Study on Multi-scale Unit Commitment Optimization in the Wind-Coal Intensive Power System

Xi YE[†], Ying QIAO*, Zongxiang LU*, Yong MIN* and Ningbo Wang**

Abstract – Coordinating operation between large-scale wind power and thermal units in multiple time scale is an important problem to keep power balance, especially for the power grids mainly made up of large coal-fired units. The paper proposes a novel operation mode of multi-scale unit commitment (abbr. UC) that includes mid-term UC and day-ahead UC, which can take full advantage of insufficient flexibility and improve wind power accommodation. First, we introduce the concepts of multi-scale UC and then illustrate the benefits of introducing mid-term UC to the wind-coal intensive grid. The paper then formulates the mid-term UC model, proposes operation performance indices and validates the optimal operation mode by simulation cases. Compared with day-ahead UC only, the multi-scale UC mode could reduce the total generation cost and improve the wind power net benefit by decreasing the coal-fired units' on/off operation. The simulation results also show that the maximum total generation benefit should be pursued rather than the wind power utilization rate in wind-coal intensive system.

Keywords: Multi-scale, Unit commitment, Coal-fired units, High wind power penetration, Coordinating operation

1. Introduction

China's wind power has been experiencing rapid development in recent years and the wind power penetration in some areas has reached a relatively high level. By the end of 2012, the installed capacity proportion of wind power in East Inner Mongolia, West Inner Mongolia and Gansu province has reached 20.2%, 22.1% and 20.7%, respectively. According to the wind power operation experience in Europe and the United States, once wind power penetration has reached a relatively high level, the impact of wind power on active power balance would become prominent gradually. For example, the emergency load shedding was applied in the United States Texas Power Grid (ERCOT) in 18:41, February 26, 2008, and investigation has shown that the rapid decline of 1640MW wind power was an important source of this accident [1]. Therefore, studying the active power balance mechanism and relevant operation scheduling strategy in system with high wind power penetration has attracted much interest.

Unit commitment (abbr. UC), especially day-ahead unit commitment (abbr. DAUC) [4-6] based on short-term wind power prediction is believed as an effective way to handle wind uncertainty. By this means, some European countries have achieved great success in bulk wind energy accommodation, such as Denmark and Ireland. The power

† Corresponding Author: State Key Lab of Power Systems, Department of Electrical Engineering, Tsinghua University, Beijing 100084, China. (yexi10@mails.tsinghua.edu.cn)
* State Key Lab of Power Systems, Department of Electrical Engineering, Tsinghua University, Beijing 100084, China.
** Gansu Electrical Power Grid Corporation, Gansu, 730000, China.

systems in those countries have favorable conventional unit mix to provide enough flexibility to keep power balance when faced with wind power fluctuation. For example, the Irish system has a considerable proportion of gas units and rich hydropower resource, and the Danish system has strong interconnection lines with other Nordic countries, through which the quick inter-area power exchange is available [2-3].

The experiences in European countries are helpful, whereas China has still more problems to solve in her wind energy accommodation. Some unfavorable characteristics make the active power balance become difficult. The main development mode of wind energy in China is centralized and massive, and as a result, the wind power penetration in some local areas could reach a relatively high level. The conventional plant mix in wind-rich areas mainly composes of coal units, which have unfavorable parameters of long start-up and shut-down time, high start-up costs and high fixed fuel fee. In addition, open power market is almost unavailable. The lack of flexibility (usually short of downward spare capacity) becomes even urgent in the winter days because the minimum operation points of coal-fired combined heat are decided by high heating demand.

Current researches mainly focus on UC problems in day-ahead or intraday, shorter time scales [4-6], but in an inflexible power grid like China, unfavorable situations may prevent DAUC from taking adequate effects. The synoptic system in monsoon climate usually influences the north of China in several days or even one week. The on-off cycle of large-scale coal units is also as long as a few or dozens of days. As a result, the mid-term variation trend of

wind power may have a relatively obvious impact on the on-off state of coal-fired units. It is necessary and beneficial for a wind-coal intensive power grid to introduce the UC of the mid-term time scale.

The paper proposes a multi-scale UC approach which includes not only DAUC but also mid-term UC (abbr. MTUC). We focus on the coordination mechanism of mid-term and short-term operation in high wind power penetration system mainly consisting of large coal-fired units. Section 2 introduces the basic concepts and main functions of multi-scale coordinating operation, and expresses the mid-term UC in detail. Section 3 then formulates the optimal model mathematically. Section 4 introduces the test system and operation performance indices and based on this, the benefits of the proposed mode are discussed in detail through simulation cases.

2. Concepts and Benefits Analysis of Mid-term Unit Commitment

2.1 Basic concepts

Day-ahead Unit Commitment has been thought as a significant approach to keep active power balance and to improve wind power accommodation. It is a fine regulation process for the daily operation which mainly focuses on scheduling the on-off states for the quick units next day and optimizing the working points of large-scale coal units. It is especially effective for the units with relatively short start time and low cost.

In the systems mainly composed by large coal-fired units, it is difficult to change units' on-off status within one single day when faced with the net load variability. Therefore, it is necessary to optimize the operation states of large coal-fired units in a longer time scale so that the wind power utilization rate could be improved and the units' on-off frequency could be cut down.

One difference between MTUC and traditional DAUC lies in the fact that they concern different units. We aim at arranging the operation status of large coal-fired units in MTUC which have a long start-up time and high start-up cost. As a result, the on-off status of those units should not be switched so frequently in one single day. On the contrary, we only take into account the working point of the large units and the start-up operation of small flexible units in the day-ahead operation optimization.

The other difference is that the precision and availability of wind power forecast. The effective DAUC usually depends on accurate short-term wind power forecast. However, MTUC requires only rough forecast in the next few days which can figure out the outline of the wind power variation trend and extreme value. In this case, absolute amplitude error and phase error within a few hours are both acceptable. The main differences between MTUC and DAUC are summarized in Table 1.

Table 1. Differences between MTUC and DAUC

Difference	MTUC	DAUC
Time Scales	D+1~D+N day	Only D+1 day
Concerning Units	Slow Start Units	Relatively Flexible Units
Requirements for Wind Power Forecast	Wind Power Variation Trend, Interval and Extreme Value Forecast	Accurate Day-ahead Wind Power Forecast
Main Model Constraints	Constraints Related to Active Power Balance and Units Regulation Capability	Also Constraints Related to Power Flow ,N-1 Security

2.2 Benefits mechanism analysis

Comparing to using the traditional DAUC only, the benefits of MTUC in a system mainly composing of coal-fired units could be discussed through the simple UC model in (1). In this case, wind power has no fuel cost, so will be dispatched in priority, but it is still allowed to be curtailed if the wind power curtailment loss is less than the thermal units' regulation cost. Take a two-day's operation scene as an example, where the wind power output is relatively large on the first day but small on the second day.

$$\min \sum_{d=1}^{D} \sum_{t=1}^{T} \left(\sum_{i=1}^{N_G} \left(C_i \left(P_{i,t} \right) + C_{up} \left(x_{i,t}^{up} \right) + C_{down} \left(x_{i,t}^{down} \right) \right) + C_w \left(c_{w,t} \right) \right)$$

s.t. Power Balance Constraints (1)
Minimum Online Time Constraints for Thermal Units
Minimum Offnline Time Constraints for Thermal Units

In Eq. (1), C_i denotes the generation cost for thermal units and C_{up}, C_{down} is the start-up and shut-down cost, respectively. C_w is the penalty cost for wind power curtailment.

A. Only Traditional Day-ahead UC

- **Day1:**

Supposing that during the period of $T_{d1,1}$-$T_{d1,2}$ in Day1, the wind power output is extremely large so that the net load becomes smaller than the total minimum output for online units, shown in Eq.(2):

$$P_{L,t} \big|_{T_{d1,1}}^{T_{d1,2}} - P_{W,t} \big|_{T_{d1,1}}^{T_{d1,2}} < \sum_{i=1}^{N_G} P_{i,\min} \big|_{T_{d1,1}}^{T_{d1,2}}$$

(2)

Where $P_{L,t}$ is the system load and $P_{W,t}$ is the predicted wind power. N_G represents the number of online units and $P_{t,min}$ indicates the minimum output of unit i. In order to keep power balance, either some wind power should be curtailed or some thermal units should be shut down. When we were to make decision for Day1 in the frame of day-ahead UC, only the net load variation trend this day could be considered. Assumed that the wind power curtailment loss and thermal units' operation cost satisfy Eq. (3), unit i
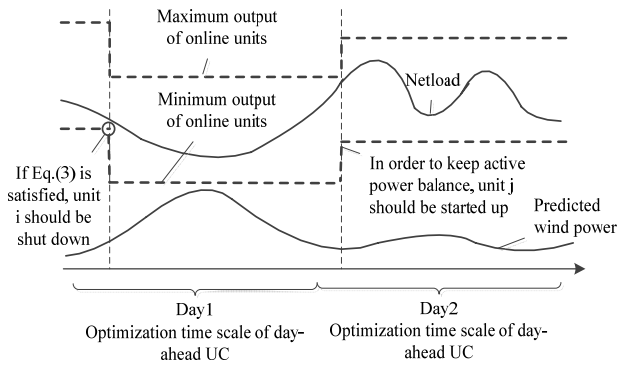
Fig. 1 Illustration of the DAUC mode only

could be shut down (see Fig. 1).

$$\int_{T_{d1,1}}^{T_{d1,2}} C_w\left(c_{w,t}\right)dt + \int_{T_{d1,1}}^{T_{d1,2}} \Delta C_1 dt \geq C_{down}\left(x_{i,T_{d1,1}}^{down}\right) + \int_{T_{d1,1}}^{T_{d1,2}} \Delta C_2 dt \quad (3)$$

In (3) ΔC_1 is the additional cost of thermal units because the load was supposed to be supplied by the curtailed wind power. ΔC_2 denotes the operating point regulation cost for other thermal units because some load carried by unit *i* should be redispatched to them. Then the total cost for thermal units is (C_0 is the original operation cost):

$$C_0 + C_{down}\left(x_{i,T_{d1,1}}^{down}\right) + \int_{T_{d1,1}}^{T_{d1,2}} \Delta C_2 dt \quad (4)$$

• **Day 2**

Supposing that during the period of $T_{d2,1}$-$T_{d2,2}$ in Day2, the wind power output is extremely small so that the net load becomes larger than the total maximum output for online units, as shown in Eq.(5):

$$P_{L,t}\big|_{T_{d2,1}}^{T_{d2,2}} - P_{W,t}\big|_{T_{d2,1}}^{T_{d2,2}} > \sum_{i=1}^{N_G} P_{i,\max}\big|_{T_{d2,1}}^{T_{d2,2}} \quad (5)$$

When we were to make decision for Day2 in the frame of day-ahead UC, unit j should be restarted to keep power balance(see Fig. 2).Then the total operation for thermal units in these two days can be expressed as:

$$C_0 + C_{down}\left(x_{i,T_{d1,1}}^{down}\right) + \int_{T_{d1,1}}^{T_{d1,2}} \Delta C_2 dt + C_{up}\left(x_{j,T_{d2,1}}^{up}\right) + \int_{T_{d2,1}}^{T_{d2,2}} \Delta C_3 dt \quad (6)$$

B. Mid-term UC

The UC decision is made based on the total net load trend variation of D days, and then the wind power variation on Day 2 would impact the units' on-off states in day1. In this case, during the period of $T_{d1,1}$-$T_{d1,2}$ on Day1 again, only if the wind power curtailment loss and thermal
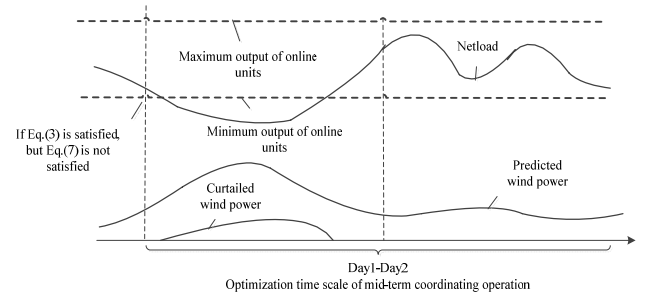
units' operation cost satisfy Eq. (7), could unit i be shut down.

$$\int_{T_{d1,1}}^{T_{d1,2}} C_w\left(c_{w,t}\right)dt + \int_{T_{d1,1}}^{T_{d1,2}} \Delta C_1 dt \geq$$
$$C_{down}\left(x_{i,T_{d1,1}}^{down}\right) + \int_{T_{d1,1}}^{T_{d1,2}} \Delta C_2 dt + C_{up}\left(x_{j,T_{d2,1}}^{up}\right) + \int_{T_{d2,1}}^{T_{d2,2}} \Delta C_3 dt \quad (7)$$

Comparing the difference between Eq. (7) and Eq. (3), it can be seen that in Eq. (7) the possible start-up cost for unit j in day 2 is considered. In the system with lots of large coal-fired units, the start-up cost is usually relatively large and it is less possible that unit i would be shut down. In this way, the unnecessary start-stop frequency of thermal units could be reduced (see Fig. 2).

In addition, if the operation mode is optimized only in day-ahead time scale, then unit i will be shut down at $T_{d1,1}$ when the operation costs satisfy Eq.(3). It is possible to happen that unit *i* cannot be started again because of the minimum offline time constraints during the low wind power output time period ($T_{d2,1}$-$T_{d2,2}$ in Day2), which might threaten the system security.

3. Multi-scale UC Model and Solution

3.1 Model for wind power uncertainty

Wind power uncertainty is usually described by fitting the wind power forecast error probability distribution model under different time scales [7-9]. Since the forecast methods, time scales and NWP accuracy both have great influences on the forecast errors, there is some commonly-used empirical distribution. If the forecast time scale is relatively short (e.g.1~60min), Cauchy distribution is usually adopted; on the contrary, if the forecast time scale is relatively long (e.g.24h), β distribution or normal distribution is used.

In the paper, we choose β distribution, which has the following advantages: First, the forecast error distribution is sometimes offset [8-9] and accordingly, β distribution can easily change its shape through adjusting the two

Fig. 2 Illustration of the MTUC mode

parameters. Second, the defined domain of β distribution is [0, 1] and the normalized forecast error exactly lies in this range. The paper adopts β distribution as empirical distribution, and then fits the probability distribution of positive error (measurement value>prediction value) and negative error (in absolute value) under different time scales, respectively.

3.2 Model for Mid-term UC

The detailed model for DAUC can be found in many materials, e.g. [11], so we just discussed the model for mid-term UC. In addition to the mid-term UC model, three constraints would be added: 1) The status of slow-start units should remain unchanged and only the operation points of those units can be regulated; 2) The status of flexible units could be adjusted according to the error between day-ahead and mid-term net-load forecast error; 3) In day-ahead operation, more accurate risk reserve constraint should be considered.

In this model, the wind power uncertainty is expressed as forecast error expectation value in the power balance constraints. The reserve constraints are established in probabilistic inequalities to take the wind power uncertainty into account in a large probability. The variables to be optimized are: 1) Operation state of thermal units i at period t. $I_{i,t}$, $I_{i,t}=1$ denotes online; 2) Binary indicator variable of thermal units i at period t $x^{up}_{i,t}$, $x^{down}_{i,t}$. $x^{up}_{i,t}=1$ denotes change from offline to online and $x^{down}_{i,t}=1$ denotes change from online to offline; 3) The power output of thermal units i at period t $P_{i,t}$; 4) Curtailed wind power at period t is denoted as $C_{w,t}$.

3.2.1 Time Scale of Mid-term UC

The time scale of mid-term operation is determined by the following two aspects in this paper: First, it should cover the start time and minimum offline/online time of slowest units. In addition, relatively reliable wind power forecast should be available. Considering the above two aspects, 3~7days is a good choice. As for China, commercial weather prediction service 3 or 4 days ahead is now available, and the time scale of mid-term UC is selected as 4 days in the following simulation cases in this paper. The effectiveness of this time scale will be discussed in Section 4.

3.2.2 The Objective Function

The objective is to minimize the total operation cost. In this objective function, wind power generation cost is not included because it is carbon-free, and as a result, the dispatching priority is given to wind power.

$$\min \sum_{d=1}^{D}\sum_{t=1}^{T}\left(\sum_{i=1}^{N_G}\left(C_i\left(P_{i,t}\right)+C_{up}\left(x^{up}_{i,t}\right)+C_{down}\left(x^{down}_{i,t}\right)\right)+C_w\left(c_{w,t}\right)\right)$$

(8)

T denotes the total time period in one day and N_G is the number of total online thermal units. $C_i(P_{i,t})=(a_iP_{i,t}^2+b_iP_{i,t}+c_i)\times I_{i,t}\times(\Delta T/60)\times K_{fuel}$ is the generation cost of thermal unit i where K_{fuel} is the fuel price. $C_w(C_{w,t})=K_{wc}\times C_{w,t}\times(\Delta T/60)$ is the penalty cost for wind power curtailment where K_{wc} is selected as wind power generation price in this paper. $C_{up}(x^{up}_{i,t})=K_{i,up}x^{up}_{i,t}$ and $C_{down}(x^{down}_{i,t})=K_{i,down}x^{down}_{i,t}$ denotes the start-up and shut-down cost, respectively.

3.2.3 Constraints

The model constraints include power balance constraints, risk reserve constraints, wind power curtailment constraints, thermal unit's output constraints, ramp rate constraints, and state variable and start-stop variable constraints, minimum online/offline time constraints. These constraints for thermal units are similar to the ones in classic UC model.

1) Power Balance Constraints

$$\sum_{i=1}^{N_G}P_{i,t}+E\left(P_{w,t}\right)=D_t$$
$$\rightarrow \sum_{i=1}^{N_G}P_{i,t}+P_{wf,t}+E\left(\varepsilon1_{wf,t}\right)+E\left(\varepsilon2_{wf,t}\right)-C_{w,t}=D_t$$

(9)

D_t is the load forecast value; $P_{wf,t}$ is the wind power forecast value and $P_{w,t}=P_{wf,t}+\varepsilon_{wf,t}-C_{w,t}$ is the scheduled wind power. $E(\varepsilon_{wf,t})$, $E(\varepsilon1_{wf,t})$ and $E(\varepsilon2_{wf,t})$ is the expectation value of total forecast error, positive error and negative error, respectively. Supposing that the $\varepsilon1_{wf,t}$ and $\varepsilon2_{wf,t}$ are independent, then $E(\varepsilon_{wf,t})=E(\varepsilon1_{wf,t})+E(\varepsilon2_{wf,t})$.

2) Reserve Constraint

$$P\left(\sum_{i=1}^{N_G}I_{i,t}P_i^{\max}+P_{wf,t}+\varepsilon2_{wf,t}-C_{wt}\geq(1+r_t^{up})D_t\right)\geq1-\alpha$$

(10)

$$P\left(\sum_{i=1}^{N_G}I_{i,t}P_i^{\min}+P_{wf,t}+\varepsilon1_{wf,t}-C_{wt}\leq(1-r_t^{down})D_t\right)\geq1-\beta$$

(11)

The risks of positive and negative error are considered in downward and upward reserve constraints, respectively. α and β is the risk for down/up reserve constraint, respectively; $P_i^{\max}$ and $P_i^{\min}$ denotes the maximum and minimum output for thermal unit, respectively; r_t^{up} and r_t^{down} denotes the upward and downward reserve rate, respectively.

Using the probability distribution of forecast error, the proposed probabilistic constraints could be transformed into determinate ones. The upward reserve constraints can be expressed as:

$$P\left(\varepsilon2_{wf,t}\leq\left(1+r_t^{up}\right)D_t-\sum_{i=1}^{N}I_i^tP_i^{\max}-P_{wf,t}+C_{w,t}\right)\leq\alpha$$

(12)

Supposing the absolute value of negative error satisfies one probability distribution and the corresponding Cumulative Distribution Function (abbr. CDF) is $F_2(X)$. Assuming that ε_2 is the α quantile of $F_2(X)$, that means $F_2(\varepsilon_2) = P(\varepsilon 2_{wf,t} \leq \varepsilon_2) = \alpha$, so Eq.(12) is equivalent equal to:

$$\left(1 + r_t^{up}\right) D_t - \sum_{i=1}^{N} I_i^t P_i^{\max} - P_{wf,t} + C_{w,t} \leq \varepsilon_2 \qquad (13)$$

Similarly, the down reserve constraints can be expressed in Eq. (14) given that $F_1(\varepsilon_1) = P(\varepsilon 1_{wf,t} \leq \varepsilon_1) = 1-\beta$:

$$\left(1 - r_t^{down}\right) D_t - \sum_{i=1}^{N} I_i^t P_i^{\min} - P_{wf,t} + C_{w,t} \geq \varepsilon_1 \qquad (14)$$

3) Wind Power Curtailment Constraints

$$0 \leq C_{w,t} \leq P_{wf,t} + E\left(\varepsilon 1_{wf,t}\right) + E\left(\varepsilon 2_{wf,t}\right) \qquad (15)$$

The curtailed wind power should not exceed the available wind power.

4. Simulation Results and Discussion

4.1 The test system design

4.1.1 Parameters of thermal units

This MTUC model is tested in the system mainly composing of large coal-fired units. Based on the data of IEEE-RTS96 [12], we construct the test system considering the typical characteristics of coal-fired units in China (Appendix A). In order to simulate the characteristic of high start-up cost, the start consumption is taken as 50 MBTU/MW and the stop consumption is chosen as 1/4 of it. In addition, considering that the minimum stable output of large coal-fired unit is high, this parameter is adjusted to 60%~65% of the rated output.

According to 3 different types of thermal units in IEEE-RTS96, the paper has changed the parameters of oil-fired unit to coal-fired unit. The simulation system with 6 units is built with the total capacity of 1599MW.

4.1.2 Wind power data

This paper assumes the time scale of mid-term coordinating operation as 4 days. The 0~72h forecast and measured power data are collected from the typical wind farms in north China during 2011.1~2012.4. .

4.1.3 Load data

A power grid in north China in 2011 winter is rated to the simulation system capacity.

4.2 Solution method

Referring to the coal price given by U.S. Energy Information Administration, this paper considers the coal price is \$ 62.47/t which equals to \$2.25/MBTU [13]. The wind power generation price is taken as \$80/(MW.h) which equals to 0.51RMB/(kW.h). This UC model is linearized according to the method in [14] and then solved using CPLEX.

4.3 The operation performance indices

The following indices are proposed to compare the optimal UC results in different cases.

4.3.1 Wind power utilization rate

$$k_w = \left(\left(E_w - E_w^c\right)/E_w\right) \times 100\% \qquad (16)$$

Where E_w is the available generation energy for wind power and E_w^c is the curtailed energy for wind power.

4.3.2 The total operation cost for unit power supply

$$C_{total}^{unit} = \frac{\sum_{i=1}^{T}\sum_{i=1}^{N_G} C_i(P_{i,t}) + \sum_{i=1}^{T}\sum_{i=1}^{N_G} C_i(x_{i,up}^t, x_{i,down}^t) + \sum_{i=1}^{T} C(C_{w,t})}{E_L} \qquad (17)$$

E_L is the total energy supply $E_L = \int_0^T D_t dt$.

4.3.3 The unit generation energy cost for thermal units

$$C_G^{unit} = \frac{\sum_{i=1}^{T}\sum_{i=1}^{N} C_i\left(P_{i,t}\right)}{E_G} \qquad (18)$$

Where E_G is the total generation energy for thermal units $E_G = \int_0^T P_{G,i} dt$

4.3.4 The net benefit for wind power

$$C_w^{benefit} = C_G^{total} - C_{total} \qquad (19)$$

Where C_G^{total} is the total generation cost for thermal units (fuel cost+ start-up/shut-down cost) without wind power and C_{total} is the cost with wind power under the same operation condition.

4.4 Simulation analysis

All the simulations are conducted in a high wind power

penetration system with total installed capacity of 693MW. The wind power capacity penetration (the installed capacity divided by the peak load) in the system is 50.41%.

4.4.1 Forecast uncertainty under different time scales

The feasibility of MTUC depends on the uncertainty of mid-term wind power forecast. As known to all, the wind power prediction precise decreases with the growth of time scale. In this section the forecast uncertainty under different time scales is compared to illustrate how the mid-term forecast data is used in this paper is acceptable.

The probability distributions of forecast uncertainty are shown in Fig.3 and the 90% quintiles of forecast uncertainty are given in Table 2.

It can be seen from Table 2 that even the 90% quantiles of 3 day-ahead forecast uncertainty are slightly larger than that of 1 day-ahead, but it is still acceptable in terms of mid-term UC.

We use wind forecast data in two ways: one is the prediction value, which indicates wind power available for dispatching, and the other is the forecast uncertainty, which mainly affects the operation of coal-fired units through probabilistic reserve constraints. Because the mid-term UC mainly focus on the online/offline status of large coal-fired units(mainly larger than 300MW in China) and even in a system with high wind power penetration (50.41% in this paper), the 90% quantiles of 3 day-ahead forecast uncertainty (132.29MW and -180.20MW) still can be handled through reserve without reregulating the online/offline status of most coal fired units in day-ahead operation.
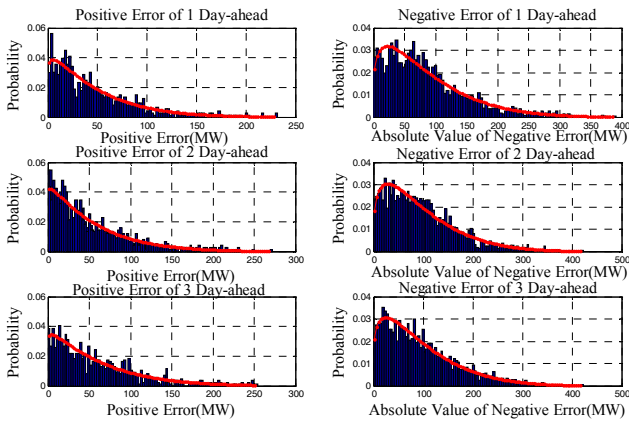

Fig. 3 Forecast uncertainty under different time scales

Table 2. 90% Quantiles of Forecast Uncertainty Probability Distribution

Positive error of 1 day-ahead 104.22MW 15.04%	Positive error of 2 day-ahead 120.16MW 17.34%	Positive error of 3 day-ahead 132.29MW 19.09%
Negative error of 1 day-ahead -149.20MW 21.53%	Negative error of 2 day-ahead -168.40MW 24.30%	Negative error of 3 day-ahead -180.20MW 26.00%

4.4.2 Validity of Mid-term UC under different wind power prediction uncertainty levels

In order to illustrate the validity of Mid-term UC, several simulations are conducted to compare the results of 3 day-ahead mid-term UC and day-ahead UC. These simulation results demonstrate that the operation schedules of most coal-fired units can be relatively accurately determined in mid-term schedule, which are significant to inflexible systems with high wind power penetration. After doing that day-ahead operation makes a few minor adjustments to the operation schedules of other relatively flexible units.

One example is shown in Figs. 4 and Fig. 5. Fig.4 shows the results of 3 day-ahead mid-term and day-ahead UC of one simulation day. In the case of Fig.5, the other conditions are kept the same as Fig. 4, except that the forecast uncertainty of mid-term operation is enlarged to 1.5 times as the original case.

The simulation results in Figs. 4 and Fig. 5 suggest that the online/offline status of most coal-fired units, especially for the slow start ones (350MW), can be relatively accurately determined in mid-term schedule. What's more, even through the mid-term forecast uncertainty is enlarged
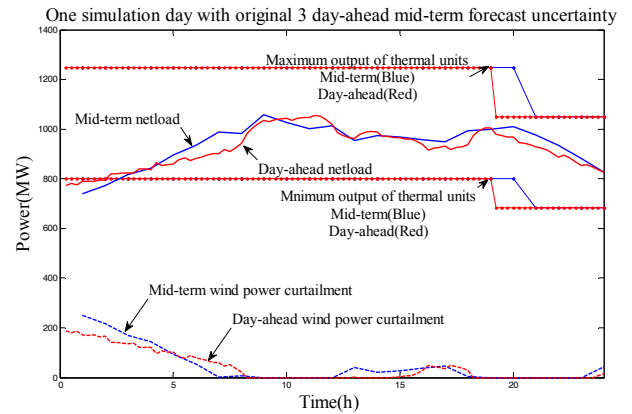

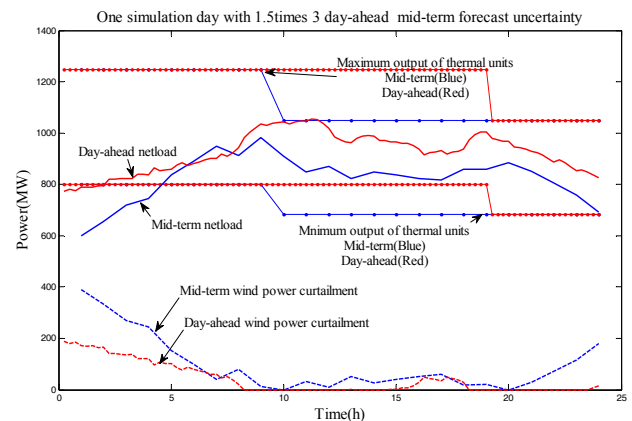**Fig. 4.** Results of one simulation day with original mid-term forecast uncertainty

Fig. 5. Results of one simulation day with 1.5times mid-term forecast uncertainty

to 1.5 times as the original case (shown in Fig. 5) the conclusion mentioned above is still applicable.

4.4.3 Benefits of the Mid-term UC

In order to compare the operation performance, two different cases are considered. In case 1, the MTUC proposed in this paper is adopted but in case 2 the unit scheduling of each day is decided by DAUC separately. Under the same sets of wind power fluctuation scene, UC simulation in case 1 and case 2 are done repeatedly. The operation performance indices are calculated averagely, shown in Table 3.

Table 3. The Average Operation Performance Indices

	k_w%	C_{total}^{unit} ($/MWh)	C_g^{unit} ($/MWh)	$C_w^{benefit}$ ($)
MTUC	80.91	35.30	20.27	377850
DAUC	82.77	35.59	20.36	342640

*Case 1: Mid-term UC; Case 2: Day-ahead UC separately

The simulation results suggest two important conclusions:

1) At first, the total operation cost for unit power supply and unit generation energy cost for coal-fired units are both higher in Case 2(35.59$/MWh and 20.36$/MWh, respectively). The reason is that in Case 2 only one day's operation cost is considered in the optimal objective and it is more possible to regulate the operation mode of coal-fired units to accommodate more wind power. Consequently, the on/off states and the operating points of coal-fired units are changed more frequently and sharply than that in Case 1 which of course results in higher operation cost.

2) In addition, the wind power utilization rate k_w in Case 2 is slightly higher than Case 1, which shows that MTUC would reduce the wind power utilization rate and the operation cost at the same time. This result demonstrates the fact that higher wind power utilization rate is not equal to lager coal saving benefit, which is an important characteristic of wind power accommodation in wind-coal intensive system. Just as the results of $C_{wbenefit}$ indicate, the benefit of wind power is reduced in Case 2 although it has a little larger wind power utilization rate, which is 377850$ in Case 1 whereas only 342640 $ in Case 2. More detailed information of two scenes is illustrated in Figs. 3-6 to testify the above conclusion. In the first scene, the wind power output is large on the second and fourth day but small on the first and third day. In the second scene, the wind power variation trend is opposite to the first one.

The results show that:

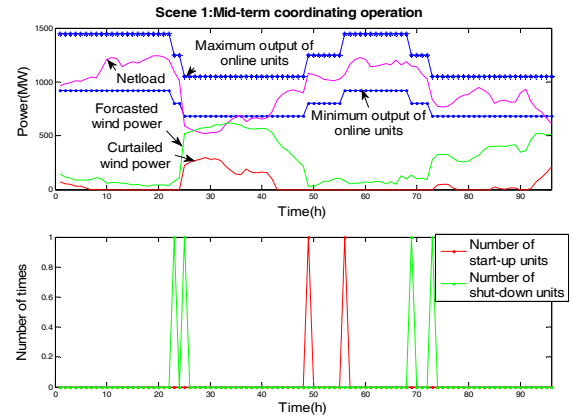1) At first, it is more possible to regulate the operation states of coal-fired units in DAUC. In this mode,

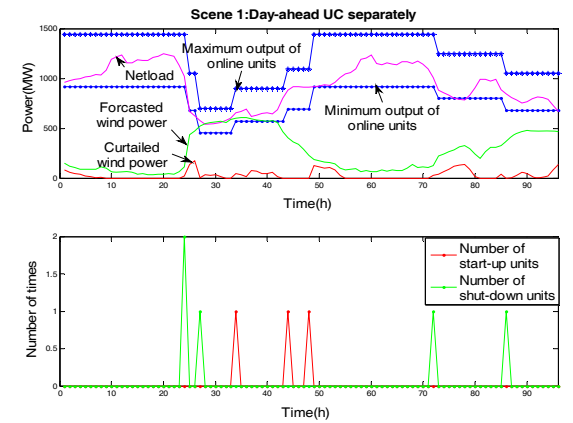**Fig. 6.** Results of mid-term coordinating operation in scene 1

Fig. 7. Results of day-ahead UC separately in scene 1
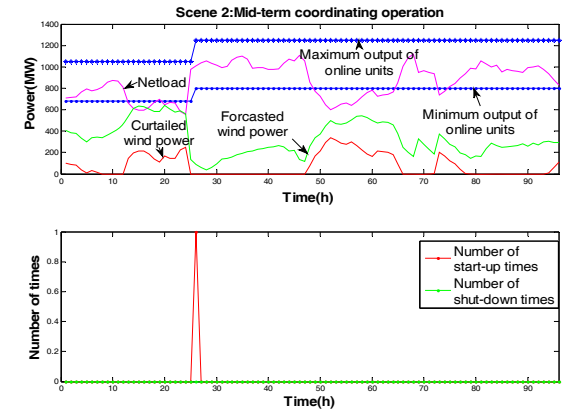

Fig. 8. Results of mid-term coordinating operation in scene 2

during the period with high wind power output, some units are shut down but restart again soon after that when wind power becomes relatively small. However, in the mode of MTUC, during some high wind power period, wind power curtailment is conducted instead of shutting down to avoid some units being restarted again.
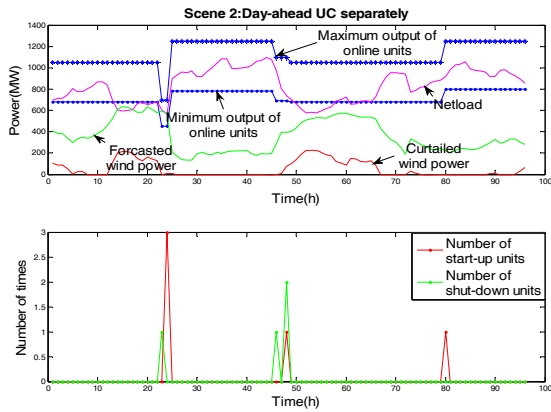
2) Secondly, the curtailed wind power is relatively larger

Fig. 9. Results of day-ahead UC separately in scene 2

in MTUC, especially during high wind power period to avoid shutting down some units. Even though it would reduce the total wind power utilization rate slightly, it also decreases the large coal consumption caused by units' on-off states change, which could maximum the wind power benefit as a whole.

5. Conclusion

The multi-scale unit commitment optimization which takes into account the operation states of large coal-fired units in high wind power penetration system is discussed in this paper. Through theoretical analysis and simulation cases, the following conclusions could be drawn:

(1) The multi-scale coordinating optimization operation mode is an important active power balance approach in the wind–coal intensive power system. The DAUC mainly focuses on scheduling the on-off states of flexible units next day, whereas the MTUC aims at arranging the operation states of units with long start-up time in the following several days.
(2) The MTUC could reduce the frequency of on/off states of coal-fired units, and in this way, cut down the total operation cost and improve the benefit of wind power.
(3) In the wind-coal intensive system, the coordinating operation mode between wind power and coal-fired units could pursue the minimal generation cost rather than the maximum wind power utilization rate. The wind power benefit is not proportional to the wind power utilization rate and the influence on coal-fired units should be considered.

Appendix A. Parameters of Thermal Units

Unit No.	Max Output (MW)	Min Output (MW)	Startup Consumption (MBTU)	Shutdown Consumption (MBTU)
1	350	227.5	17500	3500
2	350	227.5	17500	3500
3	350	227.5	17500	3500
4	197	118	9850	1970
5	197	118	9850	1970
6	155	93	7750	1550

Unit No.	Slope 1 (MBTU/MWh)	Slope2 (MBTU/MWh)	Power1 (MW)	Powe2 (MW)	Consumption at Minimum Output (MBTU/MWh)
1	8.4	8.8	52.5	70	9.1
2	8.4	8.8	52.5	70	9.1
3	8.4	8.8	52.5	70	9.1
4	9.1	9.5	39	40	9.85
5	9.1	9.5	39	40	9.85
6	9.5	10.1	31	31	10.25

Unit No.	Ramp Rate (MW/min)	Minimum Online (h)	Minimum Offline(h)
1	4	24	24
2	4	24	24
3	4	24	24
4	3	14	14
5	3	14	14
6	3	10	10

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Ying Qiao received the B.S. and Ph.D. degrees in electrical engineering from Shanghai Jiaotong Unverisity, Shanghai, and Tsinghua University, Beijing, China, in 2002 and 2008, respectively. She is now a lecturer of Electrical Engineering at Tsinghua University, Beijing, China, where she has been employed since 2010. Her research interests include renewable energy and power system security and control.

Zongxiang Lu (M'02) received the B.S. and Ph.D. degrees in electrical engineering from Tsinghua University, Beijing, China, in 1998 and 2002, respectively. He is now an associate Professor of Electrical Engineering at Tsinghua University, Beijing, China, where he has been employed since 2002. His research interests include power system reliability, renewable energy and microgrid, and large scale wind power integration.

Xi Ye (S'12) was born in Chongqing, China in 1987. She received the B.S. degree from college of Electrical and Information Engineering, Sichuan University, Chengdu, China in 2010. She is currently pursuing her Doctor's Degree in Electrical Engineering at Tsinghua University, Beijing, China. Her research interests include wind power integration operation and control