Quantity Optimization of Spare Parts For Offshore Wind Farm Based on Component Updating

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Abstract. The important parts of the offshore wind turbines are expensive. The irrational allocation of spare parts will lead to low availability of wind turbines and an increase in cost. In order to reasonably determine the number of spare parts, an optimization scheme for the number of spare parts of offshore wind farms based on component updating is proposed. First, considering the complex deterioration process of the components, the time delay theory is introduced in this paper, and time delay theory is applied to the maintenance strategy of offshore wind turbine. This article optimizes the component update cycle through the component maintenance strategy. Then, considering the cycle of spare parts, the availability of the entire wind farm components is taken as the goal with maintenance strategy. The number of spare parts of the offshore wind farm is optimized through the Markov process. Finally, taking the components of the wind turbine as an example, the traditional optimization process is compared. The example shows that the method can correctly configure the number of spare parts and effectively reduce the cost of spare parts management.

1. Introduction
In recent years, China's offshore wind power has developed rapidly. According to wind power development plan, national offshore wind power construction scale will reach 10GW, and strive for accumulative grid capacity to reach more than 5GW. The size of offshore wind farms is becoming larger and larger, and more and more wind turbines need to be maintained. The maintenance cost of the offshore wind turbine is generally at least 2 times as much as the land unit, and the operation and maintenance cost accounts for 18% - 23% of the total cost of the wind power project[1]. At present, the maintenance of offshore wind power is getting more and more attention.

Spare parts management is an important part of offshore wind power maintenance. If the number of spare parts is too small, when spare parts need to be replaced, there is no spare parts that can be used for replacement in spare parts storehouse. Wind turbine maintenance needs to wait for spare parts to make up for replacement, which will create a great downtime. If the number of spare parts is too much, it will cause the waste of resources. Therefore, the rational allocation of the spare parts of the wind farm is very important to the normal operation of the offshore wind farm.

At present, the research on the number of spare parts is mainly focused on the aircraft, ship and other fields. In document [2], the probability distribution of spare parts shortage is obtained by the finite source queuing theory, and the availability of k/N (G) structure system is established. In
document [3], based on availability analysis, through the research of spare parts characteristic parameters and spare parts guarantee rate, the scholars use marginal effect analysis method to model the number of spare parts. In document [4], an optimization method for the initial spare parts scheme based on the maximum marginal effect is proposed. Document [5] considers two factors of cost and spare part guarantee rate simultaneously. On the basis of analyzing the requirement of torpedo spare parts guarantee rate, a mathematical model of spare parts demand optimization is established. The above literature mainly optimizes the number of spare parts from the point of replacement of the components. Document [6-7] mainly optimizes the number of spare parts from the point of preventive replacement of the components. Document [6] uses genetic algorithm and particle swarm optimization to optimize the preventive maintenance strategy and spare parts inventory management. Taking electric crane maintenance as an example, it shows that the two intelligent algorithms have shorter operation time and better optimization effect. Document [7] combines condition-based maintenance and spare parts inventory management decision. The optimal inventory and condition-based maintenance threshold are determined by heuristic algorithm.

The optimization of the number of spare parts in the field of offshore wind power is different from those in the above literature: (1) the replacement of offshore wind turbine components need to be replaced after the components fail. At the same time, we need to consider the problems of personnel, ships and weather accessibility. It is easy to build up time and reduce the availability of wind turbines. Therefore, in addition to the post replacement, the replacement of offshore wind power components needs to be combined with the maintenance strategy to consider the preventive replacement to reduce the downtime. (2) the offshore wind turbines are far away from the shore, the environment is bad, and the process of the deterioration of the components is complicated. The state monitoring technology is not perfect [8]. Some parts, such as gear box, still need the on-site inspection. Therefore, it is necessary to establish an irregular detection strategy.

In view of the above problems, an optimization model for the number of offshore wind power spare parts based on component updating is established in this paper. Firstly, based on the time delay theory, a maintenance strategy for offshore wind turbines with irregular detection is established. The optimal maintenance strategy determines the detection interval of the wind turbine and the component update cycle, that is, the failure rate of the components. Secondly, considering the cycle of components, the Markov process based on component updating is built. The number of spare parts is optimized with the component availability rate as the target function, as shown in Fig 1.

2. Optimization idea of spare parts quantity based on component updating
Because wind turbine detection is not always able to detect the real state of components accurately, in order to detect component status effectively, this paper proposes an irregular detection strategy based on time delay theory. The sequence of unscheduled detection is optimized, and the component update cycle is obtained by discrete analysis of component faults. The optimized component updating cycle (reciprocal) is used to replace the component failure rate. Considering the cycle of spare parts, Markov process based on component updating is built. The number of spare parts is optimized with the component availability rate as the target function, as shown in Fig 1.
3. Component updating strategy based on time delay maintenance theory

3.1 Maintenance strategy based on time delay

The time delay theory is a maintenance model which is proposed by Christer in 1973, which takes into account the loss of equipment failure, operation risk and cost. In the time delay theory, the time interval which the equipment running from the input to the potential failure is $u$. The $u$ is a random variable, and the density function is $g(u)$. After a period of $s$, $s$ is also a random variable with a density function of $H(s)$\(^9\). As shown in Fig 2, if a test is carried out in a blank area, it will not detect a potential failure or a potential failure that has evolved successfully\(^10\). If the detection period is not reasonable, the component state cannot be predicted accurately, thus the availability of the wind turbines will be affected. Determining a reasonable detection cycle is to ensure that the delay time can be fully utilized, so that the operation and maintenance department can repair components in the slash time area, thus implementing preventive replacement.

![Figure 1: Flow chart of spare parts quantity optimization](image)

![Figure 2: A schematic diagram of time delay theory](image)

The maintenance strategy adopted in this article is to detect the equipment irregularly. Detection time sequence is \(\{I_1, I_2, I_3\}\). \(U_n = I_n - I_{n-1}\) represents the time interval between the nth test and the last test, \(I_0 = 0\). The detection time and component replacement time are negligible, and the cost of testing for the components each time is $D_p$. The cost of detecting potential faults and preventive replacement for components is $C_P$. The cost of repair replacement for functional failures is $C_c$, and downtime loss per unit time is $C_d$.

1. If a potential fault is detected in each test, the component is replaced by a preventive replacement and the preventive replacement time is $d_p$.

2. If a functional failure occurs during the detection interval, the component is replaced by a fault, and the replacement time is $d_c$.

3. If the potential fault is not detected at the time point of the kth detection, the maintenance is not carried out, the next detection time is determined by $U_{k+1} = \alpha U_k (0 < \alpha < 1)$.

After the replacement of the components, the components are restored as new. Updating parts are the following:
(1) Starting from zero time, a functional failure occurred before the first detection time of \( I_1 \). At this time the running time is \( u + s \), the update period is \( u + s + d_c \), and the replacement cost is \( C_D + C_c + C_d d_c \).

(2) A potential fault was detected at \( I_1 \). At this time the running time is \( I_1 + d_p \), and the replacement cost is \( C_D + C_p + C_d d_p \).

(3) No potential fault was detected at \( I_1 \). In this case, the following two cases are included:
   a. The potential fault was detected for the first time at \( I_n(n \geq 2) \), and no functional failure occurred in \( I_n \). At this time the update period is \( I_n + d_p \), and the replacement cost is \( nC_D + C_p + C_d d_p \).
   b. The potential failure was not detected at the previous\( n \) detection, and a functional failure occurred before \( I_{n+1} \). At this time the update period is \( I_{n+1} + d_p \), and the replacement cost is \( nC_D + C_c + C_d d_c \).

In all of the above cases, the update cycle of the component is expected to be:

\[
E(T) = \int \int (u + s + d_c) g(u) h(s) du ds + \sum_{n=1}^{\infty} \int \int (u + s + d_c) g(u) h(s) du ds + \int \int (I_n + d_p) g(u) h(s) du ds
\]

(1)

In the replacement cycle, the expected cost is:

\[
E(C) = \int \int (C_d + C_p + d_p C_d) g(u) h(s) du ds + \sum_{n=1}^{\infty} \left\{ \int \int (nC_D + C_p + d_p C_d) g(u) h(s) du ds + \int \int (nC_D + C_c + d_c C_d) g(u) h(s) du ds \right\}
\]

(2)

According to the Ross update theory:

\[
\lim_{t \to \infty} \frac{C(t)}{t} = \frac{E(C)}{E(T)}
\]

(3)

The following optimization model is set up with the goal of minimum operating cost per unit time.

\[
\min C(I_1, \alpha) = \frac{E(C)}{E(T)}
\]

s.t. \( I_1 > 0, 0 < \alpha < 1 \)

(4)

The optimization algorithm is used to obtain the optimization parameters \((I_1, \alpha)\) of the component updating cycle, and the detection sequence is obtained.

### 3.2 Parts update cycle analysis

In order to make a specific analysis of the update cycle of the component, any continuous random event will be discretized in this paper. If a probability of a random event is higher than a certain probability threshold \( \Omega \), it is considered to have occurred in practice. At time \( t \), the probability \( P_B \) of the functional failure of the component and the probability \( P_p \) of the potential failure can be obtained.
probability of a functional failure of a component at \( t \) is \( 1-R(T) \). The expression of the \( R(T) \) expression is shown in the formula.

\[
R(t) = \int_{t}^{\infty} g(u)du + \int_{t}^{\infty} g(u)h(s)ds \quad \text{for} \quad 0 < u < t < s < \infty
\]

(5)

The probability expression of a potential failure for a component at \( t \):

\[
P_u = \int_{0}^{t} g(u)du
\]

(6)

Therefore, if \( P_b > \Omega \) or \( P_u > \Omega \) is satisfied in a test interval, it is assumed that the component has to be replaced, so that the renewal period of components can be determined.

4. Optimization of spare parts for offshore wind farms based on component updating

4.1 Markoff construction based on component update strategy

For offshore wind farms, important components are expensive and will continue to be recycled through maintenance and return to spare parts warehouse after the wind turbine is replaced. In this paper, the Markov process is established by considering the recycling of spare parts. In combination with the third section, the update cycle (reciprocal) is used to replace the failure rate of the component. The Markov chain is constructed for the spare parts recycling process, and the spare parts recycling process based on the spare parts updating strategy is shown in Fig 3.

![Figure 3: Spare parts recycling based on spare parts updating and optimization](image)

In most cases, the time needed to replace spare parts is much smaller than that of spare parts renewal cycle and spare parts average circulation time. For simplified analysis, it is considered that replacement is instantaneous. Assuming that the wind farm has \( m \) wind turbines, the number of parts of the whole wind farm is also \( m \). If the initial quantity of the spare part is \( n \) in the spare part storehouse of the wind farm, the state of the Markoff process for the recycling of the spare parts of the wind farm is expressed by \((i_1, i_2, i_3)\). \( i_1 \) represents the number of parts in normal operation of the wind farm, \( i_2 \) represents the number of spare parts available in the spare part warehouse, \( i_3 \) represents the number of parts in the loop process. If within a certain period, the number of parts of the wind farm does not increase and decrease, the value of \( i_1 + i_2 + i_3 \) is unchanged for \( m+n \). All States of the system are encoded by \( j = i_3 \), and there are a total of \( m+n+1 \) states.

The initial state is \((m, n, 0)\), and the Markov process between the States is shown in Fig 4.
The formula (7) is called the Markov equation.

\[
\frac{dP_j(t)}{dt} = -\sum_{k \neq j} a_{ij} P_j(t) + \sum_{k \neq j} a_{jk} P_k(t)
\]

The formula (7) is called the Markov equation.

\[
\sum_{k \neq j} a_{ij} : \text{the rate of the system leaving the state of } j \text{ from the state } i, \text{ so } \sum_{k \neq j} a_{ij} P(t) \text{ represents the unit time reduction of the system in the state } j.
\]

\[
\sum_{k \neq j} a_{jk} : \text{the rate of the system leaving the state of } j \text{ from the state } k, \text{ so } \sum_{k \neq j} a_{jk} P(t) \text{ represents the unit time increase of the system in the state } j.
\]

Therefore, the Markov process, as shown in Figure 4, can be written as:

\[
P(0) = -m \lambda P(0) + \alpha P(1)
\]

\[
\ldots
\]

\[
P(n) = m \lambda P(n-1) - (m \lambda + n \alpha) P(n) + (n+1) \alpha P(n+1)
\]

Starting from the following state, the parts will be short of spare parts.

\[
P(n + 1) = m \lambda P(n) - [(m - 1) \lambda + (n + 1) \alpha] P(n + 1) + (n + 2) \alpha P(n + 2)
\]

\[
\ldots
\]

\[
P(n + m - 1) = 2 \lambda P(n + m - 2) - [(\lambda + (n + m - 1) \alpha)] P(n + m - 1) + (n + m) \alpha P(n + m)
\]

To sum up, the Markov process, which is constructed in this paper, considers the update and cycle of spare parts, and can characterize the state of the spare parts running.

4.2 Optimization of the number of spare parts for offshore wind farms

The traditional optimization of spare parts optimization is based on the guarantee probability of spare parts or the probability of spare parts shortage. Spare part guarantee probability and spare parts shortage probability are the values representing the adequacy of spare parts. As long as the spare parts storehouse of wind farm is in the state of 0 spare parts available, it will contribute to spare parts shortage probability. However, in actual operation, in case of shortage of spare parts, no spare parts need to be updated. Spare parts shortage will not affect operation availability. This is the shortcoming...
of traditional optimization of spare parts. In view of this, this paper uses the steady availability rate as the objective function to optimize it. \( U(L) \) indicates that the unavailability of the system under the shortage of \( L \) spare parts in the wind farm, and the unavailability is expected to be:

\[
U(L) = \sum_{q=0}^{\infty} P(q) \times U(0) + \sum_{L=1}^{\infty} P(n + L) \times U(L) = \sum_{q=0}^{\infty} P(q) \times U(0) + \sum_{L=1}^{\infty} P(n + L) \times \frac{L}{m} \quad (12)
\]

It is assumed that the replacement is completed instantaneously. That is, when there is no shortage of spare parts, the availability rate is 1, then \( U(L) = 0 \). Formula (12) changed into:

\[
U(L) = \sum_{L=1}^{m} P(n + L) \times \frac{L}{m} \quad \text{(13)}
\]

\( P(n), \dot{P}(n) \) : the probability and first derivative of the system in the state \( n \);

\( \lambda \) : failure rate, the reciprocal of the average fault interval of a component;

\( \alpha \) : cycle rate, the reciprocal of the average cycle time;

\( U(L) \) : the unavailability of the system under the shortage of \( L \) spare parts in the wind farm;

\( m \) : number of wind turbines.

For the component \( i \) of the wind farm, when the number of operation is \( m \) and the number of spare parts is \( n \), the steady state availability is as follows:

\[
A_i(n) = 1 - U_i(L) = 1 - \sum_{L=1}^{m} P(n = L) \times \frac{L}{m} \quad (14)
\]

\( A_i(n) \) : the steady state availability of the component \( i \);

\( U_i(L) \) : The unavailability of component \( i \) with a shortage of \( L \) spare parts;

\( m \) : the number of parts running normally.

From the formula (14), it can be seen that the steady state availability is related to the actual operation state of wind farms, and the number of spare parts can be optimized through steady state availability, which makes the quantity of spare parts more reasonable.

5. Simulation Analysis

The offshore wind farm consisting of 100 wind turbines is assumed. Assuming that the wind turbines of the wind farm are the same type, for the recycling of the gearbox in the whole wind farm, the number of the initial spare parts is optimized with the constraint of the whole wind farm components availability. The distribution of \( g(u) \) and \( h(s) \) distribution is exponential distribution and Weibull distribution. The parameters of the exponential distribution are 0.0205, the scale parameter of Weibull distribution is 0.0016, and the shape parameter is 1.56. The price of the gear box is 3 million yuan, the cycle time of the gear box is 32 days, and the operation and maintenance parameters reference document [11].

5.1 Maintenance strategy optimization and component update cycle acquisition

According to the second section, the optimal repair sequence of the gear box is optimized (\( I_1 = 141, \alpha = 0.26 \)), as shown in Table 1.

| Cycle times | X      | Optimization results |
|-------------|--------|----------------------|
| 0           | (90,0.75) | 2476                |
| 1           | (78,0.47) | 1152                |
| …           | …      | …                   |
| 11          | (92,0.33) | 1873                |
| 12          | (141,0.26) | 1586               |
When $\Omega=0.9$, the gear box update cycle optimization results are shown in Table 2.

| Detection sequence | I₁  | I₂  | I₃  |
|-------------------|-----|-----|-----|
| $(Pₚ,Pᵦ)$         | (0.49,0.82) | (0.89,0.92) | (0.93,0.94) |

From Table 2, we can see that in the I₂ detection time, $Pᵦ$ is greater than 0.9, then the gearbox has potential faults, and it is replaced, so that the gearbox renewal cycle is 177.66 days.

5.2 Quantity optimization of spare parts

The optimization target is optimized with the guarantee probability and the availability of spare parts which is greater than 0.95. The comparison of the spare parts optimization results of gear box is shown in Table 3.

| Spare parts type | Number of spare parts under guarantee probability | Cost / million yuan | Number of parts availability | Cost / million yuan |
|-----------------|-----------------------------------------------|--------------------|----------------------------|--------------------|
| Gear box        | 23                                            | 6900               | 11                         | 3300               |

From Table 3, we can see that for the two optimization objectives of the spare part guarantee probability and the component availability rate, the number of gearbox optimized by the two objective functions is 23 and 11 respectively, under the same constraint. The cost of the gear box is 3 million, and the cost of spare parts is 69 million yuan and 33 million yuan respectively. Using the availability rate as the objective function, the cost of spare parts of gear box (excluding inventory cost) can be saved by 36 million yuan in 5 years, and it is reduced by 52%. The reason why the difference between the two optimization results is large is that when the spare part guarantee probability is the optimization goal, the dynamic relationship between state of spare parts and update state of running parts is not considered, which will cause excessive allocation of spare parts. It can be seen that the cost of spare parts management can be greatly saved by using the component availability rate as the optimization goal.

6. Conclusion

In this paper, the number of spare parts optimization based on component updating is proposed in combination with the preventive maintenance strategy of components. Through the simulation analysis of the gear box of the wind turbine, the following conclusions are drawn:

1) In view of the particularity of offshore wind power, the optimization of spare parts quantity considering the preventive replacement of spare parts can effectively solve the problem of the quantity optimization of spare parts.

2) Taking the optimization of gear box spare parts as an example, it is verified that using availability as the optimization objective can effectively reduce spare parts management cost, and provide a new idea for optimizing the quantity of spare parts in the field of offshore wind power.

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