



# Cleaning Model of Spot Electric Energy Market Considering Improved Flexible Ramping Product

Hui Li<sup>1,a</sup>, Xiaojing Hu<sup>2,b</sup>, Lin Ye<sup>3,c</sup>, Yi Lu<sup>2</sup>, Qiang Ding<sup>2</sup>

<sup>1</sup>Automation of School, Beijing Information Science & Technology University, Beijing 100192, China

<sup>2</sup>Beijing Key Laboratory of Research and System Evaluation of Power Dispatching Automation Technology, Beijing 100192, China

<sup>3</sup>College of Information and Electrical Engineering, China Agricultural University, Beijing 100083, China

<sup>a</sup>lhbxxy@bistu.edu.cn, <sup>b</sup>huxiaojing@epri.sgcc.com.cn, <sup>c</sup>yelin@cau.edu.cn

**Abstract.** For solving some problems such as high operating costs caused by high penetration wind power and insufficient system ramping capacity caused by wind power uncertainty, a cleaning model of spot electric energy market considering improved flexible ramping product is present. The objective function of this model is to minimize the total cost of purchasing electric energy, flexible ramping product and wind curtailment penalty. The innovation of this model is to take into account the impact of the generators' start-up and shut-down process on the flexible ramping speed constraints, and the impact of net load fluctuations on flexible ramping ability constraints, so that the ladder-type instruction of the power generation plan is closer to reality. The effectiveness of the proposed clearing model is verified by a simple test system

**Keywords:** spot market; wind power consumptive; flexible climbing; wind curtailment penalty; cleaning model.

## 1 Introduction

The over-exploitation and non-renewable of traditional fossil energy sources have exacerbated the world's energy depletion and damaged the Earth's living environment. Therefore, accelerating the energy transition has become the top priority of the world to realize sustainable development, and it is also a necessary way to achieve the goal of "dual-carbon". Wind energy has the advantages of being green, low-carbon, renewable, and easy to obtain, and occupies a mainstream position in the energy transition and is highly favored. However, affected by meteorological factors, wind power output has strong intermittency, randomness and volatility, making it more difficult to balance power supply and demand, and the system is required to have better flexible resource regulation capabilities to ensure that the system can realize the grid connec-

tion and consumption of large-scale wind power under the premise of safe and stable operation.

In recent years, some independent system operators in the U.S. have introduced Flexible Ramping Product (FRP) [1-3] to solve the problem of insufficient regulation of flexible resources. Literature [4] proposed a FRP based on ramping capacity calibration to stimulate the flexible regulation of generation resources, but it improved the ramping capacity through "repeated calibration-added constraints", which increased the computation time and reduced the operational efficiency. Literature [5] presented a model for the participation of electric and thermal systems in a joint ancillary services market for energy and flexible ramping products for clearing. Literature [6] put forward a joint FRP provisioning mechanism that simultaneously considers real-time generation capacity and day-ahead spinning reserve service, which significantly improves the performance of FRP and enhances the flexibility of system operation. Literature [7] designed an enhanced FRP based on the existing day-ahead market model to improve the flexibility of the system and the fast response of available resources.

However, the above literature only consider the flexible ramping rate constraints and capacity constraints when the unit is running in the output state, ignoring the ramping rate constraints when the start-up/shut-down process, as well as the negative impacts of the unit's start-up/shut-down process on the system's flexible ramping capacity constraints. To solve the above problems, this paper proposes a spot power market clearing model that takes into account improved FRP and wind curtailment penalties.

## 2 Improved flexible climbing rate constraints

In the traditional clearing model, only considering the upward/downward ramping rate constraints for unit  $i$  in the outgoing state, it is not appropriate when unit  $i$  is in the start-up process or the shut-down process. The reason is that the unit can only provide a single-direction ramping rate constraint during startup/shutdown process. Therefore, the improved ramping rate constraints considering unit  $i$  the start-up/shut-down process is obtained in this paper, namely equation (1) and (2).

$$\begin{cases} P_{i,t+1} - P_{i,t} \leq \Delta P_i^U & P_{i,t+1} > P_{i,t} \geq P_i^{\min} \\ P_{i,t+1} - P_{i,t} \leq \Delta P_i^{SU} & P_i^{\min} \geq P_{i,t+1} > P_{i,t} \end{cases} \quad \forall i, t \quad (1)$$

$$\begin{cases} P_{i,t} - P_{i,t+1} \leq \Delta P_i^D & P_{i,t} > P_{i,t+1} \geq P_i^{\min} \\ P_{i,t} - P_{i,t+1} \leq \Delta P_i^{SD} & P_i^{\min} \geq P_{i,t} > P_{i,t+1} \end{cases} \quad \forall i, t \quad (2)$$

where,  $\Delta P_i^{SU}$  and  $\Delta P_i^{SD}$  are the start-up ramping rate and shut-down ramping rate for unit  $i$  each 15 minutes, respectively.

Equation (1) shows that, if unit  $i$  is in the output state at both  $t$  and  $t+1$  moments (both outputs are more than the minimum operating output), the change in output should be no more than the upward ramping rate; if unit  $i$  is in the start-up process at the time period of  $t \sim (t+1)$  ( the output at the time period of  $t+1$  is no more than the

minimum operating output), the change in output should be no more than the start-up ramping rate.

Equation (2) shows that if unit  $i$  is in a power outage at both  $t$  and  $t+1$ , the change in power outage during the down ramping should be no more than the down ramping rate; if unit  $i$  is in a shut-down process at  $t \sim (t+1)$  (the power outage at  $t$  is no more than the minimum operating power outage), the change in power outage during the down ramping should be no more than the shut-down ramping rate.

### 3 Improved flexible ramping capacity constraints

In addition to the unit ramping rate constraints in the output state, start-up and shut-down process, system ramping capacity constraints are need due to the variability and uncertainty of the net load. The system has to reserve a certain amount of ramping capacity in advance in order to ensure the balance of supply and demand due to the insufficient ramping capacity in the next moment.

The improved flexible ramping capability constraints proposed in this paper take into account both the upward/downward ramping capability during the operating condition and the ramping capability during the start-up/shut-down process. Figure 1 shows a schematic diagram of the unit climbing capability. As an example, when unit  $i$  is in the power state at time  $t$ , if it is located at point a1, the upward climbing capacity is  $P_i^{\max} - P_{i,t}$ . If it is located at point a2, the upward ramping capacity is  $\Delta P_i^U$ . When unit  $i$  is in the starting process (point a1), the upward ramping capacity is  $\Delta P_i^{SU}$ . Thus, the expressions for the upward and downward climbing capacities that unit  $i$  can provide at moment  $t$  are shown as equation (3).

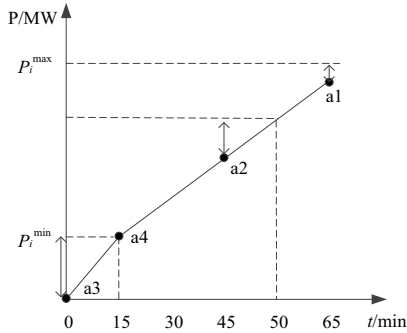


Fig. 1. Diagram of generator ramping capacity

$$\begin{cases} \Delta P_{i,t}^U = \min(P_i^{\max} - P_{i,t}, \Delta P_i^U)u_{i,t} + \Delta P_i^{SU}(1 - u_{i,t}) \\ \Delta P_{i,t}^D = \min(P_{i,t} - P_i^{\min}, \Delta P_i^D)u_{i,t} + \Delta P_i^{SD} \frac{1 - \text{sgn}(P_{i,t} - P_i^{\min})}{2} \end{cases} \quad \forall i, t \quad (3)$$

where,  $\Delta P_{i,t}^U$  and  $\Delta P_{i,t}^D$  are the upward and downward climbing capacities available to unit  $i$  at moment  $t$ , respectively;  $\text{sgn}(\cdot)$  is the sign function.

Further, if unit  $i$  is shut-down/start-up state at the next moment, it has only downward/upward ramping capability but loses upward/downward ramping capability, namely it causes negative impact to the upward/downward ramping capability. For example, if unit  $i$  is at minimum operating output at time  $t$  (point a4 in Fig. 1) and is taken out of service at time  $t+1$  due to the previous day's planned dispatch, and the system needs to provide upward ramping at this time, but the unit loses its upward ramping capability,  $P_{i,t}^{\text{stop}} = (u_{i,t} - u_{i,t+1})\Delta P_i^U$ . In other words, it is equivalent to unit  $i$  having a negative impact on the system's upward ramping capability at time  $t+1$ . If the unit is not shut-down,  $P_{i,t}^{\text{stop}} = 0$ . Similarly, if unit  $i$  is at point a4 in Fig.1 at moment  $t$  and is put into operation at moment  $t+1$ , when the system is required to provide downward ramping, it loses its downward ramping capability, which will have a negative impact on the system's downward ramping capability. At this time, the negative impact of the shut-down/start-up unit on the upward/downward ramping capacity of the system can be expressed as equation (4).

$$\begin{cases} P_{i,t}^{\text{stop}} = \max\{(u_{i,t} - u_{i,t+1})\Delta P_i^U, 0\} \\ P_{i,t}^{\text{start}} = \max\{(u_{i,t+1} - u_{i,t})\Delta P_i^D, 0\} \end{cases} \quad \forall i, t \quad (4)$$

where,  $P_{i,t}^{\text{stop}}$  indicates the negative impact of unit  $i$  is exit at moment  $t+1$  on the upward climbing capacity;  $P_{i,t}^{\text{start}}$  denotes the negative impact of unit  $i$  is input at moment  $t+1$  on downhill climbing capacity.

Combining equation (3) and (4), the combined ramping capacity that can be provided by the system is obtained, which should be more than the system's ramping capacity requirements, namely equation (5).

$$\begin{cases} \sum_{i=1}^N (\Delta P_{i,t}^U - P_{i,t}^{\text{stop}}) \geq \Delta P_{\text{sum},t}^U \\ \sum_{i=1}^N (\Delta P_{i,t}^D - P_{i,t}^{\text{start}}) \geq \Delta P_{\text{sum},t}^D \end{cases} \quad \forall t \quad (5)$$

Where,  $\Delta P_{\text{sum},t}^U$  and  $\Delta P_{\text{sum},t}^D$  are the upward and downward flexible ramping capacity demands caused by the predicted net load at moment  $t$ , respectively, which contains both variability and uncertainty, the former being the difference between the predicted net loads at the two moments, reflecting the variability of the net loads, and the latter being the uncertainty of the net loads due to the wind power prediction deviations can be expressed as equation (6).

$$\begin{cases} \Delta P_{\text{sum},t}^U = \max\{((P_{t+1}^L - P_{t+1}^{WF}) - (P_t^L - P_t^{WF})) + \alpha_{t+1}, 0\} \\ \Delta P_{\text{sum},t}^D = \max\{((P_t^L - P_t^{WF}) - (P_{t+1}^L - P_{t+1}^{WF})) + \alpha_{t+1}, 0\} \end{cases} \quad \forall t \quad (6)$$

where,  $\alpha_{t+1}$  is wind power forecasting deviation power. In this paper, take  $\alpha_{t+1} = \beta_w P_{t+1}^{WF}$ .

## 4 Improved objective function

Through the introduction of flexible climbing products, the reserve capacity for the net load uncertainty can be reduced, so the positive/negative reserve demand of the system in the objective function of the traditional clearing model is follows as equation (7).

$$\begin{cases} P_t^{\text{pr}} = \max \left( \beta_w \cdot \sum_{i=1}^M P_{i,t}^{\text{W}} + \beta_c \cdot \sum_{i=1}^N P_{i,t} - \sum_{i=1}^N (\Delta P_{i,t}^{\text{U}} - P_{i,t}^{\text{stop}}), 0 \right) \\ P_t^{\text{nr}} = \max \left( \beta_w \cdot \sum_{i=1}^M P_{i,t}^{\text{W}} - \sum_{i=1}^N (\Delta P_{i,t}^{\text{D}} - P_{i,t}^{\text{start}}), 0 \right) \end{cases} \quad \forall t \quad (7)$$

Thus, after considering the improved ramping rate constraints, system ramping capacity constraints, and the new system reserve requirements, the objective of minimizing the total cost of purchasing electricity and flexible ramping auxiliary services is obtained as equation (8), also adding the wind curtailment penalty cost to achieve the grid-connected consumption of a high percentage of wind power.

$$\begin{aligned} \min f_1 = & \sum_{t=1}^T \sum_{i=1}^N \left[ 0.25 C_{i,t} (P_{i,t} - u_{i,t} P_{i,t}^{\text{min}}) + C_{i,t}^{\text{NL}} u_{i,t} + C_{i,t}^{\text{SU}} v_{i,t} + C_{i,t}^{\text{SD}} w_{i,t} \right] + \sum_{t=1}^T 0.25 \left[ C_t^{\text{pr}} P_t^{\text{pr}} + C_t^{\text{nr}} P_t^{\text{nr}} \right] \\ & + \sum_{t=1}^T \sum_{i=1}^M (0.25 C_i^{\text{W}} P_{i,t}^{\text{W}}) + \sum_{t=1}^T \sum_{i=1}^M \left[ \lambda_i (P_{i,t}^{\text{WF}} - P_{i,t}^{\text{W}}) \right] + \sum_{t=1}^T \left[ C_t^{\text{ra}} \sum_{i=1}^N (\Delta \hat{P}_{i,t}^{\text{U}} + \Delta \hat{P}_{i,t}^{\text{D}}) \right] \end{aligned} \quad (8)$$

where,  $\lambda_i$  is curtailment penalty cost at wind farm  $i$ ;  $C_t^{\text{ra}}$  is ramping capacity price at moment  $t$ ;  $\Delta \hat{P}_{i,t}^{\text{U}}$  and  $\Delta \hat{P}_{i,t}^{\text{D}}$  are the actual upward and downward ramping plans for unit  $i$  at time  $t$ , respectively.

Combining equation (1)~(8) and the conventional constraints of traditional clearing models [4], the proposed spot electricity energy market clearing model is obtained in this paper, which takes into account the flexible ramping auxiliary services and wind curtailment penalties. The nonlinear mixed-integer programming problem can be calculated by using the high-performance solvers, such as CPLEX, GUROBI, CMIP, and so on.

## 5 Simulation results

In order to verify the validity of the proposed model in this paper, a simple test system is used for comparative analysis. In the example, the line loss rate is taken as 3.69%, the generation reserve coefficient for thermal generator is  $\beta_c = 0.05$ , and the generation reserve coefficient for wind turbine generator (WTG) is taken as  $\beta_w = 0.2$  (i.e., the wind power prediction error is 20%). Table 1 shows the various cost data. The simulation results are calculated by the yalmip optimization package with an Intel Core i5-11400 and 16GB of RAM.

**Table 1.** Various cost data.(Unit: RMB/MW·h)

Category	Value
wind turbine generation cost	350
wind curtailment penalty cost	200
positive reserve cost	200
negative reserve cost	110
ramping capacity upper limit	100

The following four models were used for testing. Model 1 is the traditional clearing model, considering only the traditional single machine ramping rate constraint. Model 2 is a clearing model that only considers improved ramping rate constraints. Model 3 is a clearing model that only considers improving ramping ability constraints. Model 4: the method proposed in this paper, namely a clearing model considering improved ramping rate and ramping capability constraints.

Simple test system concludes four thermal generators (G1~G4) and one WTG, where the WTG are rated at 100 MW. Table 2 shows the data table for each thermal power unit. Table 3 shows the wind generation forecast data and load forecast data between day-ahead 11:00 and 14:00, where the wind penetration is about 10%. It is assumed that all four units are running in the initial state (i.e.,  $u_{i,0}=1$ ,  $i=1,2,3,4$ ) and the initial value of WTG is 40 MW.

**Table 2.** Generator data of simple test system

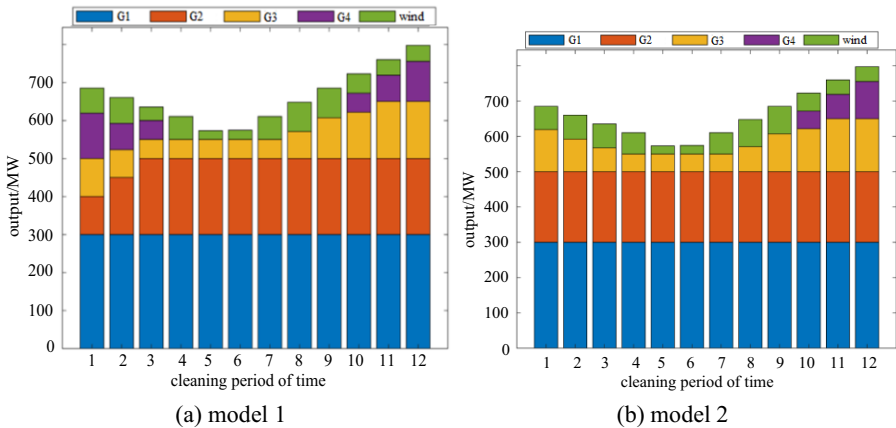
Category	Unit	G1	G2	G3	G4
generation cost	RMB/MW·h	0	140	280	420
no-load cost	RMB	0	7000	14000	28000
start-up cost	RMB	0	2100	4200	6300
shut-down cost	RMB	0	700	1400	2100
maximum output	MW	300	200	150	200
minimum output	MW	300	50	50	50
start-up ramping rate	MW/15'	0	50	50	50
shut-down ramping rate	MW/15'	0	50	50	50
upper ramping rate	MW/15'	0	45	45	45
down ramping rate	MW/15'	0	45	45	45
minimum startup duration	h	1	1	1	1
minimum downtime duration	h	1	1	1	1
initial value	MW	300	50	50	150

**Table 3.** Forecasting data of wind power and load

time	wind power	load power	wind power forecasting error	time	wind power	load power	wind power forecasting error
11:00	66	660	13.2	12:30	75	588	15.0
11:15	68	636	13.6	12:45	77	624	15.4
11:30	68	612	13.6	13:00	78	660	15.6
11:45	66	588	13.2	13:15	51	696	10.2
12:00	68	552	13.6	13:30	41	732	8.2
12:15	69	553	13.8	13:45	42	768	8.4

Fig. 2 gives a planned output of each unit under the four models. As can be seen in Fig. 2, G2 to G4 are ramping in model 1 and 3 for the first three clearing periods, while G2 are full, G3 is ramping, and G4 is shut-down in model 2 and 4, indicating that the improved flexible ramping rate constraints in model 2 and 4 reduces the ramping cost and no-load cost.

In order to highlight more the advantages of the models proposed in this paper, Table 4 gives a comparison of the total cost and each sub-cost under the four models. As can be seen in Table 4, Model 2 reduces the no-load cost, ramping cost and wind curtailment penalty cost by 16.67%, 15.03% and 22.89%, respectively, compared to Model 1, resulting in a reduction of the total cost by 6.86%, but with a slight increase in the standby cost. Model 3 reduces the reserve cost to zero compared to Model 1, using the improved flexible ramping capacity.



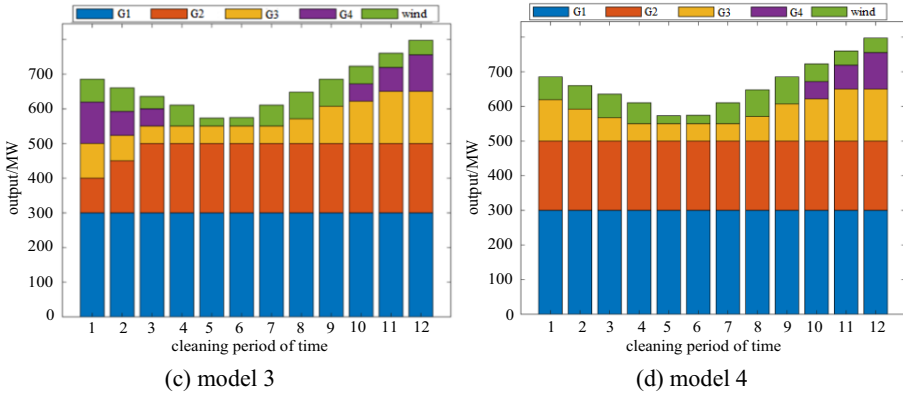


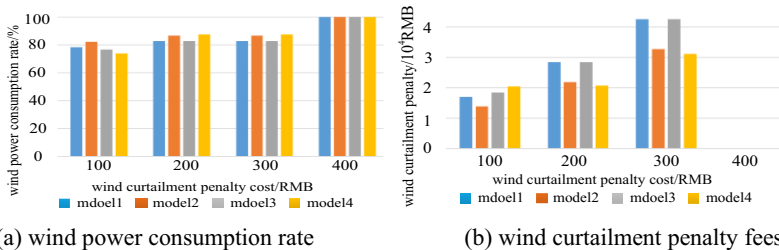
Fig. 2. Clearing results of generators under four models

constraint, and the total cost is reduced by 1.67% as the rest of the costs remain unchanged. Model 4 synthesizes the advantages of Models 2 and 3, which reduces both the ramping cost and no-load cost, as well as the wind curtailment penalty cost and reserve cost, resulting in a reduction of the total cost by about 7.18%. At the same time, the significant reduction in standby capacity can lead to a reduction in the primary investment cost of power plant construction.

Table 4. Comparison of economy under simple test system. (Unit: 10<sup>4</sup>RMB)

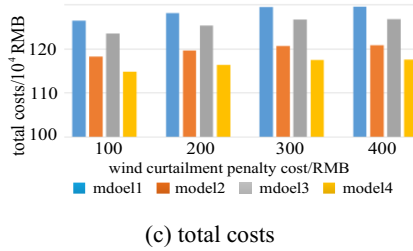
cost details	Model 1	Model 2	Model 3	Model 4
total costs	127.1	118.5	125.3	116.4
thermal costs	41.79	41.74	41.79	41.73
no-load costs	37.8	31.5	37.8	31.5
start-up and shut-down costs	0.84	0.84	0.84	0.84
reserve costs	1.81	2.12	0	0
ramping costs	20.03	17.02	20.03	17.02
wind power costs	21.95	23.09	21.95	23.11
wind curtailment penalty costs	2.84	2.19	2.84	2.17

In order to further explore the consumption capacity of the model proposed for wind power grid connection, Fig.2 gives the comparison results of the four models in terms of wind power consumption rate, wind curtailment penalty fees and total costs under different wind curtailment penalty cost. Take a wind power forecast error of 30%.



(a) wind power consumption rate

(b) wind curtailment penalty fees



**Fig. 3.** Comparison of four models under different wind curtailment penalty cost.

From Fig.3(a), it can be seen that the wind power consumption rate of all models shows an increasing trend as the cost of wind curtailment penalty increases. When the wind curtailment penalty cost is less than ¥100, all models have about 80% or more wind power consumption, but Model 4 has the least amount of wind curtailment and the most wind power consumption. When the wind curtailment penalty cost is more than ¥400, the wind power consumption rate reaches 100% for all models.

From Fig.3(b), when the curtailment penalty cost is less than ¥400, the curtailment penalty fee increases for all models, but the increase is the smallest for Model 4. When the wind curtailment penalty cost is more than ¥400, the wind curtailment penalty cost is 0 for all models because all wind power is consumed.

As can be seen in Fig.3(c), the total cost of the four models increases slightly as the cost of the wind curtailment penalty increases, but the total cost of Model 2 and 4 is significantly lower than that of Model 1 and 3.

The following conclusion is obtained from Fig.3: the proposed method in this paper can enhance the wind power consumption capacity and effectively reduce the total system operation cost under a certain range of wind curtailment penalty cost, after introducing the improved flexible ramping auxiliary service and wind curtailment penalty.

## 6 Conclusion

This paper proposes a spot electric energy market clearing model with improved flexible.

ramping product and wind abandonment penalty, comprehensively considering the single unit ramping rate constraint in the output, start-up and shut-down state, and combining the system ramping capacity constraint due to net load fluctuations. The effectiveness of the method is verified by simulation with a simple test system.

1) Compared with the traditional clearing model, the improved flexible ramping product solves the problems of insufficient system ramping capacity caused by wind power uncertainty and high total system operation cost, realizes the optimal economic allocation of each unit's output, and improves the flexibility and economy of system operation.

2) The new clearing model introduces a wind curtailment penalty in the objective function, combining the improved flexible ramping product to reduce the wind curtailment penalty cost and the total system cost, and advances the capacity of wind power consumption under a certain range of wind curtailment penalty costs.

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