International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 0218

RESEARCH ON OPTIMAL ALLOCATION METHOD OF RENEWABLE ENERGY GENERATION CONSIDERING OPERATION RISK

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ABSTRACT

To characterize the operation risk of wind power, the concept of wind power fluctuation costs is proposed, the environmental benefits of wind power integration are calculated from the perspective of wind power, which can reflect the environmental benefits of wind power more clearly. An improved economic dispatch model is proposed based on the comprehensive power generation costs calculated by the operating costs of thermal power units, wind power fluctuation costs and environmental benefits. The planned output of thermal and wind power is taken as the decision variables and solved by particle swarm optimization, and the economic change law of wind power integration is explored. The effectiveness and practicability of the proposed model are verified by IEEE 39-bus, 118-bus system.

Keywords: renewable energy generation, optimal allocation, operation risk, environmental benefits

1. INTRODUCTION

Wind power has fluctuating characteristics, its large-scale integration will have a huge impact on the power system, considering its operation risk and environmental benefits is of great significance to improve the economy and reliability of the system. Reference [1] guaranteed the probability of load shedding was lower than expected risk level through iterative correction, reasonable unit commitment and wind power curtailment. Reference [2] calculated the costs of load shedding and wind power curtailment as potential losses, but the aim was optimal flexible ramping capacity, load allocation was not too much involved. Reference [3] considered the costs of wind power curtailment and environmental benefits, but ignored the effect of spinning reserve on wind power. In [4], when adjustment occurred, its effect was regarded as the additional risk costs. Reference [5] considered the risk costs of load shedding and wind power curtailment, but neglected the environmental benefits. Reference [6] considered the costs of starting spinning reserve and wind power curtailment, but did not clearly distinguish the difference between starting spinning reserve and load shedding. In [6] the pollution costs of thermal power was used to reflect the environmental benefits, but was not conducive to reflect the environmental benefits of wind power visually.

In this paper, the costs of starting upward and downward spinning reserve, load shedding and wind power curtailment are calculated as the wind power fluctuation costs, calculating the environmental benefits of wind power based on the actual potential output of wind power and wind power curtailment condition. Particle swarm optimization (PSO) is used to solve the problem, the case study shows that this model can give the optimal output of wind and thermal power and reflect the economic change law of the system with the increase of the scale of wind power integration which is helpful for system staff to formulate generation scheduling and analyze the constituent factors of the power generation costs comprehensively.

2. MODEL

2.1 Objective function

The objective function of the model is as follows

$$f_{\text{sum}} = \min \sum_{t=1}^{T} \sum_{j=1}^{n} \left(f_{\text{fire}}(j,t) + f_{\text{wind}}(t) - f_{\text{env}}(t) \right) \tag{1}$$

Where f_{sum} is the comprehensive power generation costs of one day, T is the number of hours, n is the number of thermal power units, $f_{\text{fire}}(j,t)$ is the operating costs of unit j during period t, $f_{\text{wind}}(t)$ is the wind power fluctuation costs during period t, $f_{\text{env}}(t)$ is the environmental benefits of wind power during period t.

2.1.1 Operating costs of thermal power units

Operating costs of thermal power units mainly include fuel costs and start-up costs [7]:

$$f_{\text{fire}}(j,t) = u_{j,t}\left(a_j P_{j,t}^2 + b_j P_{j,t} + c_j \right) + u_{j,t}\left(1 - u_{j,t-1}\right) S_{j,t} \tag{2}$$

$$S_{j,t} = \begin{cases} X_j^{\text{off}} \le T_j^{\text{cold}} + T_j^{\text{off}}, Sh_{j,t} \\ X_j^{\text{off}} > T_j^{\text{cold}} + T_j^{\text{off}}, Sc_{j,t} \end{cases} \tag{3}$$

Where $u_{j,t}$ is the state of unit j during period t, $P_{j,t}$ is the active power output of unit j during period t, a_j, b_j,

c_j are coal consumption coefficient, $Sh_{j,t}$ and $Sc_{j,t}$ are respectively hot-start and cold-start costs of unit j during period t [8], X_j^{off} , T_j^{off} , T_j^{cold} are respectively continuous downtime, minimum downtime, cold-start time.

2.1.2 Wind power fluctuation costs

Generally, f_{wind} consists of two parts, f_{diff1} and f_{diff2} are respectively the fluctuation costs when the actual output of wind power is less than and greater than planned output. f_{up} , f_{dn} , f_{ls} and f_{wc} are respectively the costs of starting upward and downward spinning reserve, load shedding and wind power curtailment.

$$\begin{cases} f_{\text{wind}}(t) = f_{\text{diff1}}(t) + f_{\text{diff2}}(t) \\ f_{\text{diff1}}(t) = f_{\text{up}}(t) + f_{\text{ls}}(t) \\ f_{\text{diff2}}(t) = f_{\text{dn}}(t) + f_{\text{wc}}(t) \end{cases} \quad (4)$$

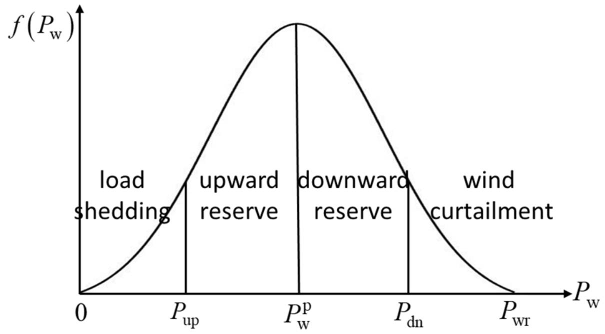

Fig 1 Probability density function of wind power

Figure 1 shows the probability density function (PDF) of wind power $f(P_{\text{w}})$, discrete and divide it into S intervals on average, $f_1(s)$, $f_2(s)$ are respectively the fluctuation costs of interval s when actual output is less than and greater than planned output.

$$f_1(s) = \begin{cases} K_{\text{ls}}\left(P_{\text{up},t} - P_{\text{w},t,s}^{\text{ac}}\right) + K_{\text{up}}\left(P_{\text{w},t}^{\text{p}} - P_{\text{up},t}\right), P_{\text{w},t,s}^{\text{ac}} < P_{\text{up},t} \\ K_{\text{up}}\left(P_{\text{w},t}^{\text{p}} - P_{\text{w},t,s}^{\text{ac}}\right), P_{\text{up},t} \le P_{\text{w},t,s}^{\text{ac}} \le P_{\text{w},t}^{\text{p}} \end{cases} \quad (5)$$

$$f_{\text{diff1}}(t) = \int_0^{P_{\text{wr}}} f_1(s) f(P_{\text{w}}) dP_{\text{w}} = \sum_{s=1}^{S} f_1(s) \cdot \eta_s \quad (6)$$

$$f_2(s) = \begin{cases} K_{\text{wc}}\left(P_{\text{w},t,s}^{\text{ac}} - P_{\text{dn},t}\right) + K_{\text{dn}}\left(P_{\text{dn},t} - P_{\text{w},t}^{\text{p}}\right), P_{\text{w},t,s}^{\text{ac}} > P_{\text{dn},t} \\ K_{\text{dn}}\left(P_{\text{w},t,s}^{\text{ac}} - P_{\text{w},t}^{\text{p}}\right), P_{\text{w},t}^{\text{p}} \le P_{\text{w},t,s}^{\text{ac}} \le P_{\text{dn},t} \end{cases} \quad (7)$$

$$f_{\text{diff2}}(t) = \int_0^{P_{\text{wr}}} f_2(s) f(P_{\text{w}}) dP_{\text{w}} = \sum_{s=1}^{S} f_2(s) \cdot \eta_s \quad (8)$$

Where K_{ls} , K_{up} , K_{wc} , K_{dn} are respectively the cost coefficient of load shedding, starting upward reserve, wind power curtailment and starting downward reserve; $P_{\text{up},t}$ and $P_{\text{dn},t}$ are actual output corresponding to upward and downward reserve capacity respectively at period t , $P_{\text{w},t}^{\text{p}}$ is the planned output, $P_{\text{w},t,s}^{\text{ac}}$ is the actual output of interval s , η_s is the probability of interval s , P_{wr} is the installed capacity of the wind farm.

The actual output of wind power P_{w}^{ac} can be regarded as the sum of forecast output P_{w}^{f} and forecast error ε_{w} , suppose ε_{w} obeys normal distribution with the mean of zeros and the standard deviation of σ_{w} [7]:

$$P_{\text{w}}^{\text{ac}} = P_{\text{w}}^{\text{f}} + \varepsilon_{\text{w}} \quad (9)$$

$$\sigma_{\text{w}} = P_{\text{w}}^{\text{f}} / 5 + P_{\text{wr}} / 50 \quad (10)$$

Dividing the PDF of forecast error into seven intervals, the midpoint of each interval is taken as the expectation, the integral of PDF for each interval is probability η [9]. So, the actual output and its probability distribution can be obtained after knowing the probability distribution of forecast error, as shown in Table 1, ΔP_{w} is the forecast error between actual output and forecast output after discretization.

Table 1 The probability distribution of forecast error

ΔP_{w}	$-3\sigma_{\text{w}}$	$-2\sigma_{\text{w}}$	$-\sigma_{\text{w}}$	0	σ_{w}	$2\sigma_{\text{w}}$	$3\sigma_{\text{w}}$
η	0.006	0.061	0.242	0.382	0.242	0.061	0.006

2.1.3 Environmental benefits of wind power

Reference [10] pointed the amount of energy saving of wind power is equal to the pollutant emissions of thermal power units, equal to the product of coal consumption and pollutant emission rate, the total pollutant emissions are the product of the amount of energy saving per unit of wind power and the active power output of wind farm. f_{env} can be expressed as:

$$f_{\text{env}}(t) = \sum_{s=1}^{S}\left(\alpha \cdot \sum_{i=1}^{3} \frac{G_{i,t,s}}{N_i}\right) \cdot \eta_{\text{s}} \quad (11)$$

$$G_{i,t,s} = P_{\text{w},t,s}^{\text{ac}} \cdot T_{60} \cdot C \cdot E_i \quad (12)$$

Where α is the charge for one equivalent of pollutants, $G_{i,t,s}$ is the emissions of pollutant i of interval s , $T_{60} = 1h$, N_i is the equivalent value of pollutant i , their units are in kg, the ratio of G_i and N_i is the equivalent number of pollutant i . According to the Environmental Protection Tax Law, environmental protection tax is levied on the first three pollutants according to the order of pollution equivalent number from large to small. C is the coal consumption, E_i is the pollutant emission rate of pollutant i .

2.2 Constraints

2.2.1 Active Power balance

$$\sum_{i=1}^{n} P_{i,t} \cdot u_{i,t} + P_{w,t} = P_{load,t} \quad (t = 1, 2, \cdots, T) \tag{13}$$

Where $P_{w,t}$ and $P_{load,t}$ are respectively active output of wind power and active load of system during period t .

2.2.2 Output limits

$$\begin{cases} P_{i,m} \cdot u_{i,t} \le P_{i,t} \cdot u_{i,t} \le P_{i,M} \cdot u_{i,t} \\ 0 \le P_{w,t} \le P_{wr} \end{cases} \tag{14}$$

Where $P_{i,m}$ and $P_{i,M}$ are respectively the minimum and maximum active power output of unit i .

2.2.3 Ramp rate

$$\Delta P_{i,down} \cdot T_{60} \le P_{i,t} - P_{i,t-1} \le \Delta P_{i,up} \cdot T_{60} \tag{15}$$

Where $\Delta P_{i,down}$ and $\Delta P_{i,up}$ are respectively maximum downward and upward ramp rate of unit i .

2.2.4 Reserve

$$\begin{cases} \sum_{i=1}^{n} P_{i,M} \cdot u_{i,t} + P_{w,t} \ge P_{load,t} + \left(r_l\% \cdot P_{load,t} + R_{w,t}^{+} \right) \\ \sum_{i=1}^{n} P_{i,m} \cdot u_{i,t} + P_{w,t} \le P_{load,t} - \left(r_l\% \cdot P_{load,t} + R_{w,t}^{-} \right) \end{cases} \tag{16}$$

Where $r_l\%$ is the spinning reserve rate without considering wind power, $R_{w,t}^{+}$ and $R_{w,t}^{-}$ are the maximum positive and negative forecast deviation at period t .

2.2.5 Running time and downtime

$$\begin{cases} X_{i,t}^{on} \ge T_i^{on} \\ X_{i,t}^{off} \ge T_i^{off} \end{cases} \tag{17}$$

Where $X_{i,t}^{on}$ and $X_{i,t}^{off}$ are respectively the continuous running time and downtime of unit i at period t , T_i^{on} and T_i^{off} are respectively the minimum running time and downtime.

2.2.6 Branch power flow

$$P_{l,m} \le P_l \le P_{l,M} \tag{18}$$

Where P_l is the power flow of line l , $P_{l,M}$ and $P_{l,m}$ are respectively maximum and minimum power flow.

3. CASE STUDY

Taking IEEE 39-bus, 118-bus system as examples. The parameters of thermal power units and wind farm are from [7] and [8], the wind power forecast output of 118-bus system is expanded by 4 times based on the data from [7]. The coal consumption C is 0.309, $\alpha = 1$ \$, the parameters of N_i and E_i are from [3]. The spinning reserve rate without wind power is 5%, the cost coefficient $K_{up} = 80$ \$/MWh, $K_{dn} = 40$ \$/MWh, $K_{ls} = 1000$ \$/MWh, $K_{wc} = 100$ \$/MWh. Particle swarm optimization parameters: population size is 30, the maximum number of iterations is 200, acceleration constant $c_1 = 2$, $c_2 = 1$.

The optimal power output of IEEE 39-bus system are shown in Table 2. Due to space limitation, the results of 118-bus system are not listed.

The spinning reserve capacity is limited by ramp rate, which have a certain impact on the costs. Original 39-bus system is regarded as system 1, system 2, 3, 4 are based on system 1. Original 118-bus system is regarded as system 5, system 6, 7, 8 are based on system 5. Table 3 shows the cost comparison of these eight scenarios, the costs are the result of 24 hours a day.

Comparing system 1 and 2, 3 and 4, 5 and 6, 7 and 8 in Table3, the wind power fluctuation costs will increase with the reduction of spinning reserve capacity, and the operating costs of thermal power will also increase due to the start-up of some units with poor economy.

Comparing system 1 and 2, 3 and 4, 7 and 8 in Table 3, the reduction of spinning reserve capacity leads to the increase of wind power curtailment and the decrease of environmental benefits.

The difference between wind power fluctuation costs and environmental benefits can be regarded as net risk costs of wind power. Compared with system 1 and 3, 2 and 4, 5 and 7, 6 and 8 in Table 3, with the increase of the scale of wind power integration, the decrease of operating costs of thermal power is more than the increase of wind power net risk costs, so comprehensive power generation costs will eventually decrease.

In order to observe the economic law of wind power integration more comprehensively, Figure 2 shows the cost comparison of IEEE 118-bus system, the abscissa is the scale of wind power integration, which is the times of the scale of wind power in [7], the ordinate is the comprehensive power generation costs.

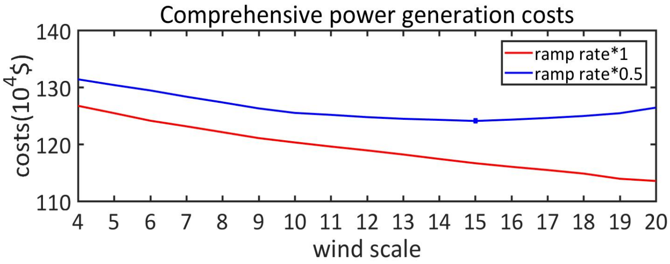

Fig 2 Cost comparison of IEEE 118-bus system

As shown in Figure 2, the comprehensive power generation costs are not always decreasing. When the spinning reserve is sufficient (red curve), the net risk costs of wind power increases slowly, the decrease of operating costs of thermal power is more than the increase of wind power net risk costs, comprehensive

Table 2 Optimal power output of IEEE 39-bus system (MW)

hour	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	P_w
1	455.00	212.71	0	0	0	0	0	0	0	0	32.29
2	455.00	264.13	0	0	0	0	0	0	0	0	30.87
3	455.00	292.06	65.00	0	0	0	0	0	0	0	37.94
4	455.00	265.63	130.00	65.00	0	0	0	0	0	0	34.37
5	455.00	248.91	130.00	130.00	0	0	0	0	0	0	36.09
6	455.00	318.36	130.00	130.00	25.00	0	0	0	0	0	41.64
7	455.00	339.85	130.00	130.00	45.00	0	0	0	0	0	50.15
8	455.00	345.72	130.00	130.00	95.00	0	0	0	0	0	44.28
9	455.00	373.00	130.00	130.00	153.54	20.00	0	0	0	0	38.46
10	455.00	407.62	130.00	130.00	162.00	47.00	25.00	10.00	0	0	33.38
11	455.00	425.13	130.00	130.00	162.00	80.00	32.00	10.00	0	0	25.87
12	455.00	429.00	130.00	130.00	162.00	80.00	51.00	17.99	10.00	10.00	25.01
13	455.00	409.33	130.00	130.00	162.00	66.00	25.00	0	0	0	22.67
14	455.00	377.86	130.00	130.00	127.00	26.00	0	0	0	0	54.13
15	455.00	352.00	130.00	130.00	79.00	0	0	0	0	0	54.00
16	455.00	275.71	130.00	130.00	0	0	0	0	0	0	59.29
17	455.00	231.16	130.00	130.00	0	0	0	0	0	0	53.84
18	455.00	314.52	130.00	130.00	25.00	0	0	0	0	0	45.48
19	455.00	347.39	130.00	130.00	90.00	0	0	0	0	0	47.61
20	455.00	410.29	130.00	130.00	162.00	20.00	25.00	10.00	10.00	0	47.71
21	455.00	377.57	130.00	130.00	128.00	20.00	0	0	0	0	59.43
22	455.00	296.84	130.00	130.00	47.00	0	0	0	0	0	41.16
23	455.00	150.00	130.00	118.78	0	0	0	0	0	0	46.22
24	455.00	150.00	78.10	57.79	0	0	0	0	0	0	59.12

Table 3 Cost comparison in different scenarios (10^4\$)

system	ramp rate	wind scale	f_{sum}	f_{fire}	f_{wind}	f_{env}	$f_{wind}-f_{env}$	f_{up}	f_{dn}	f_{ls}	f_{wc}
1	1	1	55.0317	54.5984	1.0649	0.631604	0.4333	0.7099	0.3550	0	0
2	0.5	1	56.9284	56.4929	1.0671	0.631595	0.4355	0.7080	0.3545	0.0036	0.0010
3	1	2	53.3875	52.5209	2.1298	1.263200	0.8666	1.4198	0.7081	0	0.0020
4	0.5	2	55.8925	54.9720	2.1835	1.262983	0.9205	1.3841	0.7015	0.0868	0.0110
5	1	4	126.7295	124.9887	4.2668	2.526000	1.7408	2.8063	1.4200	0.0405	0
6	0.5	4	131.3833	128.3954	5.5139	2.526000	2.9879	2.6463	1.4314	1.4362	0
7	1	8	122.1021	118.3279	8.8270	5.052830	3.7742	5.5118	2.8400	0.4752	0
8	0.5	8	127.3300	122.6087	9.7729	5.051513	4.7214	5.2037	2.7762	1.7158	0.0771

power generation costs mainly depends on the decrease of operating costs of thermal power, so it's decreasing all the time. When the spinning reserve capacity is relatively small (blue curve), as the scale of wind power integration increases to a certain degree, the increase of net risk costs of wind power will exceed the decrease of operating costs of thermal power, resulting in the increase of comprehensive power generation costs, the inflection point is marked by a rectangle. However, for the second case (blue curve), the economic law will be limited by the wind power penetration limit (whose solution is not the focus of this paper). When the wind power penetration limit appears before the inflection point, comprehensive power generation costs will always decrease; when the wind power penetration limit appears after the inflection point, comprehensive power generation costs will first decrease and then increase.

Comparing the method in this paper with methods in [5] and [6] by using system 2, the comparison is shown in Table 4. K_{up} and K_{ls} are set to the same value, K_{dn} and

K_{wc} are set to the same value in [5] and [6], so there are two situations, S1: $K_{up} = K_{ls} = 80$ \$/MWh, $K_{dn} = K_{wc} = 40$ \$/MWh; S2: $K_{up} = K_{ls} = 1000$ \$/MWh, $K_{dn} = K_{wc} = 100$ \$/MWh.

Table 4 Cost comparison of different methods (10^4\$)

cost	this paper	method in [5]		method in [6]	
		S1	S2	S1	S2
f_{sum}	56.9284	57.5236	58.1394	73.6674	74.0990
f_{fire}	56.4929	56.4587	57.0048	56.4770	56.6952
f_{wind}	1.0671	1.0649	1.1346	1.0658	1.1348
f_{env}	0.6316	-	-	16.1246	16.2690
f_{up}	0.7080	0.7084	0.1352	0.7095	0.1354
f_{dn}	0.3545	0.3541	0.9972	0.3538	0.9879
f_{ls}	0.0036	0.0015	0	0.0015	0
f_{wc}	0.0010	0.0009	0.0022	0.0009	0.0117

As can be seen from Table 4, the environmental benefits of wind power are not considered in [5], so the total costs are higher. For method in [6], f_{env} represents the pollution costs of thermal power units, which is not conducive to directly observe the clean and pollution-free advantages of wind power, nor can it effectively reflect the change of environmental benefits of wind power when wind power curtailment occurs.

Generally, the costs of load shedding and wind power curtailment are higher than that of starting spinning reserve and depend on the relevant policies. Therefore, the methods in [5] and [6] are not consistent with the fact, when the cost coefficients are relatively low (S1), the wind power output is higher, the operating costs of thermal power are reduced; when the cost coefficients are high (S2), the wind power output is lower, so the operating costs of thermal power increase. Therefore, the cost coefficients have a great impact on the optimization results and the final costs, so it's necessary to correctly distinguish the various situations of wind power fluctuation.

4. CONCLUSIONS

In this paper, the operation risk and environmental benefits of wind power are transformed into economic indicators. The case study shows that this model can obtain the optimal output of wind and thermal power and the comprehensive indicator and sub-indicators proposed can both reflect the economic change law with the increase of the scale of wind power integration. The proposed model can directly obtain the risk costs caused by wind power fluctuation and the environmental benefits saved by replacing thermal power with wind power of the same power output, with the increase of the scale of wind power integration, those two costs can not be ignored. In the future, in order to describe wind power fluctuation costs more accurately, we will adopt multi-scenario model and cluster analysis to study, in addition, we will study the economic dispatch model including photovoltaic (PV), energy storage and other renewable energy grid-connected.

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