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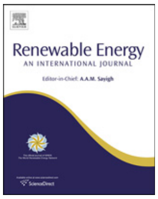

Opportunistic maintenance for wind farms considering multi-level imperfect maintenance thresholds

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A B S T R A C T

Few methods are available for optimizing corrective maintenance and time-based maintenance for wind farms, although these strategies are currently widely used in practice. Economic dependencies exist among wind turbine systems and their components in the wind farm. That is, it may be more economical to maintain multiple turbines or turbine components when a corrective or preventive maintenance opportunity presents. In this paper, opportunistic maintenance approaches are developed for wind farms to take advantage of the maintenance opportunities. Imperfect maintenance actions are considered, which addresses the practical issue that preventive maintenance does not always return components to as-good-as-new status. The proposed opportunistic maintenance policies are defined by the component's age threshold values, and different imperfect maintenance thresholds are introduced for failure turbines and working turbines. Three types of preventive maintenance actions are considered, including perfect, imperfect and two-level action. Simulation methods are developed to evaluate the costs of proposed opportunistic maintenance policies. Numerical examples are provided to illustrate the proposed approaches. Comparative study with the widely used corrective maintenance policy demonstrates the advantage of the proposed opportunistic maintenance methods in significantly reducing the maintenance cost. The developed methods are expected to bring immediate benefits to wind power industry.

1. Introduction

Global warming and high oil and gas price present urgent needs to explore competitive clean and renewable energy. Wind energy is one of most important renewable energy sources in the world, and its installed capacity worldwide has grown significantly in recent years. Operation & maintenance have drawn increasing interests for reducing the significant investment in the wind power projects, and appropriate and practical maintenance strategies need to be heavily studied for successful future developments. Maintenance management aims at improving the availability of the systems and reducing the overall maintenance cost. The existing maintenance methods for wind power systems can be classified into failure-based (corrective), time-based, and condition-based maintenance (CBM). Failure-based maintenance is carried out only after a failure occurs. In time-based maintenance, preventive maintenance is performed at predetermined time intervals. CBM applies the health condition prediction techniques to continuously monitor the components so that components are used the most effectively. However, the availability of condition monitoring data is a big challenge for CBM applications in wind turbine systems today. Currently corrective maintenance and time-based preventive maintenance are widely used in wind power industry, which take advantage of ease of management, particularly in the case of extreme conditions and high load associated with offshore farms. However, they have not been studied adequately and few models and methods are developed to optimize the time-based maintenance strategies.

Europe Wind Energy Report (2001) proposed four maintenance strategies for European offshore wind farms, and one of them is opportunistic maintenance. In opportunistic maintenance, whenever a failure occurs in the wind farm, the maintenance team is sent onsite to perform corrective maintenance, and take this opportunity to simultaneously perform preventive maintenance on the other components in the failed turbines and the running turbines and their components which show relatively high risks. There are typically multiple wind turbines in a wind farm and a wind turbine

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Abbreviations: CBM, condition-based maintenance; PM, preventive maintenance; MTTF, mean time to failure.

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has multiple components. Economic dependencies exist among various components and systems in the farm. When a down time opportunity is created by the failed components, maintenance team may perform preventive maintenance for other components satisfying pre-specified decision conditions, such as certain age thresholds. As a result, substantial cost can be saved comparing to separate maintenance for the components.

In the general maintenance engineering field, various opportunistic maintenance policies and applications have been reported. Laggoune [2] considered hydrogen compressors with different component failure distributions, and made maintenance decisions based on if performing replacements can lower the expected costs. An age-based policy was used by Crocker [3] to optimize the maintenance of a military aero-engine, and they concluded that opportunistic maintenance should be performed on relatively cheap components in their application. Mohamed-Salah et al. [4] proposed an opportunistic maintenance policy for ball bearings based on the time difference between expected preventive maintenance time and failure instant. Kabir et al. [5] assumed that the components are identical following the same Weibull distribution, and presented a maintenance method for multi-unit systems. However, very few studies are reported on opportunistic maintenance for wind power systems. Besnard [7] proposed an opportunistic maintenance method for offshore wind turbine systems based on both failure chance and real wind data. They presented an optimization model with a series of constraints aiming at minimizing the cost, and an optimal maintenance schedule for a 5 turbines wind farm was presented. Tian et al. [6] developed a CBM method for wind farms by considering the economic dependencies among components, and determined the maintenance actions based on the optimized failure probability threshold values and the condition monitoring data.

In most existing studies on preventive maintenance of wind turbines, one disadvantage is that preventive maintenance actions are generally considered to be replacement, which is the perfect action to return a component to the as-good-as-new state. In practice, however, preventive maintenance does not always return components to the as-good-as-new status. According to Spinato et al. [1], repair actions for wind turbine components may include addition of a new part, exchange of parts, removal of a damaged part, changes or adjustment to the settings, software update, lubrication or cleaning, etc. Ding and Tian [10] developed opportunistic maintenance methods for wind farms considering imperfect maintenance actions. However, they did not distinguish between the failed turbines and working turbines regarding if preventive maintenance should be performed, and used the same maintenance thresholds for all the wind turbines.

To address the issues above, in this paper, opportunistic maintenance approaches are developed for wind farms to take advantage of the maintenance opportunities and consider imperfect maintenance actions. The proposed opportunistic maintenance policies are defined by the component's age threshold values, and different imperfect maintenance thresholds are introduced for failure turbines and working turbines. Three types of preventive maintenance actions are considered, including perfect, imperfect and two-level action. Simulation methods are developed to evaluate the costs of proposed opportunistic maintenance policies. Numerical examples will be provided to illustrate the proposed approaches.

2. The proposed opportunistic maintenance approaches

In this paper, the preventive maintenance actions are considered as perfect, imperfect and two-level action, respectively, and accordingly three opportunistic maintenance strategies for wind farms are proposed. At each failure instant in the wind farm, a preventive maintenance task for a certain operational component is determined based on whether its age exceeds the age threshold, which is defined to be different between the components in the failed turbine and running turbines. Simulation approaches are developed to evaluate the maintenance cost of each proposed method. The optimal age thresholds corresponding to the lowest average cost can be found for optimizing each proposed maintenance strategy.

In the case of an imperfect maintenance action, a ratio of age reduction, q $(0 \le q \le 1)$, is defined. The component's failure age after maintenance is updated, and the imperfect action cost varies according to different age reduction effort. Specifically, the age of a component is reduced by q after maintenance, and its failure age is updated as-good-as-new with probability q and unchanged with probability with $1 - q$. That is, failure age $= q \times T_{\mathrm{Renew}} + (1-q) \times T_{\mathrm{old}}$. In other words, if a component is performed 100% age reduction maintenance (i.e. perfect maintenance), it is equivalent to preventive replacement because the component's lifetime is completely updated with a new one. In addition, the cost of imperfect action is defined as a function of q, which is given by

$$\mathrm{Cp} = \begin{cases} q^2 C_{\mathrm{pv}} + C_{\mathrm{pf}} & 0 < q \le 1 \\ 0 & q = 0 \end{cases} \tag{1}$$

where C_{pv} is the variable preventive replacement cost, and C_{pf} is the fixed maintenance cost. The total preventive replacement cost is $C_{\mathrm{pv}} + C_{\mathrm{pf}}$, which corresponds to 100% age reduction $(q = 1)$. C_{pf} is incurred as long as an imperfect action is required for the component. The more the age of component is reduced, the faster the cost increases, and this leads to an increasing nonlinear feature of the maintenance cost.

2.1. Overview of the proposed approaches

As mentioned earlier, the proposed opportunistic maintenance actions are determined by the age threshold values, and they are different for the components in the same wind turbine with failed component and all components in other running turbines. Therefore, a maintenance task will be performed on the components that reach the corresponding age threshold values. Fig. 1 generally illustrates the proposed policy. Suppose there is a failure occurring in the farm at present. The maintenance crew is sent to perform failure replacement, and take this opportunity to perform preventive maintenance on other qualified components. For example, component i and j are in the same wind turbine with a failed

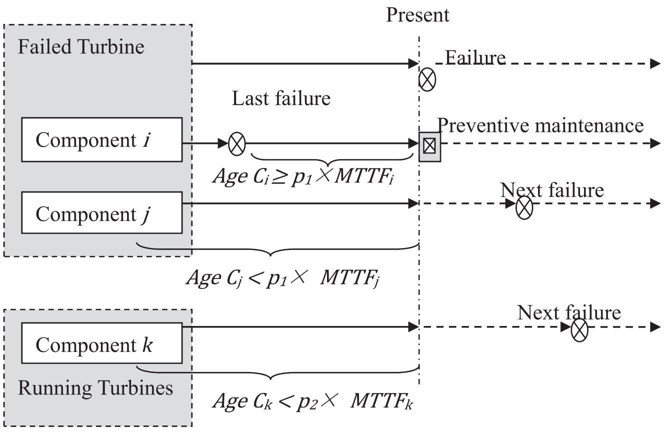

Fig. 1. The proposed opportunistic maintenance concept.

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component, which is defined as the failed turbine, while component k is in one of the running (working) turbines. Component i will be performed a preventive maintenance action because its age reaches the threshold, which is a ratio of its mean time to failure, denoted by $p_1 \times \text{MTTF}_i$ at this moment. The age of component j does not reach the threshold $p_1 \times \text{MTTF}_j$ so that a maintenance task will not be performed and it will continue to work till the next opportunity, or it may fail first in the farm.

For all the rest components in the running turbines (e.g. component k), a different age threshold $p_2 \times$ MTTF is applied, which is expected to take fewer actions on running wind turbine such that the cost could be lower. In two-level action method, similarly, four age thresholds p_{1L}, p_{1H} (for the failed turbine) and p_{2L}, p_{2H} (for the running turbines) are applied ($p_{2H} > p_{2L}$, $p_{1H} > p_{1L}$). A preventive replacement is to be performed if the current age reaches the large age threshold $p_{1H} \times$ MTTF for the components in the failed turbine or $p_{2H} \times$ MTTF for the components in the running turbines. Otherwise, an imperfect maintenance action is to be performed since the age reaches the small age threshold $p_{1L} \times$ MTTF or $p_{2L} \times$ MTTF.

The proposed policies are based on the following assumptions or properties. (1). All components follow Weibull distribution, and the failure rate increases over time (i.e. $\beta > 1$); (2). All wind turbines in the farm are identical, and the deterioration process of each component is independent; (3). Any component failure leads to turbine system failure; (4). The maintenance time is negligible comparing the long lifetime of components.

Suppose there are M wind turbines in the wind farm, and K critical components are considered for each turbine. The related costs are defined as following: C_f, C_{pv} and C_{pf} are the failure replacement cost, the variable preventive maintenance cost and the fixed preventive maintenance cost for a component, respectively. C_{Access} is the access cost to a wind turbine, and C_{fix} is the fixed cost of sending a maintenance team to wind farm.

In terms of preventive maintenance actions, three proposed strategies are discussed in the following subsections.

2.2. Construction of models and the solution methods

2.2.1. Strategy 1: opportunistic maintenance with perfect action only

The maintenance policy is described as follows. 1. Perform failure replacement if a component fails. 2. At the moment of failure, this opportunity is taken to perform preventive replacement (i.e. perfect action) on component k ($k = 1,\ldots,K$) in wind turbine m ($m = 1,\ldots,M$) if $\text{age}_{k,m} \geq \text{MTTF}_k \times p$, where $p = p_1$ if the components are in the failed turbine, and $p = p_2$ if the components are in the running turbines. 3. If the component will not be performed preventive maintenance on, it will continue working until the next failure occurs in the wind farm.

The brief objective function is given by:

$$\min C_E(p_1, p_2) \tag{2}$$

where C_E is the total expected maintenance cost per turbine per day, and p_1 and p_2 are design variables corresponding to failed turbine and running turbines, respectively. The objective is to determine the optimal age threshold p_1 and p_2 to minimize the total expected maintenance cost per turbine per day.

Due to the complexity of optimization problems, it is extremely hard to develop accurate numerical methods for cost evaluation of different maintenance policies. Thus, in this work, simulation methods are developed to evaluate the average cost C_E. Suppose the failure distribution of components are known, the age values of

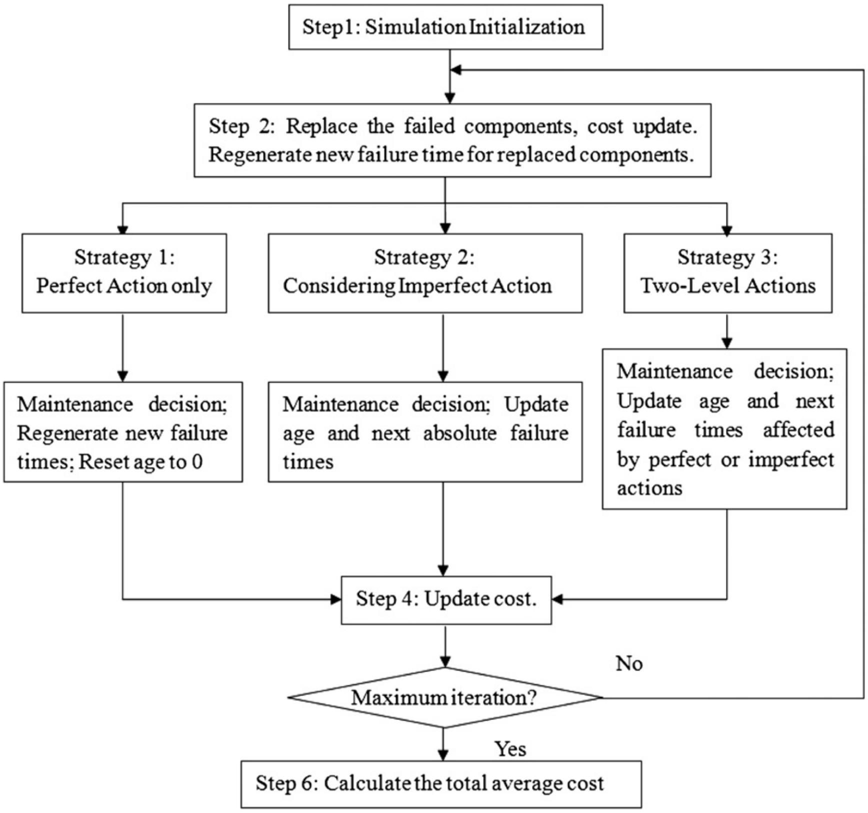

Fig. 2. Simulation process for cost evaluation.

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each component at each failure instant can be obtained, and thus the optimal policy can be decided with respect to the minimum average cost C_E. Fig. 2 shows the flow chart of the simulation procedures in general. Strategy 2 and 3 are also integrated, but the detailed descriptions for them will be given in the related subsequent subsections.

The simulation process of strategy 1 is explained in detail as follows.

Step 1: Initialize the simulation. Specify all of the parameters used in the simulation process, which includes the maximum simulation iterations I, the number of wind turbines M and K components in a system, and the upper bound of design variables, p_1 and p_2. Specify all of related cost mentioned previously in Section 2.1, C_f, C_{pv} and C_{pf} for each component in the turbine, C_{fix} and C_{Access} as well. The total cost C_T at the beginning is set to be 0, and will be updated during the simulation process. The Weibull distribution parameters α_k and β_k of each component are given, which are presented in Section 3.1. The absolute time, $\mathrm{TA}_{k,m}$, is defined as the accumulative time of every failure for that component k in turbine m. At the beginning, generate the lifetimes $\mathrm{TL}_{k,m}$ for each component in each turbine by sampling the Weibull distribution for component k with parameter α_k and β_k. Thus, the age values for all components are zero at the beginning, that is, $\mathrm{age}_{k,m} = 0$, and $\mathrm{TA}_{k,m} = \mathrm{TL}_{k,m}$ at the moment of first failure.

Step 2: Replace the failed component and cost update. The failure of the ith iteration occurs at t_i, and $t_i = \min(TA_{k,m})$. Δt_i represents the time to failure of the ith iteration, $\Delta t_i = t_i - t_{i-1}$, and $t_0 = 0$. Once there is a failed component in the wind farm, for instance, component k in turbine m fails, the failure replacement cost C_{fk} and the fixed cost of sending a maintenance team to the wind farm, C_{fix}, are incurred simultaneously. The total cost due to failure replacement is updated as:

$$C_T = C_T + C_{\mathrm{fk}} + C_{\mathrm{fix}} \tag{3}$$

Regenerate a new lifetime $\mathrm{TL}_{k,m}$ by sampling the Weibull distribution for this component with parameter α_k and β_k, and reset its age to 0. Its absolute time is moved to next failure, i.e. $\mathrm{TA}_{k,m} = t_i + \mathrm{TL}_{k,m}$.

Step 3: Make decision on maintenance activities for the rest of the components in the wind farm. According to the policy described earlier in this section, at the moment of failure instant, a perfect action (i.e. preventive replacement) is determined to perform on component k in turbine M if $\mathrm{age}_{k,m} \geq \mathrm{MTTF}_k \times p$, where $p = p_1$ for the components in the failed turbine, and $p = p_2$ for the components in the running turbines. Regenerate a new lifetime $\mathrm{TL}_{k,m}$ for this component with parameter α_k and β_k, and reset its age to 0. Its absolute time will be moved to next failure, i.e. $\mathrm{TA}_{k,m} = t_i + \mathrm{TL}_{k,m}$.

Step 4: Cost update. The total cost due to perfect preventive maintenance action is updated as:

$$C_T = C_T + \sum\nolimits_{m=1}^{M}\left(\sum\nolimits_{k=1}^{K}\mathrm{Cp}_k \times \mathrm{IP}_{k,m} + C_{\mathrm{Access}} \times \mathrm{IA}_m\right) \tag{4}$$

where $\mathrm{IP}_{k,m} = 1$ if a preventive maintenance is to be performed on component k in turbine m; Otherwise it equals 0. $\mathrm{IA}_m = 1$ if any preventive maintenance is to be performed on turbine m, and otherwise it equals 0. Note that Cp_k represents the total preventive maintenance cost, and it equals to $C_{\mathrm{pv}} + C_{\mathrm{pf}}$ in this strategy.

Step 5: After performing perfect maintenance on all qualified components, set $i = i + 1$. If i does not exceed the maximum simulation iteration I, repeat step 2, 3 and 4.

Step 6: Total expected average cost calculation. The simulation process with current variable value is completed when the maximum simulation iteration is reached, which is $i = I$. The total expected cost per wind turbine per day can be calculated as:

$$C_E = \frac{C_T}{M \times t_I} \tag{5}$$

If variable's upper bound is not reached, repeat step 2, 3, 4, 5 and 6.

With the method for cost evaluation and the general optimization model described in Equation (2), the optimal variable value can be searched which corresponds to the minimal expected total cost per turbine per day C_E. The optimal maintenance strategy is determined once the optimal values of variables p_1, p_2 are found.

2.2.2. Strategy 2: opportunistic maintenance considering imperfect actions

The maintenance policy is described as follows. 1. Perform failure replacement if a component fails. 2. At the moment of failure, this opportunity is taken to perform an imperfect preventive maintenance action (i.e. reducing the component age by q) on component k ($k = 1,\ldots,K$) in wind turbine m ($m = 1,\ldots,M$) if $\mathrm{age}_{k,m} \geq \mathrm{MTTF}_k \times p$, where $p = p_1$ for the components in the failed turbine, and $p = p_2$ for the components are in the running turbines. 3. If the component will not be performed preventive maintenance, it will continue working until the next failure occurs in the wind farm.

The brief objective function is

$$\min C_E(p_1, p_2, q) \tag{6}$$

where p_1, p_2 and q are design variables. Similarly, p_1 and p_2 represent the age thresholds of the components in the failed turbine and running turbine, respectively, and q is the percentage of age reduction. The objective is to determine the optimal age threshold p_1, p_2 and age reduction ratio q to minimize the total expected maintenance cost per turbine per day.

The simulation process is much similar to the strategy 1. Only the differences in the procedure in the related steps are described.

Step 1: Initialize the simulation. In addition to the all of parameters specified in strategy 1, one more design variable q, the ratio of age reduction requires to specify. Moreover, the other term $\mathrm{FA}_{k,m}$ is applied in strategy 2, which denotes the new failure age of the component k in turbine m after imperfect maintenance action, and $\mathrm{FA}_{k,m} = \mathrm{TL}_{k,m}$ at the beginning.

Step 3: Make decision on maintenance activities for the rest of the components in the wind farm. If $\mathrm{age}_{k,m} \geq \mathrm{MTTF}_k \times p$, where $p = p_1$ for the component in the failed turbine, and $p = p_2$ for the component in the running turbines, an imperfect maintenance is performed on component k in turbine m. Regenerate a new lifetime $\mathrm{TL}_{k,m}$, and its age, failure age and absolute time are updated as:

$$\mathrm{Age}_{k,m} = \mathrm{Age}_{k,m} \times (1 - q) \tag{7}$$

$$\mathrm{FA}_{k,m} = q \times \mathrm{TL}_{k,m} + (1 - q) \times \mathrm{FA}_{k,m} \tag{8}$$

$$\mathrm{TA}_{k,m} = t_i + \mathrm{FA}_{k,m} - \mathrm{Age}_{k,m} \tag{9}$$

Step 4: Cost update. Note that in this strategy, Equation (4) is also applicable. However, Cp_k varies with different ratio q according to Equation (1), where q can be considered to be maintenance effort.

Step 2, 5, 6 and 7 are similar to those in strategy 1.

2.2.3. Strategy 3: opportunistic maintenance with two-level actions

The maintenance policy is described as follows. 1. Perform failure replacement if a component fails. 2. At the moment of failure in the wind farm, perform imperfect preventive maintenance action, which reduces the age by q on component k ($k = 1,\ldots,K$) in wind turbine m ($m = 1,\ldots,M$) if $\mathrm{MTTF}_k \times p_{1H} \geq \mathrm{age}_{k,m} \geq \mathrm{MTTF}_k \times p_{1L}$ when the components are in the failed turbine, and if

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Table 1
Failure distribution parameters and cost data for major components ($k).

Component	α (days)	β (days)	C_f	C_{pv}	C_{pf}	C_{fix}	C_{Access}
Rotor	3000	3	112	28	40	50	7
Bearing	3750	2	60	15			
Gearbox	2400	3	152	38			
Generator	3300	2	100	25			

$\text{MTTF}_k \times p_{2H} \geq \text{age}_{k,m} \geq \text{MTTF}_k \times p_{2L}$ when the components are in the running turbines. Perform preventive replacement on this component if $\text{age}_{k,m} \geq \text{MTTF}_k \times p_{1H}$ (for the failed turbine) and $\text{age}_{k,m} \geq \text{MTTF}_k \times p_{2H}$ (for the running turbines). This policy implies that the older a component is, the more it tends to be replaced. Note that in this policy, 'q', described as the maintenance effort, is a certain value rather than a variable. 3. If the component will not be performed preventive maintenance on, it will continue working until the next failure occurs in the wind farm.

The brief objective function is

$$\begin{aligned} &\min C_E(p_{1L}, p_{1H}, p_{2L}, p_{2H}, q) \\ &\text{s.t.} \\ &0 < p_{1L} < p_{1H} < 1 \text{ and } 0 < p_{2L} < p_{2H} < 1 \end{aligned} \tag{10}$$

where p_{1L}, p_{1H} and p_{2L}, p_{2H} are design variables corresponding to two age thresholds of the components in the failed turbine and running turbines, respectively. The objective is to determine the optimal variable values to minimize the total expected maintenance cost per turbine per day.

Similarly, only the differences from strategy 1 are described.

Step 1: Initialize the simulation. In addition to the all of parameters specified in strategy 1, the design variables are modified since more design variables are introduced. The term $\text{FA}_{k,m}$ is also applied in strategy 3, which denotes the new failure age of the component k in turbine m after imperfect maintenance action, and $\text{FA}_{k,m} = \text{TL}_{k,m}$ at the beginning.

Step 3: Make decision on maintenance activities for the rest of the components in the wind farm:

If $\text{MTTF}_k \times p_{1H} \geq \text{age}_{k,m} \geq \text{MTTF}_k \times p_{1L}$ for the component in the failed turbine and if $\text{MTTF}_k \times p_{2H} \geq \text{age}_{k,m} \geq \text{MTTF}_k \times p_{2L}$ for the component in the running turbines, imperfect maintenance is performed on the component. Regenerate a new failure time $\text{TL}_{k,m}$. age, failure age and absolute time are updated similarly according to Equations (7)–(9).

If $\text{age}_{k,m} \geq \text{MTTF}_k \times p_{1H}$ for the component in the failed turbine and if $\text{age}_{k,m} \geq \text{MTTF}_k \times p_{2H}$ for the component in the running turbines, preventive replacement is performed on the component. Regenerate a new lifetime $\text{TL}_{k,m}$, and reset its age to 0. Its failure age is updated as $\text{TL}_{k,m}$, denoted by $\text{FA}_{k,m} = \text{TL}_{k,m}$. The absolute time is updated as: $\text{TA}_{k,m} = t_i + \text{FA}_{k,m}$.

Step 4: Cost update. In this strategy, Equation (4) is applicable and Cp_k varies with different ratio q according to Equation (1).

Step 2, 5, 6 and 7 are similar to those in strategy 1.

3. Numerical examples

In this section, examples are provided to illustrate the proposed approach. Comparative study is conducted with the policy using the same age threshold for failed turbines and operational turbines, and with the corrective maintenance strategy as well. The comparison results demonstrate the advantage of proposed approaches, and significant cost savings are achieved.

3.1. Optimization results with the proposed approaches

Consider 10 2 MW turbines in a wind farm at a remote site. Four key components in each components are studied in order to simplify the discussion: the rotor, the main bearing, the gearbox and the generator [8]. Assume all components follow Weibull distributions with increasing failure rates ($\beta > 1$), and all components and turbines are identical and independently deteriorate. The related cost and failure distribution parameters α (scale parameter) and β (shape parameter) are given in Table 1 based on the data in [6] and [9]. Note that the C_{pf} in Table 1 is the fixed preventive maintenance cost for a wind turbine, and it is shared by all the components in the turbine.

The total maintenance cost can be evaluated using the proposed simulation method presented in Section 2.2. The optimization results for each proposed opportunistic maintenance strategy are presented as follows. Note that due to more than two design variables in each proposed strategy, it is impossible to show the cost versus all variables in one figure. Thus the following figures are the cost versus one variable while the other variables are kept at the optimal values.

Strategy 1. Perfect maintenance only.

As shown in Fig. 3, the optimal average maintenance cost per unit time is $167.2/day, the corresponding policy is that the preventive replacement is performed on the components in the failed turbine with age exceed 50% of its mean lifetime, and on the components in the running turbines with age exceed 60% of its mean lifetime at the failure instant in the wind farm. Note that the optimal values are rounded to integer percentage values.

Strategy 2. Considering imperfect maintenance.

As can be seen in Fig. 4, when there is a failure occurs, the 50% age reduction maintenance actions are performed on the

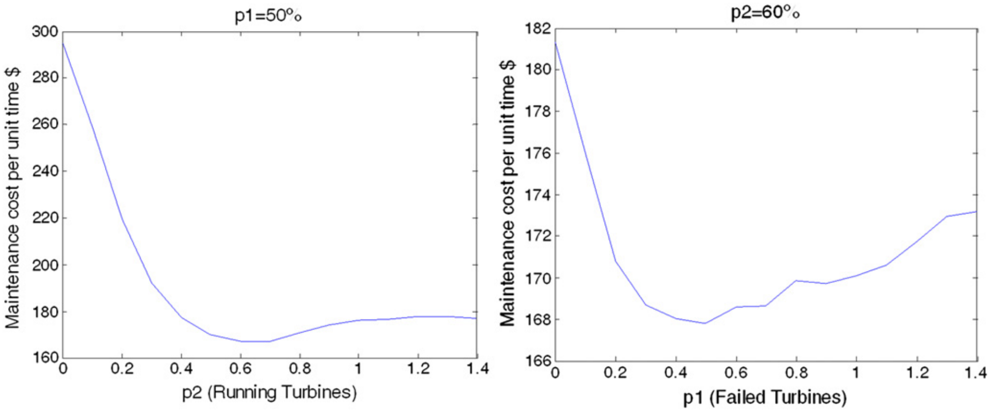

Fig. 3. Cost versus p_1 and p_2 respectively.

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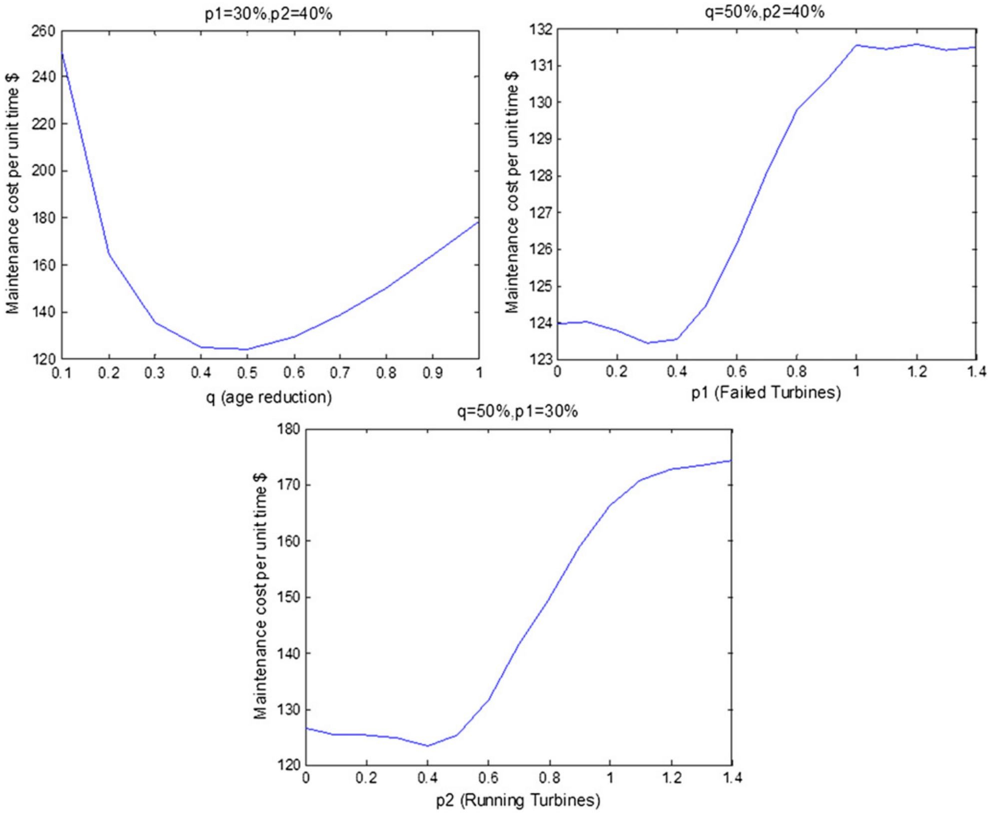

Fig. 4. Cost versus p_1, p_2 and q.

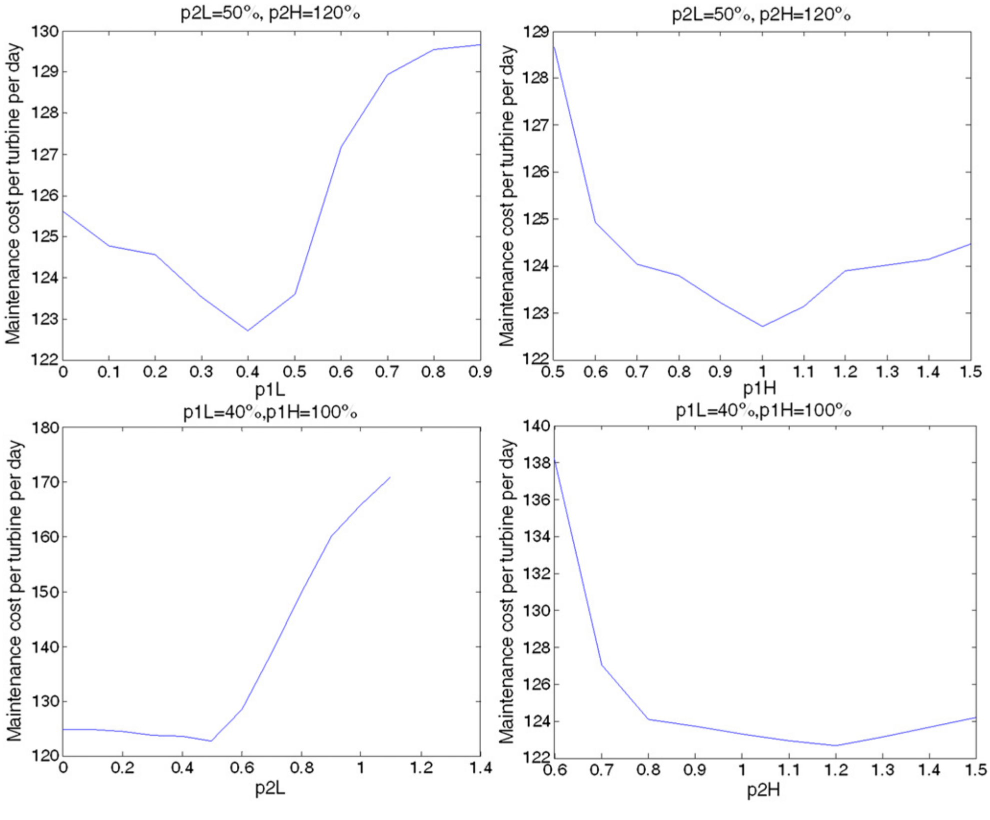

Fig. 5. Cost versus p_{1L}, p_{1H}, p_{2L}, p_{2H} respectively.

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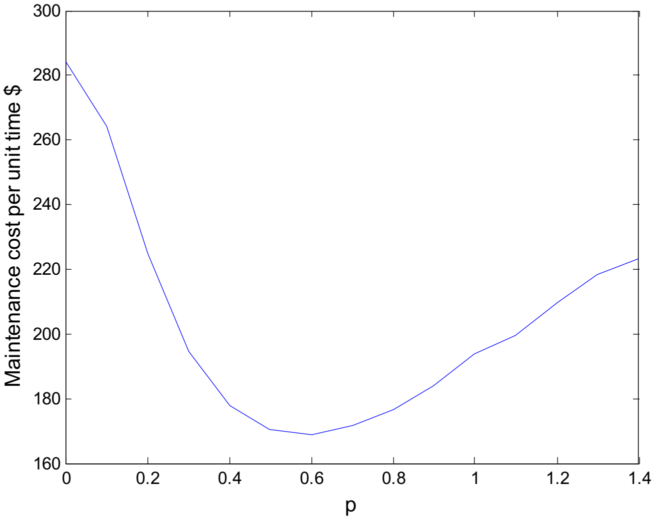

Fig. 6. Cost versus preventive replacement age threshold value (p).

component reach 30% of its mean lifetime in the failed turbine, and on the component reach 40% of its mean lifetime. This optimal maintenance policy leads to the minimum cost of $123.4/day.

Strategy 3. Two-level maintenance.

Two-level maintenance defines that the low level maintenance is imperfect and the high level is perfect, and they are supposed to be performed at different age thresholds. A replacement will be considered when a component is older, while the imperfect action tends to be performed at the younger age. There are 4 age thresholds, two for the components in the failed turbine, denoted by p_{1L} and p_{1H}, while the other two for the components in the running turbines which are denoted by p_{2L} and p_{2H}. To simplify the problem, based on the optimization result of strategy 2, the imperfect maintenance action of reducing the component's age by 50% is applied to this optimization problem.

As can be seen in Fig. 5, the two-level maintenance optimization model leads to the minimum cost of $122.7/day. Due to the constraints $p_{1H} > p_{1L}$ and $p_{2H} > p_{2L}$ in this proposed model, the costs of area out of constraints are set to be null and are not shown in each figure. The optimal policy shows that at the moment of a failure in the farm, imperfect preventive maintenance action is taken on the component whose age is between 40% and 100% of its mean lifetime in the failed turbine, and on the component whose age is between 50% and 120% in the running turbines. Otherwise, preventive replacement is performed on the component whose age exceeds 100% and 120% of its mean lifetime in the failed and running turbines respectively.

3.2. *Comparative study*

As mentioned earlier, Ding and Tian [10] developed opportunistic maintenance methods for wind farms considering imperfect maintenance actions without distinguishing the age thresholds between the failed turbines and working turbines. In this section, the average maintenance cost is investigated considering only one age threshold for all components in the farm, regardless the failure turbine or working turbines. The advantage of the proposed methods is also investigated comparing to the corrective maintenance policy, where only failure replacement is performed when a component fails in the wind farm. A comparison table is given to show the significant cost saving of proposed approaches in this paper.

3.2.1. *Optimization results of same threshold for all turbines*

- Perfect maintenance only:

The minimum cost is $168.8/day, a preventive replacement will be performed on all components older than 60% of mean lifetime. The results are shown in Fig. 6.

- Considering imperfect maintenance:

The minimum cost is $125.1/day, the 40% age reduction maintenance actions will be performed on all components older than 40% of mean lifetime.

- Two-level maintenance:

In the optimal policy, 40% age reduction maintenance action is performed on the components according to the optimal result in strategy 2A. The optimal cost is $123.6/day, and all the components with age between 50% and 120% will be performed imperfect action, while the components with age above 120% will be performed preventive replacement.

3.2.2. *Corrective maintenance cost result*

The total average cost of corrective maintenance policy is calculated for the same wind farm studied in previous examples. By applying the corrective maintenance policy, the optimal total average cost per turbine per unit time is found to be $237/day.

3.2.3. *Comparison results*

The optimal cost results of each proposed strategy are given in Table 2. In Section 3.1, the optimization results show the optimal average cost of $167.2/day, $123.4/day and $122.7/day for the proposed strategies with perfect action only, imperfect action and two-level action policies, respectively. Thus, significant cost savings of 29.4%, 47.9% and 48.2% can be achieved comparing to the corrective maintenance policy, and the two-level action method produces the lowest cost. It is found that the optimal results considering the same age thresholds are close to those distinguishing the failed turbines and running turbines. Thus, if the wind farm operators want to be accurate in wind farm performance evaluation and optimization, the accurate models considering the difference between failed turbines and running turbines should be preferred.

Table 2
Optimal cost of proposed opportunistic maintenance strategies.

Corrective maintenance		$237/day		
Proposed methods		Perfect action only	Considering imperfect action	Two-level action
	Minimum Cost	$167.2	$123.4	$122.7
	Cost-savings	29.4%	47.9%	48.2%
Same age threshold for failed and operational turbines		$168.8	$125.1	$123.6
Fixed imperfect actions (age reduction)	25%	/	$144.2	$144.9
	50%	/	$123.4	$122.7
	75%	/	$143.2	$142.1

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In addition, imperfect maintenance actions are also considered with discrete values, where only certain ratios of age reduction actions can be implemented in an imperfect maintenance task, instead of any age reduction maintenance actions being available. This is the case in many real-world applications, where a certain age reduction level corresponds to a certain preventive maintenance technology or routine. This tends to evaluate the average cost payoff taking into account the ease of control and administration of imperfect maintenance actions. For this specific example, it is assumed that there are three possible age reduction options, 25%, 50%, and 75%. In this example with the specific settings, the 50% age reduction imperfect action is found to be the most cost-effective, while 25% and 75% age reduction actions cost 16.6% more.

4. Conclusions

Preventive maintenance optimization is relatively new for wind power industry, which has been growing very rapidly in recent years due to the highly increasing requirements on clean and renewable energy. The maintenance cost is very high for the wind turbine systems, which are generally erected on the remote or offshore sites in order to harvest the wind energy more efficiently. This leads to high expectation of responsibility to manage the wind farm with lowest operation & maintenance cost.

Few methods are available for optimizing corrective maintenance and time-based preventive maintenance for wind farms, although these strategies are currently widely used in practice. Economic dependencies exist among wind turbine systems and their components in the wind farm. In this paper, opportunistic maintenance optimization approaches are developed for wind farms to take advantage of the maintenance opportunities to perform preventive maintenance actions. Imperfect maintenance actions are considered, which addresses the practical issue that preventive maintenance does not always return components to as-good-as-new status. The proposed opportunistic maintenance policies are defined by the component's age threshold values, and different imperfect maintenance thresholds are introduced for failure turbines and working turbines. Three types of preventive maintenance actions are considered, including perfect, imperfect and two-level action. Simulation methods are developed to evaluate the costs of proposed opportunistic maintenance policies. The numerical examples illustrate the proposed approaches. Comparative study with the widely used corrective maintenance policy demonstrates the advantage of the proposed opportunistic maintenance methods in significantly reducing the maintenance cost. The developed methods have great potential to bring immediate benefits to wind power industry.

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