Ming ZENG, Limin CHEN, Minjuan MA, Song XUE, Min CHENG

School of Economics and Management, North China Electric Power University

The best scheduling model of wind power pumped-storage power station based on improved harmony search algorithm

Abstract .*For the problem of integrating wind power in a large scale, constructing an objective function which minimize the total production cost of the pumped storage and thermal power unit. Improved harmony search algorithm with examples are applied in solving the objective function,and the case analysis the change of the operation cost of wind storage system and greenhouse gas emission with different power demand and wind speed forecasting scenes. The results show that the increase of wind power installed capacity can reduce the operation cost of wind storage system and reduce greenhouse gas emission. At the same time,it also can effectively smooth wind power output and lower the volatility of the wind power integration.*

Streszczenie. *Artykuł dotyczy zagadnienia tworzenia dużych ferm wiatrowych i kontroli kosztów wytwarzania energii. Proponowany algorytm minimalizacji strat, poddaje analizie czynniki taki jak koszty magazynowania energii, emisja gazów cieplarnianych przy różnym stopniu zapotrzebowania energetycznego i prędkości wiatru. Przedstawiono wyniki badań oraz wnioski. (****Model najlepszego planowania w energetyce wiatrowej z magazynem szczytowo-pompowym - algorytm ewolucyjny****).*

Key words: wind power, pumped storage power station, Scheduling, Harmony search algorithm
Słowa kluczowe: energetyka wiatrowa, elektrownia szczytowo-pompowa, planowanie, algorytm ewolucyjny.

Introduction

Wind power is random, intermittent and verse-peak regulation, so it will increase the load pressure of power system when integrating wind power in a large scale, and it may influence the safe and stable operation of power system---heavily restrict the integration of wind power[1-3]. Pumped-storage power station(PSP) can make up the conversion time between wind power installed capacity and demand, and it is the most reliable, economic long life cycle and large capacity energy storage device in system now[4-8]. Therefore, optimizing and coordinating the wind - pumped storage power station scheduling has an significant meaning in theory and practice. At present, the domestic and overseas scholars have already carried out some research on pumped-storage applied in intermittent power, such as wind. Literature presents results of preliminary research focused on applicability of genetic algorithm to the problem of scheduling and optimisation of power systems with pumped-storage hydroelectric plants. Literature optimize the hybrid pumped storage power station reservoir scheduling through solving the mathematical model of dispatching operation of cascade hydropower stations and hybrid pumped storage power station. Literature calculates in the interconnection analysis on the basis of the data provided by the wind turbines manufacturer and their values measured during the power plant. Literatures above analyze the operation and scheduling of wind storage system, which provides a strong basis for policy makers, but yet nobody make a system research and quantitative analysis on the problem of wind storage scheduling by the improved harmony search algorithm. In view of this, based on mixed integer nonlinear programming method we establish wind power - pumped storage power station joint scheduling model with the target of lowest cost. Wind power-pumped storage power station joint scheduling model: Optimizing short-term attemper optimization problems of pumped storage power station and thermal power unit can be solved by the mixed integer nonlinear programming method.The objective function(1) follows:

(1)
$$\min \sum_{t \in T} \left(C_a^{\min} + \sum r_l^a Q_{lk} \right)$$

In the equation(1), C_a^{min} is the minimum generation cost of peak-shifting fossil power plants,as shown in equation(2); r_l^a is the slope of a curve of peak-shifting fossil power plants(yuan/MWh); Q_{lk} is the generation of peak-shifting fossil power plants(MWh);T is on behave of time(h).

(2）
$$\min_{p_{li,u_i}} \sum_{i \in I} (w_i C_i^{\min} + \sum_{l \in L_i} r_{li} Q_{li})$$

In the equation(2), w_i is the binary variable of pitch peak which fossil power plant i participant in and value area change between [0,1]; c_i^{min} represents generating cost of the least production corresponding to pitch peak thermal power unit (yuan); r_{li} is the scope of a curve of pitch peak thermal power unit's generation cost(yuan/MWh); Q_{li} represents the production of pitch peak fossil power plant unit i(MWh);*I* is the total number of pitch peak thermal power units. The objective equation(1) subject to (3)-(12) as followed:

(3)
$$Q_t^a + Q_{ht} - Q_{pt} = Q_{dt} - Q_{wt} \, , \forall t \in T$$

(4)
$$S_t = S_{t-1} + \left(V_{pt} - V_{ht} \right) \eta \, , \forall t \in T$$

(5)
$$V_{pt} = w_p V_{p,\min} + \sum_{l \in L^p} r_{lp} Q_{pt} \, , \forall t \in T$$

(6)
$$V_{ht} = w_h V_{p,\min} + \sum_{l \in L^p} r_{lh} Q_{pt} \, , \forall t \in T$$

(7)
$$V_{ht} = w_h V_{h,\min} + \sum_{l \in L^h} Q_{ht}$$

(8)
$$w_h + w_p \leq 1 \, , \forall t \in T$$

(9)
$$S_0 = S_i$$

(10)
$$P_t \geq P_0$$

where, Q_t^a are the generated production of pitch peak thermal power unit at time *t*(MWh); Q_{ht} were calculated as the generation of pumped storage unit at time t(MWh); Q_{pt} are the generation that pumped-storage unit pumping consume at time t(MWh); Q_{dt} are the power demand at time *t* (MWh); Q_{wt} are the generation of wind power unit at time *t*; S_t and S_{t-1} represent the reservoir storage on t stage and *t-1* stage respectively (hm^3); V_{ht} is the Pumping Water speed and V_{pt} is the generating water speed at time t(m^3/s); η is conversion factors which value is 0.0036; $V_{p,min}$ is the lowest power water speed and $V_{h,min}$ is the lowest pumping water speed （m^3/s）; W_p is a binary variables indicating the generation of pumped-storage unit whose scope for [0,1]; W_h is a binary variables of pumped-storage unit pumping and its scope for [0,1] on t stage;S_0 and S_t are the initial reservoir storage and reservoir storage on t stage(hm^3).

Improved Harmony search algorithm

1. Traditional HS algorithm

Traditional HS algorithm described as follows:

Step 1: optimization problem initialization

Optimization problems are shown as follows:

Target equation: *minF (x)*

Among them, the x is a set for every design variables (x_i); Xi is the scope of every design variables ($L_{xi} < X_i < U_{xi}$); N is the number of design variables.

Step 2: sound memory initialization

Equation (22) gives the Sound memory (HM) matrix:

$$HM = \left[\begin{array}{ccccc|l} x_1^1 & x_2^1 & \dots & x_{N-1}^1 & x_N^1 & \Rightarrow\ f(x^{(1)}) \\ x_1^2 & x_2^2 & \dots & x_{N-1}^2 & x_N^2 & \Rightarrow\ f(x^{(2)}) \\ . & . & . & . & . & .\quad . \\ . & . & . & . & . & .\quad . \\ . & . & . & . & . & .\quad . \\ x_1^{HMS-1} & x_2^{HMS-1} & \dots & x_{N-1}^{HMS-1} & x_N^{HMS-1} & \Rightarrow f(x^{(HMS-1)}) \\ x_1^{HMS} & x_2^{HMS} & \dots & x_{N-1}^{HMS} & x_N^{HMS} & \Rightarrow f(x^{(HMS)}) \end{array}\right] \tag{11}$$

Step 3: improve a new harmony from an HM set

Based on the random selection, memory consider and controllable pitch mechanism criterion can produce a new harmonic vector*x'=(x$_1$',x$_2$', ⋯x$_3$')*, and random selection, memory consider and controllable pitch agency rules are described as follows:

Random selection: New harmonic vector *x'=(x$_1$',x$_2$', ⋯ x$_n$')* can be choosed between (1-HMCR) when HS decide x_i'.Random selection can also be used to harmonic memory initialization.

Memory Consider: You can choose any value for x_i^j when HS decide x_i', where the value scope of HM is HMCR, j = {1, 2... HMS}.

$$x_i' \leftarrow \begin{cases} x_i' \in \left\{x_i^1, x_i^2 \cdots x_i^{HMS}\right\}, & \text{with}HMCR \\ x_i' \in X_i, \text{with}(1\text{-}HMCR) \end{cases} \tag{12}$$

Controllable pitch mechanism: through testing each new harmonic vector $x'=(x_1',x_2',\cdots x_n')$ can decide whether adjust pitch or not. From HM set we randomly select x_i', we make a further adjustment in range of the possibility of PAR so we can make it close to the optimal value. The Using process of parameter *PAR*'s institution adjustment rate is shown below:

$$x_i' \leftarrow \begin{cases} Yes, & \text{with}PAR \\ No, \text{with}(1\text{-}PAR) \end{cases} \tag{13}$$

(1-PAR) value does not affect the institution regulation rate, and if the institution adjustment decision for Yes, x_i'. will be replaced by:

$$x_i' \leftarrow x_i' \pm bw \tag{14}$$

Where, b_w is the distance bandwidth of continuous design variables.

In each step of traditional harmony search algorithm, we may decide the new harmonic vector value through the controllable pitch institutions or random selection.

Step 4: update HM

If the new harmonic vector $x'=(x_1',x_2',\cdots x_n')$ can be choosed between (1-HMCR) when HS decide $x_{i'}$. *R* is better than the worst HM harmony, new harmony will enter the HM, and HM will leave out the existing worst harmonic.

Step 5: approved suspended standard

If meet the suspended standard based on the maximum number, calculation terminated. Otherwise, repeat step 3 and 4.

2. Improved harmony algorithm

At present, the IHS algorithm has been successfully applied to many kinds of problems in basic engineering optimization. The empirical results show that HIS algorithm can quickly get more optimal solutions, and it's a kind of powerful search algorithm in solving engineering optimization problems. The main difference between *IHS* algorithm and the traditional algorithm *HS* is that it adjust the value of *PAR* and b_w. In order to improve the *HS* algorithm and reduce defects of PAR and b_w, IHS algorithm used a *PAR* and b_w value in step 3. The dynamic change of *PAR* value are shown below:

$$PAR(gn) = PAR_{\min} + \frac{(PAR_{\max} - PAR_{\min})}{NI} \times gn \tag{15}$$

Where, *PAR* is institutional adjustment rate; PAR_{min} for minimum mechanism adjustment rate; PAR_{max} for maximum mechanism adjustment rate; *NI* is the number of vectors and g_n represent for equation numbers.

The dynamic relationship of b_w shown below:

$$bw(gn) = bw_{\max} \exp(c \cdot gn) \tag{16}$$

$$c = \frac{Ln(\frac{bw_{\max}}{bw_{\min}})}{NI} \tag{17}$$

Among them, *bw(gn)* is the bandwidth of variables; bw_{min} means the minimum bandwidth and bw_{max} for maximum bandwidth.

Calculation analysis of samples

1. Power demand and forecasting of wind speed

Four different power demand forecasting scenes are shown in figure 1. According to Figure 1, power demand has obvious seasonal characteristic, and scenario simulation 1~4 respectively correspond to fourth quarter phase in 2011. Forecasting scene of wind speed shows in Figure 2, corresponding four electric power demand forecasting scenes in Figure 1. In order to study the penetration level of wind power in wind storage system, wind power installed capacity on wind speed forecasting scene are divided into six kinds, namely 50MW, 100 MW, 150MW, 200MW, 250MW, 300MW and 350 MW.

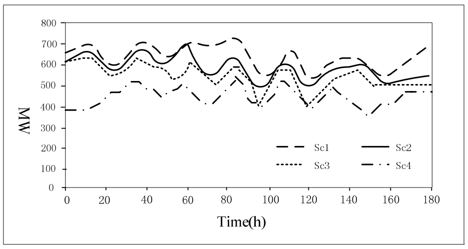

Fig. 1 Demand scenarios

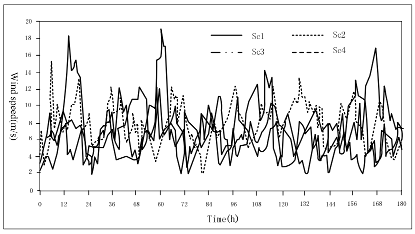

Fig. 2 Wind speed scenarios

2 Scenario simulation

Figure 3 and Figure 4 respectively corresponding to the system operation plan of electric power demand forecasting scene and wind speed forecasting scene, and wind power installed capacity respectively are 150MW and 300MW. From Figure 3 and Figure 4 we can see that pumped storage power station play a good role in peak clipping especially in the scene 2, and some time wind power installed capacity are up to 300MW.

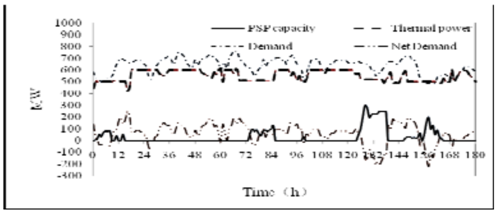

Fig. 3 System operation schedule for Dsc4 and WSsc1 (150 MW)

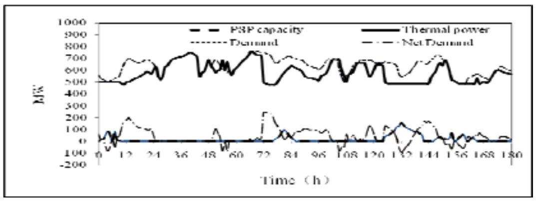

Fig. 4 System operation schedule for Dsc4 and WSsc1 (300 MW).

Avoid-cost in Figure 3 is 129,100yuan and 306,000yuan in Figure.4, accounted for 0.17% and 0.44% of capitalized cost respectively. Meanwhile, cost-recovering AC of generator also can be calculated, for example, pumping cost of pumped storage unit is 3.33 million yuan/MW, generating cost is 4.16 million yuan/MW, and reservoir construction cost is 16.65 yuan/m3. Table 1~4 are the simulation results of parameters. In tables, *POPr* represents for peak/valley power demand ratio, and s_d is the standard deviation of power demand index; *Ic* is the covariance between power demand and wind power installed capacity.

(1) Cost can be avoided. From the simulation results, for a particular electricity demand, the maximum avoid-cost is higher on wind speed forecasting scenarios with a smaller covariance. Similarly, for specific wind speed, avoid-cost in a larger POP_r and s_d electric power demand forecasting scenarios is higher, such as demand scene 1~3 shows.

(2) Each year the change of recovery cost AC. Similar with the change trend of avoid-cost, AC add as the increase of wind power installed capacity, but its value depends on the biggest pond age and power generation of wind storage system. Therefore, unlike power demand situation 4, among wind speed prediction scene 2~4, AC reduce when wind power installed capacity is less than 150MW or 200MW.But when wind power installed capacity increases, the AC reduce. At the same time, on the demand situation 1& wind speed scene 4 and demand situation 3 &wind speed scene 4, avoiding-cost accounted for 1.78% and 0.52% of capitalized cost, and AC accounted for 2.38% and 3.19%. For the time being, in the two scenarios, the largest installed capacity of pumped storage units respectively are 229MW and 72MW.

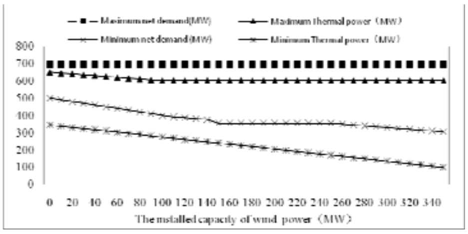

Fig. 5 Effects of the PSP on the maximum and minimum thermal power

Conclusions

This paper establish a wind power-pumped storage power station joint scheduling model based on mixed integer linear programming, and use improved harmony search algorithm with examples to study operation cost of wind storage system and the change of greenhouse gas emission. The results of the study show that: (1)Under certain electricity demand, the maximum avoiding-cost is higher in wind speed scenarios with a smaller covariance; Under certain wind speed, the maximum avoiding-cost in power demand forecasting scenario which have a larger POP_r and s_d is higher. (2) It shows that wind power-pumped storage power station integrated operation system helps to reduce the whole operation cost of power system, and decreasing amplitude will increase if the wind power installed capacity increase. (3) Pumped-storage unit can instead of thermal power unit to do peak shaving to a certain extent, and then reduce installed capacity of small-scale unit, this will help to reduce greenhouse gas emission, and avoid the reduction of wind power installed capacity at the same time.

Table 1 Demand scenarios 1 & Wind speed scenarios 1-4

	Wind speed scene 1		Wind speed scene 2		Wind speed scene 3		Wind speed scene 4	
	I_C	1.15	I_C	9.33	I_C	-2.52	I_C	3.20
Pd_{Max}/Pd_{Min}	AC_{Max}	1.14	AC_{Max}	1.58	AC_{Max}	2.88	AC_{Max}	1.78
1.82	E_B^{Max}	1.33	E_B^{Max}	1.70	E_B^{Max}	3.25	E_B^{Max}	1.88
$\sigma / \overline{pd}$	$E_B(P_W^{Max})$	1.33	$E_B(P_W^{Max})$	1.70	$E_B(P_W^{Max})$	3.25	$E_B(P_W^{Max})$	1.88
0.17	V_R^{Max}	0.35	V_R^{Max}	0.31	V_R^{Max}	0.86	V_R^{Max}	0.47
	$V_R(P_W^{Max})$	0.35	$V_R(P_W^{Max})$	0.31	$V_R(P_W^{Max})$	0.86	$V_R(P_W^{Max})$	0.47

Table 2 Demand scenarios 2 & Wind speed scenarios 1-4

	Wind speed scene 1		Wind speed scene 2		Wind speed scene 3		Wind speed scene 4	
	I_C	0.53	I_C	7.62	I_C	-1.50	I_C	2.77
Pd_{Max}/Pd_{Min}	AC_{Max}	0.68	AC_{Max}	0.56	AC_{Max}	1.35	AC_{Max}	0.63
1.80	E_B^{Max}	1.20	E_B^{Max}	0.72	E_B^{Max}	1.53	E_B^{Max}	0.72
$\sigma / \overline{pd}$	$E_B(P_W^{Max})$	0.76	$E_B(P_W^{Max})$	0.58	$E_B(P_W^{Max})$	1.53	$E_B(P_W^{Max})$	0.72
0.14	V_R^{Max}	0.30	V_R^{Max}	0.12	V_R^{Max}	0.39	V_R^{Max}	0.18
	$V_R(P_W^{Max})$	0.23	$V_R(P_W^{Max})$	0.12	$V_R(P_W^{Max})$	0.39	$V_R(P_W^{Max})$	0. 18

Table 3 Demand scenarios 3 & Wind speed scenarios 1-4

	Wind speed scene 1		Wind speed scene 2		Wind speed scene 3		Wind speed scene 4	
	I_C	1.17	I_C	8.60	I_C	-1.91	I_C	3. 03
Pd_{Max}/Pd_{Min}	AC_{Max}	0.89	AC_{Max}	0.55	AC_{Max}	1.23	AC_{Max}	0.52
1.79	E_B^{Max}	3.12	E_B^{Max}	2.34	E_B^{Max}	3.16	E_B^{Max}	2.72
$\sigma / \overline{pd}$	$E_B(P_W^{Max})$	2.06	$E_B(P_W^{Max})$	0.55	$E_B(P_W^{Max})$	1.38	$E_B(P_W^{Max})$	0.49
0.16	V_R^{Max}	0.78	V_R^{Max}	0.56	V_R^{Max}	0.79	V_R^{Max}	0.72
	$V_R(P_W^{Max})$	0.50	$V_R(P_W^{Max})$	0.11	$V_R(P_W^{Max})$	0.38	$V_R(P_W^{Max})$	0.11

Table 4 Demand scenarios 4 & Wind speed scenarios 1-4

	Wind speed scene 1		Wind speed scene 2		Wind speed scene 3		Wind speed scene 4	
	I_C	0.67	I_C	6.64	I_C	-1.50	I_C	2.16
Pd_{Max}/Pd_{Min}	AC_{Max}	0.45	AC_{Max}	0.31	AC_{Max}	0.69	AC_{Max}	0.35
1.54	E_B^{Max}	5.36	E_B^{Max}	2.52	E_B^{Max}	3.82	E_B^{Max}	3.15
$\sigma / \overline{pd}$	$E_B(P_W^{Max})$	5.36	$E_B(P_W^{Max})$	2. 03	$E_B(P_W^{Max})$	2.52	$E_B(P_W^{Max})$	2.24
0.12	V_R^{Max}	1.19	V_R^{Max}	0.40	V_R^{Max}	1.06	V_R^{Max}	0.62
	$V_R(P_W^{Max})$	1.19	$V_R(P_W^{Max})$	0.39	$V_R(P_W^{Max})$	0.64	$V_R(P_W^{Max})$	0.55

Acknowledgments

The work described in this paper was Supported by Doctoral Fund of Ministry of Education of China (200800790007) and The Energy Foundation of U.S (G-1006-12630).

REFERENCES

[1] Zeng M, Xue S, Zhu XL, Ma MJ, China's 12th Five-Year Plan Pushes Power Industry in New Direction, POWER, 156(2012), No. 1, 50-55

[2] Zhang JW, Cheng MZ. CX, Short-term Wind Speed Prediction Based on Grey System Theory Model in the Region of China, PRZEGLAD ELEKTROTECHNICZNY, 88(2012), No. 7A, 67-71

[3] Klos Mariusz, Paska Jozef, Wind power plant with energy storage, Przegląd Elektrotechniczny, 84 (2008), No. 2, 58-62

[4] Ejdys J., Broniewicz E. ,Impact of wind power plants on acoustic climat, *Przegląd Elektrotechniczny*, 88 (2012), No. 3a, 199-202

[5] Glinka, Tadeusz; Glinka, Marcin, Variants of the wind turbines solutions, *PRZEGLAD ELEKTROTECHNICZNY*, 88(2012), No. 1B, 239-244

[6] Guerrero, Miguel A.; Romero, Enrique; Barrero, Fermin, Supercapacitors: Alternative Energy Storage Systems, *PRZEGLAD ELEKTROTECHNICZNY*, 88(2009), No. 10, 188-195

***Authors**: prof. Zeng Ming, School of Economics and Management, North China Electric Power University, Beijing 102206, China, E-mail: zengmingbj@vip.sina.com; dr Chen Liming, School of Economics and Management, North China Electric Power University, Beijing 102206, China, E-mail: cylcz@126.com; Ma Mingjuan, School of Economics and Management, North China Electric Power University, Beijing 102206, China, E-mail: crazyhi01@sina.com; dr Xue Song, School of Economics and Management, North China Electric Power University, Beijing 102206, China, E-mail: xuesongbjhd@163.com; dr Cheng Min, School of Economics and Management, North China Electric Power University, Beijing 102206, China, E-mail: chengmin616@163.com*