Research on accurate quantification of membership of distribution terminal index based on cloud model

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Abstract. In order to accurately assess the health status of distribution terminals, it is necessary to solve the problems of strong subjectivity and high redundancy of the index membership results in the evaluation index system. According to the empirical score given by experts, the cloud model is used to describe the actual index state and the level boundary interval respectively to form floating cloud and standard state cloud space, and the overlapping area of the two is used to represent the membership degree of the actual index. This can not only directly determine the results, but also eliminate the influence of redundant factors, and realize the accurate quantification of the index membership degree results, which widens the direction for further improving the final evaluation effect.

1. Introduction
As the construction of distribution automation continues to advance, more and more distribution terminals are being put into use. However, the distribution terminals in the transportation stage have problems such as low maintenance accuracy, expensive replacement costs, and unclear elimination boundaries, which are likely to cause waste of resources. Therefore, to strengthen the fine management of power distribution terminals, research on the evaluation of the health status of power distribution terminals is also gradually carried out [1-2].

Since the fuzzy comprehensive evaluation method does not rely too much on a priori data, it has been widely used in the evaluation of the health status of power equipment. Among them, the fuzzy comprehensive evaluation needs to be based on the gradual fusion of the base layer indexes to the target layer indexes based on the fuzzy synthesis operator. Therefore, it is a key factor to evaluate the rationality and effectiveness of the membership of the base layer indexes of the distribution terminal. However, the existing methods are still inadequate: for example, reference [3] proposed to directly quantify secondary equipment indexes by scoring method, but the subjectivity is too strong. Reference [4] proposed fuzzy statistics and fuzzy membership functions to determine the quantitative and qualitative index membership of the relay protection device, but does not reduce the divergence of opinions. Reference [5] proposed the whitening weight function to solve the membership of indexes related to the operating state of the energy metering device, but it lacks consideration of the randomness of the evaluation system. Reference [6] proposed the grey correlation degree method to evaluate the performance of smart meters, but the optimal membership degree needs to be determined subjectively. In addition, the above methods all attribute the possibility of the actual state of the index
to the standard state level that has been divided in the project, and completely ignore the existence of other states between adjacent standard state levels, which will lead to the requested affiliation. Degree is not a valid value, which in turn affects the assessment of the status of distribution terminals.

In view of the mature application of cloud models in the fields of system evaluation, inaccurate knowledge representation, and data prediction [8-10], the deficiencies can be better compensated. Therefore, this article first objectively presents the scores given by experts subjectively and the set status levels in the same coordinate system based on cloud model. Then, according to the position of the floating cloud in the state space, directly observe the state level near the actual state of the index. Meanwhile, the degree of overlap between the floating cloud and each state cloud is used to remove the redundant state between adjacent state levels to obtain a more accurate degree of membership. Finally, taking the evaluation index system of a certain feeder terminal as an example, the membership of the relevant basic layer indexes is quantitatively solved and analyzed.

2. Presenting standard state space of Indexes based on cloud generator

The actual state of each index of the power distribution terminal cannot exist independently, and it is meaningful to measure against the standard state. According to the test data, operation and maintenance situation and expert experience, this paper divides the standard status of the distribution terminal indexes into 4 status levels: severe, abnormal, attentive, and normal, and the symbol \( s_k \) represents the \( k \)-th status level (\( k=1,2,3,4 \), respectively represent severe, abnormal, attentive, normal), and the boundaries of the standard status level is shown in Table 1.

| Status Level \( s_k \) | Severe Condition \( (s_1) \) | Abnormal Condition \( (s_2) \) | Attentive Condition \( (s_3) \) | Normal Condition \( (s_4) \) |
|------------------------|--------------------------|------------------------|------------------------|------------------------|
| \( (d_{min}, d_{max}) \) | \( (0, a) \) | \( (a, b) \) | \( (b, c) \) | \( (c, 1) \) |

Considering the ambiguity of the division of state levels, the cloud generator of the cloud model forms state clouds corresponding to each state level, namely severe cloud, abnormal cloud, attentive cloud, and normal cloud. Because each state level directly gives the level boundary interval, based on the cloud model 3\( \sigma \) rule, the boundary interval \( (d_{min}, d_{max}) \) of the \( k \)-th state level and the interval range \( [Ex_k-3En_k, Ex_k+3En_k] \) of the corresponding state cloud form an equation relationship as follows:

\[
\begin{cases}
Ex_k - 3En_k = d_{min} \\
Ex_k + 3En_k = d_{max}
\end{cases}
\]

(1)

By the formula (1), the expected \( Ex_k \) and entropy \( En_k \) of the \( k \)-th state cloud can be obtained; and the super-entropy \( He_k \) of the \( k \)-th state cloud can be adjusted according to the operation of the equipment, usually 0.005. Therefore, the result of acquiring the numerical eigenvalues of a single state cloud is shown in equation (2).

\[
\begin{align*}
Ex_k &= \frac{d_{min} + d_{max}}{2} \\
En_k &= \frac{d_{max} - d_{min}}{6} \\
He_k &= 0.005
\end{align*}
\]

(2)

where \( Ex_k \) represents the ideal score that best reflects the \( k \)-th state; \( En_k \) is a measure of the fuzzy range of the \( k \)-th state, and according to the 3\( \sigma \) rule of the cloud model, it is known that each state range basically falls within the interval \( [Ex_k-3En_k, Ex_k+3En_k] \); \( He_k \) not only reflects the randomness of the occurrence of the scores in the \( k \)-th state, but also reflects the uncertainty of the degree of membership of the scores in the \( k \)-state.

Finally, the numerical eigenvalues of each state cloud are listed in Table 2.
Table 2. The numerical eigenvalues of each state cloud.

| Status          | Severe Cloud | Abnormal Cloud | Attentive Cloud | Normal Cloud |
|-----------------|--------------|----------------|-----------------|--------------|
| $E_{\text{X}}$  | $a/2$        | $(a+b)/2$      | $(b+c)/2$       | $(c+1)/2$    |
| $E_{\text{N}}$  | $a/6$        | $(b-a)/6$      | $(c-b)/6$       | $(1-c)/6$    |
| $E_{\text{n}}$  | 0.005        | 0.005          | 0.005           | 0.005        |

However, the above numerical eigenvalues are only quantitative representations of the standard state, which cannot achieve the intuitive evaluation and judgment effect, so this paper uses the forward cloud generator to present them macroscopically. Among them, a single state cloud is composed of a large number of cloud droplets, and each cloud droplet is a random realization of the numerical characteristic value by the forward cloud generator. In this paper, the coordinates $(g, \mu(g))$ represent a cloud droplet, $g$ and $\mu(g)$ relationship as formula (3).

$$
\mu(g) = \exp\left[-\frac{(g - E_x)^2}{2(En')^2}\right]
$$

where $En'$ refers to a normal random entropy generated with $E_{\text{n}}$ as expectation and $He_{\text{n}}$ as standard deviation; $g$ refers to a normal random score generated with $E_{\text{X}}$ as expectation and $En'$ as standard deviation; $\mu(g)$ refers to the random score $g$ in the actual state range relative to the ideal score $E_x$, which can represent the strength of the state (hereinafter referred to as "strength"). To observe the reduction effect, this paper uses the forward cloud generator to randomly generate 5000 cloud drops to present. In the end, the state space cloud diagram formed by the four state clouds is shown in Figure 1.

![Figure 1. State space cloud diagram of the standard state.](image)

In addition, this paper analyzes the index of intelligent terminal in the distribution terminal, and finally selects $a=0.2$, $b=0.4$ and $c=0.7$ according to expert opinions.

3. Floating cloud based on cloud generator presenting actual status of indexes

This article considers that there is a strong uncertainty in the rating of such indexes by a single expert, and it does not make any sense to represent the actual state of the index within a standard state interval with an accuracy value, so it is necessary to obtain a sufficient number of expert ratings to characterize the actual state of the index. Therefore, this paper invites $m$ industry experts to score a certain index ($m$ will be given later) according to the inspection situation of the equipment, test results and related data. The $j$-th index score set is listed in formula (4).

$$
G^j = [g_1^j, g_2^j, \ldots, g_n^j] = (g_i^j)_{i=m}
$$

where $g_i^j$ represents the score of the $i$-th expert ($i=1,2,\ldots,m$) for the $j$-th index ($j=1,2,\ldots,n$), and the score adopts a 1-point scale.

Although the score set is a rough judgment on the status of the $j$-th index, it is also the result given in combination with the test and inspection, and the consensus level of the experts is relatively
4. Determine index membership

This article has described the actual state of the index with a floating cloud, and the standard state is also presented with a standard cloud diagram of the state space. Since the expectations of the floating cloud and the standard cloud of each state are the ideal scores that can best reflect their respective states, after the floating cloud is superimposed on the state space, the minimum value of the difference between the expected $Ex_j$ of the floating cloud and the expected $Ex_k$ of each state cloud is $\delta_{\min}$ determines the status level close to the actual status of the j-th index. The specific relationships are listed in equations (8) and (9).

$$\begin{align*}
\delta_i^j &= Ex_j^f - Ex_i \\
\delta_2^j &= Ex_j^f - Ex_2 \\
\delta_3^j &= Ex_j^f - Ex_3 \\
\delta_4^j &= Ex_j^f - Ex_4 \\
\delta_{\min}^j &= \min\{\delta_i^j, \delta_2^j, \delta_3^j, \delta_4^j\}
\end{align*}$$

$$\begin{align*}
\delta^j &= \frac{1}{m} \sum_{i=1}^{m} g_i^j - Ex_j^f
\end{align*}$$

$$\begin{align*}
En_j^f &= \sqrt{\frac{\pi}{2} \sum_{i=1}^{m} g_i^f - Ex_j^f}
\end{align*}$$

$$\begin{align*}
He_j^f &= \frac{1}{m-1} \sum_{i=1}^{m} (g_i^f - Ex_j^f)^2
\end{align*}$$

Among them, it should be noted that the greater the number of scores in the score set, the smaller the error of the obtained feature value, the higher the reliability of the restoration result, and the $3\sigma$ rule stipulates that the number of score inputs $m > 10$. Therefore, on the basis of not violating the guidelines, this article uses a small number of experts to ensure that the method of this article is still valid, so we selected four on-site operation and maintenance personnel, technicians from the equipment manufacturing plant and related scientific researchers, namely $m = 12$.

Subsequently, the numerical eigenvalues of the j-th index is sent to the forward cloud generator. The process is the same as the state cloud, and the description will not be repeated. Figure 2 shows the floating cloud generated by the actual state of the j-th index.

Figure 2. The floating cloud generated by the actual state of the j-th index.
where $\delta_1$ represents the difference between the $j$-th index floating cloud expectation and severe cloud expectation; $\delta_2$ represents the $j$-th index floating cloud expectation and the abnormal cloud expectation; $\delta_3$ represents the difference between $j$-th index floating cloud expectation and the attentive cloud expectations; $\delta_4$ represents the difference between the $j$-th index floating cloud expectations and normal cloud expectations. Figure 3 visually shows that the position of the floating cloud superimposed on the state space is closest to the normal cloud, and it is determined that it is at the "normal" level.

![Figure 3. Position of $j$-th index floating cloud in state space.](image)

At the same time, it can be observed from Figure 3 that there may still be non-overlapped regions after the floating cloud overlaps with the adjacent standard state. Based on its characteristics, this area is determined to be a redundant factor. If the area of the index floating cloud is completely allocated to each state level according to the limit interval, the redundancy of the index membership will inevitably increase. For this reason, in view of the larger overlapping area of the floating cloud and the $k$-th state cloud in the state level $s_k$, the more cloud droplets the floating cloud falls within the range of the $k$-th state cloud, the stronger the correlation with the $k$-th state cloud. Therefore, in this paper, the overlapping area of the $j$-th index floating cloud and each state cloud is used as the index membership degree. Moreover, since the expected curve can simply and effectively reflect the overall characteristics of the floating cloud and each state cloud, this article ignores the inner and outer boundary contours of the floating cloud and each state cloud, and only uses the expected curve of the floating cloud and each state cloud for characterization. The curve is as formula (10).

$$
\mu_i(g) = \exp\left[-\frac{(g - Ex)^2}{2(En)^2}\right]
$$

where: $Ex$ and $En$ are brought into the floating cloud or the numerical eigenvalues of the state cloud to get the corresponding expected curve.

Subsequently, this article takes the floating cloud and normal cloud expectation curve to have only one intersection point (see Fig. 4) as an example to calculate the overlapping area of the two, as shown in equation (11).

$$
A_j^i = \int_{-\infty}^{g_j} \mu_i(g) \, dg + \int_{g_j}^{g_i} \mu_i(g) \, dg
$$
Figure 4. There is only one intersection point between the expected curve of floating cloud and normal cloud (assuming \( g_{j2} \)).

where \( A_{jf} \) is the overlapping area of the expected cloud of the \( j \)-th index and the expected cloud of the normal cloud; \( \mu_j(g) \) is the expected curve of the floating cloud of the \( j \)-th index; \( \mu_j(g) \) is the expectation of the normal cloud curve; \( g_{j1} \) and \( g_{j2} \) are the intersection values of the \( j \)-th index floating cloud expected curve and the normal cloud expected curve. The intersection values \( g_{j1} \) and \( g_{j2} \) are further explained here: when \( \mu_j(g) = \mu_j(g) \), two intersection values \( g_{j1} \) and \( g_{j2} \) must be obtained in the interval \((-\infty, +\infty)\), as equation (12) and equation (13), but the 3σ rule of the cloud model limits the distribution range of floating and normal clouds to \([Ex_{j} - 3En_{j}, Ex_{j} + 3En_{j}]\) and \([Ex_{4} - 3En_{4}, Ex_{4} + 3En_{4}]\) is within the range, so the value of the intersection point only falls within the intersection of the two ranges to be truly effective.

\[
g_{j1} = \frac{Ex_{j}En_{j} - Ex_{4}En_{4}}{En_{j} - En_{4}} \tag{12}
\]

\[
g_{j2} = \frac{Ex_{j}En_{j} + Ex_{4}En_{4}}{En_{j} + En_{4}} \tag{13}
\]

The calculation of the overlapping area of the expected curve of the floating cloud and the expected curve of other state clouds is the same, and will not be repeated here. However, after determining the overlapping area of the \( j \)-th index floating cloud and the expected curve of each corresponding state cloud, we should standardize each overlapping area to compare them, and use the processed result as the \( j \)-th index in the \( k \)-th index. The degree of membership of each state level is \( r_{jk} \), as in equation (14).

\[
r_{jk} = \frac{2A_{jk}^{k}}{\sqrt{2\pi} (2En_{j} + En_{k})} \tag{14}
\]

where \( A_{jk}^{k} \) is the overlapping area of the \( j \)-th index floating cloud expectation curve and the corresponding state cloud expectation curve.

The \( r_{jk} \) at this moment is to retain the group expert consistency information, take into account the boundary value of the grade boundary interval, and eliminate the final result of the other redundant states between adjacent standard state levels, which is more in line with the actual situation. In addition, the overall distribution of \( r_{k} \) and corresponding floating clouds in the state space can be directly presented to the operation and maintenance personnel, so that they have a comprehensive understanding of the indexes that affect the health status of the distribution terminal, and have a guiding role in the maintenance of the distribution terminal.

5. Case study

This article takes a 10kV feeder terminal as an example, obtains status information by using existing technical means such as operation inspection, periodic shutdown or live detection, online monitoring, etc., and divides the influencing factors of the health status of the distribution automation terminal into on-site detection status and the master station detects two types of state quantities (belonging to the
criterion layer), and then refines a total of 10 individual indexes (belonging to the index layer) for it. Finally, the evaluation index system shown in Figure 5 is formed.

![Evaluation index system of feeder terminal health status.](Image)

In view of space limitations, only "voltage, current infrared temperature" and "remote signal state" are used as examples to illustrate. At the same time, in a state evaluation cycle, 12 experts scored the results as shown in Table 3.

**Table 3.** Experts' scoring results of "voltage, current infrared temperature" and "remote signal status".

| Number | Qualitative index | Expert 1 | Expert 2 | Expert 3 | Expert 4 | Expert 5 | Expert 6 | Expert 7 | Expert 8 | Expert 9 | Expert 10 | Expert 11 | Expert 12 |
|--------|-------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|-----------|-----------|
| 1      | Voltage, current infrared temperature | 0.74     | 0.78     | 0.76     | 0.85     | 0.8      | 0.88     | 0.8      | 0.77     | 0.85     | 0.8       | 0.77      | 0.75      |
| 2      | Remote status     | 0.77     | 0.71     | 0.75     | 0.72     | 0.75     | 0.73     | 0.78     | 0.78     | 0.79     | 0.79      | 0.78      | 0.76      |

According to the data in Table 3, use formula (5) to formula (7) to obtain the numerical eigenvalues of the actual state of the index; use formula (9) to determine the closest state level of the actual state of the index; use formula (14) to calculate the membership of the two indexes degree. Finally, the calculation results of the two index parameters are shown in Table 4.

**Table 4.** Parameter calculation results.

| Result Number | Qualitative index | Ex | En | He | δmn | Close Status level | Degree of membership |
|---------------|-------------------|----|----|----|-----|-------------------|---------------------|
| 1             | Voltage, current infrared temperature | 0.7942 | 0.0437 | 0.0052 | 0.0558 | Normal | 0 | 0 | 0.0094 | 0.5509 |
| 2             | Remote status     | 0.7608 | 0.0303 | 0.0043 | 0.2108 | Normal | 0 | 0 | 0.0086 | 0.2666 |

Then, the numerical eigenvalues of each index in Table 4 are sent to the forward cloud generator, and the floating cloud is overlapped with the state space using *matlab* to obtain the distribution of the floating cloud in the state space, as shown in Figure 6.
Through Figure 6, the actual states of "voltage, current infrared temperature" and "remote signal state" can be directly observed. At this moment, the actual states of both are close to the "normal state" level, and it is not necessary to participate in the screening of fault indexes after evaluation. Moreover, by observing Figure 6, it is not difficult to find that there are different degrees of redundancy between the normal and attention levels. In this paper, the floating clouds of "voltage, current infrared temperature" and "remote signal state" are compared with those of the set state level. The overlapping area between the state clouds is used as the membership degree, and the influence of the redundant state between adjacent state levels is eliminated, which is helpful to improve the reliability and accuracy of the membership results of the two. In addition, combining with the data in Table 4, it is known that the floating cloud of "voltage and current infrared temperature" belongs to the normal cloud up to 55.09%, which is 43.97% larger than the redundant area of the floating cloud in the state space (1-0.5509-0.094= 0.4397), which means that the index is still within the acceptable range of the normal state; the "remote signal state" corresponds to 26.66% of the floating cloud belonging to the normal cloud, while the total area belonging to the normal cloud and the attention cloud only accounts for 27.52% (0.2666+0.0086=0.2752), which is much lower than 72.48% of the redundant area of floating clouds in the state space (1-0.2666-0.0086=0.7248), which has exceeded 50%. To avoid the risks caused by uncertain factors Sexual failure can be further determined by relevant tests. The above results show that, while accurately quantifying the index membership results, the actual situation of the index is reflected through the visualization of the cloud image, and finally the operation and maintenance personnel can better identify the indexes with potential risks.

6. Conclusions
In this paper, the cloud model theory is used to characterize the actual state of each index in the distribution terminal and the standard state space, and the cloud map formed by the two is superimposed to directly observe the standard state of an indicator. At the same time, the overlapping area of the actual state and the standard state is defined as the degree of membership of the index, which can not only reflect the degree of each index approaching to a certain standard state, but also remove the influence of redundant factors to improve the accuracy of the index after quantization, and lay a good foundation for improving the accuracy of the evaluation results of the health status of distribution terminals.

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