12th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference and 14th AIAA/ISSM
17 - 19 September 2012, Indianapolis, Indiana

AIAA 2012-5435

Optimal Preventive Maintenance Time Windows for Offshore Wind Farms Subject to Wake Losses

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The maintenance cost of wind farms is one of the major factors influencing the profitability of wind projects. During preventive maintenance, the shutdown of wind turbines results in downtime wind energy losses. Appropriate determination of when to perform maintenance and which turbine(s) to maintain can reduce the overall downtime losses significantly. This paper uses a wind farm power generation model to evaluate downtime energy losses during preventive maintenance for a given group of wind turbines in the entire array. Wakes effects are taken into account to accurately estimate energy production over a specified time period. In addition to wind condition, the influence of wake effects is a critical factor in determining the selection of turbine(s) under maintenance. To minimize the overall downtime loss of an offshore wind farm due to preventive maintenance, an optimal scheduling problem is formulated that selects the maintenance time of each turbine. Weather conditions are imposed as constraints to ensure the safety of maintenance personnel, transportation, and tooling infrastructure. A genetic algorithm is used to solve the optimal scheduling problem. The maintenance scheduling is optimized for a utility-scale offshore wind farm with 25 turbines. The optimized schedule not only reduces the overall downtime loss by selecting the maintenance dates when wind speed is low, but also considers the wake effects among turbines. Under given wind direction, the turbines under maintenance are usually the ones that can generate strong wake effects on others during certain wind conditions, or the ones that generate relatively less power being under excessive wake effects.

I. Introduction

The U.S. Department of Energy's 2008 report, 20% Wind Energy by 2030, envisioned that wind power should supply 20% of all U.S. electricity, which included a contribution of 4% to the nation's total electricity from offshore wind power.[1] Offshore winds generally tend to blow stronger and more uniformly than those on land. Hence, offshore wind turbines can operate at a smoother and steadier rate, providing increased electricity generation than onshore turbines.[2] The U.S. has extensive and yet unutilized offshore wind energy resources along its long coastline. The further development of clean, renewable wind energy can help the U.S. meet important energy, environmental, and economic targets.[1] The first offshore wind farm in the U.S., Cape Cod wind farm, has been planned to comprise 130 Siemens 3.6 MW wind turbines, which will produce 420 MW of clean energy.[3]

Wind turbines are usually located in remote areas, exposed to highly variable, harsh weather conditions. In consequence of unsteady wind condition and other external variations, wind turbines undergo constantly varying loads. The changing loads cause high mechanical stresses on wind turbines. Therefore, a high degree of maintenance is required to provide a safe, cost effective, and reliable power output with an acceptable equipment life.[4]

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Maintenance cost for offshore wind turbines is generally higher than that for the same number of onshore turbines. Existing reports estimate that the offshore Operation and Maintenance (O&M) cost can be two to three times higher than that on land (for the same installed capacity), primarily because of accessibility issues.[2] Maintenance cost is therefore one of the major factors influencing the profitability of offshore wind projects. Poorly planned O&M strategy can compromise project operability, and trigger significant revenue losses of even a well-designed project.[5] Therefore, careful maintenance strategies are key to the success of offshore wind projects.

A. Literature Review

Researchers have been investigating the impacts of different factors on project costs, and developed various decision support models for offshore wind farms. Existing commercial and non-commercial decision support models for offshore wind farms were reviewed by Hofmann.[6] These models consider a series of factors that affect wind farm economy including operation, maintenance, offshore logistics, power production, and total project cost. A notable model, Opti-OWECS, was developed to identify the primary drivers of wind farm project costs, and demonstrate practical solutions to significantly reduce the cost of energy.[7] An overall cost model has been developed by the DOWEC project to evaluate and optimize designs of large-scale offshore wind farms.[8] Some of these models specifically focus on the O&M of wind farms. RECOFF model analyzes the fault detection and the repair cycle for offshore wind farms to improve O&M strategies.[9] Since most operational offshore wind farms are located in Europe, a majority of the existing cost models have been developed by European researchers. In the U.S., Fingersh et al.[10] have developed wind turbine design cost and scaling model to estimate cost of wind turbine components and subsystems. A cost model for low wind speed turbine projects was developed to identify ways to reduce the cost of energy for wind projects in low wind speed areas.[11] These cost models consider the scheduling of maintenance as an important aspect of offshore wind farm economy. Some of them can be used to simulate and optimize the scheduling.

Issues on scheduling are investigated regarding specific offshore wind farms to improve their profitability and reliability. An optimization problem is formulated to schedule maintenance operations at a set of wind farms maintained by a fixed group of maintenance personnel.[12] The scheduling problem is formulated and solved as a mixed-integer programming problem to minimize the total expected production loss. Since access to wind farm sites is a key factor of maintenance cost, access methods for maintenance personnel have been investigated and compared to pertinent literature. Guidelines and recommendations for access and transfer operation are provided with respect to the structures of offshore wind farms.[13] The optimum access system for a specific site can be selected using these guidelines and recommendations. Bussel and Bierbooms investigated access methods for O&M crew to the DOWEC offshore wind farm using a Monte Carlo simulation model.[14] A case study for the DOWEC offshore wind farm is performed by optimizing the O&M strategy using two models.[15]

The decision support models in the literature have considered various factors on wind farm maintenance, e.g. the availability of various resources, spare parts, and appropriate skilled personnel. Some of the models studied how O&M costs are affected by the fatigue damage of wind turbines caused by wake effects.[16–19] However, the loss of energy production due to wake effects has not been considered for the scheduling of wind farm maintenance. This paper studies the optimal scheduling of preventive maintenance to minimize downtime energy loss subject to wake effects.

B. Preventive Maintenance

Wind farm maintenance can be broadly classified into three major categories:[4]

1. **Preventive Maintenance:** Scheduled maintenance performed to keep a turbine in satisfactory operating condition, thereby preventing failures or major defects.
2. **Predictive Maintenance:** Maintenance performed after one or more indicators show that a turbine is likely to fail.
3. **Reactive Maintenance:** Maintenance performed only after a turbine fails or experiences problems.

Preventive maintenance is essential to ensure efficient operation of offshore wind farms. It includes systematic inspection, detection, and correction of incipient failures to prevent occurrence of failures. Preventive maintenance activities should be followed according to turbine manufacturer's manual.[4] These activities are usually scheduled twice a year, resulting in about two to three days of downtime per turbine for each maintenance event.[20, 21] Generally, only a few turbines in a facility are maintained at a time. The shutdown of the turbines under maintenance results in downtime losses. The amount of downtime losses can be basically determined by wind conditions. Preventive maintenance should be planned during time periods when shutdown will have the least impact on the net energy production capacity. To this end, the downtime loss of energy under specific wind condition can be accurately evaluated, and the scheduling of preventive maintenance is optimized to select appropriate time to shut down wind turbines. Accessibility of offshore wind farms is significantly affected by site weather conditions.[13] The safety of maintenance personnel should be considered with respect to weather conditions. Often weather conditions also affect the safety of the transport and landing of tools and spare parts. Maintenance implementation of personnel also requires weather conditions to satisfy certain requirements.[22]

This paper illustrates wake effects and the power generation model of a wind farm in Section II. The suitability of weather conditions for access to offshore wind farm sites is discussed in Section III. The optimization problem of maintenance scheduling is formulated in Section IV. Section V presents a case study for a utility-scale offshore wind farm. Concluding remarks are presented in Section VI.

II. Wind Farm Power Generation

A. Wake Effects

Wind turbine wakes are caused by the momentum deficit and increased level of turbulence created by turbines in a wind farm, which can lead to a reduction in the power output and unsteady loads on other turbines.[23] There are two major influences of wake effects: (i) a power deficiency due to velocity deficit, and (ii) the reduction of turbine lifetime due to increased structural loading caused by high turbulence intensity. It has been shown that, owing to wake effects, the total power extracted by a wind farm is significantly less than the simple product of the power extracted by a stand-alone turbine and the number of identical turbines in the farm.[24]

As it is known that the energy extracted from a turbine is depending on a series of natural factors, namely, wind speed, wind direction, and air density. In general sense, the power deficiency decreases as the turbine spacing increases. Since the wake recovers at some distance downstream. However, the spacing between turbines cannot be infinitely large enough for the wake recovery due to some limits. There are many methods to reduce or weaken the wake effects by adjusting the locations of turbines or shutting down appropriate turbines. Additionally, many other factors, such as the variation in atomspherical conditions, the topography (for onshore), and the turbine characteristics (hub-height, rotor diameter, etc), can affect the power output of a wind turbine. Those existing factors and the wake effect are always inter-dependent on each other, which causes many uncertainties and thereby makes it extremely challenging to consider the combined influence from all of them. For the sake of simplicity, they are not considered in this paper.

The wake model used in this paper is adopted from Frandsen et al.[25] It uses the control volume concept to relate the thrust and power coefficients to the velocity deficit.[26, 27] At a distance s behind a turbine with a diameter D, the diameter D_{wake} of the expanding wake front is given by

$$\begin{aligned} D_{wake} &= (1 + 2\alpha\bar{s})D, \\ \text{where} \qquad \bar{s} &= s/D. \end{aligned} \tag{1}$$

The parameter α is the wake spreading constant,[28] which is determined using the formula

$$\alpha = \frac{0.5}{\ln\left(\frac{z_H}{z_0}\right)}. \tag{2}$$

where z_H and z_0 are the average hub height of the turbines and the average surface roughness of the wind farm region, respectively.

If the wind approaches a turbine at velocity U, the velocity U_{wake} in the wake is given by[29]

$$U_{wake} = \left(1 - \frac{2a}{(1 + 2\alpha s)^2}\right)U. \tag{3}$$

where a is the induction factor, which can be determined from the coefficient of thrust. The latter is one of the design characteristics of a turbine rotor.

If these wake effects are ignored, each turbine of the same type can generate the same power given the same topography and wind speed. If labor force is sufficient and other constraints are neglected, at an offshore wind farm, preventive maintenance of all turbines can be performed at the same time when wind speed is the lowest in a maintenance window. In this situation, it is unnecessary to select turbines since they generate the same power without consideration of wake effects. In this paper, wake effects are taken into account in the power generation of an entire wind farm. Due to wake effects, given specific wind speed and wind direction, turbines at different locations in a wind farm can generate manifold power.

B. Wind Farm Power Generation Model

In this study, a wind farm power generation model is used to evaluate the power generated by a certain number of turbines with specified locations under given wind conditions. The model is adopted from the Unrestricted Wind Farm Layout Optimization (UWFLO) method developed by Chowdhury et al.[30] A rectangular wind farm of given dimensions, consisting of a specified number of turbines, is considered in the model. The UWFLO power generation model employs the wake model in Section A to accurately evaluate the power generation of the whole wind farm influenced by wake effects. Site wind speed and direction are inputs to the model used to evaluate power output.

Under certain wind conditions, the power generated by N turbines, P_{farm}, is given by the algebraic sum of the powers generated by individual turbines, which is expressed as

$$P_{farm} = \sum_{i=1}^{N} P_i. \tag{4}$$

To calculate downtime energy loss of a wind farm during preventive maintenance, the energy generated by the farm if all turbines were operating and that when the turbines not being maintained are operating should be evaluated under the wind conditions in the maintenance period. The difference between these two energy outputs is the downtime energy loss. When a set, S, of M turbines are under maintenance, these turbines are not accounted for in the power generation model; we evaluate the power generated by the operating turbines. The wake effects of the non-operating turbines (under maintenance) are not considered in this model. The power generated without the M turbines is expressed as

$$P_{rem} = \sum_{\forall i \notin S} P_i. \tag{5}$$

The power loss is given by

$$P_{loss} = P_{farm} - P_{rem}. \tag{6}$$

Given the wind speed and direction during a maintenance time interval from t_{start} to t_{end}, the energy loss can be represented as

$$E_{loss} = \int_{t_{start}}^{t_{end}} P_{loss}(t)\,\mathrm{d}t. \tag{7}$$

In order to accurately calculate the energy loss E_{loss} by integration, a continuous record of wind speed and direction should be available for the evaluation of power output at any time. To evaluate the energy loss at an acceptable accuracy within reasonable computational cost, wind power is evaluated using hourly averaged wind speed and direction. The hourly energy loss is the multiplication of the hourly average power and the time of an hour. This approach assumes the future wind variation will remain exactly similar to the historically recorded wind variations. It should be however noted that the UWFLO model is capable of modeling and using such wind variations in terms of wind distribution estimates.

In this paper, the scheduling of maintenance is considered at an hourly time frame. The start and end time of maintenance, t_{start} and t_{end}, can be expressed as the numbers of hours. The energy loss during the time interval from t_{start} to t_{end} is the sum of hourly energy losses P_{loss}^k, $k = t_{start}, \ldots, t_{end}$, which is given by

$$E_{loss} \approx \sum_{t_{start}}^{t_{end}} P_{loss}^k. \tag{8}$$

The objective of the optimization problem formulated in Section IV is to minimize the energy loss of a wind farm in one year, attributed to preventive maintenance.

III. Suitability of Weather Conditions

At a specific offshore wind farm site, weather conditions are predicted using historical weather data. During maintenance time interval, t, the different weather condition expectations are:

- $v_{wind}(t)$ (unit: m/s): The expected wind speed at t.
- $v_{gust}(t)$ (unit: m/s): The expected wind gust at t.
- $T(t)$ (unit: K): The expected temperature at t.
- $h_{wave}(t)$ (unit: m): The expected significant wave height at t.

Among the above predicted weather conditions, the wind speed and the wind direction are used as inputs to the UWFLO power generation model in Section II to evaluate wind energy loss during maintenance.

As discussed in Section I, accessibility and maintenance feasibility of offshore wind farms are significantly affected by site weather conditions.[13] Among them, wind speed, wind gust, air temperature, and wave height are the main factors to be considered. Under high wind speeds of more than 20 m/s, maintenance personnel are not allowed to climb up a turbine.[22] Since preventive maintenance usually does not require cranes, the operation conditions for cranes are not considered in this study. For small vessels to carry maintenance personnel to a site, wind speed should be less than 13.8 m/s; wind gust should be less than 17 m/s; and significant wave height should be less than 2 meters.[31] According to guidelines for working outdoor, the highest and the lowest temperatures allowed for personnel to perform maintenance are 24 °C and −26 °C, respectively.[32, 33] Wind chill is also considered for skin temperatures.[34] The weather conditions during specified working hours are subjected to these constraints.

To ensure the weather conditions are suitable for maintenance, the expected weather conditions should be between the following lower and upper bounds.

- $L_{v_{wind}}$ and $U_{v_{wind}}$ (unit: m/s): The lower bound and upper bound of wind speed.
- $L_{v_{gust}}$ and $U_{v_{gust}}$ (unit: m/s): The lower bound and upper bound of wind gust.
- L_T and U_T (unit: K): The lower bound and upper bound of temperature.
- $L_{h_{wave}}$ and $U_{h_{wave}}$ (unit: m): The lower bound and upper bound of wave height.

IV. Optimization Problem of Maintenance Scheduling

This research investigates the preventive maintenance performed within one year's time span. Preventive maintenance is performed twice a year for each turbine in a wind farm. It usually takes two to three days to complete the maintenance of one turbine. The time schedule for each of the two times of maintenance is restricted to a specified interval. Weather conditions vary over the time interval. An optimal selection of maintenance time of turbines can reduce the energy loss during maintenance, consequently increasing the energy production capacity of the wind farm over the whole year.

Since each wind turbine is maintained twice a year, in order to minimize the downtime loss in one year, there are $2N$ starting time parameters for a wind farm with N turbines. The two starting time parameters to perform the preventive maintenance for the i^{th} turbine is denoted as t_i and t_{i+N}. They are expressed as the numbers of hours counted from the beginning of a year, which are integers. The maintenance of each turbine is constrained within a specified time interval, determined by its specific mechanical condition. The earliest and the latest available time to start the first maintenance for the i^{th} turbine are respectively denoted as t^i_{start} and t^i_{end}. For the second maintenance, they are denoted as t^{N+i}_{start} and t^{N+i}_{end}. These time variables are also expressed as the numbers of hours from the beginning of a year. During each time of maintenance, each turbine is shutdown for a specified number of days, which include consecutive n hours. On any given day, there can be no turbine, one turbine, or multiple turbines under maintenance. The wind conditions during the shutdown days are inputs to the UWFLO power generation model, used to evaluate the energy loss due to the shutdown turbines.

In order to ensure safe access to an offshore wind farm, the lower and the upper bounds of the weather conditions are constrained during working hours in the scheduling problem. The working hours are determined by the selection of dates when turbines are maintained. A set of Q days are selected for maintenance. On each day ($j \in Q$), maintenance personnel start working from t_j, and continue working for m hours. During these working hours, the weather conditions should satisfy requirements.

Due to limited capacity of maintenance personnel,only a limited number of turbines can be maintained each day. The number of turbines under maintenance at each day in Q is H_j. To ensure the number of turbines under maintenance is within the capacity of maintenance personnel, H_j should be less than or equal to the maximum number of turbines under maintenance, G.

To schedule the preventive maintenance, weather forecast during specified time interval should be used. Expected weather conditions can be used if weather forecast is unavailable. The average of previous records is a way to calculate expected weather conditions.

For one year, the optimization problem for the scheduling of preventive maintenance is formulated as follows:

$$\min_{t_1,\ldots t_N, t_{N+1},\ldots t_{2N}} E_{loss} \tag{9}$$

subject to

$$t^i_{start} \leq t_i \leq t^i_{end} \qquad i = 1, ..., N \tag{10}$$

$$t^{i+N}_{start} \leq t_{i+N} \leq t^{i+N}_{end} \qquad i = 1, ..., N \tag{11}$$

$$L_{v_{wind}} \leq v_{wind}(t) \leq U_{v_{wind}} \qquad t \in [t_j, t_j + m] \qquad j \in Q \tag{12}$$

$$L_{v_{gust}} \leq v_{gust}(t) \leq U_{v_{gust}} \qquad t \in [t_j, t_j + m] \qquad j \in Q \tag{13}$$

$$L_T \leq T(t) \leq U_T \qquad t \in [t_j, t_j + m] \qquad j \in Q \tag{14}$$

$$L_{h_{wave}} \leq h_{wave}(t) \leq U_{h_{wave}} \qquad t \in [t_j, t_j + m] \qquad j \in Q \tag{15}$$

$$H_j \leq G \qquad j \in Q \tag{16}$$

The design variables for the optimization problem are the numbers of hours counting from the start of a year, and hence are integers. The objective function and some of the constraints are nonlinear. The optimization problem is therefore an integer nonlinear programming problem. Genetic Algorithms (GA) are powerful tools for solving such problems with discrete variables.[35] It is used to iteratively minimize the downtime energy loss of an offshore wind farm over one year.

V. Case Study

The Cape Wind will be America's first offshore wind farm.[3] It is located on Horseshoe Shoal in Nantucket Sound of Cape Cod in the state of Massachusetts, as shown in Fig. 1. Its historical weather data in 2010 and 2011 were obtained from NOAA National Data Buoy Center.[36]

The scheduling optimization of preventive maintenance is applied to a utility-scale offshore wind farm involving twenty-five 3.6 MW wind turbines. The optimization can be applied to the scheduling of any offshore wind farm with any layout of any number of turbines. The layout of wind turbines used in this case study is chosen for the demonstration of optimization. The locations of the 25 turbines with their assigned numbers are shown in Fig. 2. In the figure, the arrow on the upper right shows the 0° wind direction, which is defined as wind flowing from north to south.

The weather conditions at the Cape Cod location are used to evaluate power generation and to address site accessibility. To optimally schedule the preventive maintenance of an offshore wind farm in a specified time interval, the forecast of site weather conditions during this interval should be used as inputs to the optimization problem. Due to unavailability of weather forecast, we use the hourly averaged climatic data

Figure 1. Location of Cape Wind[37]

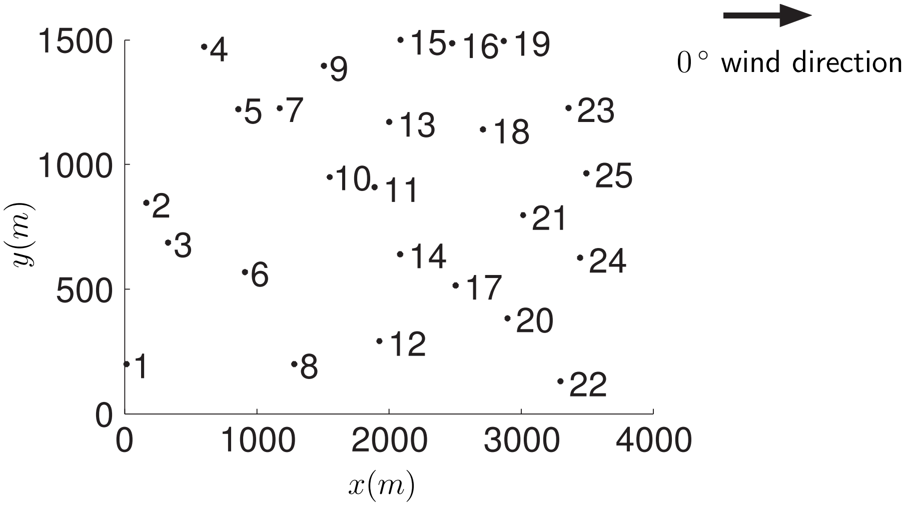

Figure 2. Locations of 25 wind turbines

recorded at the Cape Cod location in 2011. Assuming the weather conditions are expected to be similar with those in 2011, the optimum scheduling is performed to reduce downtime loss during preventive maintenance.

When all the turbines are operating, an annual average power output of 66.2 MW is evaluated by the UWFLO power generation model. The annual energy production is 5.8×10^8 kWh. In this scenario, each turbine is maintained twice a year, and it takes 3 days to complete the maintenance for each. The first maintenance date of each turbine is constrained within the interval between the 60^{th} and the 92^{th} dates in a year. The second is constrained within the interval between the 240^{th} and the 272^{th} dates. Figure 3 shows these two time intervals and monthly average wind speeds.

On each maintenance day, maintenance personnel are assumed to work from 9am to 5pm. The number of turbines maintained each day cannot exceed 10. Maintenance can only be performed on a three consecutive day time period when the weather conditions during working hours satisfy constraints 12 to 15.

After the optimization is performed for 60 generations using GA, the value of the downtime energy loss is minimized to $8.22 \times 10^6 kWh$. Compared with the average energy production of $9.49 \times 10^6 kWh$ of the first generation of GA optimization, $1.27 \times 10^6 kWh$ is saved through the optimization of the maintenance scheduling. It is 15% of the minimum downtime energy loss. The average power of the entire wind farm in a year is $6.62 \times 10^4 kW$. The saved energy is equal to 19 hours of average power generated by the entire wind farm. Figure 4 shows the mean values and the best values in the 60 generations.

The turbines under maintenance in different days in two maintenance intervals are shown in Tables 1 and 2, respectively. These two tables also show wind speed, wind direction, and downtime energy loss in

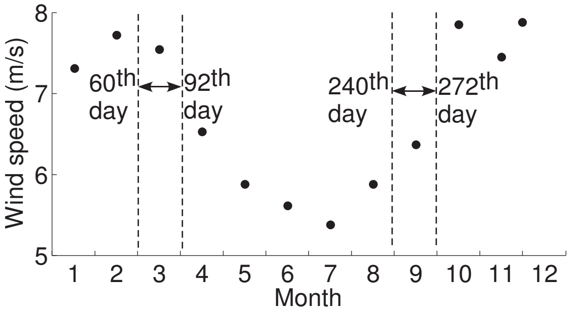

Figure 3. Two maintenance intervals in a year

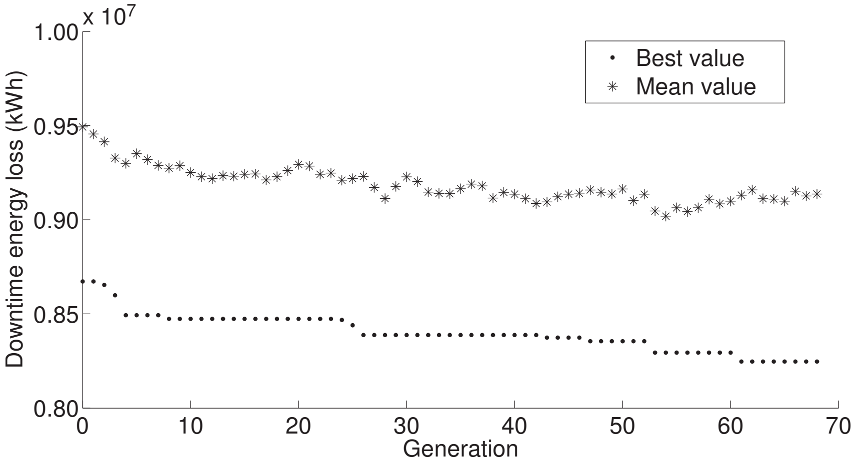

Figure 4. Minimization of energy loss using Genetic Algorithm

each day. The wind speed and maintenance days in two maintenance intervals are plotted in Figs. 5 and 6, respectively.

Wind speed and wind direction are two main factors that influence the optimal selection and arrangement of turbines for maintenance. Since low wind speed produces low wind power, it saves energy to shut down turbines during low wind speed time periods. The two tables and the two figures show that the optimized maintenance time is generally at the dates when wind speed is low. The days, 242^{nd}, 243^{rd}, and 244^{th}, have the lowest three-day-average wind speed. Hence, a high number of turbines are maintained during these three days.

The other important factor is wind direction. Observed from Fig. 2, the turbines under maintenance are usually the ones that can generate strong wake effects on other turbines, or the ones that generate less power than others since they are in the strong wake effects of others. If the first type of turbines are shut down, the power generation of other turbines in their wake effects can increase. If the second type of turbines are shut down, they have less impact on power generation than the other turbines. The description of how wind speed and wind direction affect the optimal selection of turbines are based on careful observations of the optimization results. Further research is necessary to quantitatively investigate the effects of wind speed and wind direction on turbine selection for maintenance.

Figures 7 and 8 show the wind directions and the turbines under maintenance on the 74^{th} day and the 86^{th} day. The turbines labeled by red numbers are under maintenance. On the 74^{th} day, a significant number of turbines are in the wake of turbine 5, if it is operational. Turbine 22 is in the strong wakes of a significant number of upstream turbines, which reduce its wind power. Turbine 11 is in the wakes of upstream turbines, and it also produces wakes on its downstream turbines if it is operational. On the 86^{th} day, turbines 16 and 25 generate wakes on their downstream turbines. On the 84^{th} day and the 85^{th} day, turbine 7 is under the wakes of its upstream turbines. Since every turbine requires three consecutive days of maintenance, it is also selected on the 86^{th} day. If the constraints are not considered, the selection of these turbines for maintenance

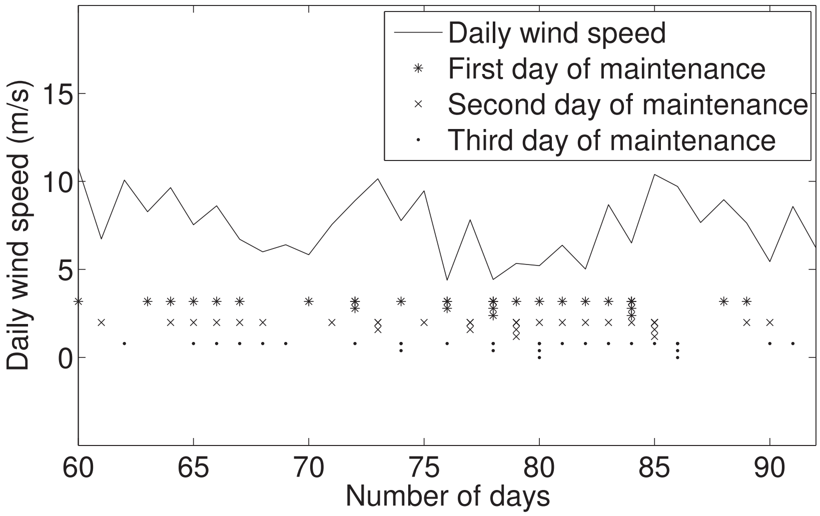

Figure 5. First maintenance interval

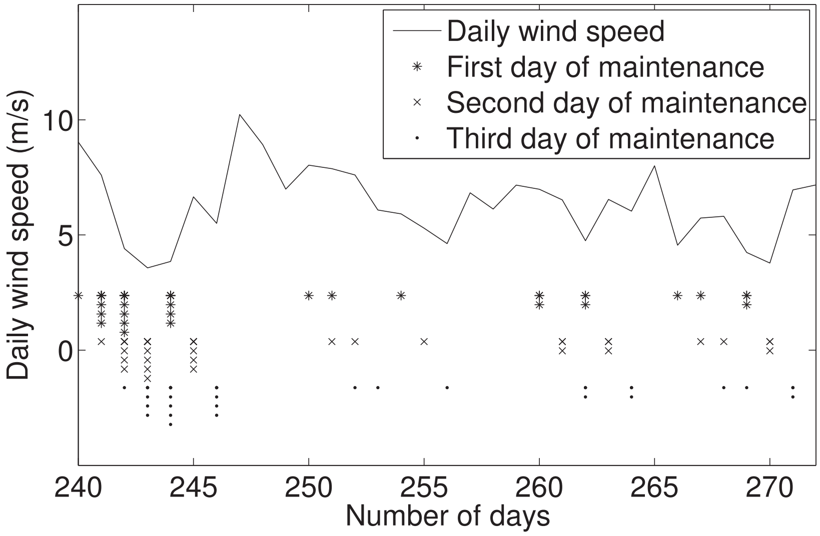

Figure 6. Second maintenance interval

are not optimum for the given wind condition on each day. However, they are optimum considering the whole maintenance time frame, the wind conditions, and the constraints.

VI. Concluding Remarks

This paper presents an approach to optimally schedule preventive maintenance of an offshore wind farm subject to wake effects. An optimization problem is formulated to optimally select the turbines under maintenance. The objective of the optimal scheduling is to minimize downtime energy losses during one year. Accessibility to the farm site is constrained by predicted local weather conditions. The time intervals for preventive maintenance are specified by the mechanical conditions of turbines. The power generation model used in the study accounts for wake effects to accurately evaluate downtime energy losses. To solve the formulated optimization problem, a standard genetic algorithm is used. The optimal scheduling is performed for a utility-scale offshore wind farm with 25 turbines. The selection of turbines for maintenance is mainly determined by wind speed and wind direction. The result shows that the downtime energy loss is significantly reduced using the proposed maintenance scheduling approach. Since the scheduling optimization considers

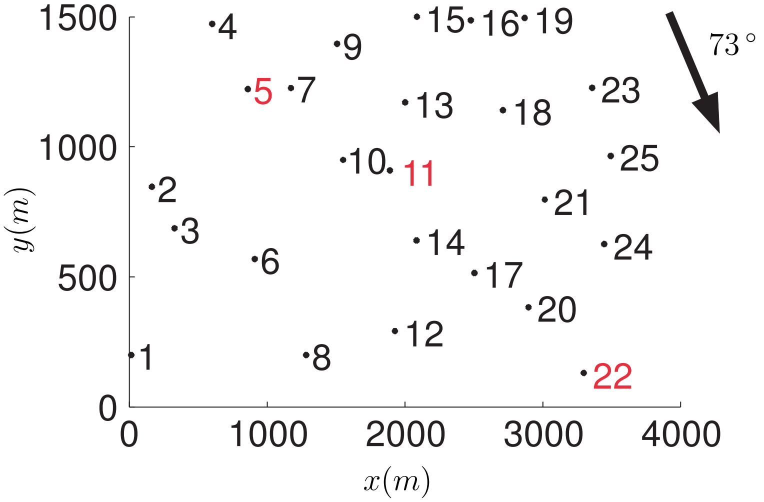

Figure 7. Turbines under maintenance on the 74th day

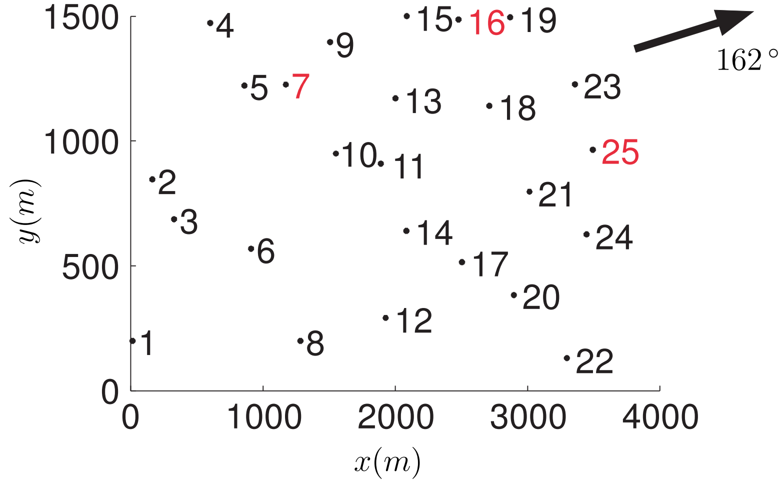

Figure 8. Turbines under maintenance on the 86th day

wake effects among turbines, the selected turbines under maintenance are generally the ones that significantly reduce overall wake effects of the whole wind farm under prevailing wind direction. They are usually the ones that can generate strong wake effects on other downstream turbines, or the ones that generate less power than others since they are in the strong wake effects of other upstream turbines.

Acknowledgements

Support from the National Found Awards CMMI-1100948, and CMMI-0946765 is gratefully acknowledged.

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Table 1. Turbines under maintenance in the first interval

Date	Wind speed (m/s)	Wind dir. (°)	Turbines	Energy loss (kWh)
60	10.8	313	6	5.42×10^4
61	6.7	182	6	7.06×10^4
62	10.1	198	6	7.94×10^4
63	8.3	118	23	8.49×10^4
64	9.7	87	23, 21	1.72×10^5
65	7.5	177	23, 21, 12	2.42×10^5
66	8.6	227	21, 12, 8	2.45×10^5
67	6.7	215	12, 8, 13	2.10×10^5
68	6.0	146	8, 13	1.27×10^5
69	6.4	112	13	5.92×10^4
70	5.8	120	17	6.40×10^4
71	7.6	155	17	7.18×10^4
72	8.9	160	17, 11, 22	2.58×10^5
73	10.1	151	11, 22	1.50×10^5
74	7.8	73	11, 22, 5	2.42×10^5
75	9.5	97	5	8.51×10^4
76	4.4	237	5, 3, 19	1.05×10^5
77	7.8	225	3, 19	1.62×10^5
78	4.4	191	3, 19, 4, 9, 20	2.01×10^5
79	5.3	165	4, 9, 20, 2	2.30×10^5
80	5.2	157	4, 9, 20, 2, 10	2.40×10^5
81	6.4	225	2, 10, 18	2.06×10^5
82	5.0	222	10, 18, 15	1.25×10^5
83	8.7	198	18, 15, 1	2.29×10^5
84	6.5	242	15, 1, 7, 16, 25	3.05×10^5
85	10.4	210	1, 7, 16, 25	3.03×10^5
86	9.7	162	7, 16, 25	2.23×10^5
87	7.7	203	None	0
88	9.0	216	14	7.59×10^4
89	7.6	206	14, 24	1.54×10^5
90	5.4	133	14, 24	9.15×10^4
91	8.6	170	24	8.04×10^4
92	6.2	193	None	0
Sum				4.95×10^6

Table 2. Turbines under maintenance in the second interval

Date	Wind speed (m/s)	Wind dir. (°)	Turbines	Energy loss (kWh)
240	9.0	208	20	6.54×10^4
241	7.6	253	20, 2, 4, 7, 10	3.11×10^5
242	4.4	215	20, 2, 4, 7, 10, 3, 5, 11, 16, 17	3.09×10^5
243	3.6	224	2, 4, 7, 10, 3, 5, 11, 16, 17	1.71×10^5
244	3.9	151	3, 5, 11, 16, 17, 6, 9, 13, 18	1.93×10^5
245	6.7	135	6, 9, 13, 18	2.87×10^5
246	5.5	169	6, 9, 13, 18	1.75×10^5
247	10.2	212	None	0
248	8.9	224	None	0
249	7.0	201	None	0
250	8.0	152	12	8.62×10^4
251	7.9	140	12, 19	1.59×10^5
252	7.6	211	12, 19	1.52×10^5
253	6.1	228	19	6.27×10^4
254	5.9	162	14	4.75×10^4
255	5.3	143	14	4.42×10^4
256	4.6	168	14	2.89×10^4
257	6.8	204	None	0
258	6.1	230	None	0
259	7.2	280	None	0
260	7.0	132	8, 22	1.33×10^5
261	6.5	65	8, 22	1.50×10^5
262	4.8	133	8, 22, 23, 25	1.54×10^5
263	6.5	134	23, 25	1.03×10^5
264	6.0	255	23, 25	1.12×10^5
265	8.0	187	None	0
266	4.6	171	21	3.16×10^4
267	5.7	181	21, 1	1.12×10^5
268	5.8	222	21, 1	1.22×10^5
269	4.2	171	1, 15, 24	9.43×10^4
270	3.8	130	15, 24	4.62×10^4
271	7.0	131	15, 24	1.27×10^5
272	7.2	172	None	0
Sum				3.28×10^6