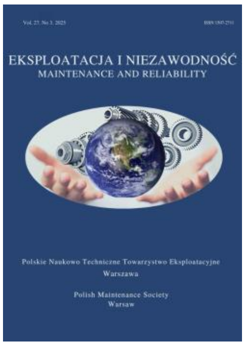

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Multi-reliability index evaluation and maintenance period optimization method of wind turbine considering failure correlation

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Highlights

- The Multi-reliability indexes of wind turbine are obtained.
- The optimal maintenance period of wind turbine is determined.
- The failure correlation among wind turbine components is considered.
- The validity of the proposed method is verified by example analysis.

Abstract

A multi-reliability index evaluation and maintenance period optimization method of wind turbine considering failure correlation is proposed to address the problems that the most existing reliability evaluation methods of wind turbine fail to consider the failure correlation among system components and often rely on a single reliability index to conduct reliability evaluation. Firstly, considering the failure correlation among system components, the reliability model of wind turbine and its comprehensive reliability model for component are established. Secondly, based on the sequential Monte Carlo simulation, a multi-reliability index evaluation method of wind turbine considering failure correlation and maintenance combination strategy is presented. Moreover, the maintenance period optimization method of wind turbine is proposed by using the unit time cost as the objective function. Finally, the effectiveness of the proposed method is verified through example analysis.

Keywords

wind turbine, failure correlation, sequential Monte Carlo, reliability evaluation, maintenance period optimization

1. Introduction

Currently, the global energy landscape is undergoing profound changes, and high-quality development of renewable energy is an inevitable choice to enhance national energy security capabilities [1, 2]. The large-scale and high proportion installation of wind turbine is an important part to build the modern energy system dominated by renewable energy. With the optimization of onshore wind power bases and the orderly development of offshore wind power bases, the reliability of wind turbine has received high attention from both developers and users. Improving the reliability of wind turbine has become a research focus and hotspot [3, 4].

At present, many research results have been made in the reliability evaluation of wind turbine. Zhu et al. [5] proposed a reliability analysis method for evaluating the real-time operating states of wind turbine. Mareike et al. [6] presented an integrated framework for reliability optimization of floating wind turbine. Li et al. [7] established a system reliability evaluation model of wind turbine based on load sharing. Song et al. [8] studied a short-term dynamic reliability evaluation model of floating offshore wind turbine. Duan et al. [9]

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considered the effects of wind speed and temperature to propose a reliability evaluation model of wind turbine based on Copula function. Chen et al. [10] proposed a reliability evaluation method for wind farms based on Copula function. Zhu et al. [11] proposed a reliability evaluation model of wind turbine based on Markov theory, taking into account environmental conditions. Verstraeten et al. [12] incorporated failure targets into wind farm control strategies, and proposed a reliability improvement method of wind turbine based on a multi-layer framework. Li et al. [13] proposed a component reliability evaluation method under small sample data condition.

The maintenance strategies for wind turbine mainly include corrective maintenance, opportunity maintenance, condition-based maintenance, preventive maintenance, and so on [14-17]. For the study of maintenance period optimization, Mirosław et al. [18] established a preventive maintenance model based on semi-Markov process to determine the optimal maintenance interval of wind turbine. Zhang et al. [19] established a maintenance period optimization model aiming at minimum expected cost rate, and discussed the impact of degradation and random impact. Li et al. [20] established a non-isoperiodic incomplete preventive maintenance model to determine the optimal maintenance period. Liu et al. [21] considered the degradation characteristics of different equipment and incomplete maintenance to determine the optimal preventive maintenance period. Su et al. [22] considered minimum maintenance and preventive maintenance, established a non-equal periodic preventive maintenance model to determine the optimal maintenance period of the system. Liu et al. [23] proposed predictive maintenance strategy optimization model of offshore wind turbine considering component maintenance priority to predict the next maintenance interval. He et al. [24] proposed a data-driven efficiency model of multi-component system, and determined the optimal maintenance period.

As mentioned above, research on reliability evaluation and maintenance period optimization method of wind turbine have achieved better result, but further research is needed in the following areas:

(1) The existing reliability evaluation and maintenance strategy of wind turbine often assume that the components are independent of each other, neglecting the failure correlation among them. However, in engineering practice, interactions and couplings among component failures are prevalent within wind turbine. Consequently, the failure correlation among system components should be taken into consideration when implementing wind turbine reliability evaluation and maintenance strategy.

(2) The existing reliability evaluation methods of wind turbine have mostly focused on a single reliability index, failing to form a comprehensive reliability evaluation system. It is unable to comprehensively evaluate the reliability level of wind turbine from multiple reliability indexes.

Based on the above analysis, the mainly contributions of this paper are as follows:

(1) Based on directed graph theory and Pagerank algorithm, a comprehensive reliability model of component is established considering the failure correlation among wind turbine components. Moreover, reliability evaluation and maintenance period optimization method of wind turbine considering failure correlation is analyzed and discussed in detail.

(2) Based on the sequential Monte Carlo simulation, a novel reliability evaluation multi-reliability index evaluation method of wind turbine considering maintenance strategy is proposed. This method can not only obtain the reliability index of wind turbine system, but also obtain other multiple reliability indexes, such as the mean time to failure (MTTF), failure state probability, failure frequency and downtime duration. It can comprehensively analyze the reliability of wind turbine.

In our study, the reliability model of wind turbine and its comprehensive reliability model for component are firstly established considering the failure correlation among system components. And then, a multiple reliability indexes evaluation method of wind turbine is proposed based on sequential Monte Carlo simulation, which consider multiple reliability indexes such as reliability, MTTF, failure state probability, failure frequency and downtime duration. On this basis, an optimization method of wind turbine maintenance period is proposed, with the goal of minimizing unit time cost. Finally, through example analysis, the reliability of the wind turbine is studied using various reliability indexes, and the optimal maintenance period is determined.

The rest of this paper is organized as follows: The relevant reliability models and maintenance strategy of wind turbine are constructed in Section 2. In Section 3, based on sequential

Monte Carlo method, the reliability evaluation and maintenance period optimization method of wind turbine considering failure correlation and maintenance combination strategy is proposed. In Section 4, the objective function of wind turbine maintenance period optimization is presented. The reliability of wind turbine is discussed in detail from multi-reliability index, and the optimal maintenance period of wind turbine is determined in Section 5. Conclusion is given in Section 6.

2. Reliability models and maintenance strategy related to wind turbine

2.1. Reliability models of wind turbine

The Weibull distribution is the commonly used life distribution model in the field of reliability, which can effectively characterize the variation law of mechanical and electrical equipment during the life period [25- 27]. In this paper, it is assumed that the failure time of wind turbine components follows the Weibull distribution model [28], and the corresponding failure distribution function $F(t)$, failure rate function $\lambda(t)$ and reliability function $R(t)$ can be respectively expressed as:

$$F(t)=1-\exp\left[-\left(\frac{t}{\eta}\right)^{m}\right] \tag{1}$$

$$\lambda(t)=\frac{m}{\eta^{m}}t^{m-1} \tag{2}$$

$$R(t)=\exp\left[-\int_{0}^{t}\frac{m}{\eta^{m}}t^{m-1}dt\right]=\exp\left[-\left(\frac{t}{\eta}\right)^{m}\right] \tag{3}$$

In Eqs. (1)-(3), t, η and m are the failure time, scale parameter and shape parameter, respectively.

In this paper, six key components of wind turbine including hydraulic system, gearbox, principal axis, main bearing, generator and frequency conversion system are taken as research objects [29], and their reliability block diagram is shown in Fig. 1.

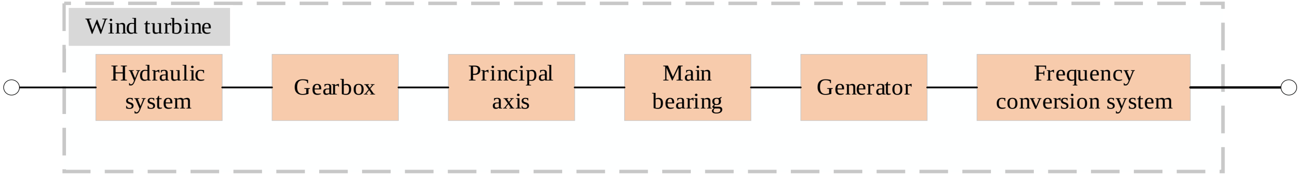


Fig. 1. Reliability block diagram of wind turbine.

Assuming that the life of each component of wind turbine is independent of each other, it can be seen from Fig. 1 that the failure of each component will lead to the failure of the wind turbine system. The reliability function of the wind turbine can be expressed as:

$$RWT(t)=\prod_{i=1}^{6}R_i(t) \tag{4}$$

In Eq. (4), R_{WT} is the reliability of wind turbine; R_i is the reliability of wind turbine component i.

2.2. Comprehensive reliability model of wind turbine components considering failure correlation

In the process of failure propagation, if a component is affected by the failure of other components, the degree of failure correlated impact of the component will be more significant. *CK* value is used to express such degree of impact, which can reflect the failure probability of the component due to the failure of other components [30]. Based on the digraph theory and Pagerank algorithm [31], *CK* value can be expressed as:

$$CK^{(x+1)}=\frac{1-d}{n}\cdot E+d\cdot\left(C'\right)^{T}\cdot CK^{(x)} \tag{5}$$

In Eq. (5), n is the number of components; E is the $n\times1$ matrix with all 1 element; d is the damping factor, generally 0.85 according to the experience value. C' is the state transition matrix obtained according to the transformation of the adjacency matrix.

Assuming that the wind turbine is composed of n components, and if the component i is regarded as a unit and the other n-1 components are regarded as another combined unit. Considering the impact of the failure of other n-1 components on the failure rate of component i, the comprehensive failure rate of component i can be obtained as:

$$\lambda_i=\lambda_{Ii}+(1-\lambda_{Ii})\varphi_{I(1,2,\cdots,i-1,i+1,\cdots,n)}\lambda_{I(1,2,\cdots,i-1,i+1,\cdots,n)} \tag{6}$$

In Eq. (6), $\lambda_{I(1,2,\cdots,i-1,i+1,\cdots,n)}$ is the failure rate of other combined components in the wind turbine except component i. $\varphi_{I(1,2,\cdots,i-1,i+1,\cdots,n)}$ is the probability of component i affected by other combination failure components, namely, $\varphi_{I(1,2,\cdots,i-1,i+1,\cdots,n)}$ is *CK* value of component i. λ_{Ii} is the failure rate of component i without considering failure correlation.

According to the Eq. (6), λ_{Ii} can be approximated, and assuming that 1-$CK(i)\lambda_{I(1,2,\cdots,i-1,i+1,\cdots,n)}=1$, we can obtain:

$$\lambda_{Ii}=\lambda_i-CK(i)\lambda_{I(1,2,\cdots,i-1,i+1,\cdots,n)} \tag{7}$$

According to Eq. (2), Eq. (3) and Eq. (7), the comprehensive reliability model of component *i* considering failure correlation can be expressed as:

$$R(t)_i=R(t)_{Ii}R(t)_0^{CK(i)} \tag{8}$$

In Eq. (8), $R(t)_i$ is the comprehensive reliability of component *i* when failure correlation is considered; $R(t)_{Ii}$ is the reliability of component *i* without considering failure correlation; $R(t)_o$ is the reliability function of other combined components except component *i*; $CK(i)$ is the impact level of component *i* affected by other component failures.

2.3. Maintenance combination strategy

Periodic maintenance is a kind of preventive maintenance. Combination with corrective maintenance, periodic maintenance is often used in major engineering equipment, which can effectively improve the reliability of equipment [32, 33].

In our study, a maintenance combination strategy is adopted, which combine periodic maintenance and corrective maintenance, as shown in Fig. 2. Namely, the wind turbine system at equal interval time kT carry out maintenance; and if failure occurs before T, corrective maintenance is performed. T is fixed periodic maintenance time, and k= 1, 2, ..., n.

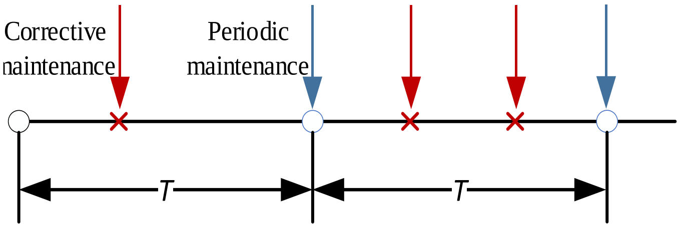


Fig. 2. Maintenance combination strategy.

3. Reliability evaluation and maintenance period optimization of wind turbine considering failure correlation and maintenance combination strategy

3.1. Component states duration sampling

The reliability of each component of the wind turbine is determined by Eq. (3). By inverting Eq. (3), the relationship between the component life and its reliability can be obtained, as shown in Eq. (9):

$$t=R^{-1}=\eta\cdot(-\ln R(t))^{1/m} \tag{9}$$

Therefore, the life τ of each component can be determined by sampling from Eq. (10):

$$\tau=\eta\cdot(-\ln E1)^{1/m} \tag{10}$$

In Eq. (10), E_1 is a uniformly distributed random number over [0,1].

Considering the failure correlation among wind turbine components, the sampling function of component state duration can be expressed as:

$$\tau=R(t)_i^{-1} \tag{11}$$

3.2. Reliability indexes

Reliability indexes are measures used to assess the normal operation of equipment or systems over a specified period. For wind turbine, reliability indexes typically include reliability and MTTF [34]. When considering their reparability, system reliability can also be analyzed by using other reliability indexes.

(1) Failure state probability P_f: the proportion of total downtime (including periodic maintenance time and corrective maintenance time) of the wind turbine to total operating time.

$$P_f=\frac{1}{\sum_{m=1}^{N}(T_{U\_m}+T_{D\_m})}\sum_{m=1}^{N} T_{D\_m} \tag{12}$$

(2) Failure frequency F_f: the ratio of the total number of failure shutdowns of wind turbine to the total operating time.

$$F_f=\frac{N_f}{\sum_{m=1}^{N}(T_{U\_m}+T_{D\_m})} \tag{13}$$

(3) Downtime duration D_f: the average downtime of wind turbine per operating period.

$$D_f=\frac{1}{N}\sum_{m=1}^{N} T_{D\_m} \tag{14}$$

In Eqs. (12)-(14), T_{U_m} and T_{D_m} indicate the working duration and maintenance duration of period m, respectively. N is the number of operating periods, and N_f is the number of corrective maintenances in N operating periods.

3.3. Reliability evaluation and maintenance period optimization processes considering failure correlation

Compared with Monte Carlo method, sequential Monte Carlo method can effectively simulate system timing and state duration randomness of wind turbine [35-36]. In our study, Sequential Monte Carlo method is selected, and the reliability evaluation and maintenance period optimization of the system are carried out. The corresponding process is shown in Fig. 3, with specific steps as follows:

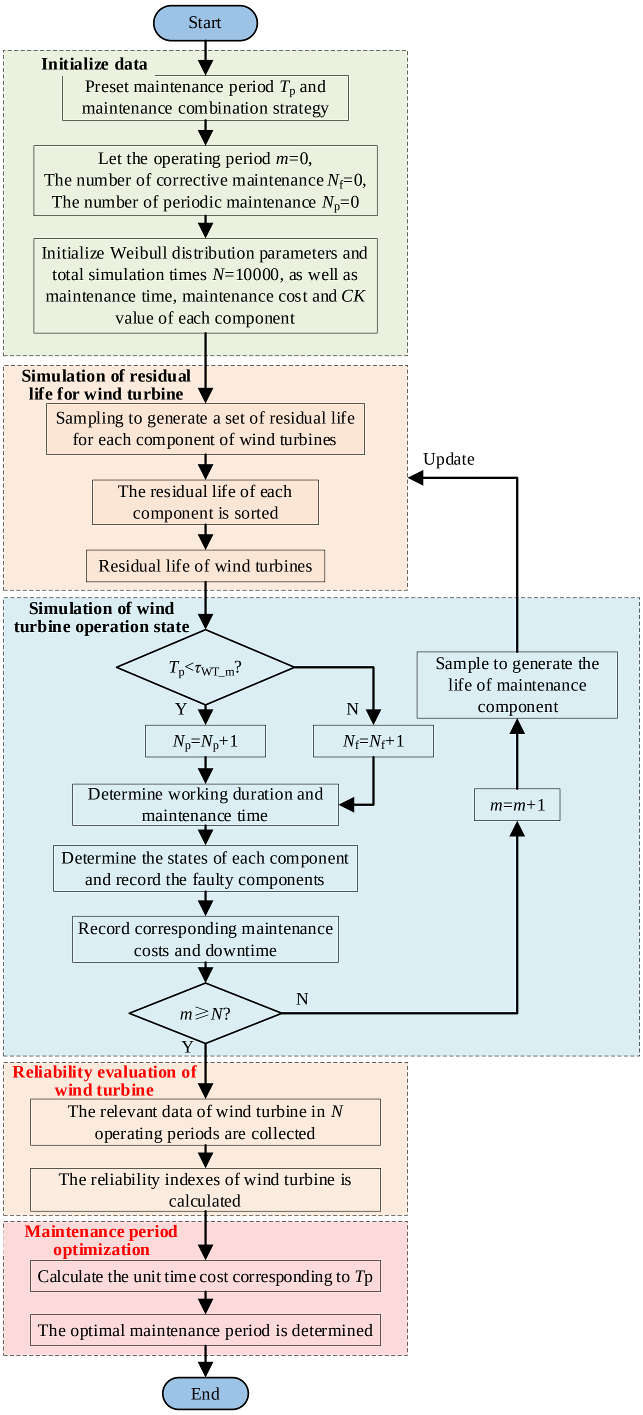


Fig. 3. Flow chart for reliability evaluation and maintenance period optimization of wind turbine.

Step 1: Parameter initialization. Set maintenance period T_p, maintenance combination strategy (periodic maintenance and corrective maintenance), Weibull distribution parameters, CK value of component, total simulation times N, corrective maintenance time and periodic maintenance time of wind turbine component.

Step 2: Determine the residual life of each wind turbine component by sampling according to Eq. (11).

Step 3: Determine the working duration and maintenance duration for the m operating period of wind turbine. Among them, the maintenance time is equal to the corrective maintenance time or periodic maintenance time of the wind turbine, as detailed in Section 4.1, and the working duration can be expressed as:

$$T_{U\_m}=\min(T_p, \tau_{WT\_m}) \tag{15}$$

In Eq. (15), τ_{WT_m} is the residual life of the wind turbine in the m operating period. When the residual life of the wind turbine is less than the preset maintenance period, the wind turbine fails before the preset maintenance period, and then the working duration is the residual life of the wind turbine.

When the residual life of the wind turbine is greater than the preset maintenance period, the wind turbine operates normally within the preset maintenance period, and the working duration is the preset maintenance period value of wind turbine. The residual life τ_{WT_m} of wind turbine simulation process is detailed in Section 3.4.

Step 4: Record the corresponding maintenance costs and downtime.

Step 5: Repeat steps 3-4 until the number of simulate reaches N operating period, and calculate the state (normal state and failure state), state duration (working duration and maintenance time), number of repair maintenance N_f and number of corrective maintenance N_p of the wind turbine in N operating period.

Step 6: According to the data calculated in Step 5, the reliability indexes of the wind turbine are obtained and the optimal maintenance period is determined.

3.4. Simulation process of wind turbine residual life

The detailed simulation process of the residual life of wind turbine is shown in Fig. 4, and the specific steps are as follows:

1）Based on the known residual life of all components in the m-1 operating period, the residual life matrix of all components of the wind turbine is constructed:

$$A_{m-1}=[B_1, B_2, B_3, B_4, B_5, B_6] \tag{16}$$

In Eq. (16), theA_{m-1} elements of the matrix are the residual life of the six key components in the m-1 operating period.

2) Determine the state of each component of the wind turbine.

For the m-1 operating period, if the residual life of any component does not exceed the working duration of the corresponding operating period, the component will fail during the operating period; If the residual life of a component exceeds the operating period of the operating period, the component is always in normal condition during the operating period.

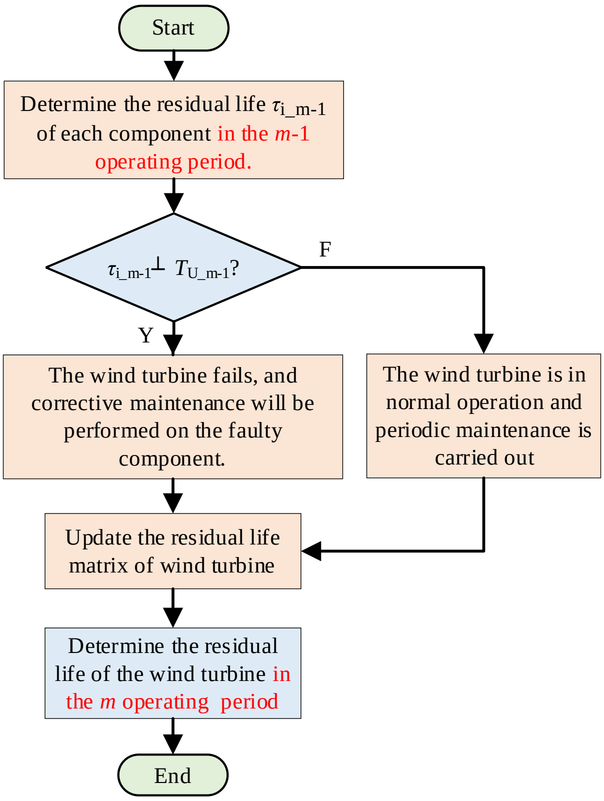


Fig. 4. Flow chart for residual life simulation of wind turbine.

Therefore, the state of any component during the m-1 operating period can be expressed as:

$$S_{i\_m-1}=\begin{cases}1 & \tau_{i\_m-1}>T_{U\_m-1}\\ 0 & \tau_{i\_m-1}\leq T_{U\_m-1}\end{cases} \tag{17}$$

In Eq. (17), S_{i_m-1} is the working state of component i during the m-1 operating period, and 1 and 0 indicate the normal state and failure state, respectively. τ_{i_m-1} indicates the residual life of component i.

3) Perform corrective maintenance on failure components or periodic maintenance on wind turbine, and update the residual life matrix of the wind turbine.

When maintenance activities are carried out on wind turbine at the end of the m-1 operating period, the residual life A_{m-1_rl} of each component is:

$$A_{m-1\_rl}=A_{m-1}-T_{U\_m-1}U_{[1\times 6]} \tag{18}$$

In Eq. (18), $U_{[1\times 6]}$ represents a 1×6 all-ones matrix.

If a component fails, the failure component is identified according to Eq. (17), and corrective maintenance is performed. The post-repair component life is sampled and updated according to Eq. (11). Periodic maintenance is performed on wind turbine generators provided that no component failures have occurred. The life of all components after periodic maintenance is obtained and updated according to Eq. (11). As a result, the residual life matrix A_m of wind turbine in the m operating period is obtained.

4) The residual life τ_{WT_m} of the wind turbine in the m operating period is determined.

The residual life matrix A_m of wind turbine in the m operating period can be expressed as:

$$A_m=[\tau_1,\tau_2,\tau_3,\tau_4,\tau_5,\tau_6] \tag{19}$$

In Eq. (19), the elements of matrix A_m are respectively the residual life of the six key components of the wind turbine in the m operating period. And the residual life τ_{WT_m} of the wind turbine in m operating period can be expressed as:

$$\tau_{WT\_m}=\min(A_m) \tag{20}$$

4. Maintenance period optimization objective function

In engineering practice, the unit time cost during the total operating period of a wind turbine is a key concern for both its developers and users. Based on the wind turbine reliability evaluation and maintenance period optimization method proposed in Section 3, an objective function to minimize the unit time cost is established in this section.

Assuming the maintenance period of the wind turbine is T_p, and the total simulated operating period is N. The expected unit time cost $c(T_p)$ over the total operating period can be expressed as:

$$c(Tp)=\frac{1}{\sum_{m=1}^{N} T_{U\_m}}\left(\sum_{i=1}^{N_f} C_{f\_i}+\sum_{j=1}^{N_p} C_{p\_j}\right) \tag{21}$$

In Eq. (21), T_{U_m} represents the working duration in the m operating period; N_f and N_p are the number of corrective maintenance and periodic maintenance over the N operating periods, respectively; C_{f_i} and C_{p_j} represent the total cost of the i corrective maintenance and the j periodic maintenance, where:

$$C_{f\_i}=C_{f\_loss\_i}+C_d T_{Df\_i} \tag{22}$$

$$C_{p\_j}=\sum_{i=1}^{n} C_{p\_loss\_i}+C_d T_{Dp\_j} \tag{23}$$

In Eq.s (22)-(23), C_d represents the unit time loss cost caused by maintenance activities; $C_{p\_loss\_i}$ and $C_{f\_loss\_i}$ are the periodic maintenance cost and the corrective maintenance cost for component i, respectively.

5. Example analysis

Based on the reliability evaluation and maintenance period optimization method of wind turbine considering failure correlation and maintenance combination strategy proposed in Section 3, as well as the maintenance period optimization objective function established in Section 4, this section conducts reliability analysis for six key components of wind turbine including hydraulic system, gearbox, principal axis, main bearing, generator and frequency conversion system. And the optimal maintenance period is also determined. Number the components of wind turbine as components A to F in sequence, and the *CK* values of each component are shown in Table 1. The corresponding relevant parameters are shown in Table 2 [37]. The unit time loss cost caused by maintenance activities is C_d=1310 euro.

Table 1. *CK* values for key components of wind turbine.

Component	**A**	**B**	**C**	**D**	**E**	**F**
CK value	0.09	0.13	0.09	0.06	0.06	0.05

Table 2. Maintenance data for key components of wind turbine.

Component	***m***	***η***	**C_{f_loss}/ euro**	**C_{p_loss}/ euro**	**t_f /d**	**t_p /d**
A	1.93	723.4	48.37	57.52	0.6	0.5
B	1.79	1056.8	477.12	317.65	2.6	0.85
C	1.52	978.3	117.65	64.05	1.3	0.4
D	2.14	411.5	118.95	78.43	0.5	0.6
E	1.64	1205.5	339.87	143.79	0.9	0.6
F	2.03	825.7	71.90	60.13	0.55	0.4

5.1. Reliability evaluation and maintenance period optimization of wind turbine without considering failure correlation

This section discusses the reliability and maintenance period of wind turbine without considering failure correlation.

5.1.1. The reliability of wind turbine without considering the maintenance combination strategy

In this section, the reliability of the wind turbine and its key components are studied without considering the maintenance combination strategy by using the reliability indexes MTTF and reliability *R*. The total number of simulations is *N*=10,000. The reliability evaluation results are shown in Fig. 5 and Fig. 6.

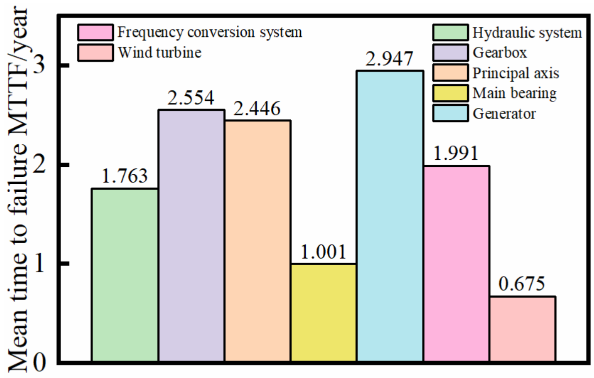


Fig. 5. The MTTF of the wind turbine and its components during maintenance combination strategy is not considered.

According to Fig. 5, the MTTF of the wind turbine is 0.675 years without considering the maintenance combination strategy. Compared the MTTF of key components of the wind turbine, the order from highest to lowest is generator, gearbox, principal axis frequency converter system, hydraulic system and main bearing. Among these, the MTTF of the main bearing is the shortest at 1.001 years, while the generator has the longest MTTF at 2.947 years. Therefore, during the maintenance order process of wind turbine is main bearing, and hydraulic system, frequency converter system, principal axis, gearbox and generator.

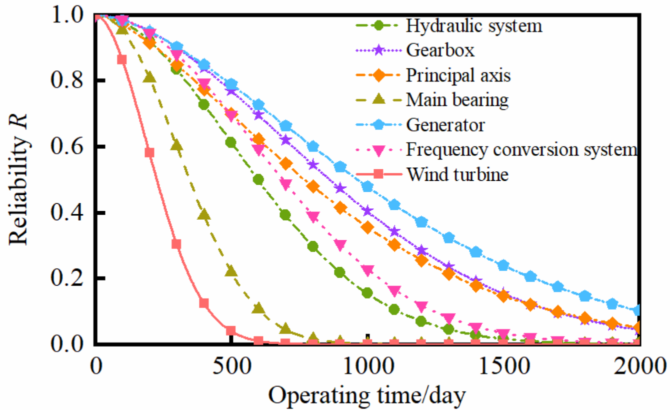


Fig. 6. The variation of reliability of wind turbine and their components over operating time without considering maintenance combination strategy.

According to Fig. 6, for each key component of wind turbine, the reliability of the main bearing decreases the fastest with increasing operating time. When the operating time is 700 days, main bearing reliability drops to 0.04. The reliability of generator decreases the slowest compared to other components. When the operating time is 700 days, generator reliability is 0.66, and when the operating time is 2000 days, its reliability is 0.11. Overall, the reliability of key components of wind turbine shows a continuous decrease with increasing operating time. For wind turbine, the overall reliability decreases rapidly when the operating time is less than 500 days, and drops to 0.002 when the operating time reaches 700 days.

5.1.2. The reliability of wind turbine when considering maintenance combination strategy

In this section, considering maintenance combination strategy, the reliability of wind turbine is studied by using three reliability indexes such as failure state probability P_f, failure frequency F_f, and downtime duration D_f. The maintenance period T_p is set to range from 0 to 2 years, and the total simulation times N=10000 times. The reliability index results of wind turbine are shown in Figs. 7-9.

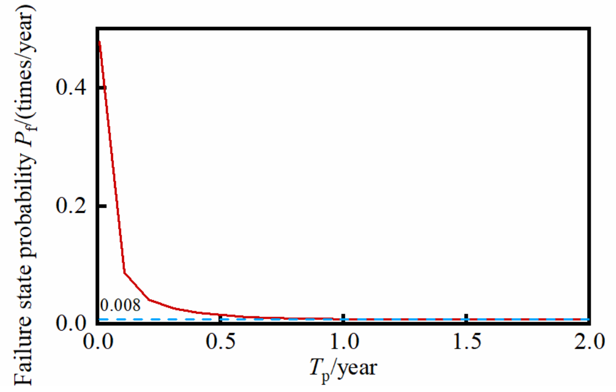


Fig. 7. Failure state probability.

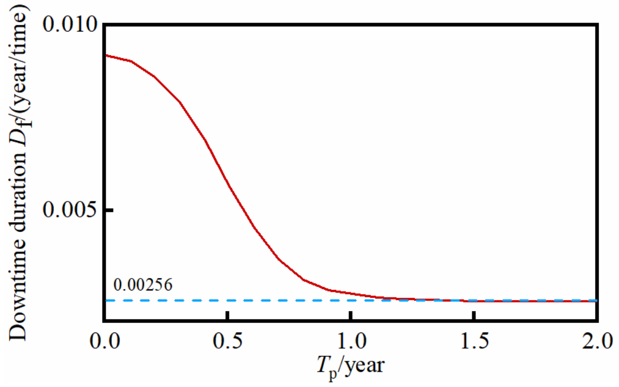


Fig. 8. Downtime duration.

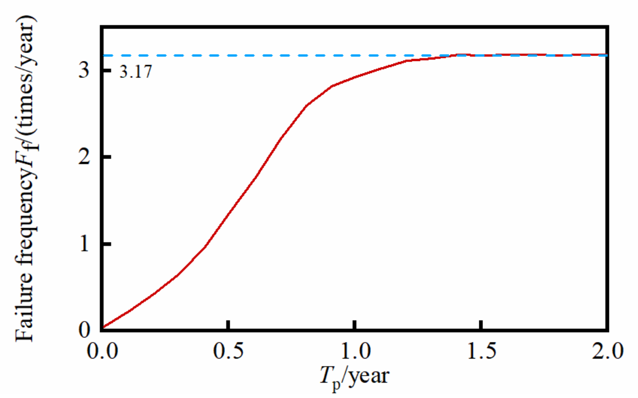


Fig. 9. Failure frequency.

According to Fig. 7, when T_p is between 0 and 0.2 years, P_f declines rapidly. Once T_p exceeds 0.2 years, the decline in P_f slows down and eventually stabilizes at 0.008 times/year. According to Fig. 8, when T_p is small, the downtime of wind turbine is mainly caused by periodic maintenance, and D_f is approximately equal to the time required for one periodic maintenance, which is 0.00917 years/time. When T_p exceeds 1.3 years, D_f stabilizes at 0.0025 years/time. At this time, the downtime duration of wind turbine is mainly caused by corrective maintenance, so this value is approximately equal to the average time required for corrective maintenance of wind turbine. According to Fig. 9, with the increase of T_p, the number of failures of wind turbine before periodic maintenance increases, and F_f gradually increases, finally stabilizes at 3.17 times/year.

According to Figs. 7-9, all three reliability indexes tend to be stable as T_p increases. This is because when the T_p is large, the wind turbine will almost fail before periodic maintenance. And there is only corrective maintenance behavior, without periodic maintenance. Consequently, the maintenance mode is relatively single, and the reliability index tends to be stable.

5.1.3. Maintenance period optimization of wind turbine under maintenance combination strategy

In this section, the maintenance period of wind turbine is optimized considering the maintenance combination strategy with the minimum unit time cost as the goal. The maintenance period T_p is set to range from 0 to 2 years, and the total simulation times N=10000 times. The variation of unit time cost with T_p is shown in Fig. 10. The variation of the frequency of periodic maintenance and corrective maintenance with T_p is shown in Fig. 11.

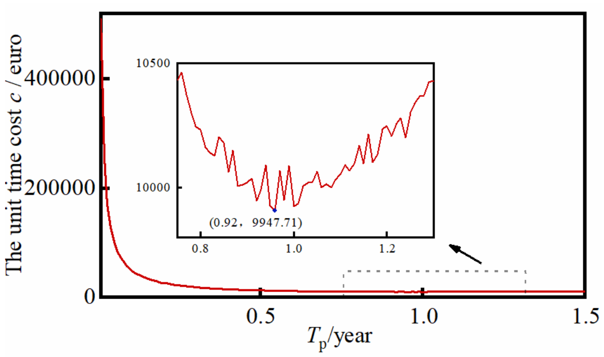


Fig. 10. The unit time cost c varies with T_p.

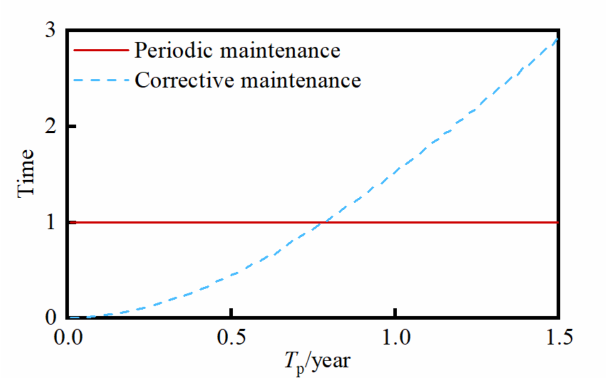


Fig. 11. The number of the two maintenance methods varies with T_p.

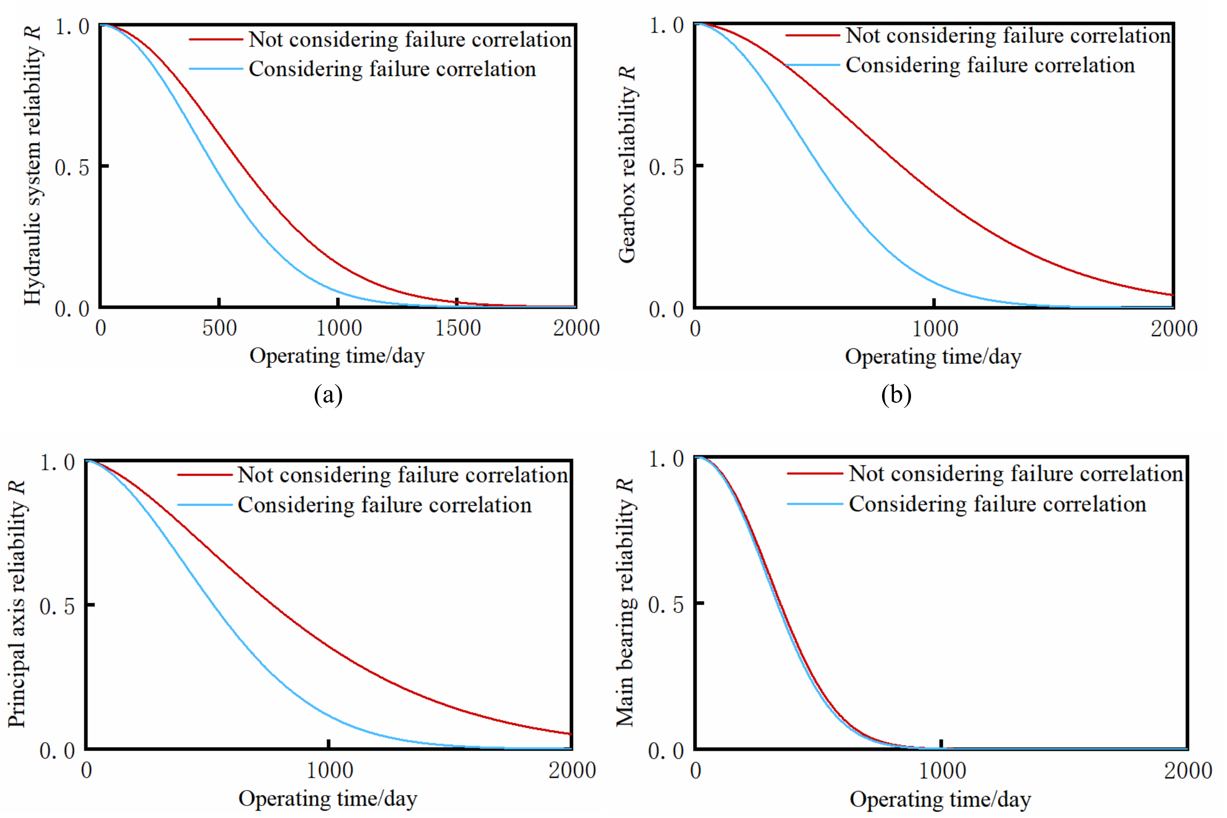
According to Fig. 10, when T_p is between 0.8 and 1.2 years, the unit time cost c shows a variation of first decreasing and then increasing. Moreover, T_p is 0.92 years when the minimum value of unit time cost c is 9947.71 euro. According to the comprehensive analysis of Fig. 11, when T_p is 0.92 years, the number of failures of wind turbine in each operating period is 1.32 times.

5.2. Reliability evaluation and maintenance period optimization of wind turbine considering failure correlation

This section considers failure correlation to discuss the reliability and maintenance period optimization of wind turbine, and contrasts these research results with scenarios where failure correlation is not taken into account.

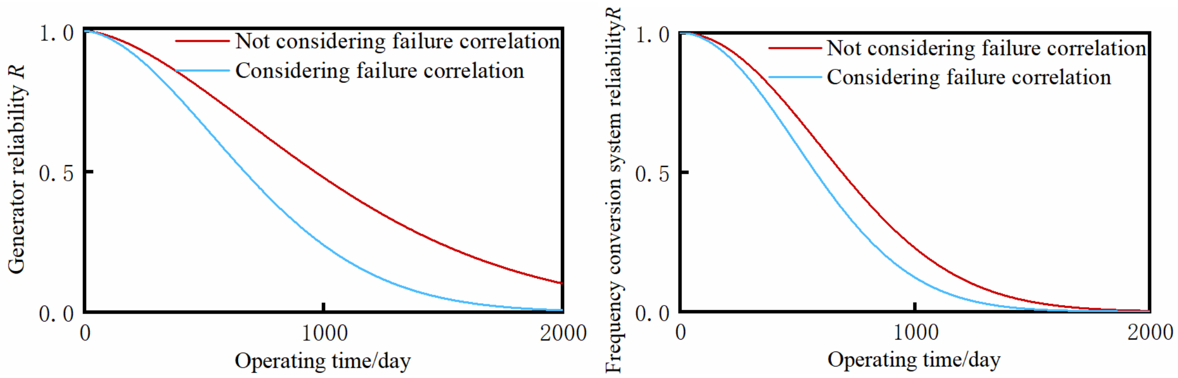
5.2.1. The reliability of wind turbine without considering the maintenance combination strategy

Based on section 5.1.1, the reliability of wind turbine and its key components is studied considering the failure correlation among wind turbine components, and the results are shown in Figs. 12-14.



(a) (b)

(c) (d)



(e) (f)

Fig. 12. The variation of reliability of wind turbine key components over operating time when whether considering the failure correlation.

According to Fig. 12, the reliability of key components of wind turbine will be reduced when the failure correlation among components is considered. Among them, the reliability of the main bearing shows the smallest change, with a maximum decrease of 0.027. The reliability of the gearbox changed the most, with a maximum decrease of 0.34, and the reliability is less than 0.01 when it operates to 1396 days.

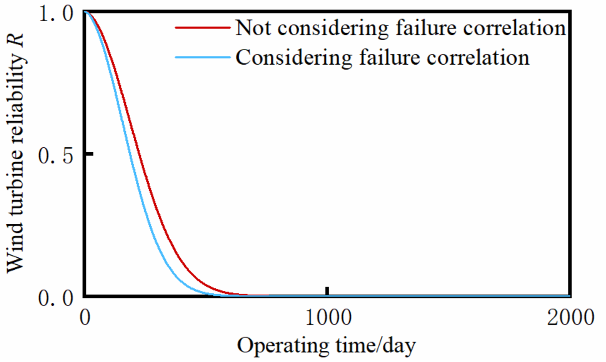


Fig. 13. The variation of reliability of wind turbine over operating time when whether considering the failure correlation.

According to Fig. 13, when the failure correlation among wind turbine components is considered, the reliability of wind turbine decreases, and the maximum decrease is 0.128. When the reliability of the wind turbine decreases to 0.002, it reaches 584 days of operation, with the reduction of 116 days compared with those without considering failure correlation.

According to Fig. 14, the MTTF of the wind turbine and its key components will decrease when the failure correlation among the wind turbine components is considered. Among them, the MTTF of the main bearing changes the least, decreasing by 0.044 years, and the MTTF of the gearbox changed the most, decreasing by 0.98. It is consistent with the results in Fig. 13. For wind turbine, when failure correlation is considered, the MTTF is 0.56 years, with the reduction of 0.115 years.

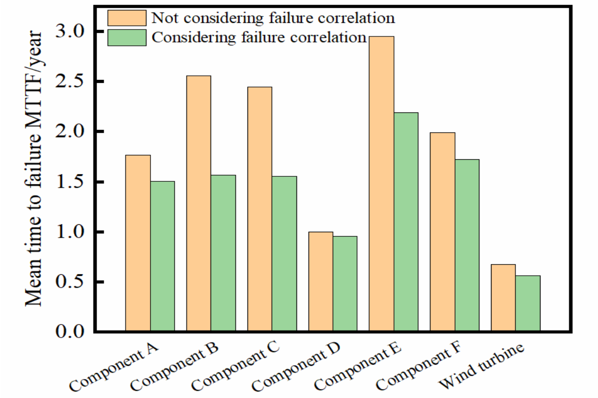


Fig. 14. The MTTF of wind turbine and its key components when whether considering the failure correlation.

5.2.2. The reliability of wind turbine when considering maintenance combination strategy

Based on section 5.1.2, considering the failure correlation among wind turbine components, the reliability of wind turbine is analyzed from three reliability indexes including P_f, D_f and F_f, and the results are shown in Figs. 15-17.

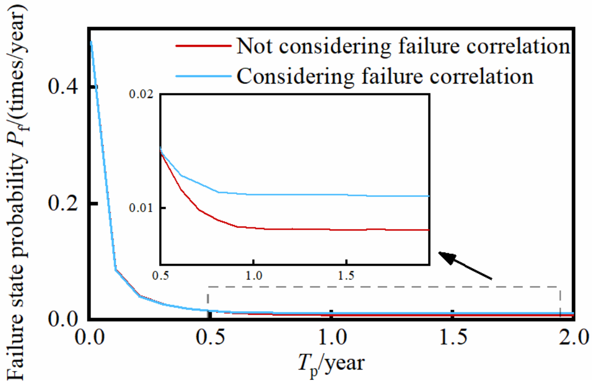


Fig. 15. The failure state probability when whether considering the failure correlation.

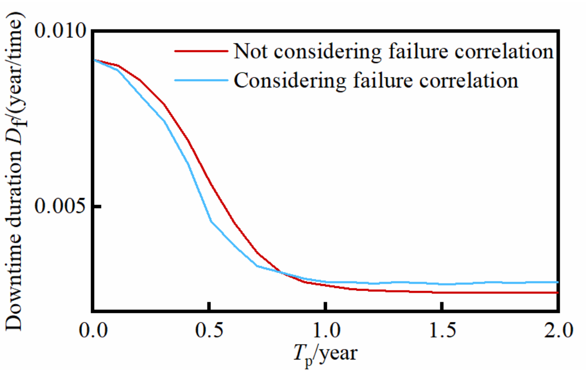


Fig. 16. The downtime duration when whether considering the failure correlation.

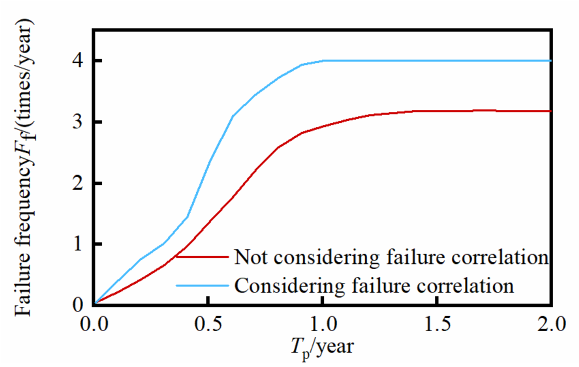


Fig. 17. The failure frequency of whether to consider the failure correlation or not.

According to Fig. 15, when T_{p} is less than 0.5 years, the failure correlation among wind turbine components has little effect on the reliability index P_{f}. When T_{p} exceeds 0.5 years, with the influence of component failure correlation, P_{f} increases and eventually stabilizes at 0.011 times/year, with an increase of 0.003 times per year compared to those without considering failure correlation.

According to Fig. 16, when the T_p is less than 0.8 years, the D_f considering the failure correlation of wind turbine is less than the D_f when the failure correlation is not considered. When T_{p} exceeds 0.8 years, the D_f considering the failure correlation of wind turbine is greater than the D_f when the failure correlation is not considered. When considering failure correlation, D_{f} finally stabilizes at 0.0028 years/time, with an increase of 0.0003 years/time compared to those without considering failure correlation.

According to Fig. 17, both whether to consider the failure correlation or not, F_{f} increases over time. And considering the failure correlation of wind turbine, F_{f} is greater than the D_f when the failure correlation is not considered. When considering failure correlation, F_{f} finally stabilizes at 3.99 years/time, with an increase of 0.82 years/time compared to those without considering failure correlation. In totally, the failure correlation among wind turbine components will reduce the reliability of the wind turbine to some extent, which can make the reliability evaluation results of wind turbine more accurately.

5.2.3. Maintenance period optimization of wind turbine under maintenance combination strategy

Based on section 5.1.3, considering the failure correlation among wind turbine components and the maintenance combination strategy, the maintenance period of wind turbine is optimized with the minimum unit time cost as the goal, and the result is shown in Fig. 18. The variation of the unit time cost is also shown in Fig. 19.

According to Fig. 18, F_f, both whether to consider the failure correlation or not, shows a trend of first decreasing and then increasing. When T_{p} is 0.76 years, the minimum c is 12745.13 euro with consider failure correlation. And compared with not considering failure correlation, the minimum c increased by 2797.42 euro. According to Fig. 19, the variation of c shows an upward trend as T_{p} increases, with a maximum increment reaching 6588.05 euro.

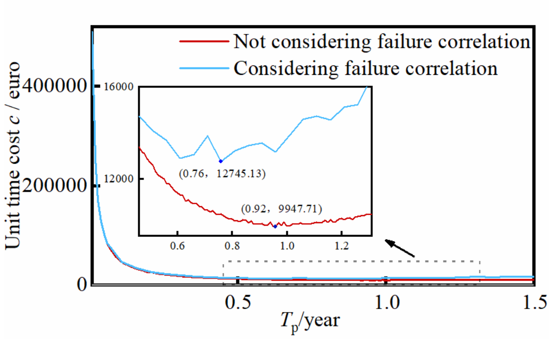


Fig. 18. The unit time cost c varies with Tp when whether considering the failure correlation.

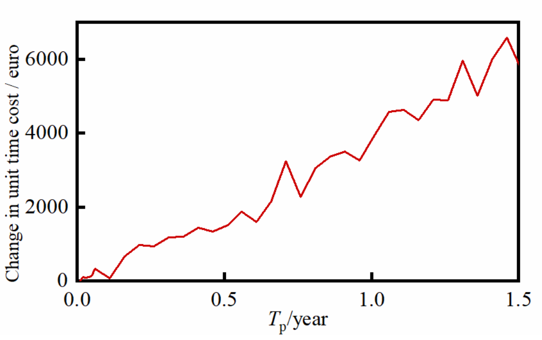


Fig. 19. The change in unit time cost variation with T_{p} when considering failure correlation.

Based on the reliability evaluation and maintenance period optimization method proposed in this paper, along with the established objective function for maintenance period optimization, a reliability analysis is conducted for wind turbine, and the optimal maintenance period for the wind turbine is determined. By comparing scenarios with and without considering failure correlation, and with and without considering maintenance combination strategy, the reliability and maintenance period of wind turbine are studied in depth.

6. Conclusion

This paper proposes a multi-reliability index evaluation and maintenance period optimization method of wind turbine considering failure correlation based on sequential Monte Carlo simulation. Firstly, a reliability model for wind turbine and a comprehensive reliability model considering failure correlation are established. Then, considering maintenance combination strategy, the reliability of wind turbine is comprehensively analyzed through multiple reliability indexes (reliability, MTTF, failure state probability, failure frequency, and downtime duration). Based on the above, the optimal maintenance period for wind turbine is determined with the goal of minimizing cost per year. Finally, the effectiveness of the proposed model and method is verified through example analysis.

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