-mounted switch of primary and secondary.
Construction of State Index System

Switch State Indexes

There have been many researches on the state indexes of switch itself. By reference \[9, 10\], this paper chooses four online monitoring indexes as follows: vacuum(V), relative wear degree of contact(CW), contact temperature(CT) and vibration signal(VS).

Secondary Equipment Online Monitoring Indexes

The pole-mounted switch runs in harsh outdoor environment. However, the second equipment with many electronic components, requires so high operating environment that it is easy to break down. According to statistics, among the reasons of distribution secondary equipment faults, battery failure accounts for more than 50\% [11]. Others include wireless communication failure and distribution terminal failure, whose reasons are more complex, such as condensation, short circuit, and so on.

It was difficult to carry out on-line monitoring for the pole-mounted switch secondary equipment before. But as microcomputer monitoring and communication technology develop, online monitoring methods\[7,11\] of secondary equipment has been enriched.

Thus, this paper proposes some online monitoring indexes of secondary part as follows:

1. Battery state-of-health(SOH): SOH can be characterized by the ratio $\varepsilon$ between the actual capacity and rated capacity of the battery:

$$\varepsilon = \frac{S}{S_N} \times 100\%$$  \hspace{1cm} (1)

In Eq. 1, $S$ is the actual capacity of the battery, Ah; $S_N$ is the rated capacity of the battery, Ah.

2. Communication channel state(CCS): CCS can be measured by the terminal online rate $\rho$:

$$\rho = \frac{\Delta T}{T} \times 100\%$$  \hspace{1cm} (2)

In Eq. 2, $\Delta T$ is total abnormal time of terminal, s; $T$ is the total running time since last overhaul, s.

3. Controller temperature(CtrlT): to monitor the overheating of the controller.

4. Controller humidity(CtrlH): to monitor the condensation of equipment.

5. Abnormal frequency of self-test(AFST): FTU can realize a variety of self-test functions. Therefore, self-test’s abnormal frequency is of high importance to characterize the running state of secondary part.

Other State Indexes

Besides the above operating state indicators, some other indicators can also reflect the state evolution trend of switches to a certain extent, including environmental factors such as air temperature(AT), atmospheric humidity(AT), atmospheric pollution level(AP), and historical data such as cumulative number of interruptions (CNI) and the mean failure times (MFT).

Bidirectional Weighing Fuzzy State Assessment

The state of the fusion pole-mounted switch of primary and secondary cannot be described clearly. For this problem, the method of fuzzy comprehensive evaluation is very suitable.

How to determine index weights is one of the keys of fuzzy comprehensive evaluation. Generally speaking, when considering multiple indicators comprehensively, most of researches determine weights based on failure rate. However, the index deterioration of a certain device is a probabilistic event, and the sensitivity to identify the index deterioration with small weight will be greatly reduced through that way.

In order to solve this problem, this paper proposes a bidirectional weighing method to comprehensively consider the data deterioration weight and the index importance weight. As shown
in Figure 1, the operating time of switches is shown on the vertical axis while the indexes from different switches are shown on the horizontal axis. From the perspective of data, the changing trend of state data in these two directions reflect different information about switch. Longitudinal data reflect that the deterioration trends of different indexes at different stages are also different in a whole life of pole-mounted switch, while horizontal data reflect the index importance. The bidirectional weight determined on this basis, on the one hand, can avoid the problem of low sensitivity to identify the index deterioration with small weight when only considering the index failure rate; On the other hand, it can avoid the weight imbalance caused by only comparing deterioration trend of each index.

Fuzzy Comprehensive Evaluation

There are three elements in the fuzzy comprehensive evaluation:

(1) Factor set: a set composed of $n$ indexes, $U = \{u_1, u_2, \ldots, u_n\}$.

(2) Comment set: a set composed of $m$ comments on the switch state. Four comments are selected in this paper to form a comment set, $V = \{\text{normal}, \text{careful}, \text{abnormal}, \text{serious}\}$.

(3) Degree of membership: that is the degree of conformity between the comments and the actual state. According to the properties of the selected indexes, the membership function is calculated by the combination of semi-trapezoidal distribution and triangular distribution. Due to the large number of indexes and limitation of space, typical membership functions are shown as Figure 2.

Determination of Index Weights

Variable Data Deterioration Weights. Variable data deterioration weights are calculated by entropy-weighing method:

① Standardize data:

$$N_i = \frac{\max(u_i) - u_{ij}}{\max(u_i) - \min(u_i)} \quad (3)$$

In Eq. 3, $\max(u_i)$ and $\min(u_i)$ are the border point in the worst and the best range of index $u_i$ respectively.

② Calculate the entropy value $E_i$: 

Figure 1. Curves of pole-mounted switch state data over time.

Figure 2. Typical membership functions.
\[ E_i = \frac{1}{\ln k} \left( \sum_{j=1}^{k} H_{ij} \ln H_{ij} \right) \]  

(4)

In Eq. 4, \( k \) is the data amount of a single index; \( H_{ij} = N_{ij}/\sum_{i=1}^{n} N_{ii} \), define \( \lim_{H_{ii}\to0} (H_{ij} \ln H_{ij}) = 0 \) if \( H_{ij} = 0 \).

③ Calculate data deterioration weights:

\[ W'_i = \frac{(1 - E_i)}{(m - \sum_{i=1}^{m} E_i)} \]  

(5)

In Eq. 5, \( m \) is the number of indexes.

**Fixed Index Importance Weights.** As for index importance weights, this paper adopts analytic hierarchy process (AHP) to calculate:

1. Construct judgment matrices of switch, secondary equipment and other indexes:

\[
A_i = \begin{bmatrix}
1 & 2 & 3 & 1/2 \\
1/2 & 1 & 2 & 1/3 \\
1/3 & 1/2 & 1 & 1/4 \\
2 & 3 & 4 & 1 \\
\end{bmatrix}
\]

2. Conduct consistency checks and calculate the weights by reference [12]: \( W_1'' = [0.2772 0.1601 0.0954 0.4673], W_2'' = [0.2329 0.1486 0.0615 0.0615 0.4956], W_3'' = [0.0621 0.1029 0.0621 0.3106 0.4623]. \)

**Comprehensive Bidirectional Weights.** Based on the above results, calculate the comprehensive bidirectional weights \( w_i \):

\[
w_i = w'_i \cdot w'' = \left( \sum_{i=1}^{n} w'_i \cdot w'' \right)
\]

(6)

**Result Analysis**

Combining the membership matrix \( R \) and the comprehensive weight matrix \( W \), the final fuzzy evaluation results can be calculated as follows:

\[ B = W \circ R \]  

(7)

In Eq. 7, \( \circ \) is \( M(\cdot, \cdot) \), a fuzzy operator means multiply them and then take the maximums of each row.

**Example Verification**

Take a ZW20 type 10kV pole-mounted switch before maintenance as an example, to verify the state assessment method proposed in this paper. Its on-line monitoring indexes data are shown in table 1.

| Project  | The switch itself | The secondary part | Others |
|----------|------------------|--------------------|--------|
|          | V [mPa] | CW [%] | CT [℃] | VS | SOH [%] | CCS [%] | CtrlT [℃] | CtrlH [%] | AFST [l/month] | AT [℃] | AH [%] | AP [Lv.] | CNI | MFT [l/year] |
| Data 1   | 0.8    | 9      | 51     | 0.7 | 98     | 99.8   | 56      | 72      | 0          | 31    | 92     | 1      | 47   | 1        |
| Data 2   | 1.3    | 14     | 54     | 0.7 | 97     | 99.4   | 53      | 90      | 0          | 28    | 86     | 1      | 53   | 1        |
| Data 3   | 1.7    | 18     | 53     | 1.1 | 95     | 99.5   | 56      | 86      | 0          | 32    | 82     | 1      | 55   | 1        |
| Data 4   | 1.9    | 23     | 60     | 1.5 | 95     | 99.5   | 56      | 81      | 0          | 30    | 97     | 1      | 59   | 1        |
| Data 5   | 2.3    | 27     | 75     | 1.8 | 93     | 98.7   | 52      | 83      | 0          | 30    | 90     | 1      | 54   | 1.5      |

According to Table 1, calculate data deterioration weight matrices of switch, second part and other indexes are as follows: \( W_1' = [0.0450 0.1285 0.7272 0.0992], W_2' = [0.8007 0.1283 0.0038 0.0672 0], W_3' = [0.0031 0.9145 0 0.0490 0.0333], \) and comprehensive weight matrices are as
follows: \( W_1 = [0.0382 \quad 0.0628 \quad 0.7576 \quad 0.1414], W_\Pi = [0.8884 \quad 0.0908 \quad 0.0011 \quad 0.0197 \quad 0], W_m = [0.0043 \quad 0.7289 \quad 0 \quad 0.1325 \quad 0.1343]. \) And membership matrices are as follows:

\[
R_I = \begin{bmatrix}
0.7357 & 0.2643 & 0 & 0 \\
0.1500 & 0.8500 & 0 & 0 \\
0 & 0 & 0.3333 & 0.6667 \\
0.5455 & 0.4545 & 0 & 0
\end{bmatrix}
\]

\[
R_\Pi = \begin{bmatrix}
0.6 & 0.4 & 0 & 0 \\
0.85 & 0.15 & 0 & 0 \\
0 & 0.8 & 0.2 & 0 \\
0 & 0.7 & 0.3 & 0 \\
1 & 0 & 0 & 0
\end{bmatrix}
\]

\[
R_m = \begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0.5 & 0.5 & 0
\end{bmatrix}
\]

The final score matrices of this pole-mounted switch are as follows: \( B_1 = [0.1147 \quad 0.1277 \quad 0.2525 \quad 0.5051], B_\Pi = [0.6102 \quad 0.3836 \quad 0.0061 \quad 0], B_m = [0.0022 \quad 0.7982 \quad 0.1996 \quad 0]. \) That means the state of switch itself is 0.5051(serious), second part state is 0.6102(normal), and other state is 0.7982 (careful). So the switch is in poor condition. Generally, it is easy to break down when contact temperature reaches to 80°C\(^{[1]}.\) Table 1 shows that at that time it had reached 75°C and was rising which might cause serious consequences without a deal. Therefore, the method proposed by this paper is effective.

If only considering the index importance weights as literature [9], set weights as follow: \( W_1 = [0.5127 \quad 0.2733 \quad 0.0314 \quad 0.1826], \) and then the final score matrix \( B_1 = [0.5178 \quad 0.4508 \quad 0.0293 \quad 0.0021], \) which means the state of switch itself will be misjudged as "normal". Therefore, the comprehensive weights obtained in this paper are more reasonable and the evaluation results are accurate.

Summary

Under the background of power cyber physical fusion and the primary and secondary fusion on pole-mounted switch, this paper constructs a state index system, including switch itself, second part state indexes and other indexes, to evaluate the running state of fusion pole-mounted switch of primary and secondary comprehensively. Then the bidirectional weighting method is adopted to determine the weight of each index, so as to avoid the problem of low sensitivity to deterioration of indicators with low failure rate. Finally, use the fuzzy comprehensive evaluation method to evaluate the state of pole-mounted switch, whose effectiveness and accuracy are verified by an example.

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