Rolling scheduling of electric power system with wind power based on improved NNIA algorithm

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Abstract. This paper puts forth a rolling modification strategy for day-ahead scheduling of electric power system with wind power, which takes the operation cost increment of unit and curtailed wind power of power grid as double modification functions. Additionally, an improved Nondominated Neighbor Immune Algorithm (NNIA) is proposed for solution. The proposed rolling scheduling model has further improved the operation cost of system in the intra-day generation process, enhanced the system's accommodation capacity of wind power, and modified the key transmission section power flow in a rolling manner to satisfy the security constraint of power grid. The improved NNIA algorithm has defined an antibody preference relation model based on equal incremental rate, regulation deviation constraints and maximum & minimum technical outputs of units. The model can noticeably guide the direction of antibody evolution, and significantly speed up the process of algorithm convergence to final solution, and enhance the local search capability.

1. Introduction

Power generation with renewable energy has been developing dramatically owing to the global shortage of energy and the public attention to environmental issues [1]. As the best developed way of power generation in light of technology and economy, wind power has now gradually escalated to the significant role of substitute energy. However, as a primary energy, wind energy cannot be converted into a sustainable, stable and controllable form of energy like coal consumption of coal-fired power generation unit and flow rate of reservoir at hydropower plant. Natural wind is affected by multiple factors including temperature, topography, climate and weather, so the power output of wind turbine generator (WTG) set is highly stochastic, intermittent and fluctuating, making it much more difficult to carry out the wind power prediction. For this reason, the traditional economical and safe operation of power grid based on reliable power sources is severely challenged [2].

Advanced scheduling technology [3-6] is one of the significant ways to lower the influence of stochastic and intermittent wind power on power grid and increase the system's accommodation capacity of wind power. Nevertheless, along with the increasing amount of wind power connected to grid, the "unpredicted" fluctuation of wind power caused by the deviation of day-ahead power prediction will significantly affect the economy and practicality of scheduled output of conventional unit, and will also result in the heavy burden of regulation on AGC unit. The traditional scheduling model combining 2 temporal scales, i.e. day-ahead scheduling and AGC [7-9], has been unable to satisfy the needs, so it is necessary to develop more accurate scheduling model. The rolling modification of generation schedule is one of the key tasks in the elaborate scheduling [10]. Zhang B M *et al* [11] put forward the scheduling idea of "multilevel coordination, gradual detailing", but the study was conducted mainly based on the extended short-term load forecast, but overlooked the modification for curtailed wind power of power grid. Wang K *et al* [12] modified the day-ahead scheduled output directly, but the coal-fired power generation unit was adjusted significantly due to the influence of day-ahead prediction deviation. This paper builds a rolling scheduling model with modification based on double objectives, e.g. the operation cost increment of unit and curtailed wind power of power grid curtailed. By continuously updating and modifying the output curve of conventional unit and the maximum output curve of wind farm, the economical and safe operation of power grid will be guaranteed while reducing curtailed wind power as much as possible.

Due to the complexity of model solution, this paper presents a solution strategy for the improved NNIA algorithm based on the information on antibody preference. The NNIA algorithm is an evolutionary multi-objective optimization (EMO) algorithm based on artificial immune system. Compared with three algorithms representing the development level of EMO, i.e. NGSA2, SPEA2 and PESA2, the NNIA algorithm can obtain the optimal solution of evenly distributed Pareto, and it is less complicated to calculate, making it a very effective EMO algorithm [13]. The proposed improvement solution strategy, which has defined an antibody preference relation model based on equal incremental rate, regulation deviation constraints and maximum & minimum technical outputs of units, will guide the evolutionary direction of antibodies, speed up the search for global optimal solution, and offer stronger local search capability. In a 10-unit system with wind farm, the feasibility and effectiveness of the model and algorithm proposed in this paper have been verified.

2. Rolling optimization scheduling model with wind farm

2.1. Power balance relationship between time periods in the rolling scheduling

Assuming that the initial time of rolling scheduling is $\left[t_0,\ldots,t_{\mathrm{H}-1},\ldots,t_{2\mathrm{H}-1},\ldots,t_{h-1},\ldots\right]$, the power balance at the time periods of rolling scheduling should satisfy the following constraints:

$$\begin{array}{ll} Day-ahead & \sum_{i=1}^{N_G} p_{i,t}^{0} + \overline{W}_t - D_t^{*} = 0,\ \ t = 1,2,\ldots,96 \\ t_0 & \sum_{i=1}^{N_G} p_{i,t}^{1} + W_t^{1} - D_t^{1*} = 0,\ \ t = 1,2,\ldots,96 \\ t_{\mathrm{H}-1} & \sum_{i=1}^{N_G} p_{i,t}^{\mathrm{H}} + W_t^{\mathrm{H}} - D_t^{\mathrm{H}*} = 0,\ \ t = \mathrm{H},\mathrm{H}+1,\ldots,96 \\ t_{2\mathrm{H}-1} & \sum_{i=1}^{N_G} p_{i,t}^{2\mathrm{H}} + W_t^{2\mathrm{H}} - D_t^{2\mathrm{H}*} = 0,\ \ t = 2\mathrm{H},2\mathrm{H}+1,\ldots,96 \\ \vdots & \\ t_{h-1} & \sum_{i=1}^{N_G} p_{i,t}^{h} + W_t^{h} - D_t^{h*} = 0,\ \ t = h,h+1,\ldots,96 \\ \vdots & \end{array} \tag{1}$$

In which, N_G is the total number of units subject to rolling scheduling; i is unit No.; H stands for the cycle of rolling scheduling; $h = \mathrm{H}, 2\mathrm{H}, \ldots$; t_{h-1} is the initial time of the hth time period; $p_{i,t}^{h}$ is the rolling scheduled output of unit *i* in the *t*th time period after modification at the time t_{h-1}; $\overline{W}_t$ is the day-ahead scheduled output of wind power in the *t*th time period; W_t^h is the scheduled output of wind power in the *t*th time period after modification at the time t_{h-1}; and D_t^{h*} is the latest predicted value of system load at the *t*th time period before modification at the time t_{h-1}.

2.2. Objective of operation cost increment of unit

Normally, the operation cost of unit is fitted into the secondary function of generation power. The objective of operation cost increment of unit during modification at the time t_{h-1} can be represented as follows:

$$f_1(\Delta p_{i,\ t}^{h}) = \sum_{t=h}^{T}\sum_{i=1}^{N_{\mathrm{G}}}[a_i \Delta p_{i,\ t}^{h\ 2} + (2a_i p_{i,\ t}^{h-\mathrm{H}} + b_i)\Delta p_{i,\ t}^{h}] \tag{2}$$

In which: a_i, b_i, c_i are the secondary characteristic coefficients for operation cost of coal-fired power unit. $p_{i,\ t}^{h-\mathrm{H}}$ is the rolling scheduled output of unit i in the tth time period before modification; $\Delta p_{i,\ t}^{h} = p_{i,\ t}^{h} - p_{i,\ t}^{h-\mathrm{H}}$.

2.3. *Objective of curtailed wind power of power grid*

As the percentage of wind power in minimum load is increasing gradually, it is necessary to restrict the output of wind power, so as to maintain the system operation safety and stably after the derated output of conventional power sources reaches its limit. In this paper, it is considered that the output of conventional units may be adjusted economically and reasonably based on some logic principle reflected in the rolling scheduling model to coordinate the change of wind power and accommodate the wind power to the maximum.

The matrix E^* presents the latest predicted output of wind power in the remaining time periods, in which the element W_t^{h*} stands for the latest predicted output of wind power in the tth time period before modification at the time t_{h-1} .; the matrix E presents the scheduled output of wind power from the rolling scheduling. Taking the cycle of rolling scheduling H =1hour as an example, it is known that:

$$\mathrm{E}^* = \begin{bmatrix} W_1^{1*} & W_2^{1*} & W_3^{1*} & W_{\mathrm{H}}^{1*} & \cdots & W_{2\mathrm{H}}^{1\ *} & \cdots & W_h^{1*} & \cdots & W_{96}^{1\ *} \\ 0 & 0 & 0 & W_{\mathrm{H}}^{\mathrm{H}*} & \cdots & W_{2\mathrm{H}}^{\mathrm{H}*} & \cdots & W_h^{\mathrm{H}*} & \cdots & W_{96}^{\mathrm{H}*} \\ 0 & 0 & 0 & 0 & 0 & W_{2\mathrm{H}}^{2\mathrm{H}*} & \cdots & W_h^{2\mathrm{H}*} & \cdots & W_{96}^{2\mathrm{H}*} \\ 0 & 0 & 0 & 0 & 0 & 0 & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & W_h^{h*} & \cdots & W_{96}^{h*} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ddots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & W_{96}^{24\mathrm{H}*} \end{bmatrix} \tag{3}$$

$$\mathrm{E} = \begin{bmatrix} W_1^{1} & W_2^{1} & W_3^{1} & W_{\mathrm{H}}^{1} & \cdots & W_{2\mathrm{H}}^{1} & \cdots & W_h^{1} & \cdots & W_{96}^{1} \\ 0 & 0 & 0 & W_{\mathrm{H}}^{\mathrm{H}} & \cdots & W_{2\mathrm{H}}^{\mathrm{H}} & \cdots & W_h^{\mathrm{H}} & \cdots & W_{96}^{\mathrm{H}} \\ 0 & 0 & 0 & 0 & 0 & W_{2\mathrm{H}}^{2\mathrm{H}} & \cdots & W_h^{2\mathrm{H}} & \cdots & W_{96}^{2\mathrm{H}} \\ 0 & 0 & 0 & 0 & 0 & 0 & \ddots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & W_h^{h} & \cdots & W_{96}^{h} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \ddots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \cdots & W_{96}^{24\mathrm{H}} \end{bmatrix} \tag{4}$$

Let $\vec{\mathrm{E}}_h^*, \vec{\mathrm{E}}_h$ stand for the vectors in the h/H line of the matrixes E^* and E respectively. Thus, the objective of curtailed wind power of power grid during modification at the time t_{h-1} can be represented as follows:

$$f_2(W_t^h) = \left\|\vec{\mathrm{E}}_h^* - \vec{\mathrm{E}}_h\right\|_1 \tag{5}$$

In which, $\left\|\vec{\mathrm{E}}_h^* - \vec{\mathrm{E}}_h\right\|_1$ stands for the 1-norm of the vector.

2.4. *Other constraints*

- Constraint of Output of wind power

$$0 \le W_t^h \le W_t^{h*}, \quad t = h, h+1, \ldots 96 \tag{6}$$

- Constraint of Ramp rate of conventional unit

$$\begin{cases} p_{i,\ t+1}^h - p_{i,\ t}^h \le \Delta p_{i,up} \Delta T, & t = h, h+1, \ldots 96 \\ p_{i,\ t}^h - p_{i,\ t+1}^h \le \Delta p_{i,down} \Delta T, & t = h, h+1, \ldots 96 \end{cases} \tag{7}$$

In which: $\Delta p_{i,up}$ and $\Delta p_{i,down}$ stand for the maximum and minimum ramp rate per minute of unit i respectively; ΔT is 15 min.

- Constraint of Output of conventional unit

$$p_{i\min} \le p_{i,\ t}^h \le p_{i\max}, \quad t = h, h+1, \ldots 96 \tag{8}$$

In which, $p_{i\max}$ and $p_{i\min}$ stand for the maximum and minimum technical outputs of unit i respectively.

- Constraint of Regulation deviation of conventional unit

To guarantee the relevancy between rolling scheduled and day-ahead scheduled output of conventional unit, the limit of regulation deviation for each unit is set, to be controlled within a certain scope. The regulation deviation constraint of conventional unit during modification at the time t_{h-1} is as follows:

$$\left| p_{i,\ t}^h - p_{i,\ t}^0 \right| \le \gamma_i, \quad t = h, h+1, \ldots 96 \tag{9}$$

In which, γ_i is the permitted maximum deviation of unit i.

- Constraint of Transmission Section power flow of power grid

With regard to the key transmission section of power grid affecting the system's security and stability seriously, the restrictions over the output of wind power and conventional units in the transmission section should be taken into account. The output of conventional units in the transmission section can be modified by means of rolling scheduling, so as to effectively alleviate curtailed wind power of power grid due to its insufficient transmission capacity.

$$\delta_{W,l} W_t^h + \sum_{i=1}^{N_l} \rho_{l,i} p_{i,\ t}^h \le \overline{S_{l,t}}, \quad t = h, h+1, \ldots 96 \tag{10}$$

In which, l represents the transmission section; N_l is the number of conventional units in l; $\rho_{l,i}$ is the sensitivity of the output of unit i to l; $\delta_{W,l}$ is the sensitivity of the output of wind power to l; and $\overline{S_{l,t}}$ is the upper power limit of l in the t th time period.

2.5. Model transformation

Penalty function method is employed to transform the above model into an unconstrained single-objective optimization problem. The rolling scheduling model of electric power system with wind power is presented as follows:

$$\min f = f_1 + \kappa f_2 + \sum_{j=1}^{K} \kappa_j g_j \tag{11}$$

In which, κ is the transformation coefficient to convert the wind power into the operation cost increment of equivalent coal-fired power unit, and its value can be set as: $\max(a_i \gamma_i + 2a_i p_{i\max} + b_i),\ i = 1, 2, \ldots, N_G$; g_j stands for the j th constraint; κ_j is the penalty coefficient of the j th constraint; and K is the number of constraints.

3. Solving strategy based on improved NNIA algorithm

NNIA algorithm is an EMO algorithm based on artificial immune system. When the NNIA algorithm is employed to solve the above rolling optimization scheduling model, antibody refers to the decision variable contained in the model, that is, the rolling scheduled output of each unit in every time period and the scheduled output of wind power in each time period. The NNIA algorithm employs the proportional cloning, recombination, super mutation, and other tactics to well guarantee the diversity and integrity of the antibody population [14]. Meanwhile, it also increases the size of antibody population and the complexity of algorithm. This part will build an antibody preference relation model that taking the starting and ending points to determine the preference area and guiding the evolution of antibodies.

3.1. Strategy for improvement of algorithm through rectification based on equal incremental rate

The approach of equal incremental rate has very strict mathematical optimality in the economical scheduling of electric power system. According to the principles of equal incremental rate, equations (12) and (13) are used to obtain the theoretical optimal value of output of unit *i* in the *t*th time period.

$$\sum_{i=1}^{N_G} p_{i,t}^{h\,*} + W_t^{h*} - D_t^h = 0,\quad t = h, h+1, \ldots, 96 \tag{12}$$

$$\frac{dF_1}{dp_{1,t}^{h\,*}} = \frac{dF_2}{dp_{2,t}^{h\,*}} = \ldots = \frac{dF_{NG}}{dp_{NG,t}^{h\,*}} = \lambda_t^h,\quad t = h, h+1, \ldots, 96 \tag{13}$$

In which, λ_t^h stands for the equal consumption incremental value in the *t*th time period; $p_{i,t}^{h\,*}$ stands for the theoretical optimal value of output of unit *i* in the *t*th time period; and F stands for the operation cost function of unit.

According to the scheduled output of unit before modification and the theoretical optimal value of output of unit, i.e. $p_{i,t}^{h-\mathrm{H}}$ and $p_{i,t}^{h\,*}$, the search direction in the algorithm for the output of unit can be determined for the algorithm, as presented in figure 1, which is divided into two cases *a* and *b*:

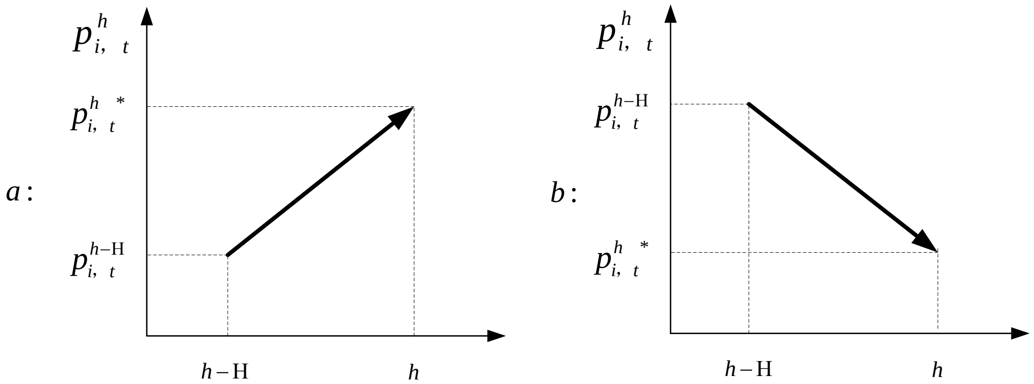

Figure 1. Search direction for the output of unit.

Due to the rolling scheduled output of unit i, $p_{i,t}^h$ must satisfies equations (8) and (9), there are six different cases as follows, i.e. *c*, *d*, *e*, *f*, *g*, *h*, based on the positional relations between $p_{i,t}^{h\,*}$ and the intervals determined by equations (8) and (9), and the rectification search direction for the output of unit is presented in figure 2.

As revealed in figure 2, the starting and ending points of each antibody can be determined, i.e. the starting and ending points indicated by "→" in figure 2.

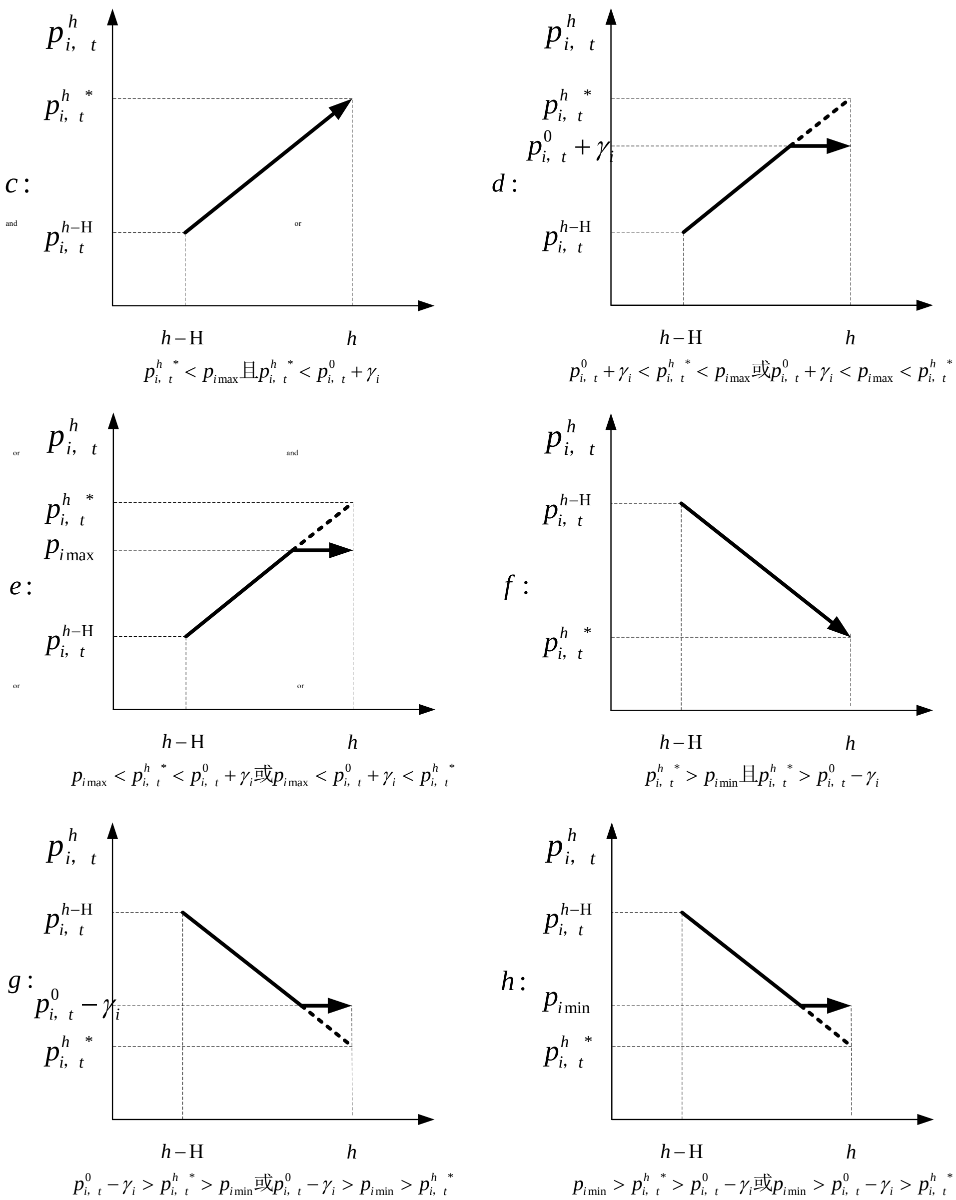

Figure 2. Rectification search direction for the output of unit.

It is assumed that each antibody contains m decision variables, the antibody preference relation model describes a preference area which is a m-dimension ultra-long square space, and the value on each dimension must fall into the scope demarcated by the values of the antibodies at the starting and ending points. It is assumed that $x_a \in X_f$ is any feasible antibody for the rolling scheduling in this paper, X_f stands for antibody population, $x_a = \left(x_a^1\ x_a^2 \cdots\ x_a^j \cdots\ x_a^m\right)$, $j=1,2,\cdots,m$, x_v is the antibody at the given starting point, and x_r is the antibody at the given ending point. φ_a^j is calculated as follows:

$$\begin{cases} \varphi_a^j = 1, & \left|x_a^j - x_v^j\right| \le \left|x_v^j - x_r^j\right| \wedge \left|x_a^j - x_r^j\right| \le \left|x_v^j - x_r^j\right| \\ \varphi_a^j = 0, & else \end{cases} \tag{14}$$

The judgment formula is obtained as follows:

$$\varphi_a = \prod_{j=1}^{m} \varphi_a^j \tag{15}$$

As we know, $\varphi_a = 1$, so the antibody x_a falls into the preference area; $\varphi_a = 0$, so the antibody x_a does not fall into the preference area. At the time of solution, after the basic NNIA algorithm is employed to generate the antibody population, the antibodies outside the preference area can be removed.

With regard to every feasible antibody in the current generation, the antibody in the current generation falling into the preference area and closest to the ending point is called most preferred solution, or "Intermediate Antibody". According to the "Intermediate Antibody" and the "Optimal Antibody" in the current generation (i.e. the optimal solution in the current generation with the lowest objective function value), the preference area of the next-generation antibody population can be determined by taking the "Optimal Antibody" as the starting point and the "Intermediate Antibody" as the ending point, so as to constantly direct the evolutionary direction of antibodies.

The "Intermediate Antibody" can be obtained in the following way. It is assumed that x_c is any feasible antibody in the current generation and d_c stands for the distance from the antibody x_c to the ending point, so there is the following definition:

$$d_c = \sum_{j=1}^{m} \left\{ \left| x_c^j - x_v^j \right| + (\rho + 1) \left| x_c^j - x_r^j \right| \right\} \tag{16}$$

In which, ρ is a positive real number lower than 1/*m*. The "Intermediate Antibody" in the current generation is the antibody with the minimum value of d_c.

3.2. *Procedure of the improved NNIA algorithm*

- Step 1 Initialize

Initialize the predicted wind power W_t^{h*}, predicted load D_t^{h*}, and the previous rolling scheduling interpolation of unit $p_{i,\ t}^{h-\mathrm{H}}$ at the current time (e.g. the time t_{h-1}). Initiate other fixed parameters.

The initial antibody population B_0 of the size N is generated. Let the preference antibody population E_0, active population A_0 and cloned population C_0 be empty, and $k = 0$.

- Step 2 Update preference antibody population

Determine all the antibodies of B_k in the antibody population. Based on the equations (14) and (15), judge whether the antibodies belong to the current antibody preference area (the k th generation). Keep the antibodies inside the antibody preference area, and place them in the temporary preference antibody population ET_{k+1}. If the size of ET_{k+1} is lower than N, let $E_{k+1} = ET_{k+1}$. Otherwise, calculate the crowding distance of all individuals in ET_{k+1} [14], sequence the individuals from large to small based on the crowding distance, and select the first N individuals to form E_{k+1}. Based on equation (16), calculate the "Intermediate Antibody" in E_{k+1}, and then the "Optimal Antibody" of E_{k+1}, and determine the antibody preference area of the $k+1$th generation.

- Step 3 Calculate the conditions for termination

If $k \geq g_{-\max}$, terminate the search; or $k = k + 1$.

- Step 4 Select the nondominated neighbor

If the size of E_k is lower than the maximum size of active population N_A, let $A_k = E_k$; or calculate the crowding distance of all individuals in E_k, sequence the individuals in descending order based on the crowding distance, and select the front N_A individuals to form the active population A_k.

- Step 5 Proportional cloning

Implement the proportional cloning of A_k to obtain the cloned population C_k.

- Step 6 Recombination and super mutation

Implement the recombination and super mutation of the cloned population C_k to obtain a new population $C_k^{'}$.

- Step 7 Combine $C_k^{'}$ and E_k to gain the antibody population B_k, and then move to step 2.

4. Analysis with calculation example

Due to the high speed development of wind power and the relative lag of construction of power grid in China, a mass of curtailed wind power of many provinces have appeared in recent years. Based on this research background, the 10-unit test system in 96 time periods of a day is taken for the simulative calculation to verify the effectiveness of the proposed rolling scheduling model and improved NNIA algorithm in this paper. The parameters of conventional units are shown in table 1. The maximum and minimum ramp rate per minute of unit are set to 1% and -1% of the unit's maximum output respectively; γ_i is set to $0.1p_{i,\ t}^{0}$; the calculated value of κ is 202.8 in this calculation example; and κ_j is consistently set to 10^5. The system contains a wind farm connected to grid. The data of actual operation from a wind farm in a region of China are used, including fifty-six 2.5 MW WTG sets with the total installed capacity of 140 MW. Among them, unit 1 and wind farm are combined into a transmission section, and its upper power limit is 500 MW.

Table 1. Parameters of conventional units.

Unit No.	$p_{i\max}$ /MW	$p_{i\min}$ /MW	a_i /(\$/(MW2·h))	b_i /(\$/(MW·h))	c_i /(\$/h)
1	470	150	0.043	21.60	958
2	460	135	0.063	21.05	1313
3	340	73	0.039	20.80	604
4	300	60	0.070	23.90	471
5	260	57	0.056	17.87	601
6	243	73	0.079	21.62	480
7	130	20	0.211	16.51	502
8	120	15	0.480	23.23	639
9	80	10	1.091	19.58	455
10	55	55	0.951	22.54	692

4.1. Analysis on effect of rolling scheduling model

The calculated effect of rolling scheduling model is presented by taking the time t_{31} as an example. The latest predicted loads of the system are presented in table 2.

Table 2. Latest predicted loads.

Time (hour)	Load/MW	Time (hour)	Load/MW
9	1984	17	1540
10	2132	18	1688

11	2206	19	1836
12	2280	20	2132
13	2132	21	1984
14	1984	22	1688
15	1836	23	1392
16	1614	24	1244

Table 3. Latest predicted wind power.

Time Period (15 min)	Wind Power /MW	Time Period (15 min)	Wind Power /MW	Time Period (15 min)	Wind Power /MW	Time Period (15 min)	Wind Power /MW
33	108.4	49	75.0	65	91.7	81	75.0
34	108.3	50	83.3	66	75.0	82	75.0
35	108.3	51	83.3	67	75.0	83	91.7
36	100.0	52	83.3	68	75.0	84	83.3
37	91.7	53	83.3	69	66.7	85	83.3
38	91.7	54	83.3	70	66.7	86	100.0
39	91.7	55	75.0	71	58.3	87	100.0
40	91.7	56	75.0	72	58.33	88	100.0
41	91.7	57	75.0	73	58.3	89	100.0
42	83.3	58	75.0	74	66.7	90	108.3
43	83.3	59	75.0	75	66.7	91	108.3
44	83.3	60	83.3	76	75.0	92	108.3
45	83.3	61	83.3	77	75.0	93	108.3
46	75.0	62	91.7	78	83.3	94	108.3
47	75.0	63	91.7	79	75.0	95	108.3
48	75.0	64	75.0	80	75.0	96	108.3

The latest predicted wind power is presented in table 3. After modification by rolling scheduling, it is calculated that curtailed wind power is reduced by 15.30 MW in average every time period. Meanwhile, accompanied by more accommodation of wind power it also reduces the system’s consumption of primary energy remarkably, and saves the operation cost by -52082USD. The objective function values before and after modification are presented in table 4.

Table 4. Objective function values before and after modification.

	Average Reduction of Curtailed Wind Power /MW	Operation Cost / USD	Incremental Operation Cost / USD	General Objective/ USD
Before	17.2031	5016455	/	59574
After	1.9029	4964373	-52082	-44267

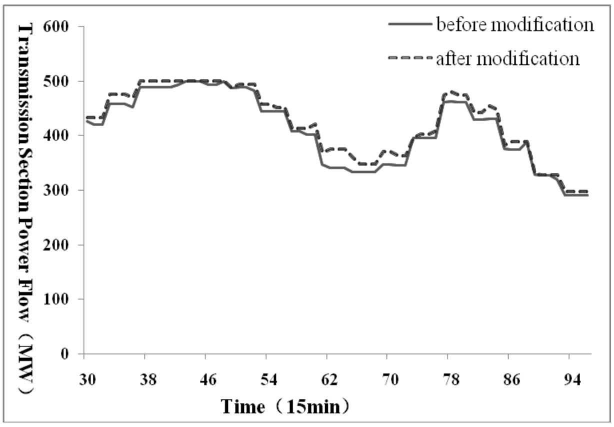

Figure 3. Curves of transmission section power flow before and after modification.

Figure 3 presents the curves of the transmission section power flow before and after modification. Clearly, the rolling scheduled outputs of wind farm and unit 1 after modification can still satisfy the transmission section power flow constraint although the output of wind power has increased.

Figure 4 presents the rolling scheduled output of unit 1 to 9 before and after modification in every time period. Unit 10 represents the fixed output unit, so its curve is no need to be drawn into the figure. The figure shows that the adjustment of output of conventional units is very small after modification due to the inhibitive effect of the constraint of regulation deviation of unit.

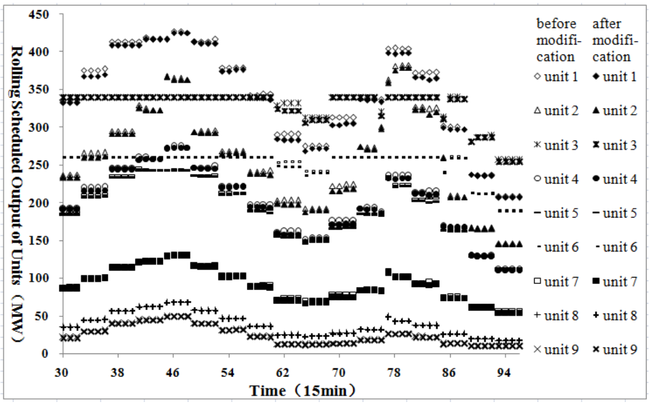

Figure 4. Rolling scheduled output of conventional units before and after modification.

4.2. Analysis on performance of algorithm

To verify the superiority of the solving strategy based on improved NNIA algorithm proposed, genetic algorithm, NNIA algorithm and improved NNIA algorithm have been comparatively analyzed for solving the rolling scheduling model.

Table 5 gives the optimization objective value and calculation time after three algorithms running for 1,000 times respectively.

Table 5. Comparison of optimization objective of three algorithms.

Algorithm	Optimization Objective/ USD	Calculation Time /s
Genetic algorithm	-41151	446.2
NNIA algorithm	-44209	549.6
Improved NNIA algorithm	-44267	177.5

Compared with genetic algorithm, NNIA algorithm obtains more ideal optimization objective value, while genetic algorithm leads to the local optimal solution. NNIA algorithm demonstrates its superiority in global search for solving the high-dimensional optimization problem. Furthermore, improved NNIA algorithm not only obtains better optimization objective value, but also reduces the calculation time significantly. Hence, it can be concluded that improved NNIA algorithm is extremely helpful to removing the non-optimal antibodies and guiding the evolution of antibody population towards the optimal antibody that significantly improve the search performance of the algorithm.

Table 6 presents the variation process of the optimization objective value with the increase of iteration count of NNIA algorithm and improved NNIA algorithm. It is clear that improved NNIA algorithm converges towards the optimal solution much faster than NNIA algorithm, and its optimization objective value is basically stable in the late iterative calculation. If the maximum iteration count is set to 800 times, improved NNIA algorithm can obtain the same optimization objective value. If the maximum iteration count is set to 600 times, improved NNIA algorithm's optimization objective value decrease by 1.4% only, while NNIA algorithm's optimization objective value decrease by 10.7%. Moreover, when it tends to be stable in the late iteration, improved NNIA algorithm's optimization objective value is still better than NNIA algorithm, which means that improved NNIA algorithm has better local search capability.

Table 6. Optimization objective value of NNIA algorithm and improved NNIA algorithm for different iteration counts.

NNIA Algorithm			Improved NNIA Algorithm		
Maximum Iteration Count/ times	Optimization Objective /USD	Calculation Time /s	Maximum Iteration Count/ times	Optimization Objective /USD	Calculation Time /s
400	-24151	227.5	400	-41151	88.9
600	-39484	339.1	600	-43656	117.3
800	-42027	442.7	800	-44267	142.5
1000	-44209	549.6	1000	-44267	177.5

5. Conclusion

The rolling scheduled model built in this paper can further optimize the operation cost of electric power system in the implementation process of intra-day rolling scheduling, and modified the key transmission section power flow the transmission power of key sections in a rolling manner to satisfy the security constraint of power grid. As the modification function for curtailed wind power of power grid is taken into account, it can also enhance the system's ability to accommodate wind power. The proposed strategy for solving the problem based on improved NNIA algorithm is characterized by quicker convergence and stronger local search capability.

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