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Multicomponent opportunistic maintenance model based on cost-effectiveness

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Abstract: With difficulties in maintaining multicomponent systems of wind turbines and formulating economical and reasonable maintenance strategies, a dynamic opportunistic maintenance strategy of multicomponent systems is applied in terms of economic relevance and opportunistic maintenance among various components. A preventive maintenance model based on cost-effectiveness is proposed by incorporating cost-effectiveness analysis into the multicomponent preventive maintenance strategy. The failure rate recovery degree is used to describe the effects of imperfect maintenance and replacement. When the reliability of the component reaches the threshold of preventive or opportunistic maintenance, a reasonable maintenance method is selected on the basis of the cost-effectiveness ratio of the failure rate. A case study is conducted by taking four components of a wind turbine as the research object and comparing them with the opportunistic maintenance model without considering cost-effectiveness. Results show that the total maintenance cost is reduced by 373 600 yuan, indicating that the preventive opportunistic maintenance based on cost-effectiveness is more economical and can provide a theoretical basis for formulating a preventive maintenance plan.

Key words: imperfect maintenance; opportunistic maintenance; cost-effectiveness; reliability; maintenance costs

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With the increasing complexity of modern equipment, maintenance technology, and costs, corrective maintenance concepts cannot satisfy the requirements of equipment maintenance reliability and economy; as such, the maintenance strategy of economic optimization has been continuously studied. With in-depth studies on preventive maintenance and the urgent need for a multicomponent maintenance economy, numerous multipart opportunity maintenance models have been developed[1-2]. In a multicomponent system, stochastic, structural, and economic dependence usually exist between components[3], and opportunity maintenance is a common strategy that involves applying economic dependence to reduce maintenance costs[4]. Xu et al. [5] quantified the economic relevance between different instruments and verified the effectiveness of opportunistic maintenance. Van Horenbeek et al. [6] considered the dependencies between components and established a dynamic predictive maintenance strategy for multicomponent systems. Salari et al. [7] created an opportunistic maintenance model for a two-component system with economic relevance and different failure modes. Hu et al. [8] used the Wiener process to establish an opportunistic maintenance model for a series of systems composed of two economically relevant degraded components. In addition to the correlation between components, opportunistic maintenance can be conducted on the basis of the relationship between external conditions and systems. Besnard et al. [9] combined failure opportunities with the measured wind farm data and developed an opportunity repair model to minimize maintenance costs. Zhang et al. [10] used a Markov chain model to describe the wind speed time series and proposed an opportunistic maintenance strategy by considering random weather conditions and spare part inventory. Yang et al. [11] established an opportunity maintenance strategy for a randomly waiting production system. Zheng et al. [12] considered the three types of failures of components and put forward an opportunistic maintenance strategy related to the influence of wind speed. Considering the opportunity of maintenance, Zhang et al. [13] created a two-level maintenance threshold strategy and applied simulation to verify the economic advantages of this strategy.

In most studies, only a single repair condition is set to determine the repair method of components. Although benefits can be guaranteed to a certain extent, comprehensive opportunity maintenance control conditions are consistent with actual operating conditions. Therefore, multipart opportunistic maintenance under cost-effectiveness and imperfect maintenance is proposed. In this study, cost-benefit analysis based on the failure rate is proposed by considering the recovery degree of the failure rate of various maintenance methods. Specific maintenance methods are determined by comparing the cost-benefit ratios of different maintenance methods. A preventive maintenance decision-making model for imperfect maintenance of wind turbines is also established. Finally, it is

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compared with a model that does not consider the cost-effectiveness ratio and opportunity maintenance to verify the economics and effectiveness of the proposed model.

1 Maintenance Model

1.1 Maintenance model assumptions and maintenance strategy

Opportunity maintenance is one of the most commonly used methods in multicomponent systems. The principle of opportunity maintenance is shown in Fig. 1. For a system composed of multiple components, each component has an opportunity maintenance reliability threshold R_o and preventive maintenance reliability threshold R_p. When one of the components runs to t_p, its reliability reaches R_p, and preventive maintenance is performed on that component while providing an opportunity for other components to be repaired.

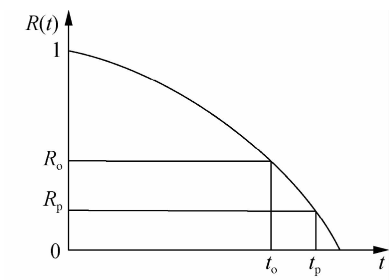

Fig. 1 Schematic of opportunity maintenance

For other components, the repair methods are as follows:

1) When the reliability of a given component is $R > R_o$, no maintenance is performed on the component.

2) When the reliability of the component is $R_p < R \leqslant R_o$, the component is in the opportunity maintenance interval. It is undergoing preventive maintenance, so it can be repaired.

Preventive maintenance and opportunistic maintenance involve two maintenance methods: imperfect maintenance and replacement. In this study, the maintenance method is selected and determined through cost-effectiveness analysis to obtain a more economical maintenance method.

The following model assumptions are made:

1) The fault distribution of components in a system is independent of one another and obeys the Weibull distribution.

2) The unexpected failure of the system is completed with minimum maintenance, which does not change the failure rate of the system.

3) The system starts in a completely new state.

4) The system has sufficient maintenance resources during maintenance.

1.2 Evolution of failure rate

If the failure of the system follows the two-parameter-Weibull distribution with the shape parameter of β and the scale parameter of γ, the expression of the failure rate is

$$\lambda_1(t) = \frac{\beta}{\gamma}\left(\frac{t}{\gamma}\right)^{\beta-1} \qquad t \geqslant 0 \tag{1}$$

The failure rate decreases after the imperfect preventive maintenance of the component. However, as the number of repairs increases, the recovery rate of the failure rate lessens, and the failure rate increases. The relationship between the failure rate function of the equipment before and after imperfect maintenance can be defined as[14]

$$\lambda_{i,m}(t) = b_{i-1}\lambda_{i-1,m}(t + \eta_{i-1}T_{i-1,m}) \tag{2}$$

where $i = 1, 2, \ldots, n$ is the amount of preventive maintenance; $T_{i-1,m}$ is the working time of the $(i-1)$-th maintenance cycle of m; η_{i-1} is the age reduction factor, and $0 < \eta_{i-1} < 1$; $b_{i-1} > 1$ is the hazard rate increase factor; $\lambda_{i,m}(t)$ is the failure rate distribution function of m before the i-th preventive maintenance.

The failure rate function in the i-th preventive maintenance cycle T_i of m can be written as

$$\lambda_{i,m}(t) = \prod_{k=1}^{i-1} b_k \lambda_{1,m}\left(t + \sum_{k=1}^{i-1}\eta_k T_{k,m}\right)$$
$$2 \leqslant i \leqslant n, \quad t \in [0, T_i) \tag{3}$$

1.3 Determination of a nonequal maintenance cycle

Each component exists independently and does not affect other components, and the reliability of components changes with the failure rate after each imperfect repair or replacement. The relationship between the failure rate and reliability is

$$R = \exp\left[-\int_0^{T_i}\lambda_i(t)\,\mathrm{d}t\right] \tag{4}$$

Considering the constraint of the preventive maintenance reliability threshold R_p, the failure risk of each preventive maintenance cycle is the same, so the reliability equation is as follows:

$$\exp\left[-\int_0^{T_1}\lambda_1(t)\,\mathrm{d}t\right] = \exp\left[-\int_0^{T_2}\lambda_2(t)\,\mathrm{d}t\right] = \cdots =$$
$$\exp\left[-\int_0^{T_i}\lambda_i(t)\,\mathrm{d}t\right] = R_p \tag{5}$$

Eq. (5) can be transformed into the following equation:

$$\int_0^{T_1}\lambda_1(t)\,\mathrm{d}t = \int_0^{T_2}\lambda_2(t)\,\mathrm{d}t = \cdots = \int_0^{T_i}\lambda_i(t)\,\mathrm{d}t = -\ln R_p \tag{6}$$

where $\int_0^{T_i}\lambda_i(t)\,\mathrm{d}t$ is the cumulative failure risk during the i-th maintenance interval.

According to Eqs. (1) and (6), T_1 can be calculated. Combining Eqs. (1), (3) and (6), the i-th nonequal maintenance cycle can be obtained as

$$T_i = \sqrt[\beta]{\left(\sum_{k=1}^{i-1}\eta_k T_k\right)^{\beta} - \frac{\gamma^{\beta}\ln R_p}{\prod_{k=1}^{i-1} b_k}} - \sum_{k=1}^{i-1}\eta_k T_k \quad 2 \leqslant i \leqslant n \tag{7}$$

Opportunistic maintenance can improve the current repair time of components and affect the subsequent repair cycles. Therefore, $T'_{i,m}$ should meet the following conditions:

$$\exp\left[-\int_0^{T'_{i,m}} \lambda'_{i,m}(t)\mathrm{d}t\right] = R_{p,m} \tag{8}$$

where $T'_{i,m}$ is the i-th maintenance cycle when opportunistic maintenance is considered for m; $\lambda'_{i,m}(t)$ is the new failure rate function, which can be determined by Eq. (3) and the previous $i-1$ actual maintenance cycle.

When opportunistic maintenance occurs, it affects the failure rate and service interval of the component in the next cycle. Therefore, in the calculation of the unequal maintenance period, the maintenance time of other components and the reliability of the current component should be considered comprehensively. Then, if the first $i-1$ maintenance interval of m is known, $T'_{i,m}$ can be obtained from Eqs. (3) and (8) as

$$T'_{i,m} = \sqrt[\beta]{\left(\sum_{k=1}^{i-1}\eta_k T_{k,m}\right)^{\beta} - \frac{\gamma^{\beta}\ln R_{p,m}}{\prod_{k=1}^{i-1} b_k}} - \sum_{k=1}^{i-1}\eta_k T_{k,m} \quad 2 \leqslant i \leqslant n \tag{9}$$

where $T_{k,m}$ is the actual operating cycle of m, $1 \leqslant k \leqslant i-1$.

1.4 Maintenance costs of multi-component systems

In the maintenance of multi-component systems, the following maintenance costs are mainly considered: minimal maintenance cost ($C_{v,m}$), imperfect maintenance cost ($C_{p,m}$), opportunistic maintenance cost ($C_{o,m}$), preventive replacement costs ($C_{f,m}$), opportunity replacement cost ($C_{r,m}$), and downtime loss (C_d).

1.4.1 Dynamic minimum total maintenance cost

When m has an unexpected failure in the i-th cycle, minimum maintenance is conducted, and no opportunity for maintenance is available. The maintenance cost in an imperfect maintenance cycle can be expressed as

$$C_{v,i,m} = C_m F_{i,m} \tag{10}$$

where C_m is the single maintenance cost; $F_{i,m} = \int_0^{T_{i,m}} \lambda_i(t)\,\mathrm{d}t$ is the minimum number of repairs in the i-th cycle of m.

1.4.2 Imperfect preventive maintenance cost

If m undergoes incomplete preventive maintenance in the i-th cycle, its total cost includes the cost of single imperfect maintenance and the downtime loss:

$$C_{p,i,m} = C_{h,m} + t_{p,m} C_d \tag{11}$$

where $C_{h,m}$ is the single imperfect maintenance cost of m; $t_{p,m}$ is the single imperfect maintenance time of m; C_d is the cost of loss per unit time.

1.4.3 Imperfect opportunity maintenance cost

When part m receives the opportunity to repair, its total costs include the costs of imperfect opportunity maintenance and penalty. The penalty cost for opportunity maintenance to repair m at the i-th maintenance is

$$C_{c,i,m} = C_{s,m}(T'_{i,m} - T_{i,m}) \tag{12}$$

where $C_{s,m}$ is the penalty fee per unit time. Therefore, the imperfect opportunity maintenance cost of m in the i-th maintenance interval is

$$C_{o,i,m} = C_{g,m} + C_{c,i,m} \tag{13}$$

where $C_{g,m}$ is the single imperfect opportunity maintenance cost of m.

1.4.4 Preventive replacement cost

When m is replaced in the i-th cycle, its cost includes the replacement cost of the component and the downtime loss:

$$C_{f,i,m} = C_{e,m} + C_d T_f \tag{14}$$

where $C_{e,m}$ is the replacement cost of m; T_f is the time required for replacement.

1.4.5 Opportunity replacement cost

When m has an opportunity for maintenance in the i-th cycle and meets the replacement conditions, m can be replaced with an opportunity. The cost includes the replacement cost of m and the penalty fee for early replacement:

$$C_{r,i,m} = C_f + C_{e,m} \tag{15}$$

where C_f is a fixed penalty fee.

The preventive maintenance of multi-component systems is an ongoing periodic process, and the components during each cycle have different maintenance methods. The following factors are introduced to facilitate calculation:

$$\psi_{i,m} = \begin{cases} 0 & R_{o,m} < R_{i,m}(t) \\ 1 & R_{o,m} \geqslant R_{i,m}(t) \end{cases}$$

where $\psi_{i,m}$ indicates whether m has maintenance activity during the i-th shutdown.

If part m needs maintenance, the reliability of the component can be determined in the opportunistic maintenance interval or the preventive maintenance interval according to the following equation:

$$\tau_{i,m} = \begin{cases} 0 & R_{i,m}(t) \leqslant R_{p,m} \\ 1 & R_{p,m} < R_{i,m}(t) < R_{o,m} \end{cases}$$

The maintenance method of m during the i-th shutdown is

$$q_{i,m} = \begin{cases} 0 & \text{imperfect preventive maintenance} \\ 1 & \text{preventive replacement} \end{cases}$$

The maintenance method of m during the i-th shutdown is

$$O_{i,m} = \begin{cases} 0 & \text{imperfect opportunity maintenance} \\ 1 & \text{opportunity replacement} \end{cases}$$

Combined with the above various maintenance methods, the maintenance cost of m during the i-th shutdown maintenance of the system can be described as

$$C_{i,m}(t) = \psi_{i,m}\left\{(1-\tau_{i,m})\begin{bmatrix}(1-q_{i,m})C_{p,i,m} \\ +q_{i,m}C_{f,i,m}\end{bmatrix} + \tau_{i,m}\begin{bmatrix}(1-O_{i,m})C_{o,i,m} \\ +O_{i,m}C_{r,i,m}\end{bmatrix}\right\} + C_{v,i,m} \tag{16}$$

The total cost of N components in the system at the i-th shutdown for maintenance is

$$C_i(t) = \sum_{m=1}^{N} C_{i,m}(t) \tag{17}$$

In the interval $[0, T]$, the system has performed M maintenance, the total maintenance cost is

$$C_M = \sum_{i=1}^{M}\sum_{m=1}^{N} C_{i,m}(t) \tag{18}$$

1.5 Choice of the maintenance method

The failure rate of the component can be restored after imperfect maintenance but cannot return to 0:

$$\left.\begin{aligned} \lambda'_{i,m}(t)^- &= \lambda'_{i,m}(T_{i,m}) = \prod_{k=1}^{i-1} b_k\lambda_1\Big(T_{i,m} + \sum_{k=1}^{i-1}\eta_k T_{k,m}\Big) \\ \lambda'_{i,m}(t)^+ &= \lambda'_{i+1,m}(0) = \prod_{k=1}^{i} b_k\lambda_1\Big(\sum_{k=1}^{i}\lambda_k T_{k,m}\Big) \end{aligned}\right\} \tag{19}$$

The difference in the failure rate before and after imperfect maintenance is used to express the repair effect, which is expressed as follows:

$$\Delta\lambda^1_{i,m}(t) = \prod_{k=1}^{i-1} b_k\lambda_1\left(T_{i,m} + \sum_{k=1}^{i-1}\eta_k T_{k,m}\right) - \prod_{k=1}^{i} b_k\lambda_1\left(\sum_{k=1}^{i}\eta_k T_{k,m}\right) \tag{20}$$

After replacement, the failure rate of the parts can decrease to 0:

$$\left.\begin{aligned} \lambda'_{i,m}(t)^- &= \lambda'_{i,m}(T_{i,m}) = \prod_{k=1}^{i-1} b_k\lambda_1\left(T_{i,m} + \sum_{k=1}^{i-1}\eta_k T_{k,m}\right) \\ \lambda'_{i,m}(t)^+ &= 0 \end{aligned}\right\} \tag{21}$$

After being replaced, the part is restored as new, and the difference in the failure rate before and after the replacement is equivalent to the failure rate before maintenance:

$$\Delta\lambda^2_{i,m}(t) = \prod_{k=1}^{i-1} b_k\lambda_1\left(T_{i,m} + \sum_{k=1}^{i-1}\eta_k T_{k,m}\right) \tag{22}$$

If the part fails unexpectedly during maintenance intervals, the failure rate of the parts cannot be changed after the minimum maintenance.

When the system shuts down for the i-th time at time t, if m is in the preventive maintenance interval, the recovery level of the failure rate is used as the maintenance effect. The cost-effectiveness ratio of the imperfect preventive maintenance can be obtained as

$$L_{p_1,i,m}(t) = \frac{C_{p,i,m}}{\Delta\lambda^1_{i,m}(t)} \tag{23}$$

After replacement, the failure rate of the component becomes 0, and the cost-effectiveness ratio of preventive replacement can be obtained as

$$L_{f,i,m}(t) = \frac{C_{f,i,m}}{\Delta\lambda^2_{i,m}(t)} \tag{24}$$

According to Eqs. (23) and (24), the method of preventive maintenance for the i-th component m can be determined, so $q_{i,m}$ is assigned as follows:

$$q_{i,m} = \begin{cases} 0 & L_{p_1 i,m}(t) \leqslant L_{f,i,m}(t) \\ 1 & L_{p_1,i,m}(t) > L_{f,i,m}(t) \end{cases}$$

When the system shuts down for the i-th time at time t, if m is in the opportunity maintenance interval, the recovery level of the failure rate as the maintenance effect is taken, and the cost-effectiveness ratio of the imperfect opportunity maintenance is

$$P_{o,i,m}(t) = \frac{C_{o,i,m}}{\Delta\lambda^1_{i,m}(t)} \tag{25}$$

After replacement, the failure rate of the component becomes 0, and the cost-effectiveness of the opportunity replacement is

$$P_{f,i,m}(t) = \frac{C_{r,i,m}}{\Delta\lambda^2_{i,m}(t)} \tag{26}$$

According to Eqs. (25) and (26), the i-th opportunity maintenance mode of m can be determined, so $O_{i,m}$ is assigned as

$$O_{i,m} = \begin{cases} 0 & P_{o,i,m}(t) \leqslant P_{f,i,m}(t) \\ 1 & P_{o,i,m}(t) > P_{f,i,m}(t) \end{cases}$$

2 Numerical Examples

In this section, an example is used to verify the effectiveness of the wind power system maintenance method proposed in this paper. In this example, four key components in each wind turbine are studied: the rotor, the main bearing, the gearbox, and the generator. The failure rate is independent of one another and obeys the two parameters of the Weibull distribution. These parameters and the reliability of each component are shown in Tab. 1. The age reduction factor is $\eta_i = i/(3i+7)$, and the hazard increasing factor is $b_i = (12i+1)/(11i+1)$ [15].

Tab. 1 Weibull distribution parameters and reliability parameters

Component	γ	β	R_p	R_o
1	2 400	3	0.85	0.90
2	3 750	2	0.80	0.90
3	3 300	2	0.88	0.92
4	3 000	3	0.88	0.92

In a previous study[16], the maintenance parameters of each component are specified (see Tab. 2).

Tab. 2 Maintenance parameters

Component	1	2	3	4
C_h	38 000	15 000	25 000	28 000
C_e	152 000	60 000	100 000	112 000
C_d	2 000	2 000	2 000	2 000
C_m	6 000	6 000	6 000	6 000
C_s	140	70	90	100
C_f	15 000	15 000	15 000	15 000
C_g	25 000	8 000	15 000	16 000
T_f	15	15	15	15
t_p	10	10	10	10

A reliability change curve for each component during the operation time of [0, 12 500] d is obtained on the basis of the data in Tab. 1, Tab. 2, and the proposed model (see Fig. 2). Several representative strategies are selected from the specific maintenance plan for analyzing the samples.

At 1 195 d, Component 3 initially reaches the preventive maintenance time. At this time, the reliability of Component 1 is 0.883 9, which is in the opportunity maintenance interval, and it can be opportunistic maintenance. The cost-effectiveness ratio of the imperfect opportunity maintenance is better than that of opportunity replacement. The reliabilities of Components 2 and 4 are 0.903 5 and 0.938 8, respectively, which are greater than their opportunity maintenance reliability threshold. As such, no maintenance is performed.

When the system runs to 9 764 d, Component 4 reaches the preventive maintenance reliability threshold. At this time, the reliability of Components 1, 2, and 3 are within the opportunity maintenance interval, and maintenance can be performed simultaneously. The cost-effectiveness ratio of the imperfect opportunistic maintenance for Components 1 and 3 is less than that of replacement; in this way, the imperfect opportunity maintenance is chosen. The replacement cost-effectiveness ratio of Component 2 is less than that of imperfect opportunity maintenance; thus, Part 2 is replaced.

By the time the system runs to 12 500 d, Part 1 has carried out nine imperfect preventive maintenances, six imperfect opportunity maintenances, and two preventive replacements. Part 2 has undergone eight opportunistic imperfect maintenances and two opportunity replacements. Part 3 has undergone eight imperfect preventive maintenances, five imperfect opportunity maintenances, and two preventive replacements. Part 4 has been under seven imperfect preventive maintenances, five imperfect opportunity maintenances, and one preventive replacement.

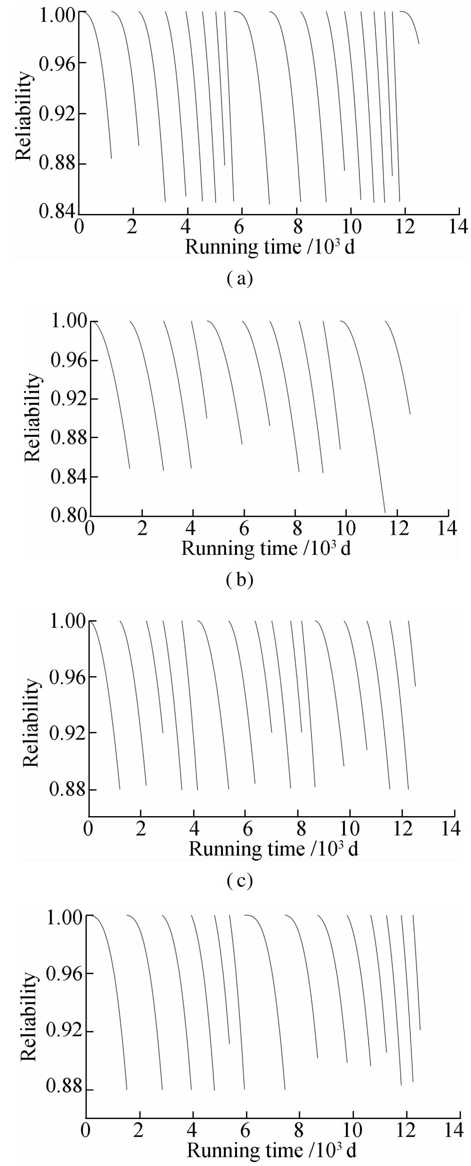

Fig. 2 Reliability curves. (a) Component 1; (b) Component 2; (c) Component 3; (d) Component 4

The maintenance strategy, combined with Fig. 2 and the specific maintenance plan described above, can reasonably determine the maintenance method according to the actual reliability of components. When the preventive maintenance of a component is performed, in most instances, one or more components can be maintained, the fixed repair costs can be shared equally, and downtime and costs can be saved. The reliability of the components has a certain periodicity. After several imperfect maintenances, the degree of system deterioration accumulates to a certain extent, and the failure rate of each part increases. Consequently, the maintenance interval shortens when it reaches a certain level. The cost-effectiveness ratio of incomplete repair is higher than the cost-effectiveness ratio of replacement. Therefore, replacement is used to restore the parts as new and ensure the stable operation of the whole system, which is consistent with the actual operation.

3 Model Comparison Study

The economy and effectiveness of the multipart opportunity maintenance strategy based on cost-effectiveness are verified by comparing it with the single-part preventive maintenance model without cost-effectiveness and opportunity maintenance. The optimization results of the single-component preventive maintenance strategy can be derived on the basis of the same maintenance parameters.

The comparison between the two models is shown in Tab. 3. Strategy 1 means single-component preventive maintenance (replacement); Strategy 2 means preventive maintenance opportunities considering cost-effectiveness; M_{pm}, M_{om}, M_{pr}, and M_{or} are the amounts of preventive maintenance, opportunistic maintenance, preventive replacement, and opportunistic replacement, respectively. The total number of preventive maintenances decreases from 34 to 24, and the number of replacements decreases from 10 to 7 in the proposed model compared with that of the single-component preventive maintenance model, although the model adds 24 opportunistic maintenances. After calculation, the maintenance cost is reduced from 3.073 2 million yuan to 2.699 6 million yuan. The cost of opportunistic maintenance is much lower than the replacement cost, and the total maintenance cost is reduced by 373 600 yuan; that is, saving 12.16% of the maintenance costs, which shows that the preventive opportunistic maintenance model based on the cost-effectiveness ratio is more economical.

Tab. 3 Maintenance strategy and cost comparison

Component	Strategy 1		Strategy 2			
	M_{pm}	M_{pr}	M_{pm}	M_{om}	M_{pr}	M_{or}
Gearbox	9	3	9	6	2	0
Bearing	7	2	0	8	0	2
Generator	10	3	8	5	2	0
Rotor	8	2	7	5	1	0

4 Conclusions

1) Cost-effectiveness analysis involving multiple maintenance methods based on the failure rate is applied to the multicomponent opportunity maintenance strategy, which effectively overcomes the lack of only considering reliability in the previous opportunity maintenance strategy. It also conforms to the actual maintenance situation.

2) The comprehensive consideration of the economic relevance between multiple components, the effect of opportunistic maintenance on the reliability of each component, the recovery degree of different maintenance methods, and the cost-effectiveness based on the failure rate are used as the control conditions of the maintenance method. The economical and reasonable maintenance method is selected to ensure that wind turbines can run with high reliability while saving on maintenance costs.

3) The cost-effectiveness maintenance model based on reliability changes is more economical and feasible. The results show that this strategy can describe the economic relevance between multiple components, improve the maintenance coordination of the system, and save maintenance costs by applying this method to wind turbines for verification.

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基于成本效益的多部件机会维修模型

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摘要：针对风力机多部件系统维修困难且较难制定经济合理的维修策略问题，考虑各部件之间存在经济相关性和机会维修，研究多部件系统的动态机会维修策略. 将成本效益分析方法融入到多部件预防性维护策略制定中，提出了一种基于成本效益的预防维护模型. 采用故障率恢复程度描述不完全维修和更换的维护效果，当部件可靠度达到预防维护或机会维护阈值时，比较基于故障率的成本效益比，选择合理的维护方式. 以某风力机的 4 个部件为研究对象进行案例分析，并与未考虑成本效益的机会维修模型进行比较. 结果表明，总维修成本减少 37. 36 万元，说明基于成本效益的预防性机会维修更具经济性，能为预防性维修计划的制定提供理论依据.

关键词：不完全维修；机会维护；成本效益；可靠度；维护成本

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