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Unit Commitment Comprehensive Optimal Model Considering the Cost of Wind Power Curtailment and Deep Peak Regulation of Thermal Unit

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ABSTRACT Clean renewable energy is given high priority to generate power in power system dispatching. Unfortunately, the objective to minimize wind power curtailment may results in additional costs, since the inverse peak regulation characteristic of wind power probably result in redundant power qualities curtailed to ensure the balance of the electric supply and demand in real time. In this paper, considering the cost of deep peak regulation of thermal unit and wind power curtailment, unit commitment comprehensive optimal model is proposed to minimize total cost by searching the optimal wind power curtailment. In order to achieve an economic strategy among the wind power curtailment and the deep peak regulation, two indexes including the amount of hourly optimal wind power curtailment and the critical value of comprehensive wind power curtailment are developed. Particle swarm optimization algorithm is employed for solving the proposed model. Afterwards, the relationship between the degree of deep peak regulation and the amount of wind power curtailment is researched, the derived conclusions can provide valuable information for system operators.

INDEX TERMS Wind power curtailment, deep peak regulation, unit commitment comprehensive optimal model, particle swarm optimization algorithm, system operators.

I. INTRODUCTION

In the structure of power sources, the thermal and wind power generations have taken a significant proportion in their respective kinds of power sources. In 2018, the accumulative power generation of China had been up to 7111.8TWh, among which thermal power generation occupied 66.5% and new energy power generation 634.2TWh, in addition, the wind power output constituted 57.7% of the whole new energy composition [1]. Thus, it is more meaningful to consider the impact of both the wind power generation and the thermal power generation at the same time on power system to ensure the economy of peak regulation.

Some troubles have been brought to the power system by the effect of the wind power due to the uncertainty of the wind speed. The fluctuation, intermittence along with the ability of inverse peak regulation for wind power pose a great challenge to the peak regulation [2]–[4]. In particular, when the wind power is in its highly output stage in the midnight, system operators may choose to shut down several thermal units to make use of the cheaper wind power, however, it although can reduce the generation cost in some extent rather than absolutely, but ignores the possibility of outage caused by relying excessively on the randomness of wind power for power supply, therefore, the coordinated peak regulation of the thermal units and wind turbine generators not only achieves the economy but also the reliability of the power system which would be a well tradeoff for system operation.

Based on the regulation of energy-saving dispatch [5], State Grid Corporation of China should prioritize the clean energy units and cheaper units according to their technical

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and economic characteristics to meet the requirements of the power balance, and avoid frequently starting and stopping thermal units, so as to operate them with satisfactory efficiency, the transformation of high capability thermal unit is paid much more attention due to its lower cost than that of the new built one.

The peak regulation ability mainly behaves in two aspects including peak regulation capacity and ramp rate, the former one represents the static characteristic if the overall unit capacities can be satisfied with the load requirement, it is realized by checking the electrical sufficiency for the power demand in each scheduling time interval. Therefore, it is essential to forecast the wind power and loads with enough accuracy to afford enough peak regulation capacity thus ensuring the safety and reliability of power system. So far, load forecasting has a satisfying accuracy in the presented literatures on the basis of mathematical theory [6]–[8], however, the accuracy of the wind output power forecasting is remaining to be furtherly improved [9], this paper takes the reserve capacity as an effective technique to cope with the issue of poor accuracy [10]. Another aspect, ramp rate, is utilized to dynamically trace the load variation in the adjacent scheduling time intervals. It majorly represents whether the load changes can be effectively caught by the power generations in time, If either of the above two aspects fails to meet the grid requirement, frequency oscillation and voltage instability may consequently happen.

At present, there are mainly two categories of reviews for the peak regulation from the regulatory point of view, namely the power demand side and the power supply side. As to the demand side, it is commonly based on the incentive measurements of policies that can bring about potential profits for both users and generators, the implement usually increases the electricity price in peak hours or reduce the price in valley hours to encourage users to adjust the power consumption time intervals [11]. As for the supply side, the transformation of capacity for the thermal unit and the reasonable arrangement of power source types is adopted to meet the peak regulation demand with economy. Specifically, the deep peak regulation ability acquired by thermal unit transformation can afford to somewhat additional electrical loads than the original one.

The thermal unit equipped with deep peak regulation ability shows that, except for the normal operation zone, it can still operate within the deep peak regulation zone which is limited between the normal minimum output power and the deep peak regulation bound determined by the unit transformation. Stable combustion without oil and with oil are two common types of deep peak regulation ability whose operation cost not only include coal consumption costs but also other additional costs. For instance, the costs of stable combustion without oil include the unit loss cost while the stable combustion with oil is constituted by environment cost and oil consumption cost apart from the unit loss. Due to the non-linear relationship between deep peak regulation cost and the active output power, the theory of subsection linearization for cost is employed in this paper to simplify the cost calculation.

Instead of taking the load curve as the original date, this paper utilizes the equivalent load curve for case study so that part of the wind output power is conserved for the proposed indexes calculation, the equivalent load curve is obtained by having the wind output power curve subtracted from the load curve in a scheduling period, when the conventional minimum output power value of the system is higher than the value of equivalent load curve in the corresponding scheduling intervals, the optimal output power point in the deep peak regulation zone and the corresponding amount of wind power curtailment is meaningful to be determined to achieve the lowest operation cost.

In [12], A methodology is developed for hydrothermal system generation scheduling in multiple provincial peak regulation demands by utilizing a novel load subsection optimization model to smooth local frequent load fluctuations. A peak regulation apportioning compensation approach with K-means employed to group and apportion units was first researched, the conclusion summarized that more units could be encouraged to participate in peak regulation via the proposed model [13]. Some significant advises for promoting wind power consumption were given to policy makers after taking the peak regulation constrains into account to evaluate the wind power accommodation capacity in [14]. In [15], An improved equivalent energy function approach for coordinating new energy resources and conventional energy to overcome the shortcoming of timing information loss was adopted. In [16], A multi-objective unit commitment model considering different demand between the operating cost and the negative peak load regulation ability was proposed, adequate scheduling scheme could be performed via this new model. A mathematical model of peak regulation strategy of pumped storage power station combined with wind-photovoltaic power generation was given in [17], which aimed at the target of complete consumption of wind and photovoltaic power generation. In [18], an optimization model based on unit commitment was presented from the perspective of both the power demand and supply side, which took special load as a reserve in peak regulation process.

There are lots of literatures about peak regulation study, a blank of coordinated optimization for wind power curtailment and the degree of deep peak regulation of thermal unit remains unexplored. In this paper, a unit commitment comprehensive optimal model considering wind power curtailment and deep peak regulation is proposed to obtain the optimal wind power curtailment with minimum cost, then two indexes including the amount of hourly optimal wind power curtailment and the critical value of comprehensive wind power curtailment are formulated to provide alternative guideline between the wind power curtailment and the deep peak regulation.

This paper is mainly organized as follows. In section II, a unit commitment comprehensive optimal model is proposed to determine the minimum cost. The amount of hourly optimal wind power curtailment and the comprehensive peak regulation value are defined in section III. Section IV provides the application of particle swarm optimization for the optimal model solution. The comparison and analysis of solutions is given in section V. section VI presents the valuable conclusion for system operators.

II. PEAK REGULATION OPTIMIZATION MODEL

In conventional scheduling strategy, the cost of deep peak regulation is usually not considered in the previous model, In the subsequently formulated model, both the cost of deep peak regulation and the wind power curtailment is taken into account:

$$\min \sum_{t=1}^{T}\sum_{i=1}^{N}\Big\{U_i^t[f_i(P_i^t)+U_i^t(1-U_i^{t-1})S_{i,\mathrm{up}} + U_i^t(1-U_i^t)S_{i,\mathrm{down}}] + x_iU_i^t g_i(P_{i,u}^t)+q(P_\mathrm{w}^t)\Big\} \tag{1}$$

$$f_i(P_i^t) = a_{i0} + a_{i1}P_i^t + a_{i2}(P_i^t)^2 \tag{2}$$

$$q(P_\mathrm{w}^t) = \rho_\mathrm{w} P_\mathrm{w}^t \tag{3}$$

where T is the scheduling period; N is the number of units; U_i^t is the on/off state of ith unit in time interval t (1 means on, 0 means off); $f_i(P_i^t)$ in formula (2) represents the coal consumption cost of the unit i in time interval t. where a_i, b_i and c_i are the coal consumption coefficient; P_i^t is the normal output power of the unit i in time interval t; $S_{i,\mathrm{up}}$ and $S_{i,\mathrm{down}}$ respectively represent the startup and shutdown cost of the unit i; $g_i(P_{i,u}^t)$ available in constraint (6) is the cost of deep peak regulation of unit i in time interval t; $q\left(P_\mathrm{w}^t\right)$ is the cost of wind power curtailment in time interval t where P_w^t is the wind power curtailment in the time interval t, and ρ_w is the cost of wind power curtailment per unit.

Except for satisfying with the conventional constraints like power balance, thermal unit output power, minimum on/off time and the ramp rate, the proposed model is also limited by the wind power output constraint, the upper reserve capacity demand constraint as well as the wind power curtailment constraint. These additional bounds are described as follows.

1) Wind power curtailment constraint

$$0 \le P_\mathrm{w}^t \le P_\mathrm{w,pr}^t \tag{4}$$

where $P_{w,pr}^t$ is the maximum generation of the wind turbine in the time interval t.

2) Upper reserve capacity demand constraint

$$\sum_{i=1}^{N} U_i^t(P_{i,\max} - P_i^t - x_iP_{i,u}^t) \ge R_\mathrm{uw}^t + \bar{r}_t \tag{5}$$

where $P_{i,max}$ is the maximum output power of the unit i, R_{uw}^t is the equivalent load in time interval t, and $\bar{r}_t$ is the upper reserve capacity in time interval t.

3) Deep peak regulation cost constraint

$$g_i(P_{i,u}^t) = \begin{cases} \rho_{i,1}P_{i,u}^t & P_{i,\mathrm{a}} < P_{i,u}^t \le P_{i,\min} \\ \rho_{i,2}P_{i,u}^t & P_{i,\mathrm{b}} < P_{i,u}^t \le P_{i,\mathrm{a}} \\ \rho_{i,3}P_{i,u}^t & P_{i,\mathrm{c}} < P_{i,u}^t \le P_{i,\mathrm{b}} \end{cases} \tag{6}$$

where $P_{i,\min}$ is the normal minimum output power of unit i; $P_{i,\mathrm{a}}$, $P_{i,\mathrm{b}}$ and $P_{i,\mathrm{c}}$ are the minimum output power of deep peak regulation of unit i at the first, second and third level respectively.

Four models are considered and solved including conventional scheduling model, deep peak regulation scheduling model without wind power curtailment, deep peak regulation scheduling model with complete wind power curtailment, and the proposed comprehensive unit commitment optimal model between wind power curtailment and the degree of deep peak regulation of thermal unit.

If the first term in equation (1) is merely considered and wind power is wholly consumed, then the model turns to be a conventional scheduling model. On the other hand, if the first two terms are concluded, that is, the deep peak regulation ability is additionally employed (deep peak regulation cost is expressed in second item in formula (1)) and at the mean time, the wind power is assumed to be completely consumed, then deep peak regulation scheduling model without wind power curtailment is established, this model indicates that when system equivalent load curve is lower than lower limit of the adjustable capacity of the original thermal units, some units may need not to shutdown but stay at the operation zone of deep peak regulation until the equivalent load is even lower, the significance of this model has a significance of effectively reduce frequent shutdown cost and startup cost of the thermal unit. For the above deep peak regulation scheduling model without wind power curtailment, if the overall wind power is discarded in contrast, deep peak regulation scheduling model with complete wind power curtailment is conserved. Although this model can effectively utilize the controllable deep peak regulation ability of the thermal power units and thus avoidance of the sudden frequency variations caused by the fluctuation and intermittent of wind power output, it still dismisses the advantage of the cheap cost characteristic of wind power.

Supposing that all the three terms in equation (1) are taken into account, a unit commitment comprehensive optimal model considering the cost of wind power curtailment and deep peak regulation of thermal unit is formulated. The reasons why the new established model has the performance of saving cost is elaborated as below: in the stage of low utilization of wind power like midnight, windy weather, the system has more wind power curtailment and thus the cost of curtailed wind power is relatively expensive, which will cause higher comprehensive operating costs. By contrast, when the availability of wind power is relatively high, i.e., the system has little wind power curtailment, in order to meet with the demand of equivalent load, the cost of thermal power generation will be also high which will also cause the total comprehensive operating cost increasing. Therefore, there must be a compromising solution that makes the cost of the comprehensive model lowest, the corresponding loss of wind power is determined as the optimal amount of curtailing wind power. Obviously, the solution of this model has important significance in making decision for system schedulers.

III. INDEX CALCULATION OF THE COMPREHENSIVE OPTIMIZATION MODEL

A. MINIMUM OUTPUT POWER CALCULATION OF CONVENTIONAL PEAK REGULATION

The system conventional peak regulation minimum output power contains relevant information to identify conventional peak regulation and deep peak regulation of thermal units, in the process of solving the comprehensive model, the minimum output power of conventional peak regulation is the sum of the minimum output power of all thermal power units in the system. For an equivalent load in a specific period, different peak regulation strategy will be considered if the thermal units equipped with different peak regulation abilities to reach the purpose of model minimization, i.e., when the equivalent load is below the boundary of system conventional peak regulation minimum output power, the units without the deep peak regulation ability will directly shutdown, while the units with such ability will allocate the load to their deep peak regulation capacity area until deep peak regulation lower boundary is reached.

B. CALCULATION OF DEEP PEAK REGULATION CAPACITY

In any time period, if the lower limit of the conventional peak regulation capacity is larger than the load, the deep peak regulation capacity is the absolute value of the conventional peak regulation margin, otherwise it is zero. The formula is as follows.

$$D_{\mathrm{UN}}^{t}=\begin{cases}\left|P_{\mathrm{Leq}}^{t}-P_{\min}^{t}\right|, & P_{\mathrm{Leq}}^{t}-P_{\min}^{t}<0\\ 0, & P_{\mathrm{Leq}}^{t}-P_{\min}^{t}\geq 0\end{cases} \tag{7}$$

where D_{UN}^{t} is the deep peak regulation capacity in time interval t, P_{Leq}^{t} is the net load in time interval t, D_{min}^{t} is the lower limit of conventional peak regulation capacity in time interval t.

Considering the peak regulation balance of power system, the relevant peak regulation indexes of the system integrated with wind power are described in Figure 1. As it can be seen that, in order to make the equivalent load curve stay above the minimum output power and avoid the excessive cost of startup and shutdown, on one hand, the normal peak regulation minimum output power can be shifted downwards, which is realized by flexibly reconstruct the thermal units to gain deep peak regulation ability; on the other hand, the wind can be curtailed to reduce the output power of wind turbine, so that the equivalent load curve is shifted upwards appropriately.

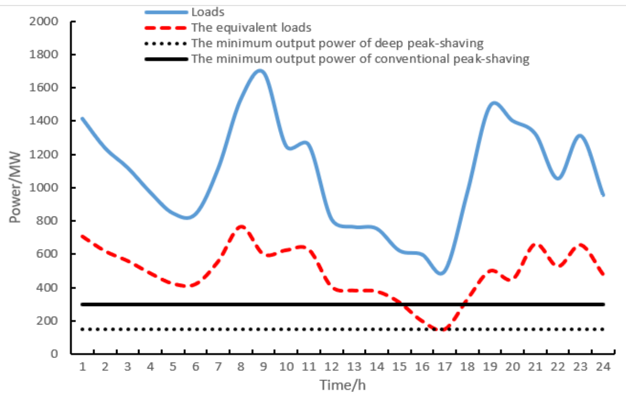

FIGURE 1. Peak regulation curve of power system.

C. CALCULATION FOR THE COST OF DEEP PEAK REGULATION AND WIND POWER CURTAILMENT

In a time period with zero deep peak regulation capacity, the load economical distribution can be realized by equal incremental principle so as to derive the optimal operation cost. Besides, in a time period with nonzero deep peak regulation capacity, the dispatching of deep peak regulation capacity can be reached by comparing the compromised cost of the wind power curtailment and the deep peak regulation with the shutdown cost, this optimal cost can be modeled as a linear programming subproblem and can be easily solved by dispatching nonzero deep peak regulation capacity. In the alternative strategy of optimization, if the compromised cost is more expensive than the shutdown cost, the corresponding thermal unit will shut down, Otherwise the coordination scheme is a reasonable choice.

D. AMOUNT OF HOURLY OPTIMAL WIND POWER CURTAILMENT AND CRITICAL VALUE OF COMPREHENSIVE WIND POWER CURTAILMENT

The amount of curtailing wind in each period corresponding to the optimal cost of the comprehensive model is defined as the amount of hourly optimal wind power curtailment $P_{t,\mathrm{loss}}^{\mathrm{op}}$. This index is satisfied: if $D_{\mathrm{UN}}^{t}>0$, then, $0\leq P_{t,\mathrm{loss}}^{\mathrm{op}}\leq D_{\mathrm{UN}}^{t}$; otherwise $P_{t,\mathrm{loss}}^{\mathrm{op}}=0$. This index can effectively indicate the optimal wind power curtailment in each time interval and provide an economic theoretical basis for short-term scheduling plans.

In order to comprehensively evaluate the peak regulation situation during the entire scheduling period, the critical value of comprehensive wind power curtailment is defined as follows (percentage value):

$$E=\sum_{t=1}^{T}P_{t,\mathrm{loss}}^{\mathrm{op}}\Big/\sum_{t=1}^{T}D_{\mathrm{UN}}^{t}(\%) \tag{8}$$

IV. MODEL SOLUTION BASED ON PARTICLE SWARM OPTIMIZATION ALGORITHM

Particle Swarm optimization algorithm is a parallel search algorithm based on population widely used in various system optimization fields [19]. This algorithm can search for multiple optimization results in the solution space in a run by the mutual cooperation of particles, including the optimal solution for the problem. The better performances of few parameters, good robustness to initial population, and easy implementation is widely accepted. This paper uses this algorithm to solve the proposed model.

A. ENCODING

Encode each particle with a binary matrix of size $N \times T$, element of the matrix represents the on/off state of the corresponding unit in specific time period, (0 denote on and 1 off). For instance, if the i row and j column element in the matrix is 1, which means the unit i is in on sate in the period j, and 0 the versus.

B. INITIAL POPULATION

Generate an initial population consists of L particles randomly, each particle is encoded by a $N \times T$ binary coding matrix.

C. MINIMUM UP/DOWN TIME STRATEGY

To dealing with the minimum on/off time constraints, the coding matrix is repaired by the minimize uptime or downtime strategy, more details can be seen in [20].

D. FITNESS VALUE

The reciprocal of the cost function value of the model to be solved is used as the fitness value to evaluate the quality of the particles. If the cost function value of the model is large, the fitness of the corresponding particles is low. On the contrary, its fitness is high.

E. TERMINATION CONDITION OF ALGORITHM

The discrepancy of the latest two fitness values of the adjacent iterations, choose the no longer changed former one as the maximum iteration number G.

F. APLLICATION OF PARTICLE SWARM OPTIMIZATION ALGORITHM

The procedures for particle swarm optimization algorithm application are described below:

1) Randomly generate L binary coding matrices and each matrix has a dimension of $N \times T$.

2) Each of the generated L matrices is repaired by the minimum up/down time strategy.

3) Calculate the fitness value of each particle matrix. The fitness value is the reciprocal of the cost function in a scheduling period.

4) Set each coding matrix as the individual extremum *pbest* of the particle, choose the particle with the largest fitness value and use its coding matrix as the global extremum *gbest*.

5) Update the particle velocity with the following formula:

$$v_{i,t,j}^{(k+1)} = \omega v_{i,t,j}^{(k)} + c_1\eta_1(pbest_{i,t,j} - u_{i,t,j}^{(k)}) + c_2\eta_2(gbest_{i,t} - u_{i,t,j}^{(k)})$$

$$i = 1, \cdots, N, t = 1, \cdots, T, \quad j = 1, \cdots L \quad (9)$$

where $\omega = \omega_{\max} - (\omega_{\max} - \omega_{\min}) \times g/G$, g is the indicator of iteration.

6) If $v_{i,t,j}^{(k+1)} > v_{\max}$, then $v_{i,t,j}^{(k+1)} = v_{\max}$; if $v_{i,t,j}^{(k+1)} < v_{\min}$, then $v_{i,t,j}^{(k+1)} = v_{\min}$.

7) Update the encoding matrix of the particle according to the following formula:

$$u_{i,t,j}^{(k+1)} = \begin{cases} 1 & rand() < S(v_{i,t,j}^{(k+1)}) \\ 0 & \text{others} \end{cases} \quad (10)$$

where *rand* () is a random number between (0,1); S () is a fuzzy transfer function.

8) Repair the coding matrix of the new particles with minimum up/down time strategy and calculate the fitness value of each repairable particle. If the fitness value of the new particle is better than that of the previous individual extreme value, the current encoding matrix of this particle is renewed as the individual extreme value *pbest*.

9) Select the particle with the maximum fitness value among all the *pbest* and take it as the global optimum value *gbest*.

10) If the indicator g is large than the maximum value G, the algorithm terminates. *gbest* is the objective function value of the model; otherwise, go to step 5) and recalculate.

TABLE 1. Peak regulation capacity and cost.

The degree of deep peak regulation	Peak regulation capacity	Peak regulation cost per unit ($/kWh)
First level	80%-100%Pmin	0.1
Second level	60%-80%Pmin	0.3
Third level	40%-60%Pmin	0.6
Wind power curtailment	Wind power generation ability	0.57

V. CASE STUDY

In this section, Power system with 10 thermal units is considered for the model solution, the parameters of thermal units without deep peak regulation ability are shown in [21]. The unit ramp rate is set to 3% the maximum output power and the upper reserve capacity is 10% the equivalent load. As the parameters for particle swarm optimization algorithm, G is set to 2000, L is set to 100, $\omega_{\max}$ and $\omega_{\min}$ are associated with 0.8 and 0.3 respectively, $v_{\max}$ and $v_{\min}$ are assumed to be 300 and −300 respectively. The accelerated constants c_1 and c_2 are both set to 200. This paper assumes that all the thermal units are equipped with the deep peak regulation ability for the proposed model, the degree of deep peak regulation capacity for thermal units and the corresponding cost per unit are shown in table 1.

The scheduling period T is 24 hours and each hour is considered as a scheduling time interval. The loads and the

TABLE 2. Power loads for 24 hours.

No.	Load（MW）	No.	Load（MW）
1	1414	13	88
2	1238	14	78
3	1120	15	59
4	972	16	87
5	847	17	494
6	842	18	971
7	1116	19	1489
8	1531	20	1401
9	1691	21	1323
10	1249	22	1054
11	1256	23	1312
12	812	24	956

TABLE 3. Maximum wind power capacity for 24 hours.

No.	The maximum generation capacity of wind power （MW）	No.	The maximum generation capacity of wind power （MW）
1	76	13	43
2	87	14	52
3	78	15	54
4	68	16	43
5	63	17	35
6	59	18	68
7	98	19	104
8	107	20	98
9	140	21	93
10	110	22	98
11	112	23	92
12	57	24	67

TABLE 4. The capacity of deep peak regulation (12-16h).

	12h	13h	14h	15h	16h	else
Hourly deep peak-shaving margin (MW)	125	395	414	435	396	0

maximum wind power capacity are shown in Table 2 and Table 3, respectively.

The minimum output power of conventional peak regulation for the power system is 440 MW, which is the sum of the normal minimum output power of 10 units. When the difference between the equivalent load and the minimum output power of conventional peak regulation is positive, the stage of conventional peak regulation is performed. Otherwise, deep peak regulation stage is activated. The deep peak regulation capacity is shown in Table 4.

TABLE 5. Solution comparison of different models.

	The optimal cost ($)	The total wind power curtailment (MW)
Conventional scheduling model	79897.0	0
Deep peak regulation scheduling model without wind power curtailment	79877.7	0
Deep peak regulation scheduling model with complete wind power curtailment	98426.7	1765
The proposed model	79858.4	936

TABLE 6. Amount of hourly optimal wind power curtailment and corresponding cost.

	12h	13h	14h	15h	16h
The amount of hourly optimal wind power curtailment (MW)	0	219	238	259	220
The cost of wind power curtailment ($)	0	124.8	135.7	147.6	125.4

In this paper, the conventional scheduling model, the deep peak regulation scheduling model without wind power curtailment and the deep peak regulation scheduling model with complete wind power curtailment are addressed respectively. The optimum cost and the associated total wind power curtailment are shown in Table 5. More concretely, the amount of wind power curtailment from time interval 12 to 16 and the corresponding cost are given in Table 6.

It can be seen from Table 5 that the optimal cost of the model proposed in this paper is $38.6 lower than the conventional scheduling model, because the deep peak regulation model reduces the startup and shutdown cost. The optimal cost of the proposed model is $19.3 and $18568.2 cheaper than the deep peak regulation scheduling model without wind power curtailment and deep peak regulation scheduling model with complete wind power curtailment respectively, this is ascribed to the following two points: (a) The wind power curtailment cost per unit is between first level and the second level of deep peak regulation, in other words, the first and second level are prioritized for cost savings. (b) The load with complete wind power curtailment is much higher than the equivalent load. These data comparison verifies that the model proposed in this paper can effectively reduce the total cost, thus bringing about potential appreciable economy in scheduling plan.

The critical value of comprehensive wind power curtailment in a scheduling period is 53.03%, that is, it is more reasonable to curtail total 936MW wind power to achieve the optimal cost. The amount of hourly optimal wind power curtailment is shown in Table 6. For thermal power plant, under the consideration of the time intervals when deep peak regulation margin is more than 176MW, if the average peak regulation degree is higher than 42.9%, the wind curtailment scheme is beneficial to saving cost, otherwise, the deep peak regulation scheme is more attractive.

VI. CONCLUSION

In this paper, a comprehensive unit commitment optimal model between wind power curtailment and the degree of deep peak regulation of thermal unit is proposed to acquire the optimum dispatching cost by determining the amount of wind power curtailment. To evaluate the effectiveness and economy of the proposed model, three other models, conventional scheduling model, deep peak regulation scheduling model without wind power curtailment as well as deep peak regulation scheduling model with complete wind power curtailment are introduced and solved. Comparison results prove that the proposed model is beneficial to system operators for saving cost. Moreover, two indexes including the amount of hourly optimal wind power curtailment and the critical value of comprehensive wind power curtailment are also formulated to give an economic alternative between the scheme of wind power curtailment and deep peak regulation of thermal unit. However, the uncertainty of wind power and the impact of the peak regulation cost have not been considered, these two factors will be taken into account furtherly in the future work.

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