Reliability Assessment for Wind Turbine Under Index Weight and Failure of Subsystem

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***Abstract*—Wind turbine is a multi-system highly integrated complex facilities, once a subsystem fails, the wind turbine will stop running, and the influence of evaluation index to reliability on each subsystem to wind turbine have large differences. It is an urgent problem that to analyze the reliability that subsystem impact on the wind turbine. Considering the weight and model to analyze evaluation index and failure on the influence of reliability. For obtaining the reliability index weight, using Analysis Hierarchical Process (AHP) to divide layers of the wind turbine, influencing factors and subsystems, and the three scales method indicates the degree of influence on the reliability evaluation index of each layer under AGREE method, the reliability weights of each subsystem to the wind turbine are acquired by calculating judgement matrix. Based on the failure data of subsystems, considering the probability that a non-halting failure becomes halting failure on the influence of reliability, and model on Weibull distribution is proposed. Finally, analyzing the influence of subsystems in series system on wind turbine, assessment is based on the reliability weights and model against the subsystems.**

Keywords—reliability, weight allocation, Weibull distribution, wind turbine, subsystem

I. INTRODUCTION

With the increasing number of installed wind turbines coupled with the harsh working environment and complex structure, higher requirements are put forward for their reliability. Each subsystem plays an important role in the daily safe operation of the wind turbine. Because of the complex environment and variable working conditions, the failure of the subsystem occurs from time to time, which affect the reliability of the wind turbine operation.

If subsystems are assigned large weights, their importance is higher and their influence on the reliability of the wind turbine is greater. The multi-feature comprehensive evaluation model based on combination weighting to calculate the objective weight is proposed [1]. There is a large amount of raw data have been collected and analyzed, and six core factors were selected to form the index layers of the model, calculates the subjective weight of each factor under the AHP expert scoring method [2]. Since the AGRRE method only considers the importance degree, a redundancy allocation method in the reliability allocation problem for complex coupled systems is in need [3]. In order to carry out for the safety assessment index system by the hierarchical comprehensive evaluation, using the three-scale AHP model to determine the weight of assessment indexes [4]. Using historical failure data to analyze the reliability, which can overcome the uncertainty error caused by the subjective scoring, but has the disadvantage of less comprehensive consideration [5]. A relative factor is introduced to describe component failure dependence and is used to calculate complexity. Additionally, a system reliability allocation model for series systems is developed, considering three types of failure modes. [6]. Based on failure data, the failure rate of the device under Weibull distribution is analyzed, but the influence of the defect data is not considered [7]. The reliability evaluation model of decision redundancy system is established to research the system reliability level under different failure mechanisms [8]. Through the daily operation status data collection to get enough sample data, and uses the mean rank order and the least squares estimation to calculate the regression equation, which can obtain the failure probability distribution function [9]. Up to know, concerned scholars consider an improved reliability allocation method about importance factor, and verifies the method on a series-parallel system [10]. In summary, reliability assignment based on weight and model have the problem of limited deliberation, finding a reliability assignment method that considers both of situations is a major research content.

This paper focuses on the reliability influence of subsystem to the wind turbine under index weight and failure. For accurately assignment of reliability weights, analyzing the influence of different factors on the reliability of subsystem and wind turbine by using three scales AHP method based on the evaluation indexes getting from AGREE method, reliability weight allocation result for subsystems to the wind turbine is acquired. Collecting the failure data of each subsystem and divide into halting and non-halting failures, considering the influence on reliability model with the probability that a non-halting failure develops into halting failure, using mean rank order and least square estimation to get the reliability curves of the subsystems under the Weibull distribution modelling. Finally, the reliability of the wind turbine is analyzed by the reliability weight allocation and model based the subsystems.

II. Reliability Weigh Allocation of Wind Turbine

Reliability index weights are assigned in the following steps, which can describe the importance degree on the influence of reliability for subsystem to wind turbine.

The AHP is based on the hierarchical model, in which the layers interact with each other, while factors in the layer are relatively independent. The upper layer of indexes as the target, analysis of the importance about the lower layer of indexes. Applying the AHP method to carry out the research on the reliability weight allocation. Establish the hierarchical model as shown in Fig. 1, which is combined by three layers as wind turbine, influencing factors and subsystems. The wind turbine is evaluated according to the six influencing factors and is divided into six subsystems. A represents wind turbine. B1 to B6 represent working environment, task situation, importance, cost, technology level, complexity in turn. C1 to C6 represent pitch system, gearbox system, generator system, hydraulic system, frequency conversion system, yaw system in turn.

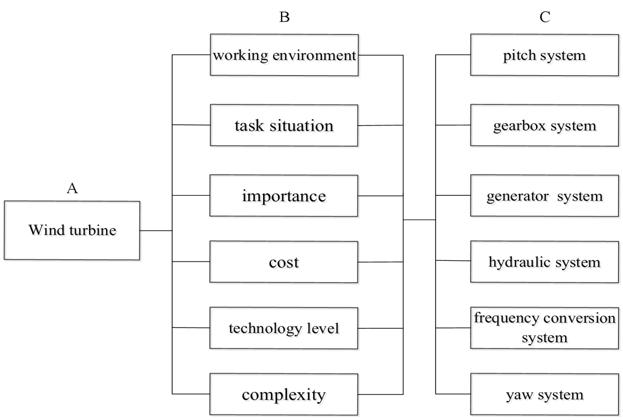

Fig. 1. Hierarchical structure of wind turbines

Analyzing the reliability relationships of the subsystems in the wind turbine and drawing a block diagram. When the subsystems fail, it can easily lead to wind turbine failure, resulting in substantial losses. It can be inferred that within the wind turbine, the subsystems operate in series as shown in Fig.2.

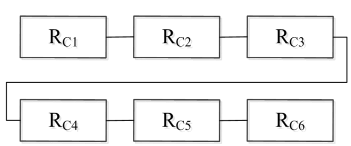

Fig.2. Block diagram of subsystem reliability

Evaluation index about expert ratings is conducted on the influence degree of reliability, if the system structure is more complex and the technical level is higher, there will be a greater influence on the wind turbine reliability. According to the AGREE method, expert ratings the wind turbine and six subsystems based on six influencing factors, resulting in higher scores indicating greater influence on reliability.

Three scales method is based on scale 1 to 3, which is used to carry out the degree of importance by comparing different factors under the evaluation index getting from AGREE method, formula (1) acquires the element p_{ij} of judgement matrix P to weight evaluation and distribution.

$$P = \left(p_{ij}\right)_{m\times m} = \begin{cases} 1, u_i < u_j \\ 2, u_i = u_j \\ 3, u_i > u_j \end{cases} \tag{1}$$

This method avoids the large error caused by too many scales and improves the accuracy of the judgement matrix. Calculating the weigh allocation factor. Firstly, multiplying the elements of each row of the judgement matrix to obtain the product of the rows q_i by (2), m is the number of evaluation indexes in the hierarchical model.

$$q_i = \prod_{j=1}^{m} p_{ij} \left(i = 1, 2, \ldots, m\right) \tag{2}$$

The influence weights of a given evaluation index for the layer by (3) and (4).

$$w_i = \sqrt[m]{q_i} \left(i = 1, 2, \ldots, m\right) \tag{3}$$

$$\overline{w_i} = \frac{w_i}{\sum_{i=1}^{m} w_i} \tag{4}$$

where, w_i is the reliability score of the i^{th} evaluation index by comparing with other indexes. $\overline{w_i}$ is the weight allocation of the i^{th} evaluation index.

The set of weight allocation between layer a and layer b can be obtained.

$$W_{LaLb} = \left(\overline{w}_{LaLb1}, \overline{w}_{LaLb2}, \ldots, \overline{w}_{LaLbm}\right) \tag{5}$$

Reliability weight allocation result of the k layer to the first layer is calculated using the set of reliability weights between the different layers.

$$W_{L1Lk} = \left(W_{L1} W_{L2}^{T}\right) W_{L3}^{T} \ldots W_{Lk}^{T} \tag{6}$$

III. Wind Turbine Reliability Modelling

In response to the reliability weights of the subsystems to the wind turbine obtained in the previous section, which has a certain subjectivity, adding failure data to analyze the influence of subsystems on the reliability to the wind turbine. The two-parameter Weibull distribution model is utilized for modeling with a cumulative failure and reliability function as shown in (7) and (8), effectively capturing wear, tear, fatigue and other failures, which proves highly adaptable in reliability.

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{m}\right] \tag{7}$$

$$R(t)=1-F(t)=\exp\left[-\left(\frac{t}{\eta}\right)^{m}\right] \tag{8}$$

where, t is the failure time. m is the shape parameter. η is the scale parameter, formula (8) can be deformed as follow.

$$\frac{1}{1-F(t)}=\exp\left[\left(\frac{t}{\eta}\right)^{m}\right] \tag{9}$$

Taking the logarithm of both sides of (9), using the reduction method to obtain the values of x and y.

$$\ln\left[-\ln R(t)\right]=m(\ln t-\ln\eta) \tag{10}$$

$$x_{\mathrm{i}}=\ln\Delta t_{\mathrm{i}} \tag{11}$$

$$y_{\mathrm{i}}=\ln\left[-\ln R(t)\right] \tag{12}$$

Least squares method is used to estimate the parameters of the Weibull distribution, which can be effective in linearizing the distribution function curve and the fitting curve is as follows.

$$y_{\mathrm{i}}=ax_{\mathrm{i}}+b \tag{13}$$

The scale and shape parameters in the Weibull distribution are obtained.

$$\begin{cases} m=a \\ \eta=\exp\left(-\dfrac{b}{a}\right) \end{cases} \tag{14}$$

Traditional mean rank order overlooks the influence of non-halting failures on reliability assessment, assuming its failure probabilities is equal between two halting failures. However, the failure probability for a non-halting failure differs between halting failures, depending not only on the failure time but also on the duration. The longer duration is associated with an increased probability of failure. Considering the effect on the accuracy of the parameter estimation after adding the non-halting failure, in order to analyze the reliability assessment results are more accurate or not. The conditional probability formula is used to define the relationship between these two type failures about interaction of the failure probability.

$$P(A\mid B)=\frac{P(AB)}{P(B)} \tag{15}$$

where, $P(A|B)$ represents the probability of event A occurring under the event B.

Recording halting failures that are greater than the non-halting failure time as t_{k},$t_{\mathrm{k+1}}$,t_{n}. Assuming that a non-halting failure occurs at t_{j}(j=1,2,…,M). Formula (16) is used to define the probability $I_{\mathrm{j,i}}$ that a non-halting failure becomes a halting failure during [$t_{\mathrm{i-1}}$,t_{i}] (i=k,$k+1$,…,n) .In this situation, non-halting failures are set to be reliably non-occurrence, only considering the probability of it turning into a halting failure.

$$I_{\mathrm{j,i}}=\frac{\int_{t_{\mathrm{i-1}}}^{t_{\mathrm{i}}}f(t)\,dt}{1-F(t_{\mathrm{j}})}=\frac{\exp\left[-\left(\dfrac{t_{\mathrm{i-1}}}{\eta}\right)\right]^{m}-\exp\left[-\left(\dfrac{t_{\mathrm{i}}}{\eta}\right)\right]^{m}}{\exp\left[-\left(\dfrac{t_{\mathrm{j}}}{\eta}\right)\right]^{m}} \tag{16}$$

where, the numerator represents the probability that a halting failure occurs during [$t_{\mathrm{i-1}}$, t_{i}], and the denominator represents the probability that a non-halting failure reliably does not occur during [$t_{\mathrm{i-1}}$, t_{i}].

Define I_{i} as the mean rank order increment of the non-halting failure t_{j} to the halting failure t_{i} during [$t_{\mathrm{i-1}}$, t_{i}]. The number of t_{j} before t_{i} are M_{i}, increasement of mean rank order to the halting failure can be obtained.

$$I_{\mathrm{i}}=\sum_{j=1}^{M_{\mathrm{i}}}I_{\mathrm{j,i}} \tag{17}$$

In the case of considering t_{j}, the updating mean rank order and the new empirical distribution function are obtained.

$$A_{\mathrm{i}}=A_{\mathrm{i-1}}+1+I_{\mathrm{i}} \tag{18}$$

$$F(t_{\mathrm{i}})=\frac{A_{\mathrm{i}}-0.3}{n+0.4} \tag{19}$$

Based on the above parameter estimates the subsystem reliability function can be obtained.

$$R_{\mathrm{C}}(t)=\exp\left[-\left(\frac{t}{\eta}\right)^{m}\right] \tag{20}$$

Considering the reliability weight allocation of subsystems to the wind turbine, and the reliability distribution function derived from historical failure data. In a series system, the reliability of each subsystem can be designated as follows.

$$R_{\mathrm{Ci}}=R_{\mathrm{ACi}}{}^{\overline{w}_{\mathrm{ACi}}} \tag{21}$$

Formula (22) is used to establish the reliability influence function of subsystem to the wind turbine.

$$R_{\mathrm{ACi}}=\exp\left(\frac{\ln R_{\mathrm{Ci}}}{\overline{w}_{\mathrm{ACi}}}\right) \tag{22}$$

where, R_{ACi} is the reliability function of i^{th} subsystem for the wind turbine. $\overline{w}_{\mathrm{ACi}}$ is the reliability weight allocation factor.

IV. CASE ANALYSIS

This study is to reveal the influence of subsystem reliability on the wind turbine by the reliability weight allocation and reliability function of subsystem. Based on the AGREE method which collects scores from dozens of wind industry experts, establishing the evaluation index on the reliability to three layers in the hierarchical structure. Comparing the degree of influence on reliability under evaluation index, the judgment matrix and the weight allocation factor can be obtained.

For the reliability weight allocation of influencing factor to wind turbine, the evaluation index is acquired by AGREE method are $U = \{u_{B1}, u_{B2}, u_{B3}, u_{B4}, u_{B5}, u_{B6}\}$. The magnitude of the influence on reliability is $u_{B2}>u_{B3}>u_{B1}>u_{B5}>u_{B6}>u_{B4}$, the judgement matrix is acquired by three scales method under this evaluation index.

$$P=\begin{pmatrix} 2 & 1 & 1 & 3 & 3 & 3 \\ 3 & 2 & 3 & 3 & 3 & 3 \\ 3 & 1 & 2 & 3 & 3 & 3 \\ 1 & 1 & 1 & 2 & 1 & 1 \\ 1 & 1 & 1 & 3 & 2 & 3 \\ 1 & 1 & 1 & 3 & 1 & 2 \end{pmatrix}$$

The set of reliability weight allocation for influencing factors to wind turbine shown as follows.

$$W_{AB} = (0.1740,0.2510,0.2090,0.1005,0.1449,0.1207) \quad (23)$$

For the reliability weight allocation of the influencing factors to subsystems, a group expert scores of influencing on reliability are collected by AGREE method as shown in Table I.

TABLE I. INFLUENCE FACTOR SCORES FOR SUBSYSTEMS

	B1	B2	B3	B4	B5	B6
C1	6	8	8	7	6	6
C2	7	8	6	9	6	9
C3	6	7	9	9	7	5
C4	6	8	9	7	7	7
C5	5	8	8	7	6	6
C6	6	7	7	8	6	7

When the expert reliability scores of different influencing factors in the subsystem are the same, for example, the expert scoring of B2 and B3 in C1 are the same, for avoiding the inaccurate allocation of the weights because of the same scores by considering score ratio. The comprehensive score of the subsystem can be calculated by formula (24), the reliability score ratio of the influencing factors for the subsystems can be obtained by (25).

$$\varepsilon_i = \prod_{j=1}^{n} \varepsilon_{ij} \left(i = 1,2,...m\right) \quad (24)$$

$$w_{Ci} = \frac{\varepsilon_i}{\sum_{i=1}^{m} \varepsilon_i} \quad (25)$$

where, ε_i is the comprehensive influencing factors score, w_{Ci} is the influence factor score ratio of subsystem. The set of score ratio is shown as follows.

$$W_C = (0.137,0.231,0.168,0.210,0.114,0.140) \quad (26)$$

From the reliability score ratio to redistribute the expert scoring, the updated evaluation indexes are shown in Table II.

TABLE II. RELIABILITY SCORE RATIO OF SUBSYSTEM

	B1	B2	B3	B4	B5	B6
C1	0.822	1.096	1.096	0.959	0.822	0.822
C2	1.617	1.848	1.386	2.079	1.386	2.079
C3	1.008	1.176	1.512	1.512	1.176	0.84
C4	1.26	1.68	1.89	1.47	1.47	1.47
C5	0.57	0.912	0.912	0.798	0.684	0.684
C6	0.84	0.98	0.98	1.12	0.84	0.98

The data above is taken to define the degree of influence on reliability about subsystem to influencing factors. Under this evaluation index, the magnitude of the effect on reliability weight is shown in Table III.

TABLE III. MAGNITUDE OF INFLUENCE ON RELIABILITY OF SUBSYSTEM

Influence factor	Weight rank					
B1	C2	C4	C3	C6	C1	C5
B2	C2	C4	C3	C1	C6	C5
B3	C4	C3	C2	C1	C6	C5
B4	C2	C3	C4	C6	C1	C5
B5	C4	C2	C3	C6	C1	C5
B6	C2	C4	C6	C3	C1	C5

The magnitude of the influence on reliability of each subsystem to influencing factor is acquired, and the judgement matrix to obtain the reliability weight assignment of layer C to layer B are shown in Table IV.

TABLE IV. WEIGHT OF SUBSYSTEM UNDER INFLUENCING FACTOR

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

Taking subsystem C1 as an example, its reliability weight distribution under six influencing factors is shown as follows.

$$W_{BC1} = (0.1207,0.1449,0.1449,0.1207,0.1207,0.1207) \quad (27)$$

Using AHP to weight combination, multiply the weight allocation W_{AB} and W_{BCi} to get the reliability allocation of subsystems to wind turbine as W_{ACi}.

$$W_{ACi} = W_{AB} W_{BCi}^{\ T} \quad (28)$$

The set of reliability weight allocation is obtained.

$$W_{AC} = (0.131,0.236,0.176,0.217,0.101,0.142) \quad (29)$$

The mean rank order and empirical distribution function can be derived from the steps in part III, and the shape and scale parameter of Weibull distribution can be accurately estimated by the least squares method, substituting the parameters can obtain the corresponding reliability curves, conducting reliability analysis on the subsystems of wind turbines. Under the collection of subsystem failure data for a wind farm, taking the gearbox system as an example and failure data as shown in Table V. T indicates a halting failure, F indicates a non-halting failure.

TABLE V. GEARBOX SYSTEM FAILURE STATUS AND DATA

No	Failure time/day	Failure type	No	Failure time/day	Failure type
1	149.4	T	11	715.8	F
2	180.1	F	12	743.6	F
3	222.9	F	13	762.5	T
4	278.1	T	14	803.4	F
5	329.3	F	15	835.8	F
6	395.7	F	16	860.3	T
7	486.4	T	17	912.6	F
8	564.3	F	18	972.1	T
9	632.9	T	19	1023.5	F
10	671.2	F	20	1120.9	T

The conventional Weibull distribution was used for parameter estimation by removing the non-halting failure data, sorting the downtime fault data by size, and calculating the mean rank order, empirical distribution function and discrete data points, the results are shown in the Table VI.

TABLE VI. PARAMETER RESULTS OBTAINED BY CONVENTIONAL METHOD

A_i	t_i	$F(t_i)$	x	y
1	149.4	0.0343	5.0066	-3.3552
2.11	278.1	0.0887	5.6279	-2.3764
3.37	486.4	0.1505	6.1871	-1.8169
4.73	632.9	0.2170	6.4503	-1.4083
6.53	762.5	0.3056	6.6366	-1.0115
8.95	860.3	0.4238	6.7573	-0.5948
11.96	972.1	0.5723	6.8795	-0.1641
13.48	1120.9	0.6461	7.0219	0.0377

The fitted curve under the conventional method is obtained as shown in Fig.3.

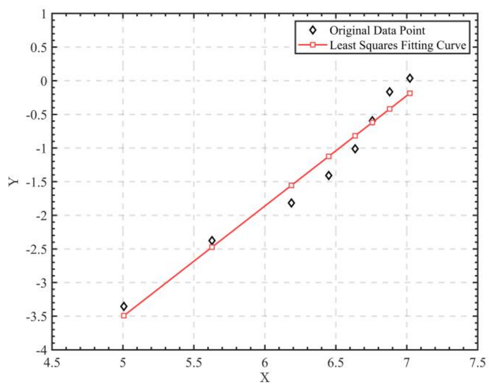

Fig.3. Conventional fitting the regression line

Under the conventional method, the linear correlation of the curve is 0.9508 that calculating by (30). Recalculating of the parameters by adding non-halting failure data, the process of obtaining parameter and methods are as follows.

$$\rho = \frac{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)\left(y_i - \bar{y}\right)}{\sqrt{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2}\sqrt{\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2}} \tag{30}$$

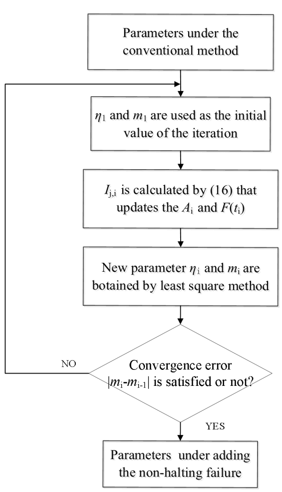

Fig.4. Parameter obtaining process diagram

Under this method, iterative error is satisfied after several iterations, and the new results were shown in Table VII.

Table VII Parameter results obtained by adding non-halting failure

A_i	t_i	$F(t_i)$	x	y
1	149.4	0.0343	5.0066	-3.3552
2.41	278.1	0.1034	5.6279	-2.2151
4.57	486.4	0.2093	6.1871	-1.4489
6.34	632.9	0.2961	6.4503	-1.0467
8.28	762.5	0.3912	6.6366	-0.7007
10.33	860.3	0.4917	6.7573	-0.3906
12.71	972.1	0.6083	6.8795	-0.0648
14.67	1120.9	0.7044	7.0219	0.1978

The fitting curve under the improved method is obtained as shown in Fig.5, and the linear correlation of the curve is 0.9943.

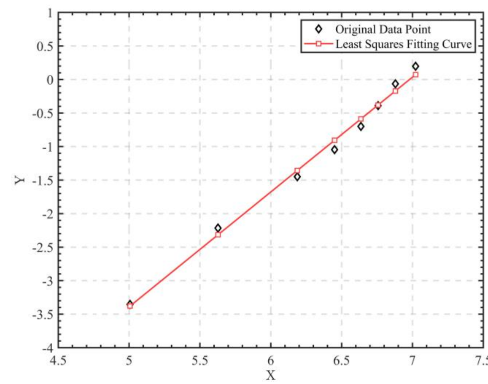

Fig.5. Improved fitting the regression line

Comparing the two curves, there was an increasement in the linear correlation of the curve, which proves that the improved mean rank order method can obtain a regression line with a higher degree of fit. The parameters to the Weibull distribution for the remaining subsystems are as follows.

Table VIII. Shape and scale parameters of the subsystems

subsystem	m	η
pitch system	2.0371	476.9
gearbox system	1.7599	1149.4
generator system	1.6085	1336.8
hydraulic system	1.8564	875.6
frequency conversion system	1.9412	893.7
yaw system	1.4207	1064.5

The reliability influence function of each subsystem and the subsystem on the wind turbine is shown in Table IX.

TABLE IX. RELIABILITY FUNCTION MODEL

i	R_{Ci}	R_{ACi}
1	$\exp\left[-\left(t/476.9\right)^{2.0371}\right]$	$\exp\left[-\left(t/476.9\right)^{2.0371}/0.131\right]$
2	$\exp\left[-\left(t/1149.4\right)^{1.7559}\right]$	$\exp\left[-\left(t/1149.4\right)^{1.7559}/0.236\right]$
3	$\exp\left[-\left(t/1336.8\right)^{1.6085}\right]$	$\exp\left[-\left(t/1336.8\right)^{1.6085}/0.176\right]$
4	$\exp\left[-\left(t/875.6\right)^{1.8464}\right]$	$\exp\left[-\left(t/875.6\right)^{1.8464}/0.217\right]$
5	$\exp\left[-\left(t/893.7\right)^{1.9412}\right]$	$\exp\left[-\left(t/893.7\right)^{1.9412}/0.101\right]$
6	$\exp\left[-\left(t/1064.5\right)^{1.4207}\right]$	$\exp\left[-\left(t/1064.5\right)^{1.4207}/0.142\right]$

The Weibull distribution model of subsystems under this method is calculated, the reliability function is obtained and the curves are as shown in Fig.6.

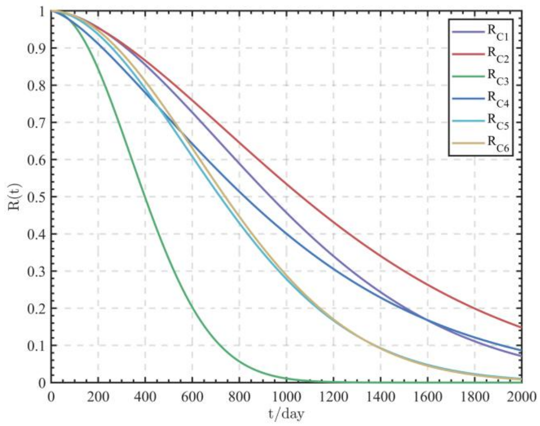

Fig.6. Reliability curves of subsystems

Analyzing the reliability curves of each subsystem reveals that the reliability decline trend of each subsystem is different. Therefore, when the subsystem fails, the influence on the reliability of the wind turbine will be different. Considering the reliability weight allocation of each subsystem to wind turbine, targeted operational and maintenance strategies can be implemented for effective failure trouble-shooting. The reliability influence curve of the subsystem on the wind turbine is shown in Fig.7.

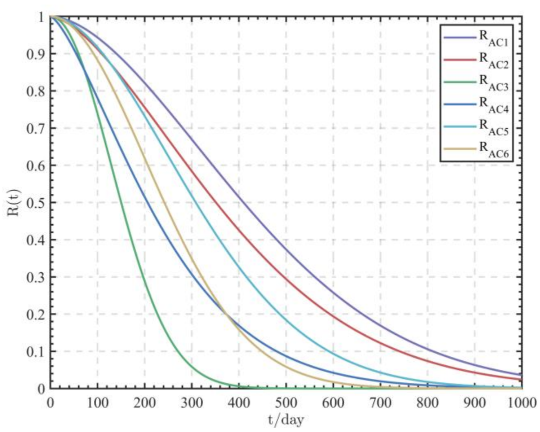

Fig.7. Reliability curves of subsystems influence on wind turbine

From the reliability curves above, it is evident that considering reliability weight assignment of the subsystems to the wind turbine, all of them exhibit a tendency to decrease wind turbine reliability. When assessing the wind turbine reliability based on the subsystems, it is crucial to consider both failure data and expert experience. Meanwhile, it can timely formulate targeted plans and save costs to maintenance, reduce the probability of failure and improve reliability.

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V. CONCLUSION

The main objective of this paper is to find a reliability assessment method considering the index weight and failure influence on reliability of subsystem to wind turbine. The reliability weight allocation for subsystems to the wind turbine are reasonably assigned by three scales AHP method based on the evaluation indexes provided by experts using AGREE method. Collecting the data of halting and non-halting failures, researching the influence of non-halting failures on the mean rank order of halting failures. Furthermore, the parameters of the Weibull distribution model are estimated using the least-squares method. The comparative analysis reveals that a more accurate parameter estimation can be achieved and modeled the reliability of each subsystem. Evaluating the reliability of the wind turbine by combining the reliability index weights of the subsystems to the wind turbine and using the reliability model of the subsystems, which can specify a more cost-effective maintenance program in a targeted manner.

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