Research on Opportunity Maintenance Strategy of Wind Turbines Based on Incomplete Maintenance

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Abstract. Aiming at the problem of single maintenance method and high cost of wind turbines, an opportunity maintenance strategy for wind turbines based on incomplete maintenance is proposed. Firstly, based on the historical fault data of the equipment operation, the reliability of each component of the wind turbine is modeled using Weibull distribution, and the service life regression factor and failure rate increasing factor is introduced to build the incomplete maintenance strategy model of the wind turbine. Secondly, according to the opportunity maintenance theory and the reliability requirements of wind turbine components, determine the preventive maintenance reliability threshold and the opportunity maintenance reliability threshold of each component, and adopt three types of maintenance methods: incomplete repair, opportunity repair and replacement of key components within the opportunity repair interval. Based on this, a multi-component opportunity maintenance model for wind turbines based on incomplete maintenance and its decision process are constructed. Finally, the model was simulated and verified through specific wind turbine maintenance cases, and the model was solved using genetic algorithms to determine the optimal opportunity maintenance strategy. Simulation results show that the strategy can coordinate the maintenance time of various components, realize the simultaneous maintenance of multiple components, improve maintenance efficiency, and reduce maintenance costs, thereby verifying the effectiveness of the proposed strategy.

1. Introduction

As a renewable energy, wind energy has the characteristics of wide distribution, high efficiency, and cleanliness, and has gradually developed into an indispensable alternative energy source. In the 1970s, China's development and utilization of wind energy were included in national key projects, and it has developed rapidly. In the 21st century, China has increased investment in the development and utilization of wind energy, so that wind energy has a place in China’s energy structure.

The wind turbine is a typical complex series repairable system. The working environment is complex. Failure of any component can lead to the shutdown of the wind turbine. So it has high wind turbine maintenance costs due to high fixed maintenance costs and frequent maintenance. According to the statistics of the European Wind Power Association, the maintenance cost of each wind turbine accounts for 15% to 25% of its total life-cycle cost. Therefore, formulating a scientific maintenance strategy is one of the keys to reducing the operating costs of wind turbines. At present, many scholars have carried out a lot of research on the maintenance methods of wind turbines, and have proposed a variety of maintenance methods such as after-the-fact maintenance, condition-based preventive
maintenance, and opportunity maintenance. Zhao et al. [1] based on the degradation of each component, defined condition indicators to characterize the operating status of each component and set the opportunity maintenance threshold to achieve minimal maintenance costs. Duan et al. [2] introduced the factors that reduce the lifespan, which can effectively describe the incomplete maintenance of repairable equipment, proposed an improved quantitative age formula; the calculation and demonstration are carried out in the maintenance of wireless relay equipment. Hou et al. [3] proposed an opportunistic maintenance strategy for a multi-unit series production system based on the analysis of the failure rate and derived the optimal preventive maintenance program. Based on the opportunity maintenance theory, Abdollahzadeh H et al. [4] established an optimization model of a multi-target wind turbine based on considering imperfect maintenance. Lu et al. [5] proposed an opportunistic repair method for offshore wind turbines and calculated the optimal threshold to minimize long-term maintenance costs. Li et al. [6] established the objective function of minimum unit maintenance cost per unit with the reliability of the single piece of the wind turbine as a constraint and obtained the optimal maintenance period and time. Zhou et al. [7] proposed a dynamic state-based opportunistic maintenance strategy, which reduces the annual maintenance cost of wind turbines. Xie [8] introduced an opportunistic maintenance strategy in the maintenance of wind turbines to reduce maintenance costs by optimizing the preventive maintenance age and the opportunistic maintenance age.

The above scholars have done a lot of research and analysis on the incomplete maintenance and opportunity maintenance of the equipment. However, it does not combine the incomplete maintenance status and the opportunity maintenance theory in line with the actual maintenance of the equipment, which is inconsistent with the actual maintenance status of the equipment. Therefore, this paper uses incomplete maintenance to describe the maintenance status of wind turbines. Based on this, an opportunistic maintenance strategy is developed, and the genetic algorithm is used to find the optimal opportunity maintenance reliability to meet the maintenance plan with the smallest maintenance cost. Through simulation results verify the effectiveness of the scheme.

2. Construction of incomplete maintenance model for wind turbine

Incomplete maintenance means that the reliability of the component cannot reach the initial state after maintenance activities. Slightly lower than before, the failure rate will increase slightly and maintain characteristics consistent with components in actual maintenance activities. To show the actual characteristics of maintenance activities, the service life regression factor $\mu_i$ and the failure rate increasing factor $\alpha_i$ are introduced to describe the process of incomplete maintenance. The service life regression factor $\mu_i$ ($0 < \mu_i < 1$) indicates that the service life of the component has fallen back by a period compared to the service life before maintenance. The level of reliability after repair returns to a certain period before the repair; the failure rate increasing factor $\alpha_i$ ($\alpha_i > 1$) indicates that the failure rate of the component after repair will increase to a certain extent compared to the initial state of each repair.

The wind turbine is a typical series system. Due to the complicated operating environment of the equipment, the structure of the wind turbine is simplified in this paper. Only the series system consisting of the gearbox, main bearing, generator and blade is studied. The maintenance process is a "repair non-new" process, so a mixed failure rate evolution process based on two adjustment factors is used to establish an incomplete maintenance model.

The failure rate relationship of the incomplete repair model is defined as follows:

$$h_{(i+1)}(t) = \alpha_i h_i \left(t + \mu_i T_i\right) \quad t \in (0, T_{(i+1)})$$

In equation (1), $i$ represents the number of incomplete cycles, $i = 1, 2, \ldots, N$, $N$ is the number of incomplete repairs, $h_{(i+1)}$, $h_i$ is the distribution functions of the $i + 1$ and $i$ failure rates; $T_i$ is the time interval between $i$ and $i + 1$ incomplete repairs.
2.1 Determination of reliability and failure rate of wind turbine

Analysis of historical fault data based on equipment operation and inspection of related literature. It can be concluded that the degradation process of the four main components obeys the two-parameter Weibull distribution, and the failure distribution density function of the component is:

$$f(t) = \frac{\beta t^{\beta-1}}{\eta^{\beta}} \exp \left(\frac{t - \eta}{\eta}\right)$$  \hspace{1cm} (2)

In equation (2), $t$ is the actual operating time of the component; $\beta$ is the shape parameter of the two-parameter Weibull distribution, and $\eta$ is the scale parameter.

The failure distribution function is:

$$F(t) = 1 - \exp \left(\frac{t - \eta}{\eta}\right)$$  \hspace{1cm} (3)

The reliability function is:

$$R(t) = 1 - F(t) = \exp \left(\frac{t - \eta}{\eta}\right)$$  \hspace{1cm} (4)

From equation (1) and equation (3), the formula for the failure rate is:

$$h(t) = \frac{f(t)}{R(t)} = \frac{\beta}{\eta} \left(\frac{t}{\eta}\right)^{\beta-1}$$  \hspace{1cm} (5)

According to the set maintenance strategy, the component is repaired when the reliability of the component reaches the preventive maintenance reliability threshold $R_p$, so the reliability equation is:

$$\exp \left[ -\sum_{i=1}^{T_i} h_i(t) \right] = \exp \left[ -\sum_{i=0}^{T_i} h_0(t) \right] = \cdots = \exp \left[ -\int_0^{T_i} h_i(t) \, dt \right] = R_p$$  \hspace{1cm} (6)

The above formula can be transformed into:

$$\int_0^{T_i} h_i(t) \, dt = \int_0^{T_i} h_2(t) \, dt = \cdots = \int_0^{T_i} h_i(t) \, dt = -\ln R$$  \hspace{1cm} (7)

Using equation (5) and equation (7), the maintenance period $T_i$ for incomplete maintenance can be solved.

2.2 Determination of service life regression factor and failure rate increasing factor for wind turbines

It is assumed that the service life regression factor $\mu_i$ and the failure rate increasing factor $\alpha_i$ of each component are equal. By analyzing the historical failure rate of each component, the failure rate fitting method can be used to obtain [9],

$$\mu_i = \frac{i}{5i + 9}$$  \hspace{1cm} (8)

$$\alpha_i = \frac{13i + 1}{12i + 1}$$  \hspace{1cm} (9)
To calculate the failure rate $h_i(t)$ under different maintenance times, the service age regression factor $\mu_i$ and the failure rate increasing factor $\alpha_i$ are substituted into equation (1), and then substituting them into equation (7) to obtain the maintenance interval $T_i$ of incomplete maintenance.

3. Opportunity maintenance of wind turbine based on incomplete maintenance

3.1 Opportunity maintenance strategy

Downtime maintenance of wind turbines will generate huge costs. The starting point of the opportunity maintenance strategy is to save equipment downtime costs. When a system component is repaired once, other components are just in the corresponding opportunity maintenance interval. At the same time, it can repair multiple parts, share the cost of downtime, labor costs, etc., and reduce equipment maintenance costs from an overall perspective. The key to the opportunity maintenance strategy is the determination of the opportunity maintenance reliability $R_0$, if the opportunity maintenance reliability $R_0$ is set too large, the preventive maintenance of components will be advanced, and the number of maintenance will be increased, resulting in excess maintenance and wasting maintenance resources. If the opportunity maintenance reliability $R_0$ is set too small, the node for preventive opportunity maintenance will be delayed, making its preventive maintenance close to regular maintenance, and it will not reasonably reduce the maintenance cost of components. Therefore, the significance of the opportunity maintenance strategy is lost, and a scientific and reasonable opportunity maintenance model is needed to solve the opportunity maintenance reliability $R_0$. The principle of opportunistic repair is shown in Figure 1. $I, J, K$ are the reliability curves of different parts. $R_0$ is the reliability of opportunity maintenance and $R_p$ is the reliability of preventive maintenance. It is assumed that the $R_p$ of each component is the same.

For component $J (J = 1, 2, J_o)$, when its running time $t_j$ reaches $t_j = T'_p$, Preventive maintenance.

For component $I (I = 1, 2, I_o)$, when component $J$ is undergoing preventive maintenance, the opportunity maintenance interval $T_o$ of $I$ satisfies. When $T'_o < t_j < T'_p < T_p$, Opportunities for parts $I$ can be repaired when $J$ parts are repaired.

For component $K (K = 1, 2, I_K)$, the time node $t_j = T'_p$ for preventive maintenance of component, $J$ does not fall within the opportunity maintenance interval $[T'_o, T'_p]$ of component $K$. Opportunity to repair parts $K$ is not allowed.

![Figure 1. Schematic of opportunity maintenance](image)

3.2 Model assumptions
The operating environment of wind turbines is complex. To simplify the problem and analysis process, the following basic assumptions are made for wind turbines:

1. Each component of the wind turbine is completely new on time. The fault distribution of each component conforms to the two-parameter Weibull distribution and is independent of each other.

2. When the reliability of the component reaches the set preventive maintenance reliability value, incomplete repair or replacement activities are performed on the component: replacement can change the reliability of the component to a new state, and incomplete maintenance will cause the state of the component Improved but not completely new.

3. The wind turbine belongs to a series system. The maintenance of any component will cause the machine to stop. Opportunity maintenance will only occur at the time when the component is incompletely repaired or the component is replaced.

4. Only the economic correlation between components is considered during component operation time, and the fault correlation and structural correlation between components are not considered. Only the coordination relationship between incomplete repair, opportunity repair and replacement is considered.

5. Maintenance resources can guarantee the progress of maintenance activities, no need to consider the limitations of maintenance resources.

3.3 Opportunistic maintenance model of wind turbine with multiple components based on incomplete maintenance

Wind turbines generally use regular maintenance methods, and their total cost maintenance model:

\[ C_T = \sum_{k=1}^{n} \left( C_0 + C_p^{(k)} \right) M_p^{(k)} + C_e^{(k)} M_e^{(k)} \]  \hspace{1cm} (10)

In equation (10), \( C_T \) is the total cost of regular preventive maintenance within the specified operating time, \( C_0 \) is the fixed maintenance cost (labor cost, material cost, downtime loss cost, etc.), and \( C_p^{(k)} \) is the single periodic maintenance cost of component \( k \). Cost, \( C_p^{(k)} \) is the single replacement cost of component \( k \); \( M_p^{(k)} \) is the number of repairs within the specified operating time, \( M_p^{(k)} = T/T_p^{(k)} \), where \( T \) is the planned operating time of the unit, \( T_p^{(k)} \) is the maintenance cycle of component \( k \); \( M_e^{(k)} \) is the number of replacements of component \( k \). According to related data, component \( k \) chooses the next maintenance method after the amount of maintenance.

The purpose of introducing opportunistic maintenance is based on the maintenance coordination. The key components within the opportunistic maintenance interval adopt three types of repair methods: incomplete repair, opportunistic repair, and replacement. The order of maintenance of each component is optimized to reduce frequent maintenance. Downtime and labor costs. Considering only the economic correlation between components, the opportunity maintenance strategy model based on incomplete maintenance during the planned operating time is:

\[ \text{Min} C_{op} = \sum_{k=1}^{n} \left[ \left( C_0 + C_p^{(k)} \right) M_p^{(k)} + C_e^{(k)} M_e^{(k)} + C_r^{(k)} M_r^{(k)} \right] \]  \hspace{1cm} (11)

s.t. \( 0 < M_p^{(k)} < M_{e}^{(k)} < 1 \)  \hspace{1cm} (12)

\[ R_p^{(k)} + \Delta R = R_0^{(k)} \]  \hspace{1cm} (13)

In equation (11), \( k = 1, 2, \ldots, n \) are different parts, \( C_{op} \) is the total maintenance cost of the opportunity repair model, and \( C_r^{(k)} \), \( C_e^{(k)} \), and \( C_i^{(k)} \) are the incomplete parts \( k \). Maintenance costs, opportunity maintenance costs, and replacement costs; \( M_r^{(k)} \), \( M_i^{(k)} \), and \( M_e^{(k)} \) are the incomplete repair
times, opportunity repair times, and replacement times for component $k$, respectively. Opportunistic maintenance strategy solves $M_r^{(k)}$, $M_j^{(k)}$, $M_e^{(k)}$ within a specified time; (12), (13) are the reliability constraints of the parts.

### 3.4 Model decision process

The flow chart of the maintenance decision-making process based on the opportunity of incomplete maintenance of the wind turbine is shown in Figure 2.

**Figure 2.** Opportunity maintenance decision process based on incomplete maintenance

In the opportunistic maintenance strategy model, the objective function is not an explicit function of the opportunistic maintenance reliability threshold $\Delta R$, so a fitting process is needed to further obtain the functional relationship between $\Delta R$ and $C_{op}$, that is, for each given $\Delta R$, a $C_{op}$ is calculated. Several points are obtained, and these points containing information are used for fitting by Excel software, and the fitting function is optimized by a genetic algorithm to obtain the best $\Delta R$, and then the corresponding minimum maintenance cost is solved.

### 4. Case study

#### 4.1 Wind turbine parameters

In this paper, a 1.5MW wind turbine is selected as the research object to verify the established model. The entire unit can be simplified into a series system of four key components, namely the blade, the main bearing, the gearbox, and the generator, and the specified operating time $T$ for 20 years, Table 1
gives the Weibull parameters of each component and their operating costs. Refer to JB / T10396 for wind turbine component reliability standards, and find out the preventive maintenance reliability threshold \( R_p \) of each component. Its reliability requirements are shown in Table 2. Today, the best preventive maintenance times for each component are 3, 4, 3, and 2 [4].

| Table 1. Weibull parameters of key components of wind turbines and their maintenance costs. |
|---------------------------------|---|---|---|---|---|---|
| Part                  | \( \beta \) | \( \eta \) | \( C_{\text{id}} \) / thousand yuan | \( C_{\text{p}(k)} \) / thousand yuan | \( C_{\text{r}(k)} \) / thousand yuan | \( C_{\text{j}(k)} \) / thousand yuan |
|------------------------|---|---|---|---|---|---|
| Impeller               | 3 | 3000 | 15 | 15 | 15 | 12 | 28 |
| Main bearing           | 2 | 3750 | 15 | 8 | 8 | 7 | 15 |
| Gear box               | 3 | 2400 | 15 | 25 | 25 | 21 | 38 |
| Generator              | 2 | 3300 | 15 | 20 | 20 | 17 | 25 |

Table 2. Reliability requirements for each component.

| Part       | Reliability | Impeller | Main bearing | Gear box | Generator |
|------------|-------------|----------|--------------|----------|-----------|
| Impeller   | 0.93        |          |              |          |           |
| Main bearing | 0.94      |          |              |          |           |
| Gear box   | 0.95        |          |              |          |           |
| Generator  | 0.94        |          |              |          |           |

4.2 Optimization process

According to the decision-making process of the built model, solve different maintenance costs \( C_{op} \) corresponding to different \( \Delta R \), select the interval of the opportunity maintenance reliability threshold \( \Delta R \) as [0.01,0.15], and the maintenance cost \( C_{op} \) and the opportunity maintenance reliability threshold \( \Delta R \) The change curve is shown in Figure 3 below. Curve a is the actual data and curve b is the fitting function.

Figure 3. Change curve of maintenance cost \( C_{op} \) and opportunity maintenance reliability threshold \( \Delta R \)

Using Excel software for data fitting processing, the approximate function relationship between the maintenance cost \( C_{op} \) and the opportunity maintenance reliability threshold \( \Delta R \) is obtained as:

\[
C_{op} = 1919 \times (\Delta R)^2 - 375.76 \times (\Delta R) + 106.91
\]  

(14)

The genetic algorithm is used to optimize the minimum value of equation (14) within the prescribed interval of the opportunity maintenance reliability threshold. The initial population size is set to 50, the maximum number of iterations is 50, the cross probability is 0.7, and the mutation
probability is 0.0017. The optimal solution of the combined function is the seventh-generation individual $\Delta R^* = 0.0979$. The relationship between the maintenance cost $C_{op}$ and the number of iterations is shown in Figure 4. The $\Delta R^*$ corresponding to its minimum value can be used as the approximate optimal solution of the opportunistic maintenance strategy model, that is, the best $\Delta R \approx \Delta R^* = 0.0979$. If the opportunity maintenance model is taken into account, the maintenance cost is 882,000 yuan. The comparison between the optimization results and the original regular maintenance strategy is shown in Table 3. As can be seen from Table 3, the total cost was reduced from 1.083 million yuan to 882,000 yuan, saving 19% of the cost. From the above analysis, it can be known that the increase in the number of opportunities for maintenance has shared a large number of fixed maintenance costs, which has saved the total maintenance cost, which illustrates the economics of the opportunity maintenance strategy based on incomplete maintenance.

**Table 3. Comparison of maintenance situation and cost.**

| Part      | Regular maintenance | Opportunity repair based on incomplete repair |
|-----------|---------------------|-----------------------------------------------|
|           | $M_p$ | $M_e$ | $C$/ thousand yuan | $M_p$ | $M_e$ | $M_f$ | $C$/ thousand yuan |
| Impeller  | 6     | 1     | 1083              | 4     | 1     | 1     | 882               |
| Main bearing | 8   | 1     |                   | 2     | 6     | 2     |                   |
| Gear box  | 7     | 2     |                   | 6     | 1     | 2     |                   |
| Generator | 7     | 3     |                   | 5     | 1     | 3     |                   |

**Figure 4. Relationship between maintenance cost $C_{op}$ and number of iterations**

**5. Conclusions**

From the perspective of the reliability and economics of wind turbines, this paper proposes an opportunity maintenance strategy model based on incomplete maintenance. Based on the use of incomplete maintenance to describe the maintenance status of wind turbine components, an opportunity maintenance strategy is introduced. The parts in the maintenance interval adopt two kinds of maintenance methods: incomplete repair or opportunity repair according to different opportunity repair reliability. Through specific cases, a comparative analysis is made with the maintenance cost as the decision target within a specified period time. The results show that the strategy can perform simultaneous maintenance of multiple components compared with the traditional periodic maintenance strategy, reducing overhaul and under repair, and saving maintenance costs. To improve the maintenance coordination between components, verify the effectiveness and feasibility of the strategy,
and provide new ideas for the maintenance of wind turbines.

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