An optimal strategy for coordinating and dispatching "source-load" in power system based on multiple time scales

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Abstract: Due to the phenomenon of abandoning wind power and photo voltage (PV) power in the "Three Northern Areas" in China, this paper presents an optimal strategy for coordinating and dispatching "source-load" in power system based on multiple time scales. On the basis of the analysis of the uncertainty of wind power and PV power as well as the characteristics of load side resource dispatching, the optimal model of coordinating and dispatching "source-load" in power system based on multiple time scales is established. It can simultaneously and effectively dispatch conventional generators, wind plant, PV power station, pumped-storage power station and load side resources by optimally using three time scales: day-ahead, intra-day and real-time. According to the latest predicted information of wind power, PV power and load, the original generation schedule can be rolled and amended by using the corresponding time scale. The effectiveness of the model can be verified by a real system. The simulation results show that the proposed model can make full use of "source-load" resources to improve the ability to consume wind power and PV power of the grid-connected system.

Key words: multiple time scales; "source-load" coordination; pumped-storage power station; wind plant; photovoltaic (PV) power station

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0 Introduction

Renewable energy has the advantages of no pollution, low carbon and so on. However, compared with traditional energy sources, renewable energy has the characteristics of stochasticity and volatility that seriously restrict its rapid development. Therefore, the study on the large-scale grid-connection of renewable energy, such as wind power and photovoltaic (PV) power, has become one of research hotspots in power industry today[1-5].

To optimize the dispatch of grid-connected renewable energy, many scholars at home and abroad have proposed many kinds of schemes. To take full advantage of abandoned wind, Cui, et al. established a system model[6], which combined wind plant with pumped-storage power station. After analyzing the output of wind power and pumped-storage power station by simulation, the maximum benefit was got. Although this method can reduce the capacity of abandoned wind to a certain degree, it cannot solve the problem of abandoning wind power at night. Zhao, et al. made an comprehensive introduction to the current energy-storage patterns, including pumped-storage, energy-storage by compressing air and thermal energy, and so on[7]. Among them, the pumped-storage technique was used more widely. Due to some technical restrictions, most of the energy-storage patterns described above faced the problems of limited storage capacity and insufficient economy except pumped-storage. Taking Jilin Provice as an example, Chen, et al. introduced peak load and vale load and employed electric boiler with thermal energy to conduct energy conversion of wind power, which realized the heating by combining grid-connected wind power with central heating enterprises so as to save coal resources and reduce the discharge of pollutant air[8]. Although the utilization of wind power has been improved effectively by this

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method, it cannot relieve the pressure on power grid during the peak load period.

As for optimization of power system from the perspective of load side resource dispatching, scholars have made some achievements. Zhang, et al. pointed out that the implementation of demand response is helpful to improve the reliability of power supply[9-10]. However, there are few studies on demand response to offer the economy to power companies. Zhao, et al. discussed the demand response, energy-storage systems and the dispatch of wind power, but they did not consider them comprehensively[11-13]. Chen, et al. discussed the optimal dispatch scheme among wind power, photo voltage and energy storage[14-16], but they did not consider the uncertainty of wind power.

In this paper, firstly, we analyze the uncertainty of wind power and PV power as well as the characteristics of load side resource dispatch based on previous studies. Then, since the predicted output error of wind power, PV power and load power will decrease with the reduction of predicted time scale, we establish an model optimal for coordinating and dispatching “source-load” in power system based on mutiple time Scales. Due to the predicted accuracy of wind power, the output of PV power and load power will increase gradually with the reduction of time scale, and the planned dispatch strategy based on multiple time scales is divided into day-ahead rolling planned dispatch for 24 h, intra-day rolling planned dispatch for 6 h and real-time dispatch for 15 min. According to the latest predicted information of wind power, the PV power and load power, planned dispatch schemes based on all the time scales coordinate each other so that the generation schedule in the remained period will be rolled and amended to reduce the predicted error gradually. Finally, combined with specific examples, the effectiveness of the optimal strategy for coordinating and dispatching “source-load” in power system based on multiple time scales is verified by actual case.

1 Analysis of characteristics of “source-load” resource

1.1 Uncertainty of wind power and PV power

Due to the influence of geography, seasons and other factors, the distribution of wind power shows great stochasticity and volatility. The anemometry data show that the daily average output of one wind plant varies from 0 to that rated. Its volatility is quite obvious, as shown in Fig. 1.

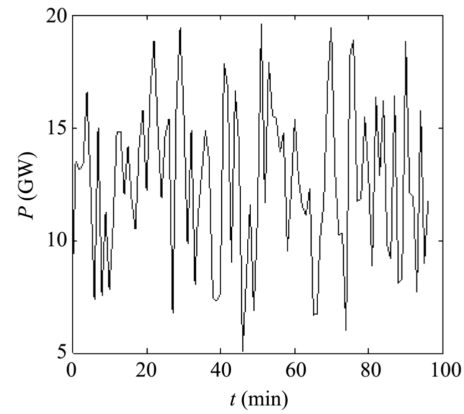

Fig. 1 Daily output distribution of wind plant

As shown in Fig. 2, the output of wind plant in spring and winter is more than that in summer and autumn. The output distribution of wind plant is quite opposite to the trend of load change, in which the anti-peak characteristic is obvious and the peaking pressure of power grid increases.

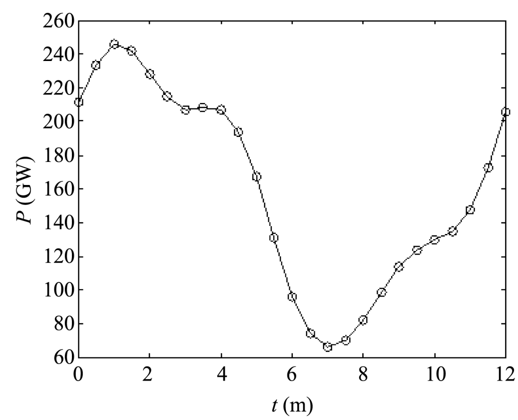

Fig. 2 Yearly output distribution of wind plant

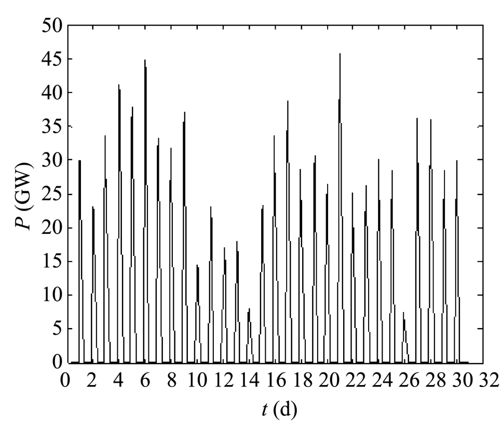

Fig. 3 Monthly output distribution of PV power station

Because the output of PV power generation is impacted by the intensity of solar radiation, its monthly distribution is certainly regular and the output is more in the daytime than 0 in the night. Therefore, the change of PV power output is similar to that of the load. Fig. 3 shows the monthly output distribution of PV power station.

1.2 Characteristics of load side resource dispatch

High-energy load has the characteristics of large capacity and great adjusting potential, and its adjusting range can reach 30% — 100% of load capacity. Two reasons contribute to local accommodation of wind power consumed: one is that the use of sillicon controlled method SCR has the characteristics of rapid adjustment and group switching, the other is that most of the high-energy load is distributed in the vicinity of the grid of large-scale wind power. Therefore, the disadvantage that conventional power supply cannot effectively adjust large-scale wind power fluctuation can be overcome through the coordinated control of high-energy load and conventional power supply.

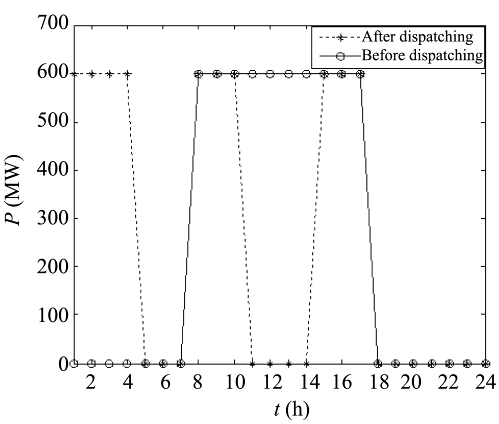

Fig. 4 Outputs of high-energy enterprise load before and after dispatch

Fig. 4 is a dispatching sketch of of high-energy industrial load. After dispatching, the load is shifted from time scale 11 — 14 to time scale 1 — 4, which means that this kind of load has a flexible adjusting ability so as to avoid the abandonment of wind power and PV power.

2 Optimal model

2.1 Overall strategy

The connected power system is composed of wind power, PV power, pumped-storage power station and high-energy enterprise, and they are optimized uniformly.

The day-ahead dispatch is for 24 h and it is divided into 96 time scales with an interval of 15 min. The day-ahead dispatch schedule is mainly responsible for essential day-ahead dispatch according to the prediction of day-ahead wind plant and PV power output as well as the predication of load.

The intra-day rolling dispatch is for 6 h and it is updated 4 times every day. According to the latest prediction of day-ahead output of wind plant and PV power as well as the predication of load, the intra-day dispatch scheme has a rolling correction on the basis of the day-ahead dispatch to get the basic dispatch scheme revised.

The real-time planned dispatch is updated every 15 min based on the dispatch scheme after the revised intra-day rolling dispatch, thus the real-time correction is constantly performed according to the latest predicted data. Finally, the output of connected power system can effectively track the curve of load power.

2.2 Control strategy

Based on the predicted data of the load, PV power generation and wind power generation, this paper presents a dispatch strategy within 15 min.

When the wind power generation and PV power generation are more than the load, the excess part is used to drive the water pump to pump the water from the lower reservoir to the upper reservoir for storage. If the rated capacity of the upper reservoir is detected, the adjustable volume of demand side needs to be dispatched. On condition that the up-regulated space of demand side load can absorb the remaining PV power and wind power, the strategy that combines the pumped-storage charge with the up-regulated demand side will be employed. If the wind power genration and PV power generation still remain, it is judged whether the main grid is allowed to sell the residual power to the grid; if it is not allowed, some wind power and PV power may be removed. When the generation capacities of wind power and PV power are less than the load, the pumped-storage power station will be used preferentially to generate power to meet the load. If the power generation capacity of the upper reservoir reaches the lower limit, the remaining part will be adjusted through the demand side response; if it still cannot meet the demand, the commercial power will be introduced.

The essential logic diagram is shown in Fig. 5.

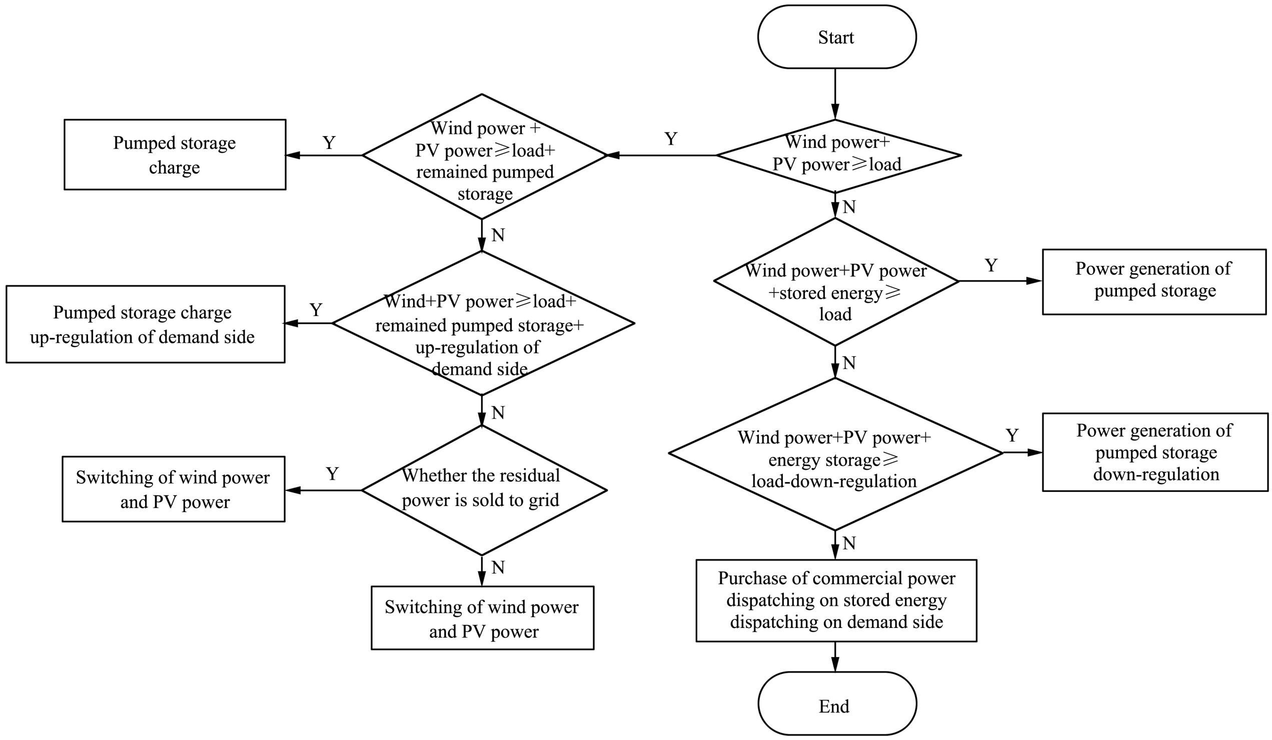

Fig. 5 Control strategy of power dispatching

2.3 Day-ahead planned dispatch model

2.3.1 Objective function

$$\min F_d = \sum_{t=1}^{N_t}\sum_{i=1}^{N_0}[u_{i,t}^R F_i(P_{i,t}^R) + u_{i,t}^R(1-u_{i,t-1}^R)S_i + u_{i,t-1}^R(1-u_{i,t}^R D_i], \quad (1)$$

$$F_i(P_{i,t}^R) = a_i(P_{i,t}^R)^2 + b_i P_{i,t}^R + c_i, \quad (2)$$

where F_d is the total power generation cost in the entire period of day-ahead dispatch; N_t is the divided time scales of day-ahead planned dispatch; N_0 is the total number of conventional generators; $u_{i,t}^R$ is the start-stop state of generators i, which is determined by day-ahead planned dispatch at time scale t; $F_i(\cdot)$ is the operating cost of the generator; $P_{i,t}^R$ is the output state of generator, which is determined by day-ahead planned dispatch at time scale t; S_i is the start-up cost of the generator i; D_i is the downtime cost of generator i; a_i, b_i and c_i are the parameters of generators with economical characteristic.

The constraints are shown as follows:

1) Balanced constraints of supply

$$\sum_{i=1}^{N_0} P_{i,t}^R + P_t^{WR} + P_t^{VR} + P_t^{PR} = \sum_{j=1}^{N_L} p_{j,t}^L, \quad (3)$$

where P_t^{WR} is the total network power (MW) of wind plants at time scale t; P_t^{VR} is the total network power (MW) of PV power at time scale t; P_t^{PR} is the total network power (MW) of pumped storage at time scale t; $P_{i,t}^L$ is the predicted value of load at time scale t.

2) Water balance of pumped-storage power station

$$\sum_{t=1}^{T}\{Q(P_t, H_t)\Delta T(t)\} = 0, \quad (4)$$

$$V_{i+1} = V_i + Q_i(P, H)\Delta T(t), \quad (5)$$

where H_t is the head or lift of pumped storage generators, and P is the output value of pumped-storage power station.

3) Output constraints of thermal power generators

$$P_{\min}^R \leqslant P_{i,t}^R \leqslant P_{\max}^R. \quad (6)$$

4) Output constraints of wind power plant

$$0 \leqslant P_t^{WR} \leqslant P^{WF}, \quad (7)$$

where P^{WF} is the total predicted power (MW) of wind power plant.

5) Output power constraints of PV power station

$$P_{\min}^{VR} \leqslant P_t^{VR} \leqslant P_{\max}^{VR}. \quad (8)$$

6) Power constraints of pumping generators

$$P_{\min}^{pump} \leqslant P_t^{pump} \leqslant P_{\max}^{pump}. \quad (9)$$

7) Power constraints of hydroelectric generators

$$P_{\min}^{\text{hydro}} \leqslant P_t^{\text{hydro}} \leqslant P_{\max}^{\text{hydro}}. \tag{10}$$

8) Climbing constraints of generators

$$-P_i^{\text{down}} \Delta t \leqslant P_{i,t}^{\text{R}} - P_{i,t-1}^{\text{R}} \leqslant P_i^{\text{up}} \Delta t, \tag{11}$$

where P_i^{down} is landside power of thermal power generators (MW/h), and P_i^{up} is the climbing power of thermal power generators (MW/h) per unit time.

9) Constraints of reserved capacity of the system

$$R_{\text{up},t}^{\text{need}} \leqslant \sum_{i=0}^{N_0} (u_{i,t} P_i^{\max} - P_{i,t}^{\text{R}}), \tag{12}$$

$$R_{\text{down},t}^{\text{need}} \leqslant \sum_{i=0}^{N_0} (P_{i,t}^{\text{R}} - u_{i,t} P_i^{\min}), \tag{13}$$

where $R_{\text{up},t}^{\text{need}}$ and $R_{\text{down},t}^{\text{need}}$ are the reserved capacities that are reserved to increase or decrease the minimum rotation for system respectively.

10) Constraints of minimum operation and downtime of thermal power generators

$$\begin{cases} T_{i,t}^{\text{on}} \geqslant T_{i,\min}^{\text{on}}, \\ T_{i,t}^{\text{off}} \geqslant T_{i,\min}^{\text{off}}, \end{cases} \tag{14}$$

where $T_{i,t}^{\text{on}}$ is the continuous uptime of generator i at time scale t; $T_{i,t}^{\text{off}}$ is the continuous downtime of generator i at time scale t; and $T_{t,\min}^{\text{off}}$ is the minimum downtime of generator at time scale t.

2.4 Intra-day planned dispatch model for 6 h

2.4.1 Objective function

$$\min F_{\text{h}} = \sum_{i=1}^{T} |\rho U^{\text{I}}(t) P_{\text{I}} \Delta t|, \tag{15}$$

where F_{h} is the cost of the load dispatch; ρ is the unit compensation cost of users; $U^{\text{I}}(t)$ is the response state of user at time scale t, $U^{\text{I}}(t)=1$ if load needs to be increased, $U^{\text{I}}(t)=-1$ if load needs to be decreased, and $U^{\text{I}}(t)=0$ if non-action; P_{I} is transfer volume of load; Δt is the time in one dispatch time scale.

In order to ensure the normal activity of industrial users, load control center only can transfer load instead of increasing or reducing it. Therefore, the introduced load transfer can balance the constraints.

1) Constraints of load transfer balance

$$\sum_{t=1}^{T} U^{\text{I}}(t) = 0. \tag{16}$$

Industrial users have the limit on flexible dispatching of supplied load capacity. Therefore, the constraints of the maximum response capacity are introduced.

2) Constraints of the maximum response capacity

$$\sum_{t=1}^{T} \max(U^{\text{I}}(t), 0) P_{\text{I}} \Delta t \leqslant q_{\text{I}}, \tag{17}$$

where q_{I} is the constraints of the maximum response capacity of users; other constraints of intra-day dispatching are basically similar to that of day-ahead dispatching. But the start time and stop time of generators participating start and stop operations are less than 6 h, namely

$$\begin{cases} 0 < T_{\text{start},i} \leqslant 6 \text{ h}, \\ 0 < T_{\text{stop},i} \leqslant 6 \text{ h}, \end{cases} \tag{18}$$

where $T_{\text{start},i}$ and $T_{\text{stop},i}$ are start time and stop time of generators, respectively.

2.5 Real-time planned dispatch model

2.5.1 Objective function

$$\min F_{\text{r}} = \min\left(\sum_{i=1}^{N_0} u_{i,t} r_{i,t} \mid \Delta P_{G_{i,t}} \mid\right) + \gamma P_{\text{WA}}, \tag{19}$$

where F_{r} is the real-time adjusting cost of conventional generators; $\Delta P_{G_{i,t}}$ is the adjustment capacity of real-time output of generators in time scale t; $r_{i,t}$ is the cost of unit output adjustment of generator i at time scale t; γ is penalty coefficient of abandoned wind and PV power; P_{WA} is the capacity of abandoned wind and PV power.

Among them, the cost of unit output adjustment of thermal power generators is

$$r_{i,t} = |F_{i,t}^{\text{real}} - F_{i,t}^{\text{rolling}}|, \tag{20}$$

where $F_{i,t}^{\text{real}}$ is the cost of power generation of real-time planned thermal power generator i at time scale t; $F_{i,t}^{\text{rolling}}$ is the cost of power generation of rolling planned thermal power generator i at time scale t.

Other constraints of real-time dispatch are basically similar to that of day-ahead dispatch. But during the real-time planned dispatch, only the generators holding the abilities of rapid start and stop can be used for the adjustment of start-stop state of the planned dispatch, namely

$$\begin{cases} 0 < T_{\text{start},i} \leqslant 15 \text{ min}, \\ 0 < T_{\text{stop},i} \leqslant 15 \text{ min}, \end{cases} \tag{21}$$

where $T_{\text{start},i}$ and $T_{\text{stop},i}$ are start time and stop time of generators, respectively.

3 Case analysis

3.1 Introduction of CPLEX

This paper uses the optimized software CPLEX to acquire the optimal solution. ILOG CPLEX, an internationally popular optimization software package with high performance, robustness and flexibility, includes CPLEX interface and CPLEX algorithm. The design philosophy of CPLEX is that the serious and complicated problems are solved quickly under the intervention of the minimum user. It is widely used in logistics industry, manufacturing industry, communication industry and ground engineering of oil field, etc., making the solutions of some complicated problems become relatively simple and efficient.

3.2 Steps of solution

The specific steps of solution are shown as follows:

Step 1: the latest predicated data of wind power, PV power and load are obtained.

Step 2: the program description is completed according to the mathematical model and constraints at each time scale.

Step 3: the experimental data are imported into the CPLEX program for calculation in order to obtain the optimal output of wind power, PV power and load at each time scale.

3.3 Case design

Taking eight conventional generators, a wind plant with the installed capacity of 200 MW, a PV power station with the installed capacity of 30 MW, pumped-storage power stations with the installed capacity of 200 MW and high-energy enterprise with the electrical load of 260 MW for simulation. The simulation results can be obtained by CPLEX. The parameter characteristics of eight conventional generators are described in detail in Ref. [17]. Fig. 6 shows the contrast curves of actual value of wind power and its predicted values in different time scales Fig. 7 shows the contrast curves of the actual value of PV power and its predicted value in different time scales Fig. 8 shows the contrast curves of the actual value of load power and its predicted values in different time scales.

Through three-layer optimal dispatch (day-head for 24 h, intra-day for 6 h and real-time), total generation of thermal power plant is 13.248 GW·h during the period of dispatching. However, it is reduced by 21% compared with the total power generation of 16.872 GW·h before optimization. The total power generation of pumped-storage power station is 6.613 GW·h during the period of dispatching. It is increased by 29.9% compared with the total power generation of 5.087 GW·h before optimization.

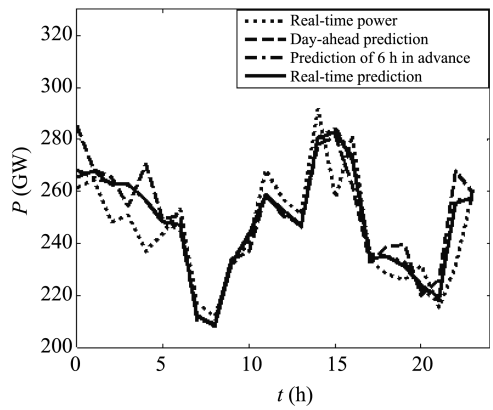

Fig. 6 Predicted curves of wind power at different time scales

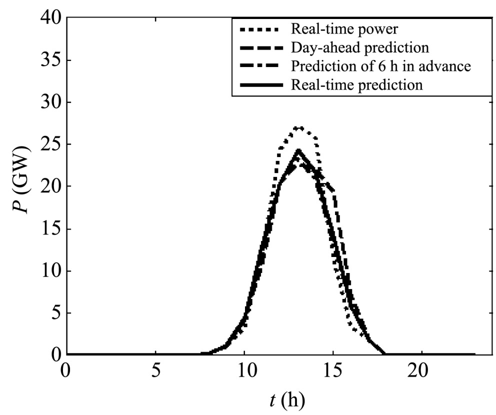

Fig. 7 Predicted curves of PV power at different time scales

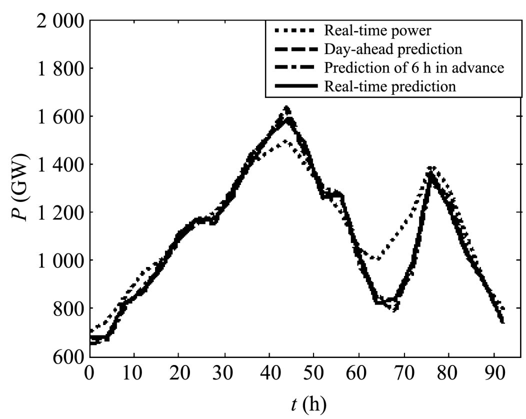

Fig. 8 Predicted curves of load power at different time scales

Table 1 shows the comparison results of the daily power generation of conventional generators before and after optimization.

Table 1 Comparasive results of daily power generation of conventional generators before and after optimization

Generators optimization number	Power generation before optimization (MW·h)	Power generation after optimization (MW·h)
1	3 009	1 944
2	3 072	1 809
3	2 856	1 987
4	1 872	1 488
5	1 992.68	1 560
6	2 160	1 920.03
7	1 824	1 752
8	1 608	1 656

The contrast curves of networked wind power and PV power at each time scale is shown in Fig. 9.

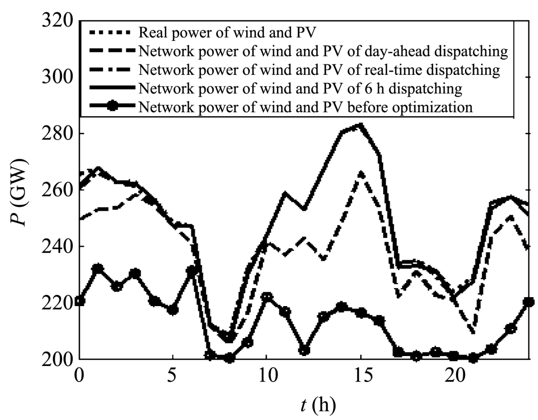

Fig. 9 Contrast curves of networked wind power and PV power at each time scale

The contrast data of abandoned wind power and PV power of planned dispatch at different time scales are shown in Table 2.

Table 2 Contrast data of abandoned wind and PV of planned dispatching at different time scales

Time scales of wind power and PV power	Capacity of abandoned wind and PV power (MW·h)	Rate of consuming (%)
Day-ahead	1 010.82	83
Intra-day for 6 h	475. 68	92
Real-time	101.82	98.3

From Fig. 9 and Table 2, it can be seen that there still exists serious phenomenon of abandoning wind power and PV power in day-head planned dispatch. The phenomenon of abandoned wind power and PV power is relieved through the intra-day dispatch for 6 h. And through the final real-time dispatch, the phenomenon of abandoning PV power is controlled well. The overall grid is basically achieved expect for a little abandoned wind power at time scales 3 and 4 as well as abandoned PV power at time scales 15 and 16. Therefore, the rate of consuming wind power and PV power will increase with the decrease of time scales.

In order to verify the validity of the model, this paper assumes that there are three different scenes based on day-ahead optimal dispatching. In scene 1, conventional thermal power generators, wind plant and PV power station are considered in optimal dispatching model; in scene 2, conventional thermal power generators, pumped-storage power station, wind plant and PV power station are considered in optimal dispatching model; in scene 3, conventional thermal power generators, pumped-storage power station, high-energy load enterprises on load side, wind plant and PV power station are considered in optimal dispatching model. The optimized model can be solved by applying optimized software CPLEX, and every operating cost of the system obtained in different scenes is shown in Table 3. The situation of abandoned wind and PV at every time scale in different scenes is shown in Fig. 10.

Table 3 Every operating cost of the system obtained in different scenes

	Situation operating cost	Costs of abandoned wind and PV power	Dispatch on load side	Total cost
Scene 1	108.6×10^4	10.4×10^4	0	119×10^4
Scene 2	97.31×10^4	9.8×10^4	0	107×10^4
Scene 3	81.45×10^4	9.4×10^4	2.8×10^4	94×10^4

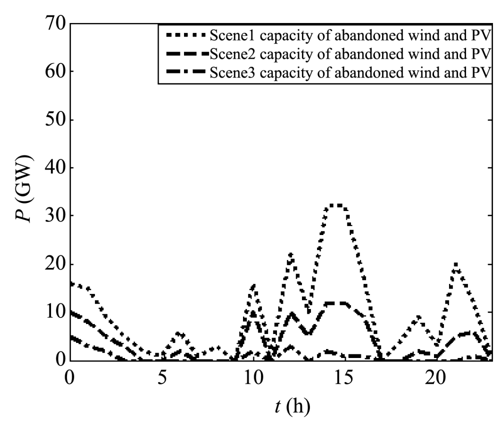

Fig. 10 Capacity of abandoned wind power and PV power at every time scale in different scenes

From Table 3 and Fig. 10, it can be seen that the system capacities of abandoned wind power and PV power and its cost will decrease conspicuously when the pumped-storage power station and the high-energy load enterprises on the load side participate in the optimization of the system. In addition, due to the influence of anti-peak characteristic and balanced constraints of load transfer, the load system with the trend of shifting load can play a role in replacing the output of generators with poor economy so as to consume more power of abandoned wind power and PV power, which makes the operating cost of conventional generators decline to some extent.

4 Conclusion

The model of coordinating and optimal dispatching "source-load" in power system based on multiple time scales is established taking the uncertainty of wind power and PV power and the dispatch characteristics of high-energy load into account. At the same time, it brings the conventional generators, wind plant, PV power station, pumped-storage power station and load side resources into dispatching at different time scales considering the penalty cost of abandoned wind power and PV power in the objective function. By utilizing the continuously updated prediction of wind power, the output of PV power and the predicted data of load, the model can adjust the dispatch scheme to ensure the reliability of the system. Furthermore, the economy of the system and the consumed ability of wind power and PV power are improved, which provides a reference to research on grid-connection of wind power and PV power in large scale.

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一种基于多时间尺度的电力系统“源-荷”协调调度优化策略

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摘　要： 针对三北地区弃风弃光问题，提出了基于多时间尺度的电力系统“源-荷”协调调度优化策略。在对风电、光伏功率的不确定性和负荷侧资源调度特性分析的基础上，建立了基于多时间尺度的电力系统“源-荷”协调调度优化模型。该模型针对日前、日内和实时 3 种不同时间尺度，将常规机组、风电场、光伏电站、抽水蓄能电站和负荷侧资源同时进行调度优化。根据风电、光伏和负荷等最新预测信息和机组电量实际完成情况，按照相应的时间周期滚动修正原有发电计划。以实际系统为例验证了模型的有效性，仿真结果表明，上述模型可以充分利用不同时间尺度上的“源-荷”资源，提高了系统对风电、光伏的消纳能力和并网后系统运行的经济性。

关键词： 多时间尺度；“源-荷”协调；抽水蓄能电站；风电厂；光伏电站

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