Large-scale Maintenance Scheduling of Wind Turbines

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***Abstract*—Current researches about maintenance scheduling problems of wind turbines only focus on small-sized instances. When the scale of the problem increases, the large number of variables and constraints is adverse for obtaining the optimal solution. This paper proposed a nonlinear integer programming model for large-scale maintenance scheduling of wind turbines. The performance of the model is less sensitive to the size of the scheduling problem than existing method. Genetic algorithm is used to identify the maintenance plan that maximizes the power production. Numerical examples are illustrated to validate the developed method.**

Keywords—maintenance scheduling; large-scale optimization; wind turbine; Genetic Algorithms; nonlinear integer programming; wind energy.

Notations:

N: Number of tasks

T: Number of time units

J: Number of wind turbines

K: Number of maintenance teams

$z_{j,t}$: Production loss of wind turbine j at time t

$x_{i.k,j}$: Indicator of whether maintenance task i is began to be performed by team k at time t

y_i: Indicator of whether maintenance task i is postponed

x_i: Start time of task i

n_i: Index of the team to perform task i

ψ_i: Penalty cost for postponing task i

q_i: Elapsed time of task i

$l^0_{i,j,t}$: Production loss at time t if task i has not started

$l^1_{i,j,t}$: Production loss at time t if task i is under execution

s_i: Fixed maintenance cost for task i

τ_i: Production loss factor of task i

pr: Revenue of per unit production

$\mu_{i,k,t}$: Indicator of whether task i can be started by team k at time t

$E'_{j,t}$: Production loss of wind turbine j at time t because of performing task

$E''_{j,t}$: Production loss of wind turbine j at time t before task execution

$e'_{j,t}$: Expected production rate of wind turbine j at time t

$e_{j,t}$: Actual production rate of wind turbine j at time t

F_t: Total production of all the wind turbines at time t

I. Introduction

Wind energy has been developing rapidly in recent years. However, the high cost of operation and maintenance(OM) is a main issue accompanied with the development of the wind power industry. During a 20-year life cycle of a wind farm , 10-15% of the whole income is expended to the OM and spare parts [1]. Therefore, effective maintenance scheduling is important to a wind farm for greater revenue. Optimization methods are widely studied in both industry and academic institutions to schedule the maintenance in wind farms.

Existing methods of maintenance scheduling for wind turbines largely adopts the linear integer programming (LIP) method and the nonlinear integer programming (NLIP) method. The LIP method contains the linear programming model, and some or all of the variables are integer. An LIP model is developed in [2], the objective is minimizing maintenance cost and find the optimal route configuration along with the maintenance schedule. Two integer linear programming models are proposed in [3], the objective is to solve the problem that maximize the revenue of a wind farm. A formal model of wind farm maintenance is developed in [4], which uses a mixed-integer programming formulation to model the maintenance scheduling problem. Gstavsson et al. [5] proposed a 0-1 integer linear programming model to model the preventive maintenance scheduling problem.

The research work is supported by the National Natural Science Foundation of China (Grant Nos. 71671041).

NLIP is another widely used approach in the field of maintenance scheduling. The non-linear multi-objective optimization model is used in [6] and [7]. Both refs. [6] and [7] utilized the maximization of asset reliability and the minimization of maintenance cost as the objective functions. Xiang et al. [8] regarded peak regulation pressure as a consideration in the nonlinear maintenance scheduling optimization problem. The NLIP model proposed in [9] used genetic algorithm to minimize the total cost during maintenance activities considering geographical and predictive failure information.

All the above reviewed methods used the 0-1 variables as the decision variables, which make the construct of the model easier. However, for large-scale problems, the solving performance of algorithm is affected by the huge number of variables and constraints. Too many decision variables can lead to time excesses and memory overflow [10]. The proposed model in [2] required more than 40 hours to solve a large problem which contains 72 turbines and 14 time units. The proposed LIP formulation in [3] is only able to solve the problem within 20 time units. The number of tasks in examples that test the LIP method is only of 2-9 in [11]. For the LIP method in [12], the time limit for finding optimal solution will be exceeded when the time horizon for the instance is more than 5 days. According to the [13], when the general solvers are used to solve large problems by NLIP methods, the performance will be limited.

In order to avoid this effect, a new NLIP method is developed in this paper. The value ranges for decision variables in the NLIP model are much larger than which for 0-1 variables. Therefore, the amount of variables is able to maintain a small quantity when the size of the problem increases. On the other hand, the small quantity of variables can help to reduce the number of constraints. It will also contribute to solve the large-scale problem efficiently. Genetic algorithm is used to obtain the solution. The investigated maintenance scheduling problem is also solved by another LIP method for comparison.

The remaining part of this paper is organized as follows: Section 2 presents the problem statement. Then Section 3 explains the optimization model and methodology. After that, Section 4 demonstrates the numerical examples.

II. PROBLEM STATEMENT

Maintenance scheduling for a wind farm is arranging maintenance tasks over a certain length of time horizon. The aim of scheduling is to maximize the power production revenue of wind turbines. Therefore, detailed information about the maintenance scheduling problem is introduced in this section.

The available time for maintenance in each day is equally divided into several time units. The length of the time unit t is selected according the requirement of the maintenance plan.

Maintenance task i is the mission for technicians to eliminate the failure on wind turbines. Each task is related to a specific wind turbine. The content of each task is different, such as troubleshooting, component replacement, or regular check, clean. To ensure the safety of technicians, wind turbines will shut down during task execution. Therefore, each task incurs a certain amount of production loss.

Production loss, fixed maintenance cost and penalty cost are the major influencing factors for the revenue. Failures on wind turbines has negative impact on power production. $l_{i,j,t}^{0}$ and $l_{i,j,t}^{1}$ are the production loss before and under the task execution. Because wind turbines will shut down during task execution, the value of $l_{i,j,t}^{1}$ is equal to the expected production revenue of wind turbine j at time t. $l_{i,j,t}^{1}$ can be calculated by

$$l_{i,j,t}^{1} = e'_{j,t} * pr. \tag{1}$$

The production loss of unsolved failure can usually be forecasted by detailed historical record. Hence, $l_{i,j,t}^{0}$ is assumed to be known before scheduling. Besides production loss, fixed maintenance cost s_i is another expense for task execution. It includes labor cost and spare parts cost. Furthermore, to enforce performing as many tasks as possible, penalty cost ψ_i is used to punish task postponement. It can be calculated by

$$\psi_i = \sum_{t=1}^{T} w_{i,j,t}^{0} * pr \ . \tag{2}$$

The value of penalty cost is equal to the production revenue loss induced by the postponement.

Each task i can only be performed under feasible condition. In this paper, binary parameter $\mu_{i,k,t}$ is used to indicate whether task i can be started by team k at time t. E.g., in order to guarantee the security, technicians are forbidden to work outside during extreme weather. It not only can be caused by weather conditions, but also other constraints. E.g., holiday off, inexperienced technicians, task interruption (e.g., a technician cannot perform half a task one day and finish it in next day), etc.

Maintenance team k is a group of technicians that handle maintenance tasks. Every maintenance team has the same capacity to performing tasks in this paper. Maintenance team can only perform one task at a time. Multiple teams are allowed to execute different tasks on the same wind turbine. When the weather is raining or snowing or wind speed is higher than a predetermined threshold, any task execution is not allowed.

III. OPTIMIZATION MODEL AND METHODOLOGY

In this section, a NLIP model and a LIP model are proposed to solve the maintenance scheduling problem of wind turbines. The NLIP model is applicable for large-scale problems. The LIP model is transformed from the NLIP model and is used for the small-scale problem. The NLIP model is written as follows:

Objective function of the NLIP model

$$\text{Maxmize } \sum_{j=1}^{J}\sum_{t}^{T} e_{j,t} - \sum_{i=1}^{N}[(\psi_i - s_i) * I(x_i == 0) + s_i] \tag{3}$$

Constraints of the NLIP model

$$x_i * (0.5 - n_i) \le 0,\ \forall i \tag{4}$$

$$I(x_i == 0) + I(x_i > 0) * n_i * \mu_{i,n_i,x_i} > 0,\ \forall i \tag{5}$$

$$I(n_i == n_j)(x_j - q_i - x_i)(x_i - q_j - x_j) I(n_i > 0) I(n_j > 0) \le 0,\ \forall i \tag{6}$$

$$E'_{j,t} = \max\{[e'_{j,t} * I(x_i > 0): x_i \le t \le x_i + q_i]\},\ \forall j,t \tag{7}$$

$$E''_{j,t} = \max\{[l^0_{i,j,t} * I(x_i \geq 0): t < x_i || x_i == 0]\},\ \forall j, t \quad (8)$$

$$e_{j,t} = [e'_{j,t} - \max(E'_{j,t}, E''_{j,t})] * pr,\ \forall j, t \quad (9)$$

$$0 \leq x_i \leq T,\ \forall i \quad (10)$$

$$x_i = 0 \text{ if task } i \text{ is postponed} \quad (11)$$

$$0 \leq n_i \leq K,\ \forall i \quad (12)$$

$$n_i = 0 \text{ if task } i \text{ is postponed} \quad (13)$$

The objective function (3) is to maximize the difference between production revenue and task cost. Constraints (4) state that each maintenance task is performed or postponed. Constraints (5) determine that each task must be performed in feasible time. Constraints (6) indicate that a maintenance team cannot execute more than one task at the same time. Constraints (7) and (8) give the production loss during and before the task execution. Constraints (9) calculate the electricity production for each wind turbine. Finally, x_i and n_i are integer decision variables in the model. Constraints (10) and (12) are the ranges for the start time and team of the task. Constraints (11) and (13) are the limits for the start time and team if the task is postponed.

Genetic Algorithm is used to obtain the solution for the NLIP model. The maintenance scheduling problem is also described as LIP model, which is given as follows:

Objective function of the LIP model

$$\text{Maxmize } \sum_{t=1}^{T} F_t - \sum_{i=1}^{N}[(\psi_i - s_i) * y_i + s_i] \quad (14)$$

Constraints of the LIP model

$$\sum_{k=1}^{K} \sum_{t=1}^{T} x_{i,k,t} + y_i = 1,\ \forall i \quad (15)$$

$$x_{i,k,t} = 0,\ \forall i, k, t: \neg\mu_{i,k,t} \quad (16)$$

$$\sum_{i=1}^{N} \sum_{t'=t-q_i+1}^{t} x_{i,k,t'} \leq 1,\ \forall k, t \quad (17)$$

$$z_{j,t} \geq (1 - \sum_{k=1}^{K} \sum_{t'=1}^{t-q_i} x_{i,k,t})\ l^0_{i,j,t},\ \forall j, t \quad (18)$$

$$z_{j,t} \geq \sum_{k=1}^{K} \sum_{t'=t-q_i+1}^{t} x_{i,k,t}\ l^1_{i,j,t},\ \forall j, t \quad (19)$$

$$z_{j,t} \geq 0,\ \forall j, t \quad (20)$$

$$\sum_{j=1}^{J}(e'_{j,t} - z_{j,t}) = F_t,\ \forall t \quad (21)$$

$$x_{i,k,t} \in \{0,1\},\ \forall i, k, t \quad (22)$$

$$y_i \in \{0,1\}\ \forall i \quad (23)$$

The objective function (14) is to maximize the difference between production revenue and task cost. Constraints (15) ensure that each task is completed once or delayed. Constraints (16) describe that task execution must under feasible time. Constraints (17) determine that one team can only perform one task at a time. Constraints(18) and (19) calculate the production loss due to breakdown and maintenance. Constraints (20) indicate the production loss should be larger than zero. Constraints (21) compute value of the production of wind turbines. Finally, $x_{i,k,t}$ and y_i are binary decision variables in the LIP model. In constraints(22), $x_{i,k,t}$ equals to 1 if task i is started by team k at time t; otherwise $x_{i,k,t}$ equals to 0. Constraints (23) define the range of y_i. y_i equals to 1 if task i is postponed, and equals to 0 otherwise.

IV. Numerical Examples

The proposed methods are applied to several assumed numerical examples in this paper. Detailed information about the wind farm and the weather data are shown in TABLE I and Fig. 1, respectively.

The wind farm contains 48 wind turbines and 2 maintenance teams. There are 25 tasks for scheduling. The time horizon is 7 days and the working hours are from 9:00 to 17:00. The time unit is half an hour. Consequently, each day contains 16 time units. The income for per unit energy is 0.5. Moreover, the wind speed and weather condition are as shown in Fig. 1. Tasks can only be executed when the value of weather condition is 1.

The information of the maintenance task is shown in TABLE I. To be noted that the calculation of production loss before task execution $l^0_{i,j,t}$ can be calculated by

$$l^0_{i,j,t} = e'_{j,t} * \tau_i * pr, \quad (24)$$

where, $e'_{j,t}$ can be obtained by the power curve in Fig. 2, and τ_i is the loss factor in TABLE II.

The general method for scheduling maintenance tasks is sequential arrangement, where technicians execute the maintenance task from the first to the last sequentially.

TABLE I. Input Parameters Of the Specific Wind Farm

Parameters	Value
N	25
T	112
J	48
K	2
pr	0.5

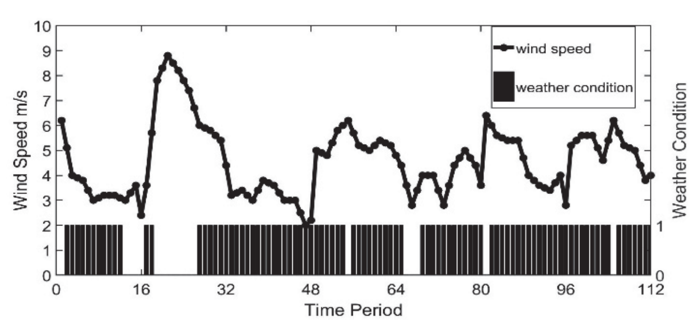

Figure 1. The weather data in wind farm

TABLE II. INFORMATION OF TASKS

Task Number	Wind Turbine	Execution Time	Execution Cost	Loss Factor
1	13	2	241	0.16
2	18	4	481	0.23
3	33	2	116	0.03
4	46	4	157	0.26
5	22	4	98	0.5
6	13	2	94	0.49
7	4	2	460	0.56
8	35	2	315	0.97
9	32	2	300	0.81
10	21	2	98	0.92
11	11	2	452	0.84
12	22	4	337	0.91
13	40	2	201	0.15
14	1	4	282	0.32
15	5	2	226	0.64
16	17	4	63	0.9
17	12	2	145	0.16
18	36	2	87	0.57
19	38	2	117	0.67
20	39	2	145	0.97
21	41	4	234	0.81
22	16	2	50	0.24
23	26	2	477	0.51
24	9	2	498	0.69
25	25	2	271	0.95

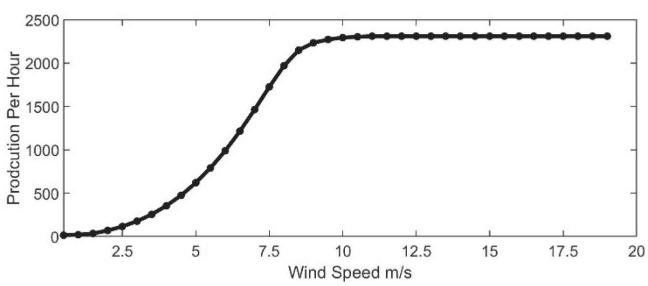

Figure 2. Power curve of wind turbine

In order to compare the NLIP, LIP, and sequential method, top 10 tasks in TABLE II are arranged using three methods. The time limit is one hour. The results are shown in TABLE III.

TABLE III. COMPUTATIONAL RESULTS OF 10 TASKS

Task Number	LIP Method		NLIP Method		Sequential Method	
	Start time	*team*	*Start time*	*team*	*Start time*	*team*
1	17	1	27	1	2	1
2	8	2	9	1	2	2
3	47	1	41	2	4	1
4	8	1	9	2	6	2
5	4	2	14	1	6	1
6	17	2	29	2	10	2
7	6	1	3	2	10	1
8	2	1	3	1	17	2
9	4	1	6	1	17	1
10	2	2	6	2	27	1
Production	1713686		1705868		1703627	

All the three methods obtain a maintenance plan that can complete the tasks within time limit. The execution time and team of maintenance tasks are listed in TABLE III. The energy production is displayed at the bottom of the table. The production of NLIP method is more than which in sequential method. The solution with the largest amount of production is obtained by the LIP method.

In order to verify the performance of the three methods in large-scale problems, other 14 numerical examples which are top 11 to top 25 tasks in TABLE II are tested for three methods. The time horizon is expanded to 2 weeks with 224 time units. The weather in second week is assumed to be as same as the first week. The time limit is 1 hour. The results are shown in Fig. 3.

As shown in Fig. 3, when the number of tasks in problem is more than 13, the LIP method cannot find the solution in one hour. The production of NLIP method is better than the sequential method. It confirms that the NLIP method is still able to obtain satisfactory solution of large-scale problem.

The number of decision variables and constraints of the LIP and the NLIP method are shown in Fig. 4 and Fig. 5.

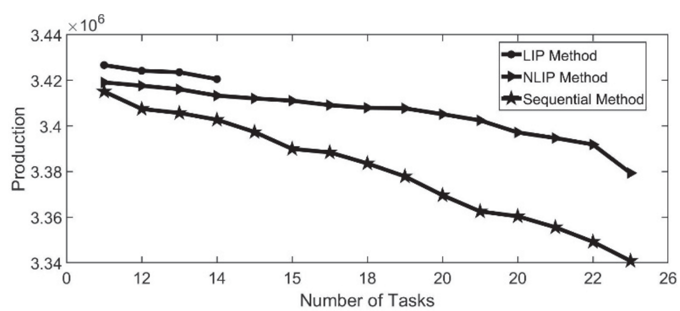

Figure 3. Energy production of different sizes problems calculated by LIP, NLIP and sequential methods

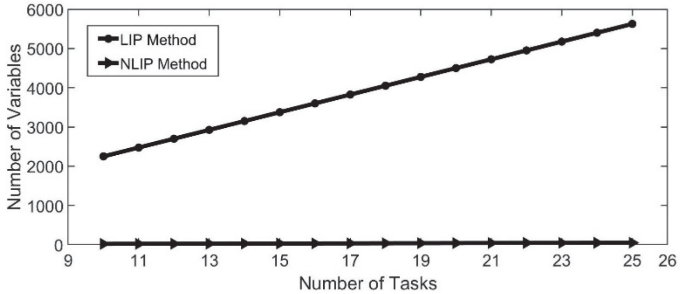

Figure 4. Number of decision variables of different sizes problems calculated by LIP and NLIP methods

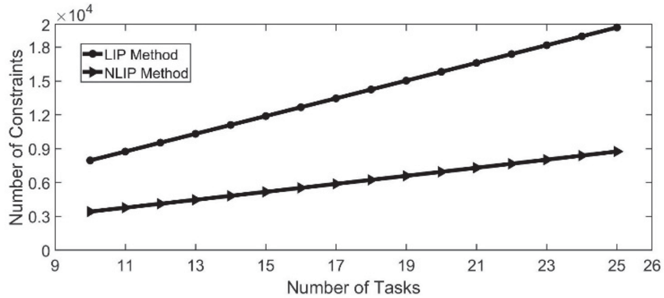

Figure 5. Number of Constraints of different sizes problems calculated by LIP and NLIP methods

As shown in Fig. 4, the number of decision variables in LIP method increases rapidly as the size of the problem is enlarged. On the other hand, the number of variables in NLIP method grows very gently. When 25 tasks are considered in the problem, the number of decision variables in NLIP method is equal to 50. As for constraints, the number of constraints in NLIP method is lower than which in the LIP method. The quantity gap of the constraints between the two methods in Fig. 5 increases continuously when the size of the problems grows. The amounts of the decision variables and constraints in the model are obviously reduced by the proposed NLIP method. Hence, the NLIP method can contribute to solve large-scale problems effectively.

V. CONCLUSION

This paper proposed a method for large-scale maintenance scheduling of wind turbines. A NLIP model is developed to model the large-scale maintenance scheduling problem by the small quantity of variables and constraints. A LIP model which is converted by NLIP model is developed for small-scale problems. The genetic algorithm and mathematical planning method are utilized to optimize the maintenance scheduling problem. Finally, the effectiveness of the method is tested by several numerical examples of different sizes. The results show that comparing with the original sequential method, the proposed methods can improve the production of the wind farm obviously. When the size of the problem is small, the LIP method is the best choice to maximize the power production. If the problem scale is too large to be solved by the LIP method, the NLIP method is able to process the problem.

ACKNOWLEDGEMENTS

The research work is supported by the National Natural Science Foundation of China (Grant Nos. 71671041) and Nanjing Kangni Mechanical & Electrical Co., Ltd.(Jiangsu Provincial Key Laboratory of Door Systems for Railway) (No.KN17-23).

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