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Identification and Effect Analysis of the Weak Parts of Large-Scale Wind Energy Conversion System Using the Reliability Tracing Technique

***Abstract**. Wind energy conversion system (WECS) is complex and multi component. The key to optimizing and improving WECS is the identification of its weak part. Based on the reliability tracking technique, the reliability-tracking model of WECS is proposed in this paper. The contribution of each subassembly to the reliability indices of WECS is calculated. According to the identification and analysis of the weak parts of WECS based on different reliability indices, annual losses due to forced outage are proposed to be the reasonable index for weak part identification because it can comprehensively reflect the reliability and economic performance of the WECS. Finally, the effects of improving the reliability of all subassemblies on the losses due to forced outage are analyzed. The present case study shows that the gearbox is the weakest part of a double-fed WECS. The correctness and validity of the proposed model are also verified.*

Streszczenie.** W artykule zaproponowano układ śledzący do systemów WECS (systemy konwersji energii wiatrowej). Układ analizuje niezawodność poszczególnych elementów systemu i wykrywa słabe punkty. Przeanalizowano wpływ systemu na straty. (**Identyfikacja słabych elementów systemu konwersji energii wiatrowej o dużej skali wykorzystująca metodę śledzenia niezawodności)

Keywords: wind energy conversion system; reliability tracing; weak part; loss due to forced outage; index sharing
Słowa kluczowe: energia wiatrowa, niezawodność, straty

I. Introduction

Wind energy conversion system (WECS) is complex and multi component [1–7]. WECS has a complex structure, multi-disciplinary intercross, and energy from continuous conversion, which contains many subassemblies, such as blade, hub, pitch system, yaw system, gearbox (except in direct-drive WECS), wind turbine generator, electric system, and control system. At present, the typical system for large-scale WECS includes the double-fed variable speed WECS and direct-drive WECS with a permanent magnet synchronous generator, as shown in Figs. 1 and 2, respectively. Different subassemblies of WECS have different effects on system reliability and economic indices, such as failure rate, availability, and losses due to outage, and so on. To determine the key subassembly resulting in system unreliability, and identify the weakest part of the system, the current study proposes the quantification of the distributions of different subassemblies to the system indices based on the power system reliability tracing in Refs. [8–10]. However, identification of the system's weak part based on only the reliability index on the probability or frequency is insufficient for WECS because the losses resulting from a system outage due to different subassemblies are very different [11–14]. Therefore, the economic loss resulting from system unavailability due to subassembly unreliability should be considered.

Reliability tracing is an important technique in identifying the weak part of a system. However, references on WECS reliability tracing and weak part identification are few. Available references are mainly focused on the control strategies and effects of wind power permeation on power system [15–20]. With increasing rated capacity of WECS, failure forced outage has more evident effects on the benefits of the grid operators, wind power producers, and other stakeholders. Therefore, seeking the key index that could determine the weak part of WECS and its decomposition method is of great significance in identifying its weak parts for the improvement and optimization of the system design.

This paper proposes the Annual Forced Outage Loss (AFOL) of WECS as a suitable and reasonable index for the identification of its weak parts because it can comprehensively reflect the reliability and economy performances of WECS. Based on the reliability tracing technique, the sharing model of the system index is presented to evaluate the contributions of different subassemblies in WECS. The present study identifies the weak parts in WECS and analyzes the effects of improving subassembly reliability on the system's indices. The proposed method and technique provide a theoretical basis for optimizing the system design and determining the key maintenance subassembly.

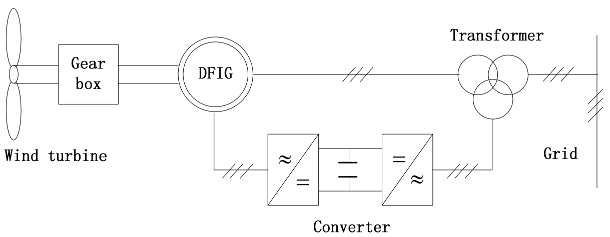

Fig.1. Wind energy conversion system with a double-fed induction generator

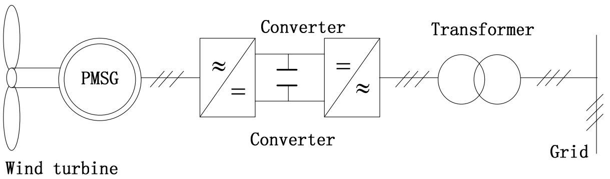

Fig.2. Direct-drive wind energy conversion system with a permanent magnet generator

II. WECS reliability tracing

A. Reliability tracing principles

In studies on power system reliability, two reliability-tracing principles are considered [8–10]:

(1) Failure component sharing principle. Healthy components have no responsibility for system outage. Therefore, they do not "contribute" to system unreliability.

(2) Proportional sharing principle (PSP). The reliability indices are proportionally distributed among all system components, according to the PSP described in Refs. [9, 10]. The PSP basically assumes that the system is a perfect "mixer" of every term; thus, identifying which particular term will go into another particular term is impossible. The

principle is fair because it treats all components similarly. In other words, no particular term is distinguished in any way.

These two principles have similar symmetries and identities, and can realize reliability index entire sharing. Therefore, the present study followed these principles in WECS reliability tracing.

B. Reliability tracing model

Based on the reliability tracing principles, the WECS reliability index sharing method can be described as follows.

Assuming that a WECS consists of n components X_i(i= *1, 2,⋯, n*), let $F(x_1, x_2, \cdots, x_n)$ represent its reliability index, such as failure rate, forced outage probability (FOP), and forced outage loss (FOL). x_i(i= *1, 2, ⋯, n*) represents the performance parameter of component X_i. For example, a failure state k resulting from two components X_1 and X_2 is considered to explain the reliability sharing technology. $F(x_1, x_2, \cdots, x_n)$ is assumed to be divided into three separate terms, as shown in Equation (1).

(1) $$F\left(x_1,x_2,\cdots,x_n\right)=F_1\left(x_1\right)\cdot F_2\left(x_2\right)\cdot\sigma\left(x_3,x_4,\cdots x_n\right)$$

where the first term $F(x_1)$ is related only to X_1, the second term $F(x_2)$ is related only to X_2, and the third term $\sigma(x_3, x_4, \cdots, x_n)$ is related to the rest of the components.

$F(k\rightarrow 1)$ and $F(k\rightarrow 1)$ are used to represent the shared reliability indices of components X_1 and X_2 [8].

(2) $$F\left(k\rightarrow 1\right)=\frac{F_1\left(x_1\right)}{F_1\left(x_1\right)+F_2\left(x_2\right)}F\left(x_1,x_2,\cdots,x_n\right)$$

(3) $$F\left(k\rightarrow 2\right)=\frac{F_2\left(x_2\right)}{F_1\left(x_1\right)+F_2\left(x_2\right)}F\left(x_1,x_2,\cdots,x_n\right)$$

By parity of reasoning, if all components in set A are responsible for a failure state k, then the shared reliability index of component X_i can be represented as follows:

(4) $$F\left(k\rightarrow i\right)=\frac{F_i\left(x_i\right)}{\sum_{j\in A}F_j\left(x_j\right)}F\left(x_1,x_2,\cdots,x_n\right)$$

Particularly, if system index $F(x_1, x_2, \cdots, x_n)$ can be divided directly into

(5) $$F\left(x_1,x_2,\cdots,x_n\right)=\sum_{i=1}^{n}F_i\left(x_i\right)$$

Then the shared reliability index of component X_i can be represented directly as follows:

(6) $$F\left(k\rightarrow i\right)=\frac{F_i\left(x_i\right)}{\sum_{j=1}^{n}F_j\left(x_j\right)}$$

Evidently, Equations (4) and (6) meet the identity of proportional sharing.

(7) $$\sum_{i\in A}F(k\rightarrow i)=F\left(x_1,x_2,\cdots,x_n\right)$$

C. Reliability tracing indices of WECS

In the reliability evaluation of WECS, common reliability indices include the failure rate λ, FOP P_f, annual losses due to outage L_o, and so on.

a. Sharing of system failure rate

In a WECS, system failure rate can be represented as follows:

(8) $$\lambda=\sum_{i=1}^{n}\lambda_i$$

where λ_i represents the failure rate of subassembly i in a WECS. According to Equation (6), when failure state k occurs, the shared failure rate of subassembly i can be calculated by

(9) $$\lambda\left(k\rightarrow i\right)=\lambda_i$$

b. Sharing the probability of a system failure state

Assuming that the outage probabilities of components X_i and X_j are p_i and p_j, respectively, then sets A and B are the sets of failure and healthy components, respectively. Therefore, the probability of a WECS failure state k can be calculated by

(10) $$P_f\left(k\right)=\prod_{i\in A}p_i\prod_{j\in B}\left(1-p_j\right)$$

According to Equation (4), the shared system failure probability of component X_i can be calculated by

(11) $$\begin{cases}P_f\left(k\rightarrow i\right)=p_i\Big/\sum_{j\in A}p_j\cdot P_f\left(k\right), & i\in A\\ P_f\left(k\rightarrow i\right)=0, & j\in B\end{cases}$$

Assuming that C represents the set of the forced outage states of a WECS and P_f is the probability of system forced outage due to failure, then the shared probability index of component X_i can be calculated by:

(12) $$P_{f,i}=\sum_{k\in C}P_f(k\rightarrow i)$$

c. Sharing the WECS failure FOL

Outage loss is an important index in the WECS reliability evaluation, an important part of the WECS operation cost, and the main basis for system assessment. The WECS failure FOL consists of the wind energy loss due to system outage and repair cost (RC), such as labour, replaced component, and transporting costs. A large difference exists in the RC of different subassemblies in a WECS [12]. Thus, sharing the system forced outage loss considering the reliability of subassembly is necessary. Therefore, failure FOL is a suitable index for the identification of a WECS's weak part because it reflects not only reliability performance, but also economic information of WECS and its subassemblies.

The AFOL resulting from the system failure state k can be represented as follows:

(13) $$L_o\left(k\right)=L_E\left(k\right)+L_{R,A}\left(k\right)$$

where $L_E(k)$ and $L_{R,A}(k)$ represent the annual wind energy losses (AWEL) resulting from system failure state k and the cost of restoring the system from state k, respectively. $L_E(k)$ can be calculated by the following equation:

(14) $$L_E\left(k\right)=P_f\left(k\right)\times E_a\times I$$

where $P_f(k)$ is the probability of the WECS state k, Ea is the annual available generating energy of a completely reliable WECS, and I is the wind power electricity price. In addition, $L_{R,A}(k)$ can be calculated as follows:

(15) $$L_{RA}\left(k\right)=P_f\left(k\right)\left(\sum_{i\in A}\lambda_i+\sum_{j\in B}\mu_j\right)\times L_{R,P}\left(k\right)$$

where $L_{R,P}(k)$ is the cost of restoring the system from failure state k per time, and A and B represent the sets of failure and healthy components, respectively. By substituting Equation (10) into (15), the following equation can be obtained:

(16) $$\begin{aligned}L_{RA}\left(k\right)&=\prod_{i\in A}p_i\prod_{j\in B}\left(1-p_j\right)\\&\times\left(\sum_{i\in A}\mu_i+\sum_{j\in B}\lambda_j\right)\times L_{R,P}\left(k\right)\end{aligned}$$

According to the reliability tracing principles, the contribution of component X_i to the AFOL L_o resulting from system failure state k can be calculated by:

(17) $$L_o(k \to i) = L_E(k \to i) + L_{RA}(k \to i)$$

where

(18) $$L_E(k \to i) = E_a \times I \times P(k \to i)$$

Let:

(19) $$\theta(k) = \prod_{i \in A} p_i \prod_{j \in B}(1 - p_j) \times \left(\sum_{i \in A}\mu_i + \sum_{j \in B}\lambda_j\right)$$

then

(20) $$L_{RA}(k \to i) = \theta(k) \times L_{R,P}(k \to i)$$

According to Equation (6), the $L_{R,P}(k)$ can be calculated by

(21) $$L_{R,P}(k \to i) = C_i \Big/ \sum_{j \in A} C_j$$

where C_i and C_j are the RCs of components X_i and X_j per time, respectively.

III. WECS weak part identification

As described above, to quantify the responsibilities of all components for WECS forced outage can be implemented based on the reliability tracing technique. The shared system index of every component can be calculated using the proposed models. The WECS weak part corresponding to a reliability index can be recognized by sorting through the share of every component on this reliability index. The process for identifying the weak part of a WECS is shown in Fig. 3.

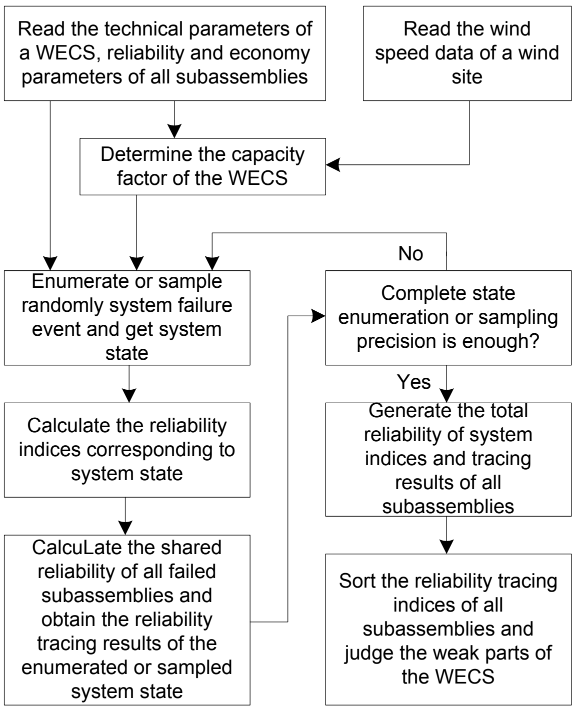

Fig.3. Flow chart of weak part identification for a wind energy conversion system

IV. Numerical examples

To verify the proposed WECS reliability tracing and weak part identification methods, this paper analyzed a double-fed WECS with the rated capacity of 3 MW. The capacity factor is assumed to be 0.3. The failure rates and repair time of all subassemblies in the WECS presented by the German Wissenschaftliches Mess-und Evaluierungs Programm (WMEP) were used, which is given in Table 16 in Ref. [11] and shown in Table 1 in this paper. The failure rate of the gearbox in Table 1 is larger than that presented by the WMEP because the WECSs in the WMEP include some direct-drive systems. As mentioned in section II-C, a larger difference exists in the RCs of a WECS's different subassemblies. This difference is affected by many factors, such as repair time, whether in the use of large-scale hoisting equipment or cost of spare component. The present paper assumes the WECS subassembly RC per time (Table 1) by combining the subassembly repair time in Table 1 with relative information on the WECS subassembly RC in [12]. In addition, the wind power electricity price is assumed to be 0.6 RMB/kWh.

Table 1. Reliability parameters and RC of some subassemblies in a doubly-fed wind energy conversion system [11-12]

Subassembly	Failure Rate (occ./year)	Repair time (Hour)	RC (10^4RMB/occ.)
Hub	0.11	85.8	4.5
Blades/Pitch	0.17	99.4	50
Generator	0.10	179.2	20
Electrical system	0.55	36.4	2.0
Control system	0.41	45.8	2.5
Drive train	0.05	137.3	7.5
Sensors	0.24	35.8	2.0
Gears	0.15	153.3	70
Mechanical brakes	0.13	64.8	3.5
Hydraulics	0.23	28.4	1.5
Yaw system	0.18	64.6	3.5
Structure	0.09	79.7	4.5

A. Results and analysis

The reliability evaluation and tracing results of a double-fed WECS are given in Table 2.

Table 2. Reliability evaluation and tracing indices of a doubly-fed wind energy conversion system

Subassembly	Failure rate (occ./year)	FOP	AFOL（10^4RMB）
WECS	2.41	0.0176	35.0
Hub	0.11	0.0011	1.00
Blades/Pitch	0.17	0.0019	9.47
Generator	0.10	0.0020	3.02
Electrical system	0.55	0.0023	2.16
Control system	0.41	0.0021	2.03
Drive train	0.05	0.0008	0.75
Sensors	0.24	0.0010	0.94
Gears	0.15	0.0026	12.0
Mechanical brakes	0.13	0.0010	0.91
Hydraulics	0.23	0.0007	0.69
Yaw system	0.18	0.0013	1.25
Structure	0.09	0.0008	0.78

The tracing results corresponding to different indices in Table 2 are sorted in descending order and listed in Tables 3, 4, and 5, respectively.

Table 3. Indices of failure rate tracing

Sorting	Subassembly	Failure rate sharing (occ./year)	Responsibility (%)
1	Electrical system	0.55	22.82
2	Control system	0.41	17.01
3	Sensors	0.24	9.96
4	Hydraulics	0.23	9.54
5	Yaw system	0.18	7.47
6	Blades/Pitch	0.17	7.05

7	Gears	0.15	6.22
8	Mechanical brakes	0.13	5.39
9	Hub	0.11	4.56
10	Generator	0.10	4.16
11	Structure	0.09	3.74
12	Drive train	0.05	2.08

Table 4. Indices of forced outage probability tracing

Sorting	Subassembly	FOP sharing	Responsibility (%)
1	Gears	0.0026	14.83
2	Electrical system	0.0023	12.91
3	Control system	0.0021	12.11
4	Generator	0.0020	11.55
5	Blades/Pitch	0.0019	10.89
6	Yaw system	0.0013	7.48
7	Hub	0.0011	6.07
8	Sensors	0.0010	5.52
9	Mechanical brakes	0.0010	5.42
10	Structure	0.0008	4.61
11	Drive train	0.0008	4.41
12	Hydraulics	0.0007	4.20

Table 5. Indices of annual forced outage losses tracing

Sorting	Subassem -bly	AFOL sharing (10^4RMB)			Responsib -ility (%)
		AWEL	RC	Total	
1	Gears	1.23	10.7	12.0	34.20
2	Blades /Pitch	0.90	8.57	9.47	27.08
3	Generator	0.96	2.06	3.02	8.64
4	Electrical system	1.07	1.09	2.16	6.19
5	Control system	1.00	1.02	2.03	5.79
6	Yaw system	0.62	0.63	1.25	3.58
7	Hub	0.50	0.50	1.00	2.87
8	Sensors	0.46	0.48	0.94	2.68
9	Mechanica l brakes	0.45	0.46	0.91	2.59
10	Structure	0.38	0.41	0.78	2.26
11	Drive train	0.37	0.38	0.75	2.14
12	Hydraulics	0.35	0.34	0.69	1.98

The following conclusions can be drawn from the results in Tables 3, 4, and 5.

1) Based on the different system indices, the recognized weakest part of a WECS may be different. In Table 3, the weakest part is the electrical system, based on failure rate. However, in Tables 4 and 5, the system's weakest parts, based on the FOP or AFOL, are the gears. In addition, based on the different indices, a large difference exists in the sorting positions of the shared indices of all subassemblies. For example, the sensors and hydraulics are third and fourth, respectively, in the sort by failure rate sharing. However, in the sort by FOP and AFOL sharing, their positions change into the eighth and twelfth.

2) Based on the different system indices, each subassembly has a different responsibility rate for system unreliability. For example, the responsibility rates of the electrical system for system unreliability are 22.82%, 12.91%, and 6.19% according to failure rate, FOP, and AFOL sharing, respectively.

3) The AWEL of a WECS is positive to outage probability. However, Table 5 shows that the AWEL sharing indices for first three subassemblies are very small compared with those in the total AFOL sharing indices. This means that the RC makes up a larger percentage of the AFOL and affects the economic performance of a WECS. Therefore, the effect of RC must be considered in identifying the WECS's weak part. In addition, the AFOL of a WECS can reflect the reliability information of FOP, failure rate, and repair time through the AWEL.

Based on the former analysis, selecting the AFOL as an index of WECS weak part identification is suitable and reasonable. The AFOL contains not only the reliability information, but also the economic information of a WECS. From the AFOL sharing of subassemblies, as shown in Table 5, the weakest part of the double-fed WECS is the gearbox.

B. Reliability improvement effect analysis

To analyze the effect of the improvement in the reliability of every subassembly, the system indices are evaluated when the failure rate of a subassembly in a double-fed WECS is changed into half of that given in Table 1. The results are listed in Table 6.

Tab.6 System indices after changing failure rate of subassembly in a doubly-fed WECS

Subassembly changed failure rate	Failure rate (occ./y)	FOP	AFOL (10^4RMB)
Raw system	2.410	0.0176	34.98
Gearbox	2.335	0.0163	29.01
Blades/Pitch	2.325	0.0166	30.24
Generator	2.360	0.0165	33.48
Electrical system	2.135	0.0164	33.83
Control system	2.205	0.0165	33.92
Yaw system	2.320	0.0169	34.33
Hub	2.355	0.0170	34.47
Sensors	2.290	0.0171	34.48
Mechanical brakes	2.345	0.0171	34.52
Structure	2.365	0.0172	34.58
Drive train	2.385	0.0172	34.61
Hydraulics	2.295	0.0172	34.61

Table 6 shows that improvement in the reliability of each subassembly can improve the system indices. However, different subassemblies have different effects. The subassembly with the best effect on system indices FOP and AFOL is the gearbox, which is the weakest part in a double-fed WECS. The sort by reliability improvement effect is in accordance with the sort by WECS weak parts in the AFOL index.

Notably, the proposed method for weak part identification is not confined to the system's structure; it can be used to recognize the weak part of a permanent magnet direct-drive WECS or its subassemblies.

V. Conclusions

This paper recommends the AFOL as the key index in the identification of a WECS's weak part, according to its characteristics. Based on the reliability tracing technique, the AFOL sharing model in a WECS is presented. The proposed method and model provide a quantitative analysis method for WECS weak part identification based on the subassembly failure rate and forced outage loss.

The identification of WECS weak parts in a wind farm can provide the foundation for the operators to determine the key subassemblies that should be monitored intensively. At the same time, it can also provide the useful information for the manufacture through the information feedback to optimize the system design scheme to improve the WECS reliability performance. The failure rates of WECS and its subassemblies are affected by wind speeds and operating conditions. A given WECS, therefore, maybe have different weak parts and their effects in different wind farms. However, it is possible to recognize the weak parts of a specific WECS using the proposed methodology by collecting the reliability data and relational forced outage loss in time.

The current case study on a double-fed WECS of 3 MW shows that the gearbox, blade/pitch, and generator are the weaker parts, which should be given great attention during system reliability design, operation, and maintenance.

Nomenclature

AFOL	Annual Forced Outage Loss
AWEL	Annual Wind Energy Loss
FOL	Forced Outage Loss
FOP	Forced Outage Probability
PSP	Proportional Sharing Principle
RC	Repair Cost
WECS	Wind Energy Conversion System
WMEP	Wissenschaftliches Mess-und Evaluierungs Programm

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