A Method of Reliability Weight Distribution of Wind Turbines

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Abstract. Aiming at solving the reliability weight distribution problems of SL1500 wind turbines from Sinovel Wind Group Co., Ltd, an integrated method of historical fault maintenance data-based, improved fuzzy hierarchy analysis process and entropy weight method is proposed to achieve the weight distribution of each subsystem of wind turbine. The method takes both maintenance data and expert knowledge into consideration, which can well avoid one-sided problem from the view of considering only subjective or objective factors. The modified weight distribution algorithm is more practical for further reliability evaluation of wind turbine.

1. Introduction

With the rapid expansion of installed capacity of wind turbine in recent years, the reliability evaluation of wind turbine is becoming critical in the meantime [1-2]. As one of the mainstream large-scale wind turbines in the market, double feedback asynchronous wind turbines are with the advantages of large power, high quality power generation, compact structure and so on [3]. In order to improve the reliability of wind turbine system, it is necessary to perform a reliability analysis on the wind turbine system, and to find out the weak links of the wind turbine system. Weight distribution is an indispensable step in the primary stage of system reliability analysis. Weighting coefficient is used not only to value the importance of each subsystem in the whole system, but also to figure the criticality of the indicator. The higher the value of weighting coefficient is, the more the importance is and also the greater the impact on the whole system is [4]. In other words, the reasonable result of weight distribution can enable to increase the accuracy of subsequent system reliability analysis.

At present, the methods for determining the weight are mainly divided into three categories: subjective weighting method, objective weighting method, subjective and objective weighting method. The commonly used subjective weighting methods include Delphi method, analytic hierarchy process (AHP), binomial coefficient method, etc. [5-6]. Zhou Huqin, Ma Jin, et al. [7] based on the AHP distribution method, the reliability weight distribution of wind turbine is carried out, but the low efficiency exist throughout the expert evaluation process, and did not consider the importance of each component in the system. In reference [8], the fuzzy theory is applied to the reliability weight distribution of mechanical products, and the fuzzy comprehensive evaluation method is proposed. Zhu Dexin and Liu Hongzhao [9] used the fuzzy analytic hierarchy process to solve the problem of weight distribution of grinding electric spindle, but this method relies on experience and judgment. Although highly interpretable, there are problems such as low accuracy.
The commonly used objective weighting methods include principal component analysis, entropy weight method, multi-objective programming, deviation and mean square deviation [10]. Yu Feng and Yang Chengwu used entropy weight method to determine the weight of factors. The entropy weight method is an objective weighting method, which contains sufficient decision-making information, avoiding the shortcomings of emphasizing only a few indicators of the process and ignoring other indicators, but ignoring the decision-makers' subjective cognition [11]. Subjective and objective weighting method include comprehensive weighting method of compromise coefficient, combined weighting method, Frank Wolfe method, etc. [12-13]. Zhou Xinjian, Li Zhiqiang [14] used the collected historical fault maintenance data to allocate the reliability weight of the wind turbine, which overcomes the uncertainty error caused by the subjective scoring of the traditional scoring method, but there are some drawbacks, such as incomplete considerations. The above methods generally born with application limitations, for instance, the distribution results are easy to be affected by decision makers, too subjective or too objective to reflect the attention of decision makers on different attributes, and the application is limited, etc. [15].

In the view of the research on the weight distribution of large-scale wind turbine system, with multi-level structure and many influencing factors [16], combining expert knowledge with fault maintenance data, this paper proposes a weight distribution method based on the combination of historical fault maintenance data, fuzzy analytic hierarchy process and entropy weight method. According to the structure, function and hierarchical structure of the double feedback asynchronous wind turbine, this method constructs the distribution model, and uses the combined weight distribution method to comprehensively consider the expert opinion score and the actual operation fault maintenance data, reasonably solves the decision-making problem in the weight distribution process including the wind turbine, and effectively distributes the weight of the wind turbine, which provides favorable conditions for reliability analysis.

2. Reliability weight distribution method of wind turbine
In order to prompt credibility of the reliability weight distribution, an innovative weighting method, which takes the advantages of both subjective and objective distribution methods, is proposed with the integration of fuzzy analytic hierarchy process, entropy and fault maintenance data-based method. The fuzzy analytic hierarchy process is used to calculate the subjective weighting indicators based on expert knowledge and the entropy weight is adopted further to modify the weight. The fuzzy analytic hierarchy process considers the evaluation indexes of each level, and compares the importance of the indexes one by one to obtain a fuzzy judgment matrix, which provides a basis for quantifying the evaluation indexes. In addition, the larger the information entropy of the index, the greater the role it plays in the evaluation. The use of information entropy is conducive to the evaluation of multiple indicators. By introducing the weight determination method based on historical fault maintenance data, the distribution result is more in line with the actual situation.

2.1. Solution of the fuzzy weight of each index
The fuzzy analytic hierarchy process is selected to solve the fuzzy weight, and the weight distribution of the wind turbine is divided into three levels. The first level is the target layer A: the reliability weight of the whole of wind turbine, which is 1; the second level is the criterion layer B: the contributory factor of the reliability weight of the wind turbine; the third level is the target layer C: the main subsystem of the wind turbine [17]. The calculation steps are as follows:

1) Set the evaluation factors as $U = \{u_1, u_2, \ldots, u_i, \ldots, u_m\}$, where $m$ is the number of evaluation factors in the hierarchical model. $p_{ij}$ indicates the relative importance of $p_i$ to $p_j$, $i=1,2,\ldots,m$, $j=1,2,\ldots,m$. The element $p_{ij}$ of the judgment matrix $P$ is decided by three-scale method, where the value is determined by comparing the $i$-th factor in the criterion layer $B$ with the $j$-th factor. $P$ can be written into
\[
\mathbf{P} = \left( p_{ij} \right)_{n \times m} = \begin{cases} 
1 & u_i < u_j \\
2 & u_i = u_j \\
3 & u_i > u_j 
\end{cases}
\]

2) Multiply the elements of each row of the judgment matrix \( \mathbf{P} \) to get the row product \( q_i \), where
\[
q_i = \prod_{j=1}^{m} p_{ij}, \ (i = 1, 2, \cdots, m)
\]  

(1)

3) To calculate the \( m \)-th root of \( q_i \) by
\[
\overline{w_i} = \sqrt[q_i]{(i = 1, 2, \cdots, m)}
\]  

(2)

4) Normalize the vector \( \overline{w_i} \) by the following equation,
\[
w_i' = \frac{\overline{w_i}}{\sum_{i=1}^{m} \overline{w_i}}
\]  

(3)

Until now, the weighting indicators for each evaluation factors can be calculated and written into the following vector,
\[
\mathbf{w'} = (w_1', w_2', \cdots, w_m')
\]  

(4)

Similarly, by repeating the calculation from formula (1) to (3), the weighting indicator \( \mathbf{V}_i \) reflecting the importance of each object in layer C under the influence of the \( i \)-th factor in criterion layer B can be obtained and represented as follows,
\[
\mathbf{V}_i = (v_i^1, v_i^2, \cdots, v_i^n)^T, \ (i = 1, 2, \cdots, m)
\]

where \( m \) represents the number of influencing factors of criterion layer B, \( n \) is the number of objects in layer C. Make as follows,
\[
\mathbf{V} = (v_1, v_2, \cdots, v_m)
\]  

(5)

Therefore, the weight vector of the object in layer C relative to the target in layer A is:
\[
\mathbf{E} = \mathbf{w'} \mathbf{V}^T
\]  

(6)

2.2. Solution of entropy weight

1) Build the normalized judgment matrix:

According to each indicator in the object layer C, the expert score is evaluated in the state of each influencing factor in criterion layer B [18]. The greater the impact, the higher the score, the score range is 1 to 10 points.

Build the initialization data matrix \( \mathbf{R} \), \( \mathbf{R} = (r_{il})_{m \times n} \)

where \( m \) is the total number of evaluation factors in the standard layer B; \( n \) is the total number of evaluation indexes in the target layer C. \( r_{il} \) is the evaluation value corresponding to the \( l \)-th evaluation index under the influence of the \( i \)-th evaluation factor. Use the formula (7) ~ (8) perform normalization calculation to obtain the judgment matrix \( \mathbf{F} \), \( \mathbf{F} = (f_{il})_{m \times n} \)

\[
y_{il} = \frac{r_{il} - \min \{r_{ij}, \cdots, r_{im}\}}{\max \{r_{ij}, \cdots, r_{im}\} - \min \{r_{ij}, \cdots, r_{im}\}}
\]  

(7)

\[
f_{il} = \frac{y_{il}}{\sum_{i=1}^{m} y_{il}}, \ \ i = 1, \cdots, m; \ l = 1, \cdots, n
\]  

(8)

where \( f_{il} \) is the normalized data of \( r_{il} \), \( f_{il} \in [0,1] \).
2) Calculate the entropy weights of each evaluation indexes \[19\]:

\[
H(r_i) = - \sum_{l=1}^{m} f_{il} \ln f_{il}, (l = 1, \ldots, n)
\]  \hspace{1cm} (9)

3) The entropy value of the evaluation indexes is converted into the weight value:

\[
d_i = \frac{1}{n} \sum_{l=1}^{m} H(r_i), (l = 1, \ldots, n)
\]  \hspace{1cm} (10)

The weight value is represented as \( \mathbf{D} = (d_1, d_2, \ldots, d_n) \).

2.3. Solving the weight based on troubleshooting data

Considering the influence of failure times \( N \) and Mean Time To Repair (MTTR) \( T \), reliability weight allocation should vary with the MTTR. The smaller the failure times \( N \), the higher the weight allocation. The longer \( T \) is, the lower allocation should be set which reduces the losses obviously.

According to the statistical historical failure maintenance data of the fan, the influencing factors of each influencing factor are calculated, as follows:

\[
E_{K_i} = \frac{(K_i / K_s)^{\alpha}}{\sum_{l=1}^{s} (K_i / K_s)^{\alpha}}
\]  \hspace{1cm} (11)

In the above formula, \( K \) is the influencing factor of the system reliability weight index allocation; \( n \) is the number of subsystem of the whole wind turbine systems, \( l \) is the \( l \)-th subsystem; \( K_s \) is the sum of the influencing factors \( K \) of all subsystems; \( \alpha \) is the influencing coefficient, representing the correlation between the influencing factor and the target weight, When the correlation is positive, \( \alpha \) is 1, and when the correlation is negative, \( \alpha \) is -1.

For each subsystem, the relationship between the number of failures is:

\[
E_{N_l} = \frac{(N_l / N_s)^{-1}}{\sum_{l=1}^{s} (N_l / N_s)^{-1}} = \frac{1/N_l}{\sum_{l=1}^{s} (1/N_l)}
\]  \hspace{1cm} (12)

where \( N_l \) is the number of failures of the \( l \)-th subsystem; \( N_s \) is the sum of failures of all subsystems; \( n \) is the number of subsystem of the whole wind turbine systems, and the smaller the value of \( E_{N_l} \) is, the more failures of the subsystem occur, the smaller the weight value is assigned. On the country, a larger weight value should be assigned.

For the average breakdown maintenance downtime of each subsystem, the relationship is as follows:

\[
E_{T_l} = \frac{(T_l / T_s)^{1}}{\sum_{l=1}^{s} (T_l / T_s)^{1}} = \frac{T_l}{T_s}
\]  \hspace{1cm} (13)

where \( T_l \) is the average failure maintenance downtime of the \( l \)-th subsystem; \( T_s \) is the sum of the average failure maintenance downtime of all subsystems. The smaller the value of \( E_{T_l} \) is, the smaller the MTTR for the subsystem and the smaller the weight assigns correspondingly.

Take the number of failures and the MTTR of each subsystem into account, the following expression:
where $\beta$ indicates the influence degree of the influencing factors on the weight distribution of the system. Choosing $\beta = 0.5$ on this operating condition, indicates that the number of failures $N$ and the MTTR $T$ cause the same influence degree on the weight distribution of the indicators. If $\beta$ is taken as 1, only the number of failures $N$ affects the weight distribution of the system; if $\beta$ is taken as 0, only the average maintenance downtime $T$ affects the weight distribution of the system.

Finally, the weight of each subsystem is as follows:

$$w_{S_i} = \frac{1}{\sum_{l=1}^{n} (1/E_{S_i})}$$

2.4. Calculation of combined weight

Considering the advantages of fuzzy analytic hierarchy process, entropy weight method and calculation method based on historical fault maintenance data, the method of evaluation factors on combination weight is obtained by combining the three methods:

$$w = \left\{ \left( \sum_{l=1}^{n} e_d d_{w_{S_1}} \right)^{1/3}, \left( \sum_{l=1}^{n} e_d d_{w_{S_2}} \right)^{1/3}, \cdots, \left( \sum_{l=1}^{n} e_d d_{w_{S_n}} \right)^{1/3} \right\} = (w_1, w_2, \cdots, w_n)$$

where $n$ is the number of subsystems of the wind turbine.

The principle of minimum relative entropy can be expressed by the following formula:

$$\min G = \sum_{l=1}^{n} w_l (\ln w_l - \ln e_l) + \sum_{l=1}^{n} w_l (\ln w_l - \ln d_l) + \sum_{l=1}^{n} w_l (\ln w_l - \ln w_{S_l})$$

Lagrange multiplier method is used to solve the problem [20], and the optimized combination weight is:

$$w = \left\{ \left( \sum_{l=1}^{n} (e_d d_{w_{S_1}})^{1/3} \right)^{1/3}, \left( \sum_{l=1}^{n} (e_d d_{w_{S_2}})^{1/3} \right)^{1/3}, \cdots, \left( \sum_{l=1}^{n} (e_d d_{w_{S_n}})^{1/3} \right)^{1/3} \right\} = (w_1, w_2, \cdots, w_n)$$

3. Weight distribution of wind turbines

3.1. Establishment of hierarchical model for fan weights distribution

The structure of wind turbine can be classified into three layers: the top system layer, intermediate layer of subsystem and base layer of components. The whole wind turbine mainly includes pitch subsystem, gearbox subsystem, generator subsystem, electronic control subsystem, water cooling subsystem and yaw subsystem. The structure diagram of wind turbine is shown in Figure 1. In order to fully consider the subjective and objective factors that affect the weight distribution of the whole machine, six factors including working environment, task situation, technical level, complexity, importance and cost are selected as the evaluation indices. Considering the complexity of components in base layer, only the subsystems in intermediate layer will be weighted.
Using fuzzy analytic hierarchy process to obtain the weight distribution model of wind turbines is shown in Figure 2. Take the entire wind turbine system as the target layer A; six factors that affect the overall weight distribution of the wind turbine as the criterion layer B; and six subsystems of the wind turbine as the target layer C.

![Figure 1. Structure diagram of wind turbine.](image)

Figure 1. Structure diagram of wind turbine.

![Figure 2. Fuzzy hierarchy model of wind turbine.](image)

Figure 2. Fuzzy hierarchy model of wind turbine.

3.2. The determination of the weights of Fuzzy AHP
According to the hierarchical model of weight distribution of wind turbines in Figure 2, the fuzzy three-level analysis is used to establish the fuzzy three-scale priority relationship of the six influence factors in the criterion layer. According to the evaluation results of experts, obtain the relationship between the weight of each influencing factor: task situation > complexity > working environment > technical level > importance > cost. Arrange the working environment, task situation, importance, cost, technical level, and complexity in order and compare them in pairs, the priority matrix \( P \) is obtained.
Using the formulas (1) to (4), the weight vector $\mathbf{W}$ of the working environment, task situation, importance, cost, technical level, and complexity could be calculated.

$$\mathbf{W} = (0.1740, 0.2510, 0.1207, 0.1005, 0.1449, 0.2090)$$

According to the scores of experts on the wind turbine under the six influencing factors of the criteria layer, the weight ranking of each subsystem under a single influencing factor can be obtained, as shown in Table 1 (B1: working environment, B2: task situation, B3: importance, B4: cost, B5: technical level, B6: complexity. C1: Pitch subsystem, C2: Gearbox subsystem, C3: Generator subsystem, C4: Electronic control subsystem, C5: Water cooling subsystem, C6: Yaw subsystem. These also apply below.).

**Table 1. Correlation weight under single influencing factor.**

| Influencing factors | Sort |
|---------------------|------|
| B1                  | C6   |
| B2                  | C4   |
| B3                  | C5   |
| B4                  | C2   |
| B5                  | C3   |
| B6                  | C4   |

The same, under each influencing factor, arrange the pitch system, gearbox subsystem, generator subsystem, electronic control subsystem, water cooling subsystem, and yaw subsystem in sequence and compare them in pairs. We can obtain the judgment matrix of each subsystem in the object layer C under a single influencing factor, and the weight of each subsystem relative to the whole wind turbine under the influence of a single factor is calculated by formula (1) - (3). As shown in Table 2, the comprehensive weight $\mathbf{E}$ of each subsystem relative to the whole wind turbine is obtained by formula (5) - (6).

**Table 2. Combined weights of subsystems relative to the entire machine.**

|                   | B1          | B2          | B3          | B4          | B5          | B6          |
|-------------------|-------------|-------------|-------------|-------------|-------------|-------------|
| C1                | 0.1005      | 0.1005      | 0.1005      | 0.1005      | 0.1005      | 0.1005      |
| C2                | 0.1449      | 0.2090      | 0.2090      | 0.1449      | 0.1740      | 0.2510      |
| C3                | 0.1207      | 0.1449      | 0.1740      | 0.2510      | 0.2510      | 0.1740      |
| C4                | 0.2090      | 0.1740      | 0.1449      | 0.1740      | 0.2090      | 0.1449      |
| C5                | 0.1740      | 0.1207      | 0.1207      | 0.1207      | 0.1207      | 0.1207      |
| C6                | 0.2510      | 0.2510      | 0.2510      | 0.2090      | 0.1449      | 0.2090      |

Comprehensive weight of each subsystem relative to the whole machine:

$$\mathbf{E} = (0.1009, 0.1962, 0.1771, 0.1762, 0.1262, 0.2235)$$

3.3. Calculation of entropy weight of index

Using the entropy weight method, the initial data matrix $\mathbf{R}$ is constructed according to the expert's opinion on each subsystem under each factor, as shown below:
The formulas (7) to (10) are used to weight the six subsystems under the six influence factors to obtain the Entropy weight $d_j$,

$$D = (0.3058, 0.0997, 0.1879, 0.1879, 0.1093, 0.1093)$$

3.4. Calculate the weight based on fault maintenance data
According to formula (11) - (15), the reliability weight distribution of each subsystem of wind turbine is shown in Table 3.

Table 3. Weight distribution of each subsystem of wind turbine.

|    | $E_{Nc}$ | $E_{Tc}$ | $E_{Sc}$ | $w_{Sc}$ |
|----|----------|----------|----------|----------|
| C1 | 0.0647   | 0.2229   | 0.8634   | 0.1762   |
| C2 | 0.2155   | 0.1150   | 1.1325   | 0.1343   |
| C3 | 0.1361   | 0.0712   | 0.7082   | 0.2148   |
| C4 | 0.0296   | 0.2447   | 0.6117   | 0.2486   |
| C5 | 0.4310   | 0.1891   | 2.0534   | 0.0741   |
| C6 | 0.1231   | 0.1570   | 1.0000   | 0.1521   |

3.5. Combination weight calculation
Use formula (16) to get the combined weight $w$,

$$w = (0.1824, 0.1431, 0.1998, 0.2095, 0.1045, 0.1607)$$

By using the fuzzy analytic hierarchy process and entropy weight method, considering six factors of working environment, task situation, technical level, complexity, importance and cost, through expert evaluation and introducing the method based on historical fault maintenance data, the reliability weight distribution of wind turbine which basically meets the requirements of rationality has been greatly improved. Moreover, the quantitative calculation of historical fault maintenance data can reduce the number of expert evaluation and improve the efficiency of weight distribution. It can be seen from the combined weight that the electronic control subsystem has the largest weight, with the weight reaching 20.95%, that is to say, it has the greatest impact on the reliability of the whole wind turbine. The second is the generator subsystem, which reaches 19.98%. It is the second key subsystem that affects the reliability of the wind turbine. The pitch subsystem is the third with the weight of 18.24%. The rest are ranked from large to small: yaw subsystem is of 16.07%, gearbox subsystem is of 14.31%, water cooling subsystem is of 10.45%.

4. Conclusions
The fuzzy analytic hierarchy process is used to clarify the weight distribution structure of the wind turbine concisely and conveniently, and the weight of each subsystem relative to the reliability of the wind turbine is obtained. However, this method is very subjective and vulnerable to the lack of knowledge of decision makers. In this article, the weight of the electronic control system obtained by the fuzzy analytic hierarchy process ranks fourth, but in fact the electronic control subsystem is the core subsystem of the wind turbine. For the entropy weight method, according to the actual distribution, the scoring mechanism is used to estimate the index. The results obtained by this method have higher credibility than subjective weighting. However, the entropy weight method
cannot reflect the degree of importance the decision makers attach to different attributes, and without empirical guidance, certain weights may be inconsistent with the actual importance of attributes. Although the entropy weight method is based on a sample score, it also has a lot to do with decision makers. In this paper, the weight of the pitch subsystem obtained by the entropy weight method is the largest, followed by the electronic control subsystem, the yaw system in the fourth place, and the gearbox subsystem has the smallest weight. The results obtained are somewhat different from those obtained by the fuzzy analytic hierarchy process. In the final analysis, the entropy weight method is also a scoring method. The method based on historical failure maintenance data is to use historical failure maintenance data for calculation. Due to the large randomness of failures and historical failure maintenance data may also be affected by human factors, so the weight of the subsystem obtained by using the fault data is very random, and the size of the weight obtained has a great relationship with the sample.

Many previous scholars have combined the fuzzy analytic hierarchy process with the entropy weight method in analyzing the weight. Based on the above problems, a calculation method based on historical fault maintenance data is added on the basis of previous scholars’ research, making the results more objective and integrating the degree of the importance of decision makers to the subsystems of wind turbines. Combining expert knowledge with historical fault repair data, and considering working environment, task situation, technical level, complexity, importance, cost, fault repair times, fault repair downtime and other factors, which can effectively solve the problems of low distribution efficiency and incomplete consideration factors.

From the point of view of the weight value obtained by fuzzy analytic hierarchy process, entropy weight method, historical fault maintenance data method and combined weight method, the weight ranking based on entropy weight method and historical fault maintenance data method is close to the combined weight ranking. However, the weight ranking obtained by the fuzzy analytic hierarchy process is a little different from the combined weight ranking. The large difference has a great relationship with the subjective score of the expert. The effectiveness of this distribution method has been verified and the result can provide a support for the further reliability evaluation of wind turbines.

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