Optimal Scheduling of Wind Turbine Generator Units Based on the Amount of Damage of Impeller

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Abstract. Impeller (blade and wheel) is one of the key components of wind turbine. According to different degrees of leaf and root damage and hub damage amount, a multi-objective scheduling model of wind farm with wind turbine impeller damage, wind turbine startup rate, and the uncertainty of the output of generator is established to improve the model output allocation strategy. Then optimize the model with the adaptive discrete particle swarm (ADPSO) and artificial bee colony algorithm (ABC), then obtaining the target power value and start-stop group. In combination with the practical example, the simulation results show that the proposed method optimizes the start-up and shut-down times of the wind turbines and improves the operating life of the wind turbines.

Keywords: The damage of the impeller · ADPSO · ABC · The mixed integer nonlinear programming

1 Introduction

The main components of wind turbine are blades, wheels, gearboxes, generators, control systems and other parts, because the wind turbine output influenced by the wind speed, wind direction uncertainty and variable speed constant frequency power generation control constraints, the operating state need to be frequently switched in different conditions, and the impeller is the most complex and the highest reliability requirements key component with high annual failure rate, long fault downtime.

What's more, Impeller accounts for about 23% of the total cost of wind turbines [1–3]. The operation and maintenance costs of wind farms can be reduced by extending the impeller life. In paper [4], the genetic algorithm is used to optimize the scheduling model considering the health status of the wind turbines. In paper [5], only the damage amount of the blade as the single target is considered to optimize the wind turbine working condition, and the unit output of the unit is not optimized.

In this paper, one multi-objective optimal scheduling is carried out by combining the times of start-stop and the relative fatigue damage value of the impeller. And this is a mixed integer nonlinear multi-objective optimization problem, in which the integer variable is the wind turbine start-up and shut-down, the continuous variable is the output power. This paper uses the improved ADPSO algorithm to optimize the

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combination of the generator start-up and shut-down, uses ABC algorithm to optimize the output, and combing the improved power output allocation strategy to solve the optimal scheduling problem.

2 Optimization Model of Wind Turbine Considering Impeller Damage Quantity and Start-Up and Shut-Down Times

2.1 Objective Function

Paper [6] takes 1.5 MW wind turbine as the research object, use the method of rain flow cycle counting to get the relative fatigue damage value of wind turbine blade and hub under different working conditions. Damage values of wind turbine under different working conditions are listed in Table 1.

Table 1. Damage values of wind turbine under different working conditions

Working condition	Damage coefficient	Code	Power output range (MW)	Blade damage values	Wheel hub damage values
Stop	*A*	000	0	0	0
Normal operation		001	0–0.093	3.80E−08/min	1.11E−10/min
		010	0.093–0.326	4.32E−08/min	2.24E−09/min
		011	0.326–0.753	6.02E−08/min	2.13E−08/min
		100	0.753–1.5	9.51E−08/min	1.84E−08/min
		101	≥ 1.5	1.53E−07/min	4.55E−09/min
Start-up	*B*	000-100	0–1.5	1.12E−09/time	2.95E−11/time
		000-101	≥ 1.5	1.18E−09/time	5.17E−11/time
Shutdown	*C*	100-000	0–1.5	2.77E−09/time	9.54E−09/time
		101-000	≥ 1.5	1.35E−09/time	4.85E−09/time

In the Table 1, ‘time’ means frequency, indicates the number of changes in the operating state of the wind turbine, ‘min’ means minute. And in the Table 1, *A* indicates the damage value of the impeller in normal operation, like the codes: 001, 010, 011, 100, 101. *B* indicates the damage value of the impeller in the process of start-up the wind turbine, like the codes: 000-100, 000-101. *C* indicates the damage value of the impeller in the process of shut-down the wind turbine, like the codes: 100-000, 101-000.

Under the different conditions, the impeller damage quantity of each condition has the corresponding numerical value, and the impeller damage value function can be defined as [7]:

$$h(u) = \sum_{j=1}^{T} \sum_{i=1}^{n} [A_i^j u_i^j t + B_i^j u_i^j (1 - u_i^{j-1}) + C_i^j u_i^{j-1} (1 - u_i^j)] \quad (1)$$

In the Eq. (1), $h(u)$ indicates the total amount of damage of the impeller wind farm, T indicates wind farms scheduling period, n indicates the total number of wind turbines, and A_i^j, B_i^j, C_i^j are respectively corresponding to damage values of wind turbine i in the wind farm during the normal running process, start-up process and shut-down process, at time j. u_i^j is the working condition of wind turbine i at time j. And the start-up and shut-down states are respectively represented by 0 and 1.

In order to avoid unnecessary start-up and shut-down of wind turbine, the times of start-up and shut-down is optimized in the scheduling period, and it can be defined as:

$$f(u) = \sum_{j=1}^{T} \sum_{i=1}^{n} \left| u_i^j - u_i^{j-1} \right| \tag{2}$$

According to Eq. (2), it is necessary to balance the proportion between the damage quantity and the start-up and shut-down times:

$$F(u,p) = \min[ah(u) \times 10^5 + bf(u)] \tag{3}$$

In the Eq. (3), a and b respectively corresponding to the weight coefficient of wind turbine impeller damage and wind turbine start-up and shut-down times.

2.2 Constraint Condition

Wind Turbine Predictive Power Constraints

$$0 \le p_{yuce}^{i,j} \le p_{\max}^{i,j} \tag{4}$$

In the Eq. (4), $p_{yuce}^{i,j}$ is power prediction value of wind turbine i at time j. $p_{max}^{i,j}$ is the output power limit of the wind turbine i at time j.

Wind Turbine Output Range Constraint

$$p_{i,\min} \le p_{i,j} \le p_{yuce}^{i,j} \tag{5}$$

In the Eq. (5), $p_{i,min}$ indicates the lower limit of the output power of wind turbine i. In this paper, it is set 20% of the rated power of the wind turbine. $P_{i,j}$ represents the actual output power of wind turbine i at time j

Load Scheduling Constraints

$$\sum_{j=1}^{T} \sum_{i=1}^{n} u_i^j p_i^j = p_w^j \tag{6}$$

In the Eq. (6), p_w^j represents dispatching command of grid to wind farm, that is, the total power required for the wind farm, at the number j.

Spinning Reserve Constraints

$$\sum_{j=1}^{T}\sum_{i=1}^{n} u_i^j (p_{\max}^{i,j} - p_i^j) \geq p_{by}^j \tag{7}$$

In the Eq. (7), p_{by}^j represents the requirements of spinning reserve, at time j. This page set it to 5% of the total output power.

2.3 Improvement of Wind Turbine Output Allocation Strategy

Because of the wind power mainly depends on the wind, rather than the installed capacity, so this paper improved the traditional strategy for the output distribution, so that the wind turbine can be controlled according to the wind power prediction value and working state adjust distribution, when the output power is greater than the total scheme generation scheduling instructions, according to the Eq. (8) of each unit of proportional output:

$$p_{ij}^* = p_{ij} - \frac{u_{ij}(p_{ij} - p_{i,\min})}{u_j(p_j - p_{i,\min})}\left(p_j \times u_j - p_w^j\right) \tag{8}$$

When the total power output is less than the dispatching instruction, according to Eq. (9) the output of each turbine and the ratio of the reverse will be increased:

$$p_{ij}^* = p_{ij} + \frac{u_{ij}(P_{yuce}^{i,j} - p_{ij})}{u_j(P_{yuce}^j - p_j)}\left(p_w^j - p_j \times u_j\right) \tag{9}$$

3 Adaptive Discrete Particle Swarm - Artificial Bee Colony Algorithm Optimization Scheduling

The mathematical model is a mixed integer nonlinear programming problem contains integer discrete variables and continuous variables. In order to avoid the combinatorial explosion caused by large-scale scheduling, this paper uses adaptive discrete particle swarm algorithm (ADPSO) [8, 9] combined with the artificial bee colony algorithm (ABC) [10, 11] to solve the model within the outer and inner optimization way [12].

Step 1: Set the particle population M of the adaptive discrete particle swarm algorithm, set the inertia weight parameter ω_{min} and ω_{max} (in this paper, take 0.01 and 1 respectively), the learning factor C_1 and C_2 (both are set to 2) and the number of iterations, set the number of artificial Bee colony population NP and other basic parameters.

Step 2: According to load scheduling constraints and spare constraints to produce the start-up and shut-down combinations:

$$U_m = \begin{vmatrix} u_{1,1} & \cdots & u_{1,j-1} & u_{1,j} \\ \vdots & \vdots & \vdots & \vdots \\ u_{i-1,1} & \cdots & u_{i-1,j-1} & u_{i-1,j} \\ u_{i,1} & \cdots & u_{i,j-1} & u_{i,j} \end{vmatrix} \quad (10)$$

In the Eq. (10), U_m represents start-up and shut-down combination matrix. $u_{i,j}$ represents the start-up and shut-down state of wind turbine i at time j.

Step 3: After selecting the start-up and shut-down combinations which satisfies the load schedule constraint and the reserve constraint, the ABC algorithm randomly generates the power allocation of each wind turbine in the scheduling cycle that satisfies the output range constraint and the predicted power constraint:

$$P_k = \begin{vmatrix} p_{1,1} & \cdots & p_{1,j-1} & p_{1,j} \\ \vdots & \vdots & \vdots & \vdots \\ p_{i-1,1} & \cdots & p_{i-1,j-1} & p_{i-1,j} \\ p_{i,1} & \cdots & p_{i,j-1} & p_{i,j} \end{vmatrix} \quad (11)$$

In the Eq. (11), P_k represents power output condition matrix. p_{ij} represents the power output condition of wind turbine i at time j.

Step 4: Calculate fitness value. According to the Eq. (3) calculates objective value, then calculates the fitness value by the Eq. (12):

$$fit_{i,k} = \begin{cases} 1/1 + F_{i,k}, & F_{i,k} \geq 0 \\ 1 + abs(F_{i,k}), & F_{i,k} < 0 \end{cases} \quad (12)$$

In the Eq. (12), $F_{i,k}$ refers to the objective function value of the kth honey source under the ith particle of the particle swarm. $fit_{i,k}$ refers to the fitness function value of the kth honey source under the ith particle of the particle swarm. And this is the minimum optimization problem, so the greater the fitness value, the corresponding solution of the better.

Step 5: Search for new solutions and make greedy choices. The colony produces a new solution by the following search method:

$$V_{ij} = p_{ij} + \varphi_{ij}(p_{ij} - p_{kj}) \quad (13)$$

In the Eq. (13), p_{kj} is different from p_{ij}, and k ∈ {1, 2, …, SN}, SN is the number of honey source. ϕ_{ij} is the random number between −1 and 1. After searching process, calculate the fitness value and choose the optimal solution through greed selection.

Step 6: Selection. According to the following bee roulette selection method with the probability $r_{i,k}$ of honey source, Calculate $r_{i,k}$ [11] according to Eq. (14):

$$r_{i,k} = \frac{fit_{i,k}}{\sum_{n=1}^{SN} fit_n} \quad (14)$$

Step 7: When the honey source always doesn't not change, honey source is abandoned, at the same time, bees for Scout bees, and by Eq. (15) random search to generate a new alternative raw honey source. And through Eqs. (3) and (12) to calculate the fitness value of new honey source.

$$p_{i,j} = p_{\min}^{i,j} + rand(0,1)(p_{\max}^{i,j} - p_{\min}^{i,j}) \tag{15}$$

Step 8: After the ending of the artificial bee colony algorithm, ADPSO algorithm choose global optimal value and individual optimal values, and then update the particle velocity and position, and generate new population processes are as follows:

(1) Generating inertia weight parameter

$$fit_{av} = (\sum_{m=1}^{M} fit_m)/M \tag{16}$$

$$w_i = w_{\min} + \frac{w_{\max} - w_{\min} * (fit_i - fit_{av})}{fit_{\max} - fit_{\min}} \tag{17}$$

In the Eqs. (16) and (17), fit_{av} is fitness value.

(2) Update particle velocity and position

$$v_i^d = w_i v_i^{d-1} + c_1(p_{best,i}^d - U_i^{d-1}) + c_2(g_{best,i}^d - U_i^{d-1}) \tag{18}$$

$$U_i^d = U_i^{d-1} + v_i^d \tag{19}$$

In the Eqs. (18) and (19), v_i^d is the velocity of ith particle at dth iteration. $p_{best,i}^d$ is the individual optimal values at dth iteration. g_{best}^d is the global optimal value at dth iteration.

(3) Discretization

$$u_{ij} = \begin{cases} 1 & if\ rand(0,1) < 1 \Big/ 1 + e^{-v_i^d} \\ 0 & else \end{cases} \tag{20}$$

Step 9: Loop iteration until the number of iterations reaches the maximum iterations.

4 Example Analysis

4.1 Example Introduction

By random selecting 10 sets of 1.5 MW wind turbine from a 49.5 MW wind farm in North China as the analysis objects, because the one hour in the short-term wind power prediction has higher credibility, this paper divided one hour to 4 scheduling cycle, each scheduling period is 15 min. The initial state and the predicted power value of the 10 wind turbines set are shown in Table 2, 0 indicates the shutdown, and 1 indicates the working. For adaptive discrete particle swarm optimization algorithm, the number of population is set to 20, the number of iterations is set to 30. For artificial bee colony algorithm, the number of population is set to 40, the number of iterations is 10, limit is 4.

Table 2. The initial state and the predictive power of the 10 wind turbines in a wind farm

Generator code	Initial state	Upper limit of predicted power (MW)			
		T1	T2	T3	T4
1	1	1.04	1.19	1.20	1.28
2	1	1.09	1.24	1.28	1.34
3	0	1.17	1.16	1.29	1.40
4	1	0.84	1.27	1.24	1.30
5	1	0.75	1.26	1.17	1.31
6	1	0.64	1.13	1.10	1.11
7	0	0.96	1.16	1.14	1.20
8	1	0.70	1.27	1.26	1.29
9	1	1.12	1.10	1.22	1.41
10	1	0.82	1.35	1.29	1.40
Total power		9.13	12.13	12.19	13.04

Under the condition of limited wind power, the sum of dispatching and the system reserve should be less than the upper limit of the wind farm. Therefore, the dispatching orders of the wind farm in the 4 scheduling periods are 7 MW, 9 MW, 9 MW, 9.5 MW, and the corresponding reserve power are 0.35 MW, 0.45 MW, 0.45 MW, 0.475 MW.

4.2 Objective Function Weight

It can be seen that only the damage values of the impeller and the times of start-up and shut-down of the wind turbine have effect on the optimal scheduling results. Therefore, the comparison of the two extreme examples is shown in Table 3.

As can be seen from Table 3, in the first case, the spinning reserve of the 4 scheduling cycles are respectively 0.74, 0.9, 0.92, 1.03 MW, the times of start-up and shut-down is 10, and the damage value is 4.1043e−05. Therefore, when the weight coefficient is relatively large, the damage value of the wind turbine plays an important role on the optimization of the scheduling trend. In another case, the spinning reserve of the 4 scheduling cycles are respectively 2.13, 3.13, 3.19, 3.54 MW, start-up and shut-down times is 2, the damage value is 5.13e−05, so when the weight coefficient is larger, wind turbine's start-up and shut-down times plays a leading role, leading to the failure to utilize the advantages of the wind turbine starting and stopping convenient, resulting in spare capacity is much greater, resulting in waste, and the damage value is bigger.

Table 3. Results of optimal dispatching of 10 wind turbines under different extreme weight

Generator code	a = 1000, b = 1				a = 1, b = 1000			
	T_1	T_2	T_3	T_4	T_1	T_2	T_3	T_4
1	0.84	1.04	1.18	1.1	0.83	1.03	1.17	1.08
2	0.96	1.03	1.01	1.21	0.63	1.06	1.26	0.94
3	1.15	1.13	1.23	1.35	0.74	0.93	0.91	0.89
4	0.74	1.21	1.22	1.12	0.54	0.81	1.2	0.8
5	0	1.18	0	0	0.47	0.83	0.75	1.2
6	0	0	0	0.97	0.45	0.74	0.84	0.78
7	0.96	1.11	1.02	0	0.91	0.77	0.75	0.78
8	0.64	1.09	1.08	1.11	0.68	0.84	0.77	0.91
9	0.94	0	1.21	1.35	1.06	0.97	0.68	1.18
10	0.77	1.21	1.05	1.29	0.69	1.02	0.67	0.94
Spinning reserve	0.74	09	0.92	1.03	2.13	3.13	3.19	3.54
Damage amount	4.1043e−05				5.1300e−05			
Start stop times	10				2			

Two kinds of extreme circumstances results are explained in this paper. In order to take into account the two indexes in engineering, scheduling planner can adjust the weight coefficients. It requires a large number of optimization tests to roughly determine a reasonable proportion. In this paper, set "8:1", "7:1", "6:1", "5:1", "4:1", "3:1", "2:1", "1:1", "1:2", "1:3" 10 groups, the results can be seen in Fig. 1.

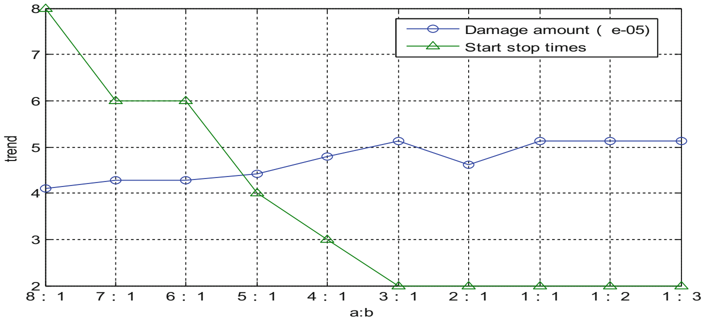

Fig. 1. Effect of a:b on optimization results

As can be seen from Fig. 1, in the process of a:b from 8:1 to 5:1, start-up and shut-down times decrease from 8 to 4, a larger decline, while the damage from 4.1e−05 to 4.45e−05, a smaller increase. When a:b from 5:1 to 1:3, the amount of damage increased from 4.45e−05 to 5.13e−05, the start-up and shut-down up to the minimum times. In order to take into account the comprehensive performance of the two indicators, therefore, take a:b as 5:1, the corresponding optimal scheduling results can be seen in Table 4.

Table 4. a = 5, b = 1, 10 wind turbines scheduling results

Wind turbine code	Wind turbine output power (MW)			
	T1	T2	T3	T4
1	0.86	1.05	1.10	1.18
2	0.73	0.95	1.09	0.99
3	0.99	0.99	1.16	1.28
4	0.71	0.93	1.02	1.26
5	0.74	1.13	1.13	1.22
6	0.00	0.00	0.00	0.00
7	0.67	0.70	0.00	0.00
8	0.68	1.20	1.23	0.97
9	0.93	1.00	1.06	1.36
10	0.69	1.05	1.22	1.24
Spinning reserve	1.49	2	0.95	1.23
Damage amount	4.2750e−05			
Start stop times	4			

Table 4 shows the column of the spinning reserve system relative to each cycle instruction scheduling, respectively is 21.28%, 22.22%, 10.5%, 12.95%, are more than 5%, and the wind turbine start-up and shut-down times is 4, scheduling iteration diagram shown in Fig. 2.

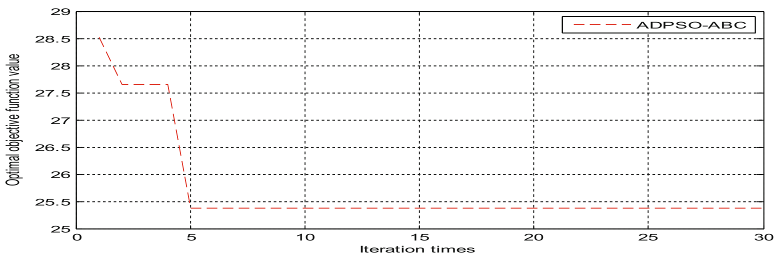

Fig. 2. Iterative process of optimal dispatching of 10 wind turbines.

5 Conclusion

In the limit of power generation, based on the premise of meet the power dispatching command, a mathematical model of multi-objective including wind turbine impeller damage quantity and start-up and shut-down times of wind turbine is established. An example is given to validate, the dispatch of 10 wind turbines in a wind farm in North China. The ADPSO-ABC algorithm is used to solve model. ADPSO algorithm has better searching ability in discrete optimization problem, and has the characteristics of simplicity and generality. ABC algorithm has better searching ability in multidimensional optimization problem, and has the characteristics of simple, practical and less parameter. The calculation results show that the reasonable use of the wind turbine's start-up and shut-down advantages, can ensure the wind power output reliability, reduce the damage of impeller, reduces the wind turbine operation and maintenance costs, improve the market competitiveness of wind power.

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