International Conference on Applied Energy 2020
Dec. 1 - Dec. 10, 2020, Bangkok / Virtual
Paper ID: 610

Coordination and Optimal Scheduling of Multi-energy Complementary System for New Energy Consumption

HU Wei[1], MA Kun [1*], Fang Baomin[2], LI Yanhe[2], SUN Yunchao [1]

1 Power Systems State Key Lab , Dept. of Electrical Engineering, Tsinghua University, Beijing 100084, China

2. Qinghai Electric Power Company, Xining, Qinghai, 810000, China

ABSTRACT

In order to solve the problem of insufficient peak-regulating capacity of the power system after the grid connection of wind power, photovoltaic and other large-scale renewable energy sources, a complementary, coordinated and optimized dispatching strategy for multi-energy storage systems of wind, water and fire is proposed. Based on the current depth peak-adjusting technology, the cost of depth peak-adjusting loss and the cost of steady fuel injection for thermal power units are analyzed. Considering the characteristics of multi-scene wind-solar complementary, a reasonable system effective reserve is determined, and an optimal scheduling model is established with the optimization objectives of maximum consumption of new energy, system operation economy and system operation security. Finally taking the modified IEEE30-bus system as an example, the benders three-stage decomposition method was used to simulate various scenarios and the results demonstrate that the strategy can effectively enhance the accommodation capacity of the new energy power, which verifies the validity of the proposed model.

Keywords: multi-energy system; complementary coordination; deep peak regulation; optimal dispatch; new energy consumption

NONMENCLATURE

Abbreviations	
UC-ED	unit commitment- economic dispatch

1. INTRODUCTION

In recent years, with the rapid development of China's power industry, the access ratio of wind power, photovoltaic and other renewable energy has been increasing. The reverse peak regulation and uncertain characteristics of wind power increase the peak and valley difference of the load, and the double pressure of source and charge increases the peak load regulation burden of power system. In order to cope with the fluctuation of wind power output, it will lead to the phenomenon of frequent start and stop of thermal power units. For example, when wind power goes out, measures may be taken to stop the operation of high-efficiency thermal power units to fully accept wind power. If wind power grid connection is restricted, a lot of wind abandoning will be generated and precious renewable resources will be wasted [1]. It is difficult to meet the consumption of renewable energy and the peak regulation demand of power system solely by relying on the existing regulation capacity of the system. Therefore, it is necessary to establish a multi-source complementary coordination mechanism to fully tap the flexible regulation capacity of power system, so as to improve the consumption of renewable energy while meeting the peak regulation demand [2].

At present, most of the research is to select several kinds of energy sources for modeling analysis, and there are few studies on joint optimization of all energy sources, such as wind power, photovoltaic, the water, thermal power units and storage. According to different optimization objectives, multi-energy optimization scheduling can be divided into traditional economic scheduling, security constrained economic scheduling, etc. At present, many researchers take economic cost and environmental cost into consideration at the same time, and also take renewable energy consumption and other factors into consideration, so as to obtain the optimal overall benefit by solving the multi-objective optimization scheduling problem.

In the literature [3-6], the combined operation and optimal scheduling mode of clean energy and flexible power supply was proposed, which had a good inspiration. In the literature [3], the multi-objective economic dispatching model with the minimum fluctuation of combined output of multi-source power and the minimum operating cost of thermal power units are established. By establishing a cost calculation model more in line with the actual operation of thermal power units, and by carrying out joint optimization scheduling with pumped storage and electrochemical energy storage, the absorption of renewable energy can be improved [4-5]. In the literature [6] ,with the goal of minimizing the total operating cost of the system, the optimal dispatch of the multi-energy complementary system is realized, and the capacity of pumped storage power station is optimized. No matter the joint operation of wind storage, joint operation of wind storage or joint operation of scenery storage, the above literatures only consider one or two goals of the system operation economy, fluctuation and new energy consumption, but do not take them into comprehensive consideration.

At present, the power supply structure of China's electric power system is still dominated by thermal power, so in this paper, in the combined system of wind power, photovoltaic, the water, thermal power units and storage, it is considered to give full play to the deep peak regulation capacity of thermal power units, and at the same time, the peak load reduction capacity of energy storage devices is used to improve the flexibility of the system and promote the consumption of renewable energy. Considering the characteristics of multi-scene wind-solar complementary, a reasonable system effective reserve is determined, and an optimal scheduling model is established with the optimization objectives of maximum consumption of new energy, system operation economy and system operation security. The model can effectively solve the fluctuations of wind power and photovoltaic power and the absorption problems of renewable energy, realize the joint optimization and dispatching of multi-energy system with high proportion of renewable energy, ensure the safe and stable operation of the system and improve the operation economy of the system. In this paper, the improved IEEE30 node system is used to carry out simulation analysis and verify the effectiveness of the proposed model and strategy.

2. ANALYSIS OF THE DEEP PEAK REGULATION COST

In the conventional peak regulation stage, peak-regulating operation cost is coal consumption cost. When deep peak regulation is carried out, the operating costs of deep peak regulation units not only include coal consumption costs, but the additional unit loss cost and oil input cost.

2.1 The unit loss cost of deep peak regulation

In this paper, the unit loss cost is roughly calculated by referring to the most commonly used Manson-Coffin formula. The unit loss cost is as follows:

$$f_{i,l} = \beta S_{unit,i}/(2N_f(P)) \quad (1)$$

Where, β is the impact coefficient of thermal power unit operation, $S_{unit,i}$ is the acquisition cost of the thermal power unit, $N_f(P)$ is the Rotor crack cycle determined by low cycle fatigue curve.

2.2 The stable fuel injection cost of deep peak regulation

In the deep peak regulation with oil, additional peak regulation costs are generated by fuel combustion. The cost of oil injection is

$$f_{y,i,t} = Q_{oil,i,t} p_{oil} \quad (2)$$

Where, $Q_{oil,i,t}$ is the amount of oil put into the deep peak regulation at time t; p_{oil} is the oil price.

3. THE ANALYSIS OF SYSTEM EFFECTIVE RESERVE CAPACITY

The safety index of system operation is related to the maximum effective rotating reserve capacity that the system can provide. In the optimization of scheduling, according to the inaccuracy of wind power, photovoltaic prediction and load prediction, for the sake of safety, the system itself needs to keep a certain reserve capacity at a certain confidence level. It is the constraint condition for the safe operation of the system. When the safe operation of the system is considered as the optimization goal, the safety index of the system operation is defined as the confidence level. It determined by the effective reserve capacity of the system does not have wind abandon, light abandon, water abandon and load lose. The formula is as follows:

$$f_4 = \sum_{t=1}^{N_T} \rho_t \quad (3)$$

Where, ρ_t is the confidence level of wind abandon, light abandon, water abandon and load loss does not occur in time period t of the system. The expression is as follows:

$$\rho_t = P(R_{up}^t) - P(R_{down}^t) \quad (4)$$

Where , $P(R_{up}^t)$ is the probability that the system will not lose load when the total effective positive rotation reserve of time period t is R_{up}^t . $P(\text{-}R_{down}^t)$ is the probability of wind abandoning, light abandoning or water abandoning in the system when the total effective negative rotation reserve of time period t is R_{down}^t .

The probability distribution is obtained by convolution of the historical data of the forward wind power prediction error and the forward load prediction. The probability distribution curve is shown in Fig 2.

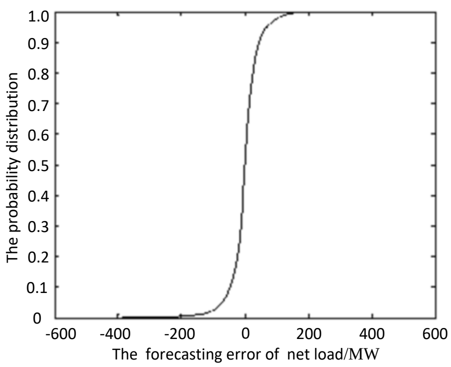

Fig 1 The empirical distribution curve of prediction error of net load

The positive and negative parts of the net load prediction error in the probability distribution curve are divided into N_{PL}^{up} and N_{PL}^{down} sections respectively using the method of piecewise linearization. Each segment corresponds to $\left[R_{P,l-1}^{up}, R_{P,l}^{up}\right]$, $\left[R_{P,l-1}^{down}, R_{P,l}^{down}\right]$ and a probability value P_l^{up} and P_l^{down} of the rotation reserve interval respectively. When the positive rotation reserve capacity is $R_{up} \in \left[R_{P,l-1}^{up}, R_{P,l}^{up}\right]$, its corresponding probability is P_l^{up} , When the reserve capacity $R_{down} \in \left[R_{P,l-1}^{down}, R_{P,l}^{down}\right]$ is rotated negatively, its corresponding probability is P_l^{down} . $I_{up,1}^t, \cdots I_{up,N_{PL}^{up}}^t$ and $I_{down,1}^t, \cdots I_{down,N_{PL}^{down}}^t$ are respectively used to represent the state variables in the interval where the effective positive and negative rotation reserve is located in the period of time, with the value of 0 or 1.

Where,

$$\begin{cases} \sum_{l=1}^{N_{PL}^{up}} I_{up,l}^t = 1 \\ \sum_{l=1}^{N_{PL}^{down}} I_{down,l}^t = 1 \end{cases} \quad (5)$$

$$\begin{cases} \sum_{l=1}^{N_{PL}^{up}} I_{up,l}^t \bullet R_{P,l-1}^{up} \le R_{up}^t \le \sum_{l=1}^{N_{PL}^{up}} I_{up,l}^t \bullet R_{P,l}^{up} \\ \sum_{l=1}^{N_{PL}^{down}} I_{down,l}^t \bullet R_{P,l-1}^{down} \le R_{down}^t \le \sum_{l=1}^{N_{PL}^{down}} I_{down,l}^t \bullet R_{P,l}^{down} \end{cases} \quad (6)$$

$$\begin{cases} P(R_{up}^t) = \sum_{l=1}^{N_{PL}^{up}} I_{up,l}^t \bullet P_l^{up} \\ P(R_{down}^t) = \sum_{l=1}^{N_{PL}^{down}} I_{down,l}^t \bullet P_l^{down} \end{cases} \quad (7)$$

4. THE MULTI-ENERGY SYSTEMS COMPLEMENTARY COORDINATED SCHEDULING MODEL

4.1 The objective function

Based on the combined system, a multi-energy system complementary coordination optimization scheduling model is established with the optimization objectives of new energy maximum consumption, system operation economy and system operation safety respectively.

4.1.1 Renewable energy absorption capacity

The absorption capacity of renewable energy is expressed by the sum of wind power abandoning, hydropower abandoning and photovoltaic abandoning within the dispatching period.

$$\begin{aligned} \min f_1 = & \sum_{t=1}^{N_T} \sum_{l=1}^{N_W} (P_{\text{curt},l,t}^{\text{wind}} \cdot \Delta t) + \sum_{t=1}^{N_T} \sum_{m=1}^{N_S} (P_{\text{curt},m,t}^{\text{PV}} \cdot \Delta t) + \\ & \sum_{t=1}^{N_T} \sum_{h=1}^{N_H} (P_{\text{curt},h,t}^{\text{hydro}} \cdot \Delta t) \end{aligned} \quad (8)$$

Where, $P_{\text{curt},l,t}^{\text{wind}}$ is the wind abandoning power of wind farm l occurring at time period t ; $P_{\text{curt},m,t}^{\text{PV}}$ is the abandoned power of photovoltaic power station m at time period t ; $P_{\text{curt},h,t}^{\text{hydro}}$ is the abandoned power of hydropower station at time period t; Δt is the length of each scheduling period , in this paper Δt=1h.

4.1.2 Economy of system operation

The economy of system operation mainly considers the running cost and start-stop cost of thermal power units. In the conventional peak regulation stage, the operation cost is mainly coal consumption cost. Additional unit loss cost and oil input cost should be considered in the process of deep peak regulation. The coal consumption cost and start-stop cost of thermal power units is as follows:

$$f_2 = f_{\mathrm{mh}} + f_{\mathrm{qt}} = \sum_{t=1}^{N_{\mathrm{T}}}\sum_{i=1}^{N_{\mathrm{G}}} a_i P_{i,t}^2 + b_i P_{i,t} + c_i + \sum_{t=1}^{N_{\mathrm{T}}}\sum_{i=1}^{N_{\mathrm{G}}} S_{it} u_{it}(1-u_{i(t-1)}) \qquad (9)$$

Where, f_2 is the conventional peak-regulation operation costs of thermal power units; f_{mh} and f_{qt} are respectively coal consumption cost and start-stop cost of thermal power units; a_i , b_i and c_i are the consumption coefficients of thermal power unit i respectively; $P_{i,t}$ is the output of thermal power unit.

So, according to different running states, the running cost of thermal power units is expressed as follows:

$$\min f = \begin{cases} f_2, & P_{i,\min} < P_{i,t} \le P_{i,\max} \\ f_2 + \sum_{i=1}^{N_{\mathrm{G}}} f_{i,l}, & P_{\mathrm{a}} < P_{i,t} \le P_{i,\min} \\ f_2 + \sum_{i=1}^{N_{\mathrm{G}}} f_{i,l} + \sum_{i=1}^{N_{\mathrm{G}}}\sum_{t=1}^{N_{\mathrm{T}}} f_{y,i,t}, & P_{\mathrm{b}} < P_{i,t} \le P_{\mathrm{a}} \end{cases} \qquad (10)$$

4.1.3 The safety of system operation

The safety of system operation is mainly related to the fluctuation of net load of the system and the maximum effective rotating reserve capacity that the system can provide. In order to make full use of the energy storage system capacity to compensate the fluctuation of the output of wind-solar and other renewable energy resources, minimize the fluctuation of the net load borne by thermal power units, avoid large and frequent adjustment of thermal power units' output, and ensure the safety of up and down peak adjustment of the system, the following minimum objective function of net load fluctuation is established.

$$\min f_3 = \frac{1}{N_T}\sum_{t=1}^{N_T} | P_{glt} - P_{glt,\mathrm{av}} | \qquad (11)$$

$$P_{glt} = P_{\mathrm{load},t} - \sum_{l=1}^{N_{\mathrm{W}}} P_{l,t}^{\mathrm{wind}} - \sum_{h=1}^{N_{\mathrm{H}}} P_{h,t}^{\mathrm{hydro}} - \sum_{m=1}^{N_{\mathrm{S}}} P_{m,t}^{\mathrm{PV}} - P_{St} \qquad (12)$$

$$P_{glt,\mathrm{av}} = \frac{1}{N_T}\sum_{t=1}^{N_T} P_{glt} \qquad (13)$$

Where, P_{glt} is the Net load at time t, $P_{l,t}^{\mathrm{wind}}$ is the actual grid-connected power of wind farm l at time t, $P_{h,t}^{\mathrm{hydro}}$ is the actual grid-connected power of hydropower h at time t, $P_{m,t}^{\mathrm{PV}}$ is the actual grid-connected power of photovoltaic m at time t, P_{St} is the discharge power at time t of the energy storage device, $P_{St}>0$ represents the discharge of the energy storage device, PSt<0 represents the charge of the energy storage device, $P_{glt,av}$ is the average value of net load within a scheduling cycle, $N_W$is the total number of wind farms, N_S is the total number of photovoltaic power stations, N_H is the total number of hydropower stations.

4.2 The constraint

4.2.1 The power balance constraint

$$\sum_{i=1}^{N_{\mathrm{G}}} P_{i,t} + \sum_{l=1}^{N_{\mathrm{W}}} P_{l,t}^{\mathrm{wind}} + \sum_{h=1}^{N_{\mathrm{H}}} P_{h,t}^{\mathrm{hydro}} + \sum_{m=1}^{N_{\mathrm{S}}} P_{m,t}^{\mathrm{PV}} + P_{St} = \sum_{j=1}^{N_{\mathrm{L}}} P_{j,t}^{\mathrm{load}} \qquad (14)$$

4.2.2 Operating constraints of generators

The constraints of thermal power unit, wind power hydropower, photovoltaic power and energy storage can refer to the reference [7].

In addition, power system operation should also meet the line transmission capacity constraints [7].

5. THE COORDINATION STRATEGY AND SOLUTION METHOD OF THE MULTI-OBJECTIVE DECISION MODEL OF THE JOINT SYSTEM

5.1 The coordination method of multi-objective decision model

In order to achieve the minimum target of the sum of wind abandoning, light abandoning and water abandoning, the sum of renewable energy abandoning can be multiplied by a large number M_1 as the loss of abandoning clean and renewable energy. The minimum objective function of net load fluctuation also can be multiplied by a large number M_1 as the penalty cost of the net load fluctuation. They are combined with the economic index representing the system cost to form a comprehensive consideration of operation safety, environmental friendliness and operation cost index, which enables it to make full use of hydropower, wind power and photovoltaic resources to minimize the operation cost under the premise of ensuring the system operation safety. To sum up, the coordination method of the multi-objective decision model can be expressed as:

$$\min M_1 \bullet f_1(x) + f(x) + M_1 \bullet f_3(x)$$
$$s.t. \quad \begin{cases} f_4(x) \ge f_{4,set} \\ x \in X \end{cases} \qquad (15)$$

Where, $f_{4,set}$ is the set value of the security indicator, x is all the decision variables, X is the feasible region of x determined by other constraints.

5.2 Benders three-phase solution method of the optimization scheduling model

Benders three-stage decomposition method is used to solve the optimization model. It decomposes large-scale mixed integer programming problems into main and sub-problems and solves them iteratively. It mainly includes the following three stages:

Stage I: preprocessing of integer variables based on heuristic rules

Stage II: The solution of UC-ED problem

Stage III: Check the feasibility and safety of the system

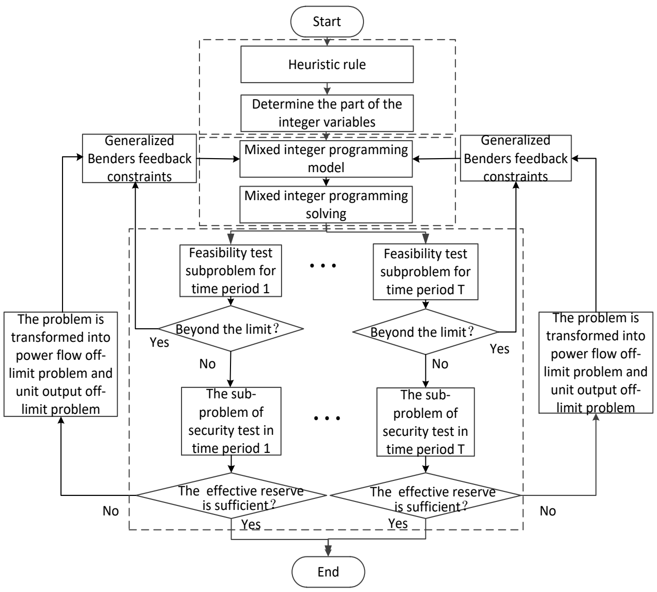

Fig 2 The Benders three-phase solution process of the optimization scheduling model

6. CASE STUDY

6.1 Basic data and parameters

In order to verify the validity of the model, IEEE30 system is used for simulation analysis [8]. The hydropower capacity is 40MW and the wind power capacity is 100MW. Refer to reference [9] for unit loss coefficient in deep peak-regulation stage. The energy storage system parameters are shown in Tab.2[7]. Wind power and load curves are shown in Fig.3.

Tab. 1 Parameters of the energy storage system

parameters	Energy storage capacity /(MW·h)	Energy storage power /MW	Upper limit of charged state	Lower limit of charged state	charge efficiency	discharge efficiency
value	80	20	0.9	0.1	0.9	0.9

6.2 Analysis of optimal scheduling results

In order to verify the effectiveness of the model proposed in this paper, four scheduling scenarios are selected to analyze the system operation economy and renewable energy consumption level under different operation modes. The simulation results of the four scenarios are shown in Tab.2.

Scenario 1: Conventional peak regulation of thermal

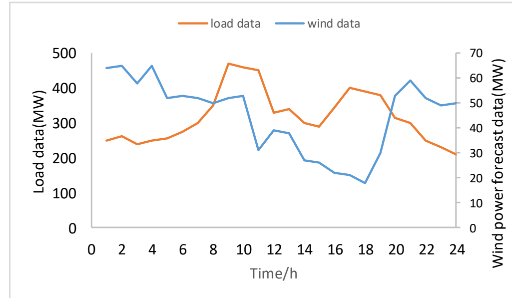

Fig 1 Wind power forecasting and load forecasting curves

power units without considering energy storage.

Scenario 2: Basic scene, conventional peak regulation of thermal power units.

Scenario 3: Basic scene, some thermal power units in the deep peak regulation stage.

Scenario 4: Some thermal power units in the deep peak regulation stage without considering energy storage.

Tab.2 Optimization results of power system in 4 models

Scenario	total cost /$	Operating costs /$	wind abandon costs /$	wind abandon rate /%
1	462231.5	449012.0	13219.4	17.52
2	452353.2	444691.0	7662.1	10.15
3	427289.2	421564.8	5724.3	7.59
4	431041.5	422857.0	8184.5	10.85

By analyzing the simulation results of scenario 1 and 2 in the Tab.2, considering the energy storage system the total operating cost of the system is reduced by $9878.3 compared with scenario 1. The total operating cost reduced by 2.13%. In the case that the total operating cost of the system is guaranteed to be minimum, the air discard volume is reduced by 7.37%.

By analyzing the simulation results of scenario 1 and 4 in the Tab.2, after deep peak regulation of some thermal power units, the total operating cost of the system is reduced by $31190 compared to scenario 1. The total operating cost reduced by 6.75%. From the perspective of the system peak regulation effect, on the premise of ensuring the lowest total operating cost of the system, the wind abandon consumption is sacrificed. The wind abandon rate is decreased by 6.67% compared to scenario 1.

By analyzing the simulation results of scenario 1 and 3 in the Tab.2, considering the energy storage system and deep peak regulation of some thermal power units, the total operating cost of the system is reduced by $34942.3 compared to scenario 1. The total operating cost reduced by 7.56%. On the premise of ensuring the lowest total operating cost of the system , the wind abandon rate is decreased by 9.93% compared to scenario 1. From the perspective of the system peak regulation effect with/without storage, energy storage can not only improve the load peak-valley difference and reduce the system wind abandon quantity., but also improve flexibility of the system operation.

6.3 Analysis of the reserve capacity effectiveness

In this paper, the multi-power combined optimization scheduling model requires the rotating reserve capacity of the system to be an effective reserve capacity, which can be successfully output through the power grid. Scenario 2 is used to analyze the impact of reserve capacity availability on optimization results. The results is shown in Tab.3.

Tab.3 The analysis of reserve capacity effectiveness impact

model	Scenario 2	
Consideration of reserve capacity effectiveness	Yes	No
The operation cost /$	444691.0	442957.7
Effective positive rotating reserve capacity /MW	79	42
Effective negative rotating reserve capacity /MW	66	30
System safety level	99.92%	99.54%

By analyzing the results of scenario 2 in the Tab.3, Without considering the effectiveness of rotating reserve capacity, it is likely to overestimate the safety level of the grid. When the net load has a large unexpected fluctuation, it is likely that the rotating spare capacity cannot be output due to network congestion, which will affect the power balance and safe operation of the power grid.

7. CONCLUSION

The main conclusions are as follows:

1）In this paper, a complementary coordinated and optimized dispatching method is proposed. This strategy can effectively reduce the total operating cost of the system and the level of new energy power abandon. It provides an effective method for the complementary coordination and scheduling decision of the multi-energy storage system of wind, photovoltaic, water and fire. 2) The participation of some thermal power units in peak shifting can improve wind power consumption of the system, and reduce the operating cost of the system. 3) Energy storage system with the depth of the thermal power unit load can effectively reduce the cost of system operation, improve the wind power absorption, improve flexibility of the system operation. 4) The effectiveness of rotating reserve capacity should be considered to cope with the impact of unexpected net load fluctuations on the power balance and safe operation.

ACKNOWLEDGEMENT

This study was supported by the Science and technology project of State Grid Corporation of China (Research on Key Technologies of Power Grid Coordination of HVDC send-side for All-Clean Energy Power).

REFERENCE

[1] Deng Tingting，Lou Suhua，Tian Xu，et al．Optimal dispatch of power system integrated with wind power considering demand response and deep peak regulation of thermal power units[J]． Automation of Electric Power Systems，2019，43(15)：34-41．

[2] Li Haibo，Lu Zongxiang，Qiao Ying．Bi-level optimal planning of generation-load-storage integrated generalized flexibility resource[J]． Automation of Electric Power Systems，2017，41(21)：46-55．

[3] Yu Jia，Ren Jianwen，Zhou Ming．A chance-constrained programming based dynamic economic dispatch of wind farm and pumped-storage power station[J]．Power System Technology，2013，37(8)：2116-2122．

[4] Sheng Siqing，Sun Xiaoxia．An economic dispatching strategy of peak load shifting by wind farm and pumped storage plant[J]． Power System Technology，2014，38(9)：2484-2489．

[5] An Lei，Wang Mianbin，Qi Xia，et al．Optimal dispatching of multi-power sources containing wind/photovoltaic/thermal/hydro-pumped and battery storage [J]．Renewable Energy Resources，2018，36(10)：1492-1498．

[6] Zhang N，Kang C，Kirschen D S，et al．Planning pumped storage capacity for wind power integration[J]． IEEE Transactions on Sustainable Energy，2013，4(2)：393-401．

[7] LI Tie, LI Zhengwen, YANG Junyou, et al． Coordination and Optimal Scheduling of Multi-energy Complementary System Considering Peak Regulation Initiative[J]．Power System Technology，2020,44(10):3622-3630.

[8] ZHOU boran. Unit commitment with wind power: model and algorithm [D]. Hangzhou ： Zhejiang University,2015.

[9] Li Yiming，Li Wenyuan，Yan Wei，et al．Daily generation scheduling for reducing losses of unit’s lives based on the chance constrained programming model[J]．Power System Technology，2014，38(7)：1885-1890．