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Multi-objective coordinated optimization of power system with wind power accommodation

Yang Liu[a,b,*], Lichao Hao[a], Zuoxia Xing[a], Zhanpeng Jiang[a], Jian Xu[a]

[a] *School of Electrical Engineering, Shenyang University of Technology, Shenyang 110870, China*
[b] *Department of Energy and Technology, Aalborg University, Aalborg DK-9220, Denmark*

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Abstract

To decrease wind curtailment rate and increase wind power accommodation, power purchase area should increase wind power purchase. However, the current electricity price of wind power is higher than that of thermal power, which makes wind power accommodation difficult to quantify. It is not practical to optimize these two objectives of the wind power accommodation and power purchase cost. Based on this contradiction, this paper describes this contradiction by constructing a multi-objective optimization model (MOOM) that considers the above two objectives. Firstly, the model is resolved by hybrid particle swarm optimization and gravity search algorithm (HPSO-GSA) to obtain Pareto optimal solution set. Then, according to fuzzy satisfaction function, Pareto optimal solution is selected from Pareto optimal frontier. Finally, the typical daily load and wind farm output value in spring of a certain region are taken as examples for simulation verification. It is verified that the proposed method can indeed provide a scientific power purchase scheme for regional power purchase.

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Keywords: Wind power; Electricity purchasing cost; Multi-objective optimization; HPSO-GSA

1. Introduction

At present, countries in the world regard carbon neutrality as a long-term goal, and wind power is vigorously developed due to its low carbon. It is expected that the global new installed capacity may be close to 1 TW from 2021 to 2030. With massive wind turbines connected to the power network, the proportion of wind power in the power structure is gradually increasing, With a large number of wind turbines connected to the grid, the proportion of wind power in the power structure is gradually increasing, which makes the stable operation of the power system challenged [1–3]. Therefore, wind power accommodation has become a key issue at present.

Previously, scholars have conducted a series of studies on wind power accommodation. In Ref. [4], a cooperative model of wind farm bidding and operation was proposed, which improve the efficiency of wind power in the

* Corresponding author at: School of Electrical Engineering, Shenyang University of Technology, Shenyang 110870, China.
E-mail address: lykers@163.com (Y. Liu).

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electricity market. Ref. [5] combined supply-side flexibility with demand-side flexibility to optimize the flexibility of power system. Ref. [6,7] concluded that the real output of wind power will exceed the uncertain region with a certain probability according to the actual operation data in reference, risk assessments were conducted in different situations. Ref. [8] proposed a two-stage robust standby scheduling model considering demand side response, which improved the operational flexibility of the system through demand side response. Ref. [9] proposed to achieve a wider range of wind power consumption across provinces and regions by expanding the transmission channel capacity. In Ref. [10,11], multi-type loads of electricity, gas and heat of integrated energy system was considered, and a robust optimization model was established considering comprehensive demand side response. However, the above research focuses on the factors affecting wind power accommodation, the countermeasures to wind power accommodation and the formulation of relevant policies. Economic factors are not taken into account, which makes wind accommodation difficult to quantify.

In order to consume more wind power, while considering economic benefits. In this paper, a MOOM is constructed to maximize the wind power accommodation and minimize the cost of electricity purchase. The traditional gravitational search algorithm (GSA) has been widely used in solving MOOM. However, when GSA solves MOOM, the converging rate is slow and the optimal solution searched is easy to plunge local scope [12]. In view of the above problems, this paper adopts a hybrid optimization algorithm that combines the advantages of GSA and particle swarm optimization (PSO), namely HPSO-GSA, this algorithm can effectively avoid the shortcomings of GSA. MOOM is solved through this algorithm and combined with fuzzy membership function. The obtained power purchase scheme is helpful to increase the economy of wind power accommodation.

This paper will be structured as follows: In Section 2, probabilistic model of wind power output, optimization objective function and related constraints are given. On this basis, a MOOM considering wind power accommodation and power purchase cost is obtained. In Section 3, the process of solving the MOOM using HPSO-GSA algorithm and fuzzy membership function is given. The simulation analysis and corresponding conclusions are presented in Sections 4 and 5.

2. The establishment of MOOM

2.1. Probabilistic model of wind power output

Weibull distribution can well fit the change of wind speed [13] v, and its mathematical expression is

$$F_V(v) = P(v \le V) = 1 - \exp[-(v/c)^k],\ \ (v \ge 0) \tag{1}$$

where, c is the size parameter, its unit is m/s, k is the shape parameter.

The probability density function of Weibull distribution can be obtained by derivation of Eq. (1), and its expression is

$$f_V(v) = (k/c)(v/c)^{k-1}\exp[-(v/c)^k] \tag{2}$$

At different wind speeds, the wind turbine output active power is

$$P_W = \begin{cases} 0, & (V \le v_{in}\ or\ V \ge v_{out}) \\ P_{rate}, & (v_{rate} \le V < v_{out}) \\ P_{rate}(V - v_{in})/(v_r - v_{in}), & (v_{in} \le V < v_{rate}) \end{cases} \tag{3}$$

where, P_{rate} is the rated output power of the wind turbine, its unit is MW. v_{in} is the cut-in wind speed of the wind turbine, v_{rate} is the rated wind speed, and v_{out} is the cut-out wind speed, their units are all m/s.

2.2. Optimization objective

A MOOM is established to maximize wind power accommodation and minimize power purchase cost, and the system network loss is not considered.

(1) Function of wind power accommodation maximization

$$\max E_W = \sum_{t=1}^{T} P_t^{load} - \sum_{i=1}^{N_G}\sum_{t=1}^{T} P_{it} \tag{4}$$

where, E_W is the electricity consumed by wind power, P_t^{load} is the load of period t, P_{it} is the active power of thermal power generating unit i in time period t, and the N_G is the quantity of thermal power generating units.

(2) Function of power purchase cost minimization

$$\min C_P = \sum_{i=1}^{N_G}\sum_{t=1}^{T} P_{it}R_G + (\sum_{t=1}^{T} P_t^{load} - \sum_{i=1}^{N_G}\sum_{t=1}^{T} P_{it})(R_w + R_l) \tag{5}$$

where, C_P is the power purchase cost on the user side, R_G is the on-grid price of thermal power, R_w is the price of wind power into the grid, R_l is the transmission price of transmission line l.

2.3. Constraint condition

(1) Power balance constraints

$$\sum_{i=1}^{N_W} P_{wt} + \sum_{i=1}^{N_G} P_{it} = P_t^{load} \tag{6}$$

where, P_{wt} is the active power of wind farm w in time period t, N_W is the number of wind farms, and without considering the system network loss.

(2) Constraint conditions of wind power

Wind farm output constraint is

$$0 \le P_{wt} \le P_{wt,\max} \tag{7}$$

where, $P_{wt,\max}$ is the highest output power of wind farm in t period.

Wind power penetration limit constraint [14] is

$$0 \le P_{wt} \le \delta_w P_t^{load} \tag{8}$$

where, δ_w is the wind power penetration coefficient.

(3) Operation constraints of thermal power generating units

The constraint condition of maximum and minimum output power is

$$P_{Gj,\min} \le P_{Gj}^t \le P_{Gj,\max} \tag{9}$$

where, $P_{Gj,\min}$ and $P_{Gj,\max}$ are respectively the highest value and the lowest value of output power of thermal power unit j, and the climbing rate constraint is

$$-\eta_{idown} \le P_{it} - P_{i(t-1)} \le \eta_{iup} \tag{10}$$

where, η_{idown} and η_{iup} are respectively the minimum of descent rate and maximum of climb rate of thermal power generating unit i.

(4) The rotating reserve constraint is

$$R_{1,t}^{down} P_t^{load} + R_{w,t}^{down} P_t^w \le \sum_{i=1}^{N_G}(P_{it} - P_{Gj,\min}) \tag{11}$$

$$R_{1,t}^{up} P_t^{load} + R_{w,t}^{up} P_t^w \le \sum_{i=1}^{N_G}(P_{Gj,\max} - P_{it}) \tag{12}$$

where, $R_{1,t}^{up}$ and $R_{1,t}^{down}$ are respectively the positive and negative rotation backup coefficients of the system responding to the load in time period t, $R_{w,t}^{up}$ and $R_{w,t}^{down}$ are respectively the positive and negative rotational backup coefficients of wind power output at time period t.

(5) Line capacity constraint

$$P_{l\min} \le P_l \le P_{l\max} \tag{13}$$

where, P_l is the transmitted power of line l, $P_{l\max}$ and $P_{l\min}$ are respectively the maximum and minimum transmission power of line l.

2.4. Multi-objective optimization model

Combined with constraint conditions (6)–(13), objective functions (4) and (5) can be expressed as a multi-objective optimization problem, whose expression is

$$\begin{cases} \min f_i(x), & i = 1, 2, 3, \ldots, m \\ s.t \begin{cases} h_j(x) = 0, & j = 1, 2, 3, \ldots, p \\ g_k(x) \le 0, & k = 1, 2, 3, \ldots, q \end{cases} \end{cases} \tag{14}$$

where, $f = (-E_W, C_P)$ is the target function, $h_j(x)$ is the equality restriction, $g_k(x)$ is the inequality restriction, x is the vector made up of the decision variables.

3. MOOM solution

3.1. Selection of optimal compromise solution

When solving the above MOOM, the optimal solution generally only needs one, therefore, it is needed to select a compromise solution most suitable for the optimization objective of this paper from the Pareto optimal solution set [15]. This paper obtains the optimal solution by fuzzy membership function [16], the expression is:

$$\mu_i = \begin{cases} 1, & f_i < f_{i\,\min} \\ \dfrac{f_{i\,\max} - f_i}{f_{i\,\max} - f_{i\,\min}}, & f_{i\,\min} \le f_i \le f_{i\,\max} \\ 0, & f_{i\,\max} \le f_i \end{cases} \tag{15}$$

where, f_i is the ith objective function value, $f_{i\,\max}$ and $f_{i\,\min}$ are respectively the maximum and minimum of the objective function.

The membership value ranges from 0 to 1, when $\mu_i = 0$, it means the lowest satisfaction. When $\mu_i = 1$, it means the highest satisfaction. The standardized satisfaction value can be solved by the formula (16).

$$\mu = \frac{1}{m}\sum_{i=1}^{m} \mu_i \tag{16}$$

where, m is the quantity of object functions, μ is the standardized satisfaction value and the solution with the largest μ value is the Pareto optimal solution.

3.2. Solving MOOM

HPSO-GSA is used to solve MOOM, assuming that the total number of particles in an n-dimensional searching space is N, the distribution of particles is expressed as:

$$X_i = (x_i^1, x_i^2, x_i^3, \ldots, x_i^n);\ \ i = 1, 2, 3, \ldots, N \tag{17}$$

Since the unknown variable in the multi-objective problem is the active power output by each wind turbine and thermal power unit, the matrix P of the corresponding particles is:

$$P = \begin{bmatrix} P_{W1}^1, P_{W1}^2, \ldots, P_{W1}^n, P_{G1}^1, P_{G1}^2, \ldots, P_{G1}^m \\ P_{W2}^1, P_{W2}^2, \ldots, P_{W2}^n, P_{G2}^1, P_{G2}^2, \ldots, P_{G2}^m \\ \ldots \quad \ldots \quad \ldots \quad \ldots \\ P_{Wi}^1, P_{Wi}^2, \ldots, P_{Wi}^n, P_{Gi}^1, P_{Gi}^2, \ldots, P_{Gi}^m \\ \ldots \quad \ldots \quad \ldots \quad \ldots \\ P_{WN}^1, P_{WN}^2, \ldots, P_{WN}^n, P_{GN}^1, P_{GN}^2, \ldots, P_{GN}^m \end{bmatrix} \tag{18}$$

where, P_{Gi}^m is the active power output of the m thermal power generating unit expressed by the i particle at the m-dimensional position. P_{Wi}^n is the active power output of the nth wind turbine expressed by the i particle at the

nth dimension position. The values m, n and N are respectively the amount of thermal power units, wind turbines and particles.

The specific solving process is as follows:

Step1 Initialization

First, initialize system data, including m, n, $P^{w}_{t,\max}$, $P_{Gj,\max}$ and $P_{Gj,\min}$. Then, initialize the algorithm data, including N, initial value G_0 and η of gravity constant of HPSO-GSA algorithm, particle swarm parameters $b1$ and $b2$, maximum number of iterations T.

Step2 Testing power balance

According to the generator output constraint in formulas (9) and (11), the generator output in particle matrix P is randomly initialized. Test whether the active power output of all particles in the system meets the power balance constraint of formula (6).

Step3 Calculation of particle inertia mass

In the gravity search algorithm, the fitness value of each particle is represented by its inertia quality. The inertia mass M_i of the i particle represents the power purchase cost. The inertia mass M_i of each particle is calculated according to the objective functions (4) and (5).

Step4 Update the parameters of $G(t)$, $best[f_i(t)]$, $worst[f_i(t)]$ and $M_i(t)$ for each particle

The best$[f_i(t)]$ is the optimal solution of the nth particle fitness, and worst$[f_i(t)]$ is the worst solution of the nth particle fitness. Based on formulas (4) and (5), the acceleration, speed and location of the particles are calculated, and the new position of each particle represents the active power output of the modified generators.

Step5 To detect whether the power of particles exceeds the limit

Check whether the active power of each particle exceeds the limit. If the active power of a particle satisfies the inequality constraints of (9) and (10), the solution represented by the particle is valid. If the particle does not meet the above inequality constraints, the solution expressed by the particle is invalid. At this time, the position update value of the particle should be discarded, and the position of the particle in the previous iteration should be adopted until all particles can meet the inequality constraints of Eqs. (9) and (10).

Step6 When the number of iterations is greater than or equal to the preset number of iterations T, the HPSO-GSA algorithm is terminated, otherwise steps 4 to 5 are repeated. At the end of the steps, the optimization results of the algorithm are saved.

Step7 Set the value of the weight coefficient k to increase 0.05 each iteration, repeat steps 2 to 6 until $k = 1$.

Step8 According to the formulas (15) and (16), select the Optimal Solution from the result of step 6.

In this paper, HPSO-GSA is applied to solve the multi-objective optimization problem, a set of uniformly distributed Pareto optimal solutions are acquired, which makes it easier for decision makers to obtain the optimal solution according to their own wishes.

4. Simulation analysis

4.1. System model parameters

This part carries on the example simulation analysis, constructs a power generation system including 7 thermal power units and 1 wind farm, and the model is simulated and verified by taking 24 h as a scheduling cycle. Thermal power unit operating parameters are given in Table 1, wind farm operating parameters are given in Table 2.

System parameters are as follows: R_W sets 0.55 yuan/KW h, R_x sets 0.01 yuan/KW h, R_G sets 0.35 yuan/KW h, $R^{up}_{w,t}$ and $R^{down}_{w,t}$ are both 0.12, $R^{up}_{1,t}$ and $R^{down}_{1,t}$ are both 0.04, $k = 2$, c=12 m/s, δ_w is 12%, regardless of system and line losses. Typical day load and power output value of wind farm in spring are taken as examples for simulation, as shown in Fig. 1.

4.2. Simulated analysis

The relevant parameters of the HPSO-GSA are shown in Table 3. A group Pareto optimal solutions are acquired after the simulation operation, as shown in Fig. 2.

The wind power accommodation and electricity purchase cost were respectively searched with the goal of minimizing, and the extreme solutions were obtained, as shown in Table 4.

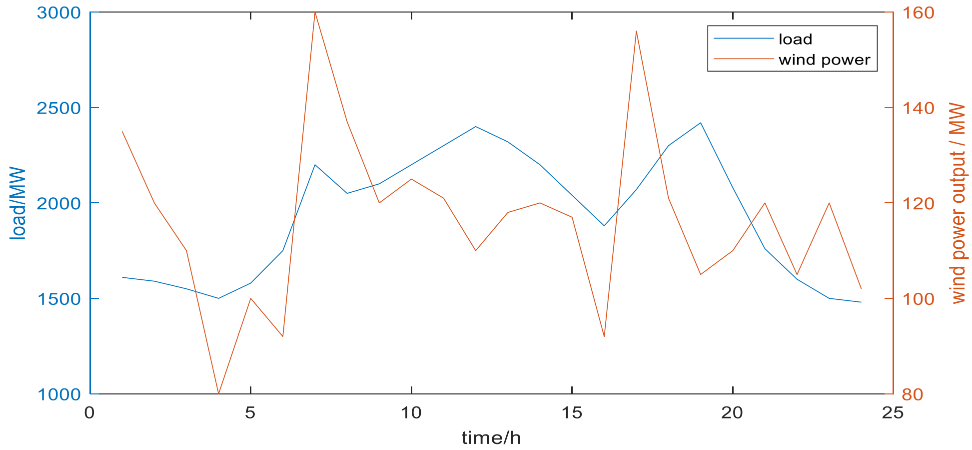

Fig. 1. Typical daily load and wind farm output value.

Table 1. Parameters of generation units.

Unit	P_{imax} (MW)	P_{imin} (MW)	η_{iup} (MW/min)	η_{idown} (MW/min)	Minimum output(%)	Maximum output(%)
1	210	105	1.6	1.6	50	100
2	210	105	1.6	1.6	50	100
3	210	105	1.6	1.6	50	100
4	630	350	4.8	4.8	55	100
5	630	350	4.8	4.8	55	100
6	630	350	4.8	4.8	55	100
7	1000	600	8	8	60	100

Table 2. Parameters of the wind farm.

Cut-in wind speed (m/s)	Rated wind speed (m/s)	Cut-out wind speed (m/s)	Rated output (MW)
3	12	25	300

Table 3. Related parameters of HPSO-GSA.

Name of parameter	Numerical value
Initial value of gravitational constant (G_0)	0.1
Initial value of gravitational constant (η)	100
Particle swarm parameters (*b1*)	0.5
Particle swarm parameters (*b2*)	1
maximum number of iterations (T)	300
Number of system particles (N)	100

where, if the wind power accommodation is only considered as the maximum, it will increase the cost of electricity purchase. If only consider to minimize the cost of electricity purchase, it will be detrimental to wind power accommodation, so there is a balance to be weighed.

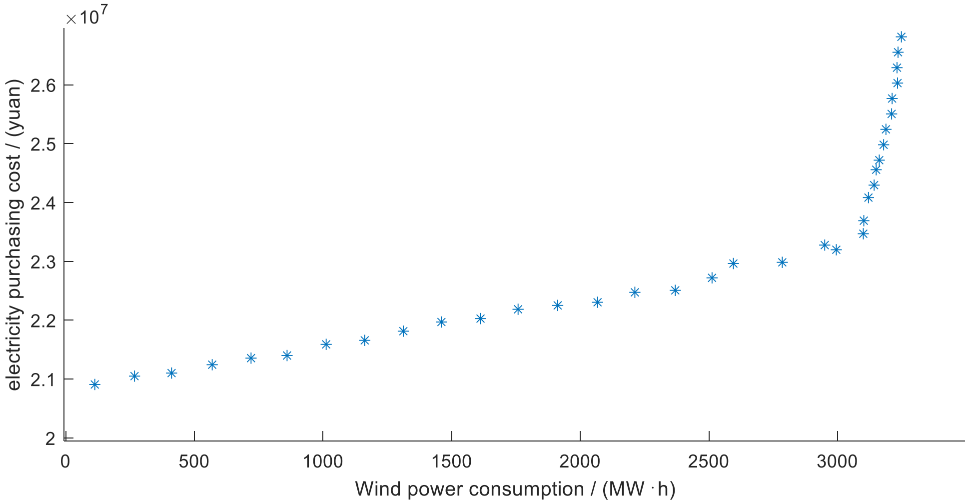

Fig. 2. Pareto optimal solution set.

Table 4. Related parameters of HPSO-GSA.

Model	The optimization goal	E_W (MW h)	C_P (yuan)
MOOM of electricity purchase cost and wind power accommodation	E_W maximum	3252.03	26814296
	C_P minimum	112.67	20908384

According to Fig. 2, the Pareto optimal front of the MOOM contains 35 non-dominated solutions, one of which represents the optimal wind power accommodation and the optimal power purchase cost. According to the fuzzy satisfaction function of Eqs. (15) and (16), the Pareto optimal solution is selected from the Pareto optimal frontier. The optimal solution is given in Table 5, the wind power accommodation is 3123.52 MW h and the power purchase cost is 23447313 yuan, which is the optimal solution of the simulation example optimization model.

Table 5. Optimal compromise solutions.

Model	E_W (MW h)	C_P(yuan)
MOOM of electricity purchase cost and wind power accommodation	3123.52	23447313

5. Conclusion

In this paper, the HPSO-GSA was used to solve the optimization model, and the corresponding Pareto optimal solution has been obtained, then the optimal compromise solution was calculated according to the fuzzy membership function. The simulation results show that the HPSO-GSA proposed in this paper can effectively jump out of the local optimum and acquire the optimal solution of global. By comprehensively considering the coordination between power purchase cost and wind power accommodation, the wind power accommodation scheme with the highest satisfaction is obtained, which is conducive to the reasonable decision-making of power purchase and promote the sustainable and healthy development of wind power.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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