

Opportunistic Maintenance Model for Wind Turbine Based on Reliability Constraint

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Abstract: Preventive maintenance of wind turbine can effectively improve the reliability of wind turbine. This paper firstly set single component reliability of wind turbine as constraint condition, single component minimum unit time maintenance cost as objective function to obtain optimal maintenance cycle and maintenance times. On this basis, repairing component which meet certain conditions, then build opportunistic maintenance model of wind turbine. Lastly, set the minimum total cost under opportunistic maintenance as objective function, the wind turbine availability as constraint condition, then solve this model to obtain optimal threshold of opportunistic maintenance and minimum total maintenance cost using genetic algorithm. The example analysis shows that the model can effectively save the total maintenance cost. This study has some reference significance for the maintenance department to make the maintenance plan.

1. Introduction

As a clean renewable energy, the development and utilization of wind energy has been paid more and more attention by various countries, and the installed capacity of wind power is also increasing year by year[1-2]. As the key equipment of the wind power system, the wind turbine is complicated and runs in the field for a long time. The working environment is bad, and it is difficult to install and repair. In order to make the wind farm with large income, the wind turbine must meet certain reliability to reduce the loss of the system. The reasonable maintenance plan not only can improve the reliability of the wind turbine, but also can effectively reduce the maintenance cost of the wind turbine.

In recent years, the maintenance of wind turbines has been highly concerned by the enterprises and the academia. For example, document [3] focuses on the maintenance of wind turbine blades. Based on the damage degree and degradation data of blade of wind turbine, the optimization of blade maintenance strategy is realized by simulation in this paper. In document [4], the semi Markov model



was used to study the maintenance decision of the gear box of the wind turbine. In document [5], the system failure model and delayed maintenance model are used to study the problem of maintenance and optimization of the key components of the wind turbine. The problem in the above literature is to optimize the maintenance of the single component of the wind turbine. Such a time based single component preventive maintenance strategy is lack of coordination and coordination for each component's maintenance, which will cause expensive overhaul costs and high downtime losses[6].

The wind turbine is composed of key parts, such as gear box, spindle, generator set and impeller. It is a typical multi component series repairable system. It is pointed out that there is correlation between components of multi-component system in document [7-8]. Batch maintenance, group maintenance and opportunistic maintenance can effectively reduce maintenance costs. The opportunistic maintenance model is proposed by Berg.M[9]. The model defines the maintenance and replacement of other components together if the other parts exceed the given threshold when a component is overhauled in the system. It is proposed an opportunistic maintenance model based on reliability of wind turbines in document [10]. This model optimizes the total maintenance cost with the opportunistic maintenance reliability as the optimization variable in order to obtain the minimum maintenance cost. It is presented a state-opportunity maintenance model for wind turbines in document [11-12]. The model is based on the system state indicator. When a component of a unit is overhauled, if the status indicator of other components exceeds its opportunistic maintenance threshold, it will be overhauled.

On the basis of the above documents, the opportunity maintenance model of wind turbine based on the requirement of reliability is proposed in this paper. The work done is as follows: First, the life distribution function of each component is obtained according to the historical data. And with the reliability of each component as a constraint condition, the best repair period and maintenance times of each component are obtained. Secondly, according to the opportunistic maintenance strategy, we define the opportunistic maintenance threshold of each component, and solve the expression of total overhaul cost of wind turbine under opportunistic maintenance strategy. Finally, we use genetic algorithm to optimize the model to get the best opportunistic maintenance threshold and minimum total maintenance cost, and compare it with the single component maintenance model to verify the validity of the established model.

2. The opportunistic maintenance strategy of wind turbine based on reliability

2.1 Principle of opportunistic maintenance

The maintenance methods of the wind turbines involved in this article mainly include the following four kinds, Unwanted corrective maintenance, the minimum maintenance mode is adopted, and the failure rate of the component is not changed after overhaul; Preventive maintenance and opportunistic maintenance using incomplete opportunistic maintenance method、 Parts replacement, Part 1 is replaced during the second preventive maintenance, replacement to restore the parts as new.

The wind turbine is a system composed of gear boxes, bearings, generators, and blades, and the reliability function of the parts of the unit is monotonically decreasing with time. The principle of opportunistic maintenance for wind turbines based on reliability is as follows: When the reliability of a component in the unit reaches the reliability of preventive maintenance, preventive maintenance is carried out. This opportunity can be used to repair the other parts of the unit in advance, so as to improve the reliability of the unit, and reduce the loss of downtime and the cost of maintenance.

3. An Opportunistic Maintenance Model for Wind Turbines

3.1 Model Hypothesis

In order to simplify the study of the model and the main problems, the following assumptions are made in the construction of the model:

- (1) All the components of the wind turbine are all new in the initial time, and the distribution of the faults of each component is independent of each other, and all of them obey the Weibull distribution.
- (2) When an unintended fault occurs in a wind turbine, it is immediately overhauled and the maintenance time cannot be ignored.
- (3) The wind turbine works continuously, and the failure of a single component will cause the whole unit to stop.

3.2 Analysis on the cost of opportunity maintenance for wind turbines

The maintenance cost of the wind turbine consists of two parts, a part of the direct overhaul cost of the unit, and the other part of the cost of the outage loss due to the maintenance. The direct overhaul cost of any part k in the unit can be divided into preventive maintenance cost C_{pk} , the replacement cost C_{rk} of the component and the cost C_{fk} of the unintended failure maintenance of the component. The cost of outage loss for wind turbines includes C_{pd} for maintenance and maintenance loss and C_{fd} for unintended failure maintenance. The failure of any part of the wind turbine will cause the shutdown of the whole unit. C_d is used to indicate the cost of shutdown loss per unit time, and the above maintenance costs are analyzed respectively.

(1) Direct Overhaul Cost

After the completion of the $n-1$ prevention and maintenance from the time t_{n-1} , the wind turbine will complete the n preventive maintenance after the time t_n , and the direct maintenance cost of the component k is:

$$C_{p(k,n)} = \begin{cases} C_{fk} \int_0^{(t_n - t_{n-1})} \lambda_{nk}(t) dt & Y(k, t_n) = 0 \\ C_{pk} + C_{fk} \int_0^{(t_n - t_{n-1})} \lambda_{nk}(t) dt & Y(k, t_n) = 1 \\ C_{rk} + C_{fk} \int_0^{(t_n - t_{n-1})} \lambda_{nk}(t) dt & Y(k, t_n) = 2 \end{cases} \quad (1)$$

In the formula, $Y(k, t_n)$ means the maintenance mode adopted by the component k at the time t_n of maintenance of the wind turbine. 0 indicates no repair for the component k , 1 means the preventive maintenance of the component k , and 2 for the preventive replacement of the components.

If the wind turbine has carried out N preventive maintenance during the limited operation period $[0, T]$, the direct maintenance cost of the component k in the cycle is as follows:

$$C_k = \sum_{n=1}^N C_{p(k,n)} \quad (2)$$

Assuming that the wind turbine is composed of S components, the direct overhaul costs of all components in $[0, T]$ are:

$$C_m = \sum_{k=1}^S \sum_{n=1}^N C_{p(k,n)} \quad (3)$$

(2) Cost of shutdown for preventive maintenance

The loss cost C_{pd} of the shutdown for the preventive maintenance of the wind turbine is proportional to the time T_{pd} of the shutdown time, and the C_{pd} is proportional to the shutdown time. And T_{pd} is related to the number of tasks per preventive maintenance. When the wind turbine carries on the n

preventive maintenance, the longest part of the maintenance time should be selected as the stop time. As shown below:

$$T_{pdn} = \max_{1 \leq k \leq S} (t_{pk_{tn}}, t_{rkt_n}) \quad (4)$$

In the formula, S is the unit number of units; $t_{pk_{tn}}$ indicates the time required for the preventive maintenance of the component k at the time of t_n ; t_{rkt_n} represents the time required for the replacement of the component k at the time of t_n . The cost of the preventive maintenance and shutdown for the wind turbine in the limited period of $[0, T]$ is as follows:

$$C_{pd} = C_d T_{pd} = C_d \sum_{n=1}^N T_{pdn} \quad (5)$$

In the formula, C_d represents the cost of outage loss per unit time of a wind turbine.

3.3 Solution of opportunity maintenance model

(1) We can obtain the shape parameter β_k 、Scale parameter η_k 、Replacement cost C_{rk} 、The cost of preventive maintenance C_{pk} 、The cost of unintended fault maintenance t_{pk} 、The time required for a preventive maintenance t_{pk} 、Time required for an unwanted troubleshooting t_{fk} and the failure rate function of the component k after each completion of the preventive maintenance $\lambda_{(i+1)k}(t) = b_k(t + a_k T_{fk})$ by statistics and analysis of the historical data of the wind turbine.

(2) According to the method in the second section, the optimal maintenance interval T_{fk} of the component k and the best number of preventive maintenance times N_k are obtained.

(3) $t_n = \min(t_{(1,n)}, t_{(2,n)}, \dots, t_{(k,n)}, \dots, t_{(s,n)})$ as the time for the n maintenance of the unit, Where $t_{(k,n)}$ indicates the time for the unit k to do a n times repair.

(4) Set the opportunistic maintenance threshold of the unit ΔR_k . Then compare $R_{kn} - R_{km}$ and ΔR_k . If $R_{kn} - R_{km} > \Delta R_k$, The part k does not require an opportunistic maintenance at the time of t_n ; If $0 < R_{kn} - R_{km} \leq \Delta R_k$, The part k require an opportunistic maintenance at the time of t_n , meanwhile, The number of preventive maintenance of component k changed to $n_k + 1$; If $0 < R_{kn} - R_{km} \leq \Delta R_k$ and $n_k = N_k + 1$, a preventive replacement of the component k is required.

(5) The time required for the repair of the component k at the time t_n can be expressed as:

$$\tau(k, n_k) = \begin{cases} 0 & Y(k, t_n) = 0 \\ t_{pk_{tn}} & Y(k, t_n) = 1 \\ t_{rkt_n} & Y(k, t_n) = 2 \end{cases} \quad (6)$$

In the formula, $t_{pk_{tn}}$ indicates the time required for a preventive maintenance of the component k ; t_{rkt_n} indicates the time required for a preventive replacement of the component k . Choose the time of maintenance for the longest time required for maintenance, as the stopping time of the unit for this maintenance, that is $T_{pdn} = \max_{1 \leq k \leq S} (\tau(k, n_k))$.

(6) The time for the next preventive maintenance of the component k after the n times preventive maintenance of the wind turbine can be expressed as:

$$t_{(k, (n+1))} = \begin{cases} t_{(k, n)} + T_{pdn} & Y(k, t_n) = 0 \\ t_n + T_{pdn} + T_{(n+1)k} & Y(k, t_n) = 1, 2 \end{cases} \quad (7)$$

(7) The model established in this paper is a multi-variable and nonlinear global optimization problem, and the MATLAB genetic toolbox can be called to solve the model. The specific process of genetic algorithm is as follows[13-14]:

Step 1: a population $P_0 = (\Delta R(1), \Delta R(2), \dots, \Delta R(n))$ of a number of initial individuals is formed using a

computer, in which $\overline{\Delta R(n)}$ represents a feasible solution of the model.

Step 2: The values of each individual's C and A are calculated, and the individuals who are not satisfied with the reliability requirements are eliminated.

Step 3: Select the sorting operation for the population. The most adaptive individuals are retained to the next generation, and the lowest adaptive individuals are eliminated, and the remaining individuals are chosen according to the roulette algorithm.

Step 4: The crossover and mutation operation of the population was carried out according to the crossover probability P_n and the mutation probability P_m , producing a new generation of population and returning to step 2.

Step 5: The optimal $\overline{\Delta R}$ is output when the population iterates enough iterations to terminate the calculation.

4. analyses of example

4.1 Determination of model parameters

To verify the reasonableness of the model built in this paper. Choose a wind turbine, The 4 key parts of the gear box, the main bearing, the generator and the impeller are analyzed in the opportunistic maintenance strategy. Through the statistical analysis of the fault data of large wind farms, it is found that the fault time of the 4 key components all obey Weibull distribution. The Weibull distribution parameters of each component and other parameters are shown in Table 1. To make the components of the age reduction factor and failure rate increase factor same. that is: $a_k = a = 0.1$, $b_k = b = 1.1$. The study cycle of the overhaul of the wind turbine is $[0, 365]$ days.

Table 1. Maintenance parameters of critical components of wind turbine

Part Number	β	η	$C_{pk} /$ Million Yuan	$C_k /$ Million Yuan	$C_r /$ Million Yuan	$t_p /$ Days	$t_k /$ Days	$t_{rk} /$ Days
1	9.1604	1207.9	3.8	6.6	16.7	2	4	2
2	7.3317	1189.1	1.5	3.1	15.6	2	3	2
3	12.3972	1204.6	2.5	5.6	19.4	4	5	4
4	10.5149	1134.8	2.8	4.8	12.5	4	6	3

The reliability requirements for no fault operation of the 4 key components are given in JB/T10396. As shown in Table 2, when the reliability of the key components of the wind turbine is lower than the data shown in Table 2, preventive maintenance is carried out.

Table 2. Preventative maintenance reliability requirements of critical components of wind turbine

Part	Gear Box	Main Bearing	Generator	Impeller
Reliability	0.95	0.94	0.95	0.96

4.2 The solution of the interval of single part preventive maintenance and the number of overhaul times

Take the parameters in the 4.1 section into the second section model, and the model is solved by MATLAB software programming. Table 3 is the change table for the maintenance costs per unit time of each component with the number of times of maintenance. The maintenance cost per unit time in the table is only calculated to $N_k + 1$ times.

Table 3. the relation of each component unit time maintenance cost versus maintenance times

Part	Maintenance cost for unit time of each component Yuan/Days					Optimal number of preventive maintenance
	1	2	3	4	5	
1	212.3	206.8	197.6	216.5	-	3
2	223.8	207.1	201.2	197.4	204.6	4
3	478.5	465.2	482.8	-	-	2
4	115.7	104.8	102.9	112.3	-	3

From the above table, it can be seen that the maintenance cost per unit time of a single unit decreases first and then rises with the increase of the number of maintenance. Therefore, there is a best maintenance times make the maintenance cost of single part unit time minimum. The best preventive maintenance cycle in its life cycle is listed in Table 4. It can be seen from table 4 that the preventive maintenance cycle of each component is gradually shortened, which is in conformity with the actual situation. Along with the increasing age of the parts should repair more frequently on the parts, to ensure its reliability.

Table 4. Single component optimal maintenance interval

Part	Maintenance cycle of each component /Days				
	T_{1k}	T_{2k}	T_{3k}	T_{4k}	T_{5k}
1	120.1	114.5	106.5	98.7	-
2	95.4	76.2	70.8	67.6	55.4
3	165.4	154.2	123.6	-	-
4	89.7	78.4	72.5	68.9	-

4.3 Solution of an opportunistic maintenance model for wind turbines

The GA toolbox in MATLAB is called to solve the opportunity maintenance model of the wind turbine. The initial population size is set to 300, the maximum number of iterations $d=100$, the cross probability $P_m=0.8$, the mutation probability $P_n=0.02$, and the variable precision of 0.01, The other parameters use the system default value, After 100 iterations, the optimal total maintenance cost is 254 thousand yuan, An optimal set of opportunity maintenance thresholds corresponding to them is $\Delta R = (0.198, 0.124, 0.167, 0.114)$.

5. Conclusions

From the perspective of operational reliability and economy of wind turbines, an opportunity maintenance model for wind turbines is built in this paper, and applies genetic algorithm to solve this model to get the best opportunity maintenance threshold and minimum total maintenance cost. On this basis, the single component maintenance model which does not consider the opportunity overhaul is compared. The results show that the opportunistic maintenance model saves about 1/3 of the total maintenance cost compared with the single component maintenance model. The model provides a new idea for the maintenance and maintenance of the wind turbine, and has a certain application prospect. It is necessary to point out that this article is aimed at the establishment and solution of the opportunity maintenance model. It is still relatively lacking in the accumulation of basic data. If the model is to be used in the formulation of the actual maintenance plan, a large amount of basic data is needed to accumulate.

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