INTRODUCTION

Global warming and energy crisis prompt the development of renewable energy. Wind energy attracts increasing attentions of governments worldwide due to its nonpolluting and inexhaustibility, and becomes one of the most widely used renewable energy. By the end of 2017, the cumulative installed capacity of wind turbines worldwide was closed to 540 GW, contributing 5.6% of the total generation of electrical energy. However, the report reveals that operation and maintenance cost of onshore wind turbines accounts for 12% of total life cycle cost; furthermore, this ratio reaches up to 18%-23% for offshore wind turbines. The cost level of operation and maintenance depends on the selection of maintenance strategy, which need to be deeply studied.

Traditional preventive replacement maintenance (TPRM) is a strategy for wind turbines through replacing each sub-assembly at an individual maintenance interval, which is widely implemented at current wind farms. These intervals are optimal at the subassembly level but not for whole wind turbines; thus, they may cause frequent shutdown and maintenance. Actually, wind turbines are typical multi-subassembly systems. During the maintenance activities at wind farm, economy, structure, and failure modes are interdependent for various subassemblies, which need to be considered as a whole while making maintenance schedules. The economic dependence implies that a part of maintenance cost of each subassembly is interdependent, which can be shared and saved by jointly maintaining several subassemblies. The structural dependence occurs if parts structurally form a subassembly,
in this case, maintenance of a failed part implies maintenance of subassembly as well. The failure dependence indicates a failure of a subassembly influences the lifetime distribution of other subassemblies, or several failures have a common cause and correlative lifetime distribution. Group maintenance strategy is a significant one solving maintenance problems of the multi-subassembly system by mainly considering the economic dependency and minimizing maintenance cost. Group maintenance enables various subassemblies to share fixed maintenance cost and optimize maintenance strategies at the turbine level. Opportunistic maintenance strategy is one of the group maintenance strategies, regarding preventive replacement and random failure of subassemblies as maintenance opportunities. Under these opportunities, the other subassemblies without preventive replacement and random failure are judged whether to be maintained during a maintenance activity. Several literatures studied the opportunistic maintenance strategy for wind turbines. An optimal maintenance strategy for a two-component system was studied in REF. and the failures of component 2 offered the periodic opportunistic maintenance strategy for the failure of component 1. An optimal proactive age-based group maintenance strategy was proposed in Ref. [11-13]. A measure to identify the subassemblies selected for preventive maintenance was proposed in Ref. [14]. The opportunistic maintenance strategy was combined with condition-based model in Ref. [15-17]. A multi-objective opportunistic maintenance strategy was implemented to optimize the income of after-sales in Ref. [18]. The economic dependence and structural dependence were simultaneously considered in Ref. [19]. The challenges related to set up cost were addressed in Ref. [20]. An opportunistic maintenance approach considering a reliability-based imperfect maintenance schedule was proposed in Ref. [21], which solved the problem that maintenance actions did not always return the system to “as good as new” condition. A wind-centered maintenance strategy integrating multiple maintenance opportunities and diverse impacts of wind conditions was designed in Ref. [22]. A multi-objective opportunistic maintenance approach with the goal of maximizing the expected rate of energy and minimizing the total expected costs related to maintenance efforts was proposed in Ref. [23]. The operational and environmental context, inspection information, and predictions were considered in the opportunistic maintenance strategy for wind turbines.

Opportunistic group replacement maintenance (OGRM) is a kind of the opportunistic maintenance strategies, only considering the maintenance opportunities from preventive replacement, not from the stochastic failures. This strategy inherits the characteristic of sharing the fixed cost of opportunistic maintenance. Meanwhile, less factors considered make the maintenance schedule of the OGRM relatively fixed and easier to be implemented. Zhao and Zhang calculated the absolute value of the slope of the reliability function at the preventive maintenance moment, divided by the opportunistic maintenance reliability margin to obtain maintenance intervals of each subassembly. The simulation analysis showed that the opportunistic group replacement maintenance saved 34% of the total cost than the preventive replacement.

The above opportunistic maintenance and OGRM have been applied to wind turbines; however, several deficiencies still exist: The analysis on maintenance cost was rough. The cost of preventive replacement or opportunity replacement was given roughly, not be further subdivided according to the stages of maintenance activities, such as waiting stage, arriving stage, and maintaining stage. Therefore, the composition of the cost and which stages could share the cost were unclear; the optimization process was two-step. The literatures above computed optimal maintenance intervals of each subassembly first, and then optimized multi-subassembly group maintenance again based on these intervals. In the two-step optimization process, the maintenance intervals were locally optimal, rather than globally results from the whole maintenance cost minimization; in wind turbines, each subassembly has different reliability requirement. However, a uniform reliability threshold was set for all subassemblies and severed as an optimization variable in the above research, which impeded a potential lower maintenance cost. Reliability thresholds should be respectively set for each subassembly and simultaneously optimized; the above cases focused on the group maintenance at the subsystem level, rather than the subassembly level. Actually, the number of the subassemblies in wind turbines is far more than the subsystems, which can get more flexible combination that is beneficial to reduce maintenance cost.

Aimed at the deficiencies above, this paper proposes an improved OGRM strategy for wind turbines. First, Weibull distribution is utilized for describing the reliability of subassemblies. Then, a uniform formula is proposed to embrace the maintenance cost at different stages to deal with the deficiency. Next, a maintenance schedule is obtained according to the OGRM theory. To solve the deficiency and an objective function with the goal of minimizing maintenance cost is established, with the reliability thresholds of opportunistic group replacement of each subassembly as its optimization variables. The coordinate rotation method is utilized for optimization solution. Finally, a specific maintenance case at the subassembly level from a wind farm in North China verifies the effectiveness of the proposed strategy and deal with the deficiency. To make maintenance schedule relatively fixed and easier to be implemented, the improved OGRM strategy only considers the maintenance opportunities from preventive replacement, ignoring the positive and negative impacts of some uncertain factors, for example, the stochastic failures and the weather conditions. Meanwhile, replacement is defined as the sole maintenance action for wind turbines in the proposed maintenance strategy.
2 | OPPORTUNISTIC GROUP REPLACEMENT MAINTENANCE (OGRM) STRATEGY

The OGRM strategy only considers the opportunistic grouping problem of three maintenance modes associated with replacement, namely, no maintenance, preventive replacement, and opportunistic group replacement. No maintenance means none actions needed for a subassembly. The latter two maintenance modes both restore the reliability of subassemblies as 1. In OGRM strategy, multiple subassemblies are simultaneously replaced as a maintenance group in view of their reliability relationship. Compared with individual subassembly replacement, the OGRM strategy saves the total maintenance cost by sharing the fixed cost of personnel, transportation, and hosting etc. The OGRM theory is illustrated in Figure 1 by taking three subassemblies as an example.

The reliability $R^{(1)}(t)$, $R^{(2)}(t)$, and $R^{(3)}(t)$ of three subassemblies are given in Figure 1. $R_{pr}^{(1)}$, $R_{pr}^{(2)}$, and $R_{pr}^{(3)}$ are, respectively, their preset reliability thresholds of preventive replacement. $R_{or}^{(1)}$, $R_{or}^{(2)}$, and $R_{or}^{(3)}$ are the corresponding thresholds of opportunistic group replacement.

After setting the thresholds above, the maintenance time can be confirmed according the reliability curves. In Figure 1, the reliability of subassembly 1 decreases below its threshold $R_{pr}^{(1)}$ of preventive replacement at the earliest. Therefore, a maintenance opportunity is generated at the corresponding time $T$. Under this opportunity, subassembly 1 needs preventive replacement. The reliability of subassembly 2 falls into the range between $R_{pr}^{(2)}$ and $R_{or}^{(2)}$, which means a lower remaining useful life and needs opportunistic group replacement. The reliability of subassembly 3 is higher than the threshold $R_{or}^{(3)}$ of opportunistic group replacement, and it needs no maintenance because of a higher remaining useful life.

The reliability of mechatronic equipment can be described by the Weibull distribution. The failure rate function and reliability function of the subassemblies are expressed as Equations (1) and (2).

$$\lambda(t) = \frac{\beta}{\eta} \left( \frac{t}{\eta} \right)^{\beta-1}$$

(1)

$$R(t) = \exp \left[ -\left( \frac{t}{\eta} \right)^{\beta} \right]$$

(2)

where $\beta$ and $\eta$ are, respectively, the shape and scale parameters of the Weibull distribution, which can be estimated by utilizing least square method for fitting the historical failure data.

3 | IMPROVED OGRM STRATEGY FOR WIND TURBINES

3.1 | Maintenance cost of subassemblies in wind turbines

In regular OGRM, the cost of preventive replacement or opportunity replacement was given roughly, not be further subdivided. As a result, the composition of the cost and which stages could share the cost were unclear. In improved OGRM, according to the diverse stages of maintenance activities for wind turbines, a uniform formula calculating maintenance cost is proposed, which includes the cost of waiting stage, arriving stage, maintaining stage etc. The total maintenance cost $C_i$ during operating life cycle $T_i$ is calculated as Equation (3).

$$C_i = \sum_{k=1}^{K} \sum_{s=1}^{S} C^{(k,s)}$$

(3)
where $K$ is the total maintenance count, $S$ is the number of subassemblies in wind turbines, $C^{[k]}_t$ is the maintenance cost at the $k$th maintenance, and $C^{[k][s]}$ is the maintenance cost of subassembly $s$ at the $k$th maintenance. For each subassembly at each maintenance, alternative maintenance modes contain preventive replacement and opportunistic group replacement. For any $C^{[k][s]}$, the notation is simplified as $C$ that is calculated as Equation (4).

$$C = C_e + C_f + C_m$$

where $C_e$ is the cost of power loss caused by maintenance, $C_f$ is the fixed maintenance cost from manpower and transportation, and $C_m$ is the direct cost of subassemblies, namely the subassembly price. According to the diverse stages of maintenance activities, the cost of power loss $C_e$ is further subdivided as follows:

$$C_e = T \cdot c_{ep}$$  \hspace{1cm} (5)$$

where $T$ is the total downtime during one maintenance, obtained by summing the maintenance waiting time $T_w$, the personnel arriving time $T_a$, the time $T_c$ of climbing tower, the time $T_h$ of hoisting equipment, and the time $T_m$ of replacing subassembly, $c_{ep}$ is the cost of power loss of unit downtime, obtained by multiplying the capacity coefficient $\tau$ of a wind turbine, the rated power $P$, with the electricity price $c_{ep}$.

Under the maintenance opportunity from preventive replacement, wind turbines keep running until the activity of climbing tower. Therefore, the maintenance waiting time $T_w$ and personnel arriving time $T_a$ of preventive replacement and opportunistic group replacement are both 0 and have no impact on power loss. For the subassembly with preventive replacement, the time $T_c$ of climbing tower and fixed maintenance cost $C_f$ are non-negligible and both need to be considered. For the subassemblies that need opportunistic group replacement, the time $T_c$ of climbing tower and fixed maintenance cost $C_f$ can be covered by the preventive replacement at the same time. The time $T_h$ of hoisting equipment, the time $T_m$ of replacing subassembly, and the direct cost $C_m$ need to be separately calculated, because they are unable to be shared during the maintenance. The maintenance time and cost of subassemblies in wind turbines under the two above maintenance modes are summarized in Table 1.

### 3.2 Simulation process of the improved OGRM strategy

The simulation process of OGRM strategy for wind turbines is illustrated as Figure 2, which can be described as following:

1. Collect the historical failure data and maintenance cost data to estimate the shape parameter $\beta^{(s)}$ and the scale parameter $\eta^{(s)}$ of the reliability curve of each subassembly in wind turbines;
2. Conduct statistics on the waiting time $T_w^{(s)}$, the personnel arriving time $T_a^{(s)}$, the time $T_c^{(s)}$ of climbing tower, the time $T_h^{(s)}$ of hoisting equipment, the time $T_m^{(s)}$ of replacing subassembly, the fixed maintenance cost $C_f^{(s)}$ from manpower and transportation, and the subassembly price $C_m^{(s)}$, where $s = 1, 2, \ldots, S$;
3. Calculate the cost $c_e^{(s)}$ of power loss of unit downtime according to the capacity coefficient $\tau$, the rated power $P$ of the wind turbine, and the electricity price $c_{ep}$;
4. Set the reliability thresholds $R_{pr}^{(s)}$ of preventive replacement and $R_{or}^{(s)}$ of opportunistic group replacement of each subassembly;
5. Initialize the total maintenance cost $C_0 = 0$ and the current maintenance count $k = 1$;
6. Calculate the interval from current time to the time with $R_{pr}^{(s)}$ ($s = 1, 2, \ldots, S$) for each subassembly. The subassembly with minimum interval will be implemented a preventive replacement and the minimum interval is regarded as the maintenance interval $T_{in}^{(s)}$;
7. For the other subassemblies, compare $R^{(s)}(T_{in}^{(s)})$ with $R_{or}^{(s)}$ ($s = 1, 2, \ldots, S; s \neq p$) to confirm maintenance modes: if $R^{(s)}(T_{in}^{(s)}) > R_{or}^{(s)}$, no maintenance; if $R^{(s)}(T_{in}^{(s)}) <= R_{or}^{(s)}$, opportunistic group replacement is taken;
8. Calculate the total maintenance cost $\sum_{s=1}^{S} C^{[k][s]}$ at the $k$th maintenance and the cumulative operating time $T_{cum} = \sum_{i=1}^{k} T_{in}^{[i]}$;
9. If $T_{cum} > T_r$, calculate the total maintenance cost $C_i = \sum_{k=1}^{K} C^{[k]}$ during life cycle of wind turbines, and export the total maintenance cost $C_i$, maintenance count $K$ and maintenance schedule; Otherwise, for the replaced

| Maintenance mode         | Maintenance time/h | Maintenance cost/¥ |
|--------------------------|--------------------|--------------------|
| Preventive replacement   | $T_w(0)$ $T_a(0)$ | $T_c$ $T_s$ $T_m$ | $C_f$ $C_m$ |
| Opportunistic group replacement | $T_w(0)$ $T_a(0)$ | $T_c$ $T_s$ $T_m$ | $C_f(0)$ $C_m$ |

### TABLE 1 Maintenance time and cost of subassemblies in wind turbines under preventive replacement and opportunistic group replacement
subassemblies, their reliabilities are restored as 1, and for the nonreplaced subassemblies, their reliabilities remain unchanged. Then, the maintenance count plus 1 and return to the step 6).

3.3 | Optimization of the reliability thresholds of the improved OGRM

From the simulation process illustrated in Figure 2, it can be seen that the preset reliability threshold $R_{pr}$ of preventive replacement and $R_{or}$ of opportunistic group replacement directly impact the total maintenance cost $C_t$ during the operating life cycle $T_t$. Currently, the thresholds $R_{or}$ of all subassemblies were represented as a uniform threshold $R_{or}$, which was served as an optimization variable to optimize the total maintenance cost $C_t$. This optimization process belongs to univariate optimization, which reduces the potential to obtain lower maintenance cost. It is noteworthy that different subassemblies of wind turbines have different reliability requirements. Therefore, the improved OGRM, respectively, sets and simultaneously optimizes the thresholds $R_{or}$ for each
subassembly. Compared with the univariate optimization, such a multivariable optimization process is more flexible and able to obtain a lower maintenance cost.

As for the regular OGRM, the optimization process includes two-step. First, the optimal maintenance intervals of each subassembly are computed, and then, multi-subassembly maintenance group is optimized again based on these intervals. During minimizing the whole maintenance cost, the two-step optimization process could only give a local optimal maintenance intervals, rather than global optimal results.

Based on the above reasons, the improved OGRM establishes a multivariable optimization model with a goal of minimizing the total maintenance cost $C_t$ shown as Equation (6), with the threshold $R_{or}^{(s)}$ of each subassembly as individual optimization variable.

$$\min C_t$$

s.t. $R_{or}^{(s)} = R_{pr}^{(s)} < R_{or}^{(s)} < 1$, $s = 1, 2, \ldots, S$ (6)

where $R_{or}^{(s)}$ represents the reliability requirement of each subassembly, which cannot be changed during the optimization.

The optimization model Equation (6) can be solved by the coordinate rotation method. The method is suitable for nonlinear optimization and has no need to solve the gradient of the objective function. The process of utilizing the coordinate rotation method to optimize the improved OGRM strategy for wind turbines is illustrated as Figure 3.

The coordinate rotation method transforms the simultaneous optimization of multiple variables into the optimization of single variable in sequence. In Figure 3, the inner loop traverses each optimization variable to seek the optimal opportunistic group replacement reliability threshold $R_{or}^{(s)}$ from the perspective of univariate, and the outer loop is utilized to control iteration precision. The specific optimization process can be described as following:

1. Initialize the optimization variable $R_{or}^{<0>}= (R_{or}^{<0>(1)}, R_{or}^{<0>(2)}, \ldots, R_{or}^{<0>(s)}) = (1, 1, \ldots 1)$ and the current iterative count $j = 1$;

2. Let $R_{or}^{<j>}= R_{or}^{<j-1>}$

3. Initialize coordinate index $i = 1$

4. Let $R_{or}^{<j>(i)}= \text{argmin} C_t \left( R_{or}^{<j>(i)}, R_{pr}^{(i)} < R_{or}^{<j>(i)} < 1 \right)$

5. Remain unchanged for $R_{or}^{<j>(i)}$, $l \neq i,$

6. $j = j+1$

7. If $i > S$, then $i = i+1$

8. If $\left\| R_{or}^{<j>} - R_{or}^{<j-1>} \right\| \leq \varepsilon$ then Y

9. Export $R_{or} = R_{or}^{<j>} = (R_{or}^{<j>(1)}, R_{or}^{<j>(2)}, \ldots, R_{or}^{<j>(s)})$ as an optimal solution

End

FIGURE 3 Optimization process of OGRM strategy for wind turbines
2. Let the optimization variable $R^{<j-1>}$ after the last iteration be the initial value of the current optimization variable $R^{<j>}$.
3. Initialize the current coordinate index $i = 1$. The index represents the variable that is being optimized;
4. Remain $R^{<j>}(l \neq i)$ unchanged and search an optimal $R^{<j>(i)}(R^{<j>}(i) < R^{<j>(i)} < 1)$ to minimizing the total maintenance cost $C_i$;
5. Compare the index $i$ with the number $S$ of subassemblies: if $i > S$, end the inner loop; if $i \leq S$, the current coordinate index $i + 1$ plus 1 and return to the step 4);
6. Calculate the norm of the difference between the current optimization variable $R^{<j>}$ and the optimization variable $R^{<j-1>}$ of the last iteration; Then, compare the norm with the pre-set precision $\varepsilon$: if the norm is less than the precision $\varepsilon$, end the outer loop and export $R = R^{<j>}$ as the optimal solution; if the norm is larger than the precision $\varepsilon$, the current iterative count $j + 1$ plus 1 and return to the step 2).

4 | CASE STUDY

4.1 | Data introduction

The regular OGRM focused on the group maintenance at the subsystem level, rather than the subassembly level. Actually, the number of the subassemblies in wind turbines is far more than the subsystems; therefore, more flexible combination can be obtained at subassembly level, which is beneficial to reduce maintenance cost. For more fully verifying the effectiveness of improved OGRM, a specific maintenance case at the subassembly level is given in this paper based on the data from a wind farm in North China.

The wind farm has 66 wind turbines with 1.5 MW rated power of each one. The wind turbines was put into operation in 2010, and thousands of fault operation tickets have been accumulated. The fault operation tickets record the details of historical failure data of each subassembly in each wind turbine, including the failure start time, failure end time, and failure subassembly. The historical failure data utilized for establishing reliability model in this paper refer to failure interval that is obtained by the following procedure:

1. Classify the fault operation tickets by subassemblies and wind turbines;
2. Extract failure start time and failure end time of each subassembly for each wind turbine, and calculate corresponding failure intervals;
3. Gather together the failure intervals of each subassembly.

The maintenance cost is another significant data and obtained from the finance department at wind farm, which includes subassembly price, labor, and transportation costs. In this paper, 13 subassemblies with complete failure data and cost data are selected to verify the effectiveness of the improved OGRM strategy for wind turbines.

First, the Weibull distribution reliability models of each subassembly are established. Based on the historical failure data, their shape parameters and scale parameters are estimated by least squares method. Then, the statistics on the maintenance count and cost is made. The results of parameter estimation and statistics of the 13 subassemblies are listed in Table 2. The other parameters are set as follows: the fixed maintenance cost $C_f = ¥2170$, turbine capacity coefficient $r = 0.23$, electricity price $c_{ep} = 0.52 ¥/kWh$, operating life cycle $T_t = 175$ 200 hours (20 years).

| No. | Subassembly         | $\beta$ | $\eta$ | $T_m/h$ | $C_m/¥$ |
|-----|---------------------|---------|--------|---------|---------|
| 1   | Crowbar resistance  | 0.941   | 604.81 | 7.62    | 5071    |
| 2   | UPS                 | 1.775   | 1372.9 | 3.76    | 1575    |
| 3   | 350A insurance      | 1.141   | 741.56 | 10.74   | 333     |
| 4   | Generator encoder   | 1.346   | 1150.11| 7.24    | 1507    |
| 5   | Pitch battery       | 1.194   | 1028.7 | 20.81   | 653     |
| 6   | Generator brush     | 1.181   | 656.75 | 7.56    | 279     |
| 7   | Antifreezing solution| 1.038  | 1590.02| 7.24    | 76      |
| 8   | Anemograph          | 1.402   | 838.39 | 9.89    | 2700    |
| 9   | Slip ring           | 1.125   | 706.14 | 13.13   | 13 676  |
| 10  | Collecting ring     | 1.054   | 861.43 | 10.21   | 16 500  |
| 11  | Filter resistance   | 1.368   | 1226.74| 8.92    | 349     |
| 12  | Oil pump motor      | 1.474   | 1026.59| 6.64    | 2600    |
| 13  | Oil-cooling fuel filter element | 1.045 | 1028.83 | 9.78 | 1902 |
4.2 | Application of OGRM strategy to wind turbines

The threshold $R_{or}^{(s)}$ of each subassembly is assumed as 0.9. The threshold $R_{or}^{(s)}$ ($s = 1, 2, \ldots, S$) is adjusted from 0.9 to 1.0. When all the subassemblies are set the same reliability threshold $R_{or}^{(s)}$, the total maintenance cost with the change of the threshold $R_{or}^{(s)}$ is illustrated in Figure 4.

From the result illustrated in Figure 4, it can be seen that the total maintenance cost is minimum when the threshold $R_{or}^{(s)}$ equals to 0.93. According to the simulation process illustrated in Figure 2, the maintenance schedule of the 13 subassemblies can be obtained and shown as Table 3 under the threshold $R_{or}^{(s)}$ of 0.93.

During the life cycle (20 years), a wind turbine need 153 count of group replacement maintenance. Table 3 only lists 11 count. In Table 3, the time, cost, and tasks of each maintenance are given. During one maintenance, three maintenance modes are alternative: No maintenance is represented as 0, opportunistic group replacement is represented as 1, and preventive replacement is represented as 2. Taking the second maintenance as an example, it causes the cost of ¥ 8883 and occurs on the 55th day. Its task contains the replacement of subassemblies 1, 3, 6, 9, 10, and 13. In detail, the preventive replacement of subassembly 9 brings a maintenance opportunity; under this opportunity, the subassemblies 1, 3, 6, 10, and 13 are replaced because their reliability is under their thresholds $R_{or}^{(s)}$.

4.3 | Improved OGRM strategy for wind turbines

In the improved OGRM strategy, the thresholds $R_{or}^{(s)}$ of the 13 subassemblies are served as individual optimization variables. An objective function with the goal of minimizing maintenance cost is established on the whole, and the coordinate rotation method is utilized for optimization solution. The optimized threshold results are shown as Table 4.

In Table 4, optimized reliability thresholds are not equal. Meanwhile, all optimized reliability thresholds are less than the threshold $R_{or}^{(s)}$ of 0.93, which narrows down the interval between the thresholds $R_{pr}^{(s)}$ and $R_{or}^{(s)}$. The narrower interval means more precise reliability control for each subassembly, and the result of which is the further decrease of maintenance cost.

The maintenance schedules of the improved strategy with the thresholds listed in Table 4 are shown as Table 5. In Table 5, the first maintenance schedule is the same as the one in Table 4. The difference starts from the second maintenance schedule. Although the time of the second maintenance is unchanged, the maintenance task of which is changed. Under the maintenance opportunity brought by the preventive replacement of subassembly 9, only subassembly 6 needs to be replaced. The replacement of subassemblies 1, 3, 10, and 13 at the second maintenance schedule listed in Table 4 is delayed, because these subassemblies will not be replaced until their reliabilities are less than the thresholds of 0.915, 0.902, 0.901, and 0.915, instead of the thresholds of 0.93. These make the reliability of each subassembly optimal and avoid the waste of their remaining useful life as much as possible.

4.4 | Comparative analysis

According to Tables 3 and 5, statistics on the maintenance count and cost during the operating life cycle is, respectively, made for each subassembly and the whole turbine. The results are compared with the TPRM strategy, shown as Tables 6 and 7.

In Table 6, comparisons are given at the subassembly level. Compared with the TPRM strategy, the frequency of replacing subassemblies increases in the OGRM strategy. The reason lies in the subassemblies with higher reliability than the threshold $R_{pr}^{(s)}$ are replaced. The replacement in advance reduces maintenance intervals and increases replacement frequency. Nevertheless, the exchanged result is a reduction of maintenance cost. Compared with the OGRM strategy, the replacement count of each subassembly decreases by the improvement of adjusting the thresholds individually in the improved OGRM; furthermore, the maintenance cost of majority subassemblies decreases.

In Table 7, comparisons are given from the perspective of a whole turbine. Due to the group replacement at a maintenance, the OGRM strategy reduces 79.10% of the maintenance count and 15.68% of maintenance cost, compared with the TPRM strategy. After the improvement of maintenance strategy, the maintenance count increases from 153 to 204, but saving 17.67% of the maintenance cost, which means the proposed improved OGRM can save ¥ 130 674 for the 13 subassemblies in a wind turbines during its life cycle of 20 years.
The maintenance cost consists of power loss of downtime, fixed cost, and direct cost. Compared with the TPRM, the direct cost increases ¥ 244,481, the fixed cost decreases ¥ 1,260,644 and the power loss decreases ¥ 14,624 in OGRM. After the improvement of individually setting the thresholds $R_{s}$ for each subassembly, the fixed cost increases to a certain extent due to the augment of maintenance count which need more manpower and transportation. But the direct cost and power loss decreases to a larger extent, which depends on less replaced subassemblies and shorter downtime in the improved OGRM. The results above demonstrate that the proposed improved OGRM strategy is superior to the TPRM and OGRM for the maintenance of wind turbines.

### 5 | CONCLUSION

This paper proposes an improved OGRM strategy for wind turbines, which deals with the inflexible reliability thresholds of each subassembly and the diseconomy two-step optimization for maintenance cost in traditional OGRM. In the improved strategy, Weibull distribution is utilized for the reliability description of subassemblies, a uniform formula is proposed to express and subdivide the maintenance cost, and the replacement maintenance schedules of multiple subassemblies are given. To further decrease the cost, an objective function minimizing maintenance cost is established on the whole, with the opportunistic group replacement reliability thresholds of all subassemblies as optimization variables. The coordinate rotation method is utilized for optimization solution. A specific maintenance case from a wind farm verifies the effectiveness of the proposed strategy.

The optimization of maintenance strategy for wind turbines is a quite complex problem, which involves several influencing factors and implementation links. However, only multiple stages has been considered in the improved OGRM. For future research, multiple state of wind turbines and multiple maintenance opportunities should be introduced to form a completed maintenance system. Imperfect
maintenance, opportunistic imperfect maintenance, and opportunistic replacement are the elements in the aspect of maintenance modes as well. Meanwhile, some uncertain factors, for example, the randomness of failure should be considered.

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