

Day-ahead Modified Dispatching Model Considering Power System Flexibility

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Abstract—The increasing penetration of uncertain generation from renewable resources poses a challenge for keeping flexibility of power system. Therefore, in order to deal with the condition of insufficient flexibility, a day-ahead modified dispatching model considering the flexibility of power system is proposed. In this modified model, the flexibility is represented by up-regulated flexibility coefficient and down-regulated flexibility coefficient, and these parameters will be used to construct the wind power deviation cost in the objective function which is used to increase the regulated capacity of power system. In the case study, two wind power nodes in the IEEE 30-bus system are connected to two actual wind power farms in Hebei province respectively to verify the validity of the modified model. Finally, Simulation results show that, compared with conventional dispatching models, the modified dispatching model can not only reduce the economic cost, but also increase available regulated capacity to enhance the flexibility of power system.

Keywords—Economic dispatching, flexibility of power system, up-regulated flexibility coefficient, down-regulated flexibility coefficient

I. INTRODUCTION

At present, the renewable energy prediction technology is quite mature. For example, in the field of photovoltaic power forecasting, the methods proposed in [1-11] achieved an extremely high prediction accuracy. In the field of wind power prediction, reference [12-20] achieved great success in reducing the prediction error. At the same time, rapid progress had also been made in load forecasting, reference [21-23] were representative examples. However, with the rapid development of forecasting methods for renewable energy and continuous increase of these energy in the grid, the lack of flexibility is increasing becoming a great challenge to power system operators [24]. Therefore, recently there has been an increased focus on the topic of flexibility in the power system.

For the problem of economic dispatching of power system considering flexibility, many scholars have done in-depth researches in this field at present. For example, [25] presented an operational flexibility metric called lack of ramp probability for evaluating system ramp capability in real-time economic

dispatch. In [26], a novel two-step framework was proposed to more accurately evaluate the operational flexibility from the perspective of both sufficiency and economics. Reference [27] proposed spatio-temporal flexibility requirement envelopes for managing flexibility and scheduling energy in power systems with significant variable renewable generation. Reference [28] proposed a power-based model to determine the generation expansion planning, which considers the flexibility capabilities of the system. In [29], the dispatch approach based on flexibility envelopes could decrease energy not served and energy curtailed in comparison to traditional approaches. In [30], the model facilitated the seamless integration of energy-constrained resources with conventional ones. It allowed for their energy levels to be prepositioned ahead of time to better optimize their potential deployment over an upcoming operational horizon. Reference [31] proposed a flexibility evaluation method for district heating networks in combined heat and power dispatch based on a generalized thermal storage model. Reference [32] formulated the real-time economic dispatch problem as a multi-stage robust program to leverage flexible resources. In general, for the economic dispatching problem of power system considering flexibility, previous researches focused on using probability density function or constructing the uncertainty set to represent the system flexibility.

However, previous dispatching model always use historical data to describe the flexibility of power system in different periods, which is insufficiently relevant to future condition of power system. In addition, the dispatching results of the robust optimization model are usually extremely conservative, which is not helpful to reduce economic cost of power system.

Thus, a modified economic dispatch model considering the flexibility of power system is proposed in this paper. By using results of conventional model, the factor of flexibility will be described by defining up-regulated flexibility coefficient and down-regulated flexibility coefficient. Then, these parameters will be used to construct the wind power deviation cost in the objective function which is used to increase available up-regulated or down-regulated capacity of power system. Finally, Simulation results demonstrate that the proposed modified

dispatching model can not only reduce the economic cost, but also increase available regulated capacity to enhance the flexibility of power system.

II. METHODOLOGY

In this paper, the proposed dispatching model is a modified version based on conventional economic dispatching model. The flexibility of each dispatching period is preliminarily mastered by using optimization results of conventional model to calculate the flexibility coefficients. After that, these flexibility coefficients will be applied to construct the wind power deviation cost in the objective function. The modified model is obtained by changing the objective function of conventional dispatching model which will make dispatching arrangements improve the flexibility of power system.

In order to illustrate the modified model clearly, the flow chart is provided in Fig. 1.

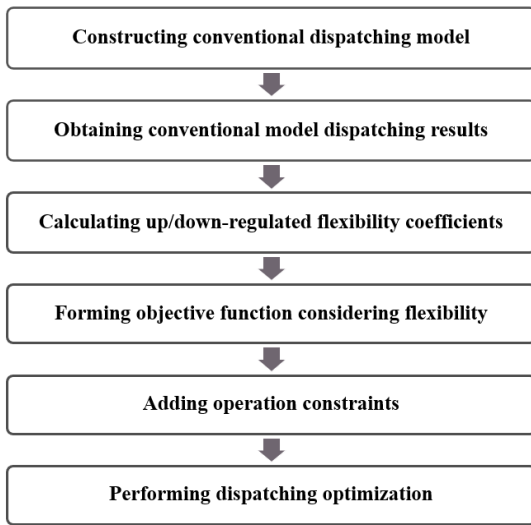


Fig. 1. The flow chart of dispatching model considering the flexibility of power system

A. The flexibility coefficient

At present, load forecasting has reached an extremely high accuracy. Therefore, by calculating the net load and using optimization results of conventional model, the flexibility of each dispatching period can be preliminarily mastered. It's worth noting that capacity which can be used to up-regulated or down-regulated is not the higher the better. When the net load increases rapidly, it is beneficial to improve the up-regulated capacity to maintain the flexibility of power system. At the same time, the down-regulated capacity is not the focus of attention. Similarly, when the net load decreases rapidly, it is extremely important to maintain enough available down-regulated capacity.

In order to clearly describe the flexibility of power system in each dispatching period, the up-regulated flexibility coefficient and down-regulated flexibility coefficient are defined in the next section.

When the net load of power system increases, up-regulated flexibility coefficient K_u is defined as follows:

$$K_u = \frac{R_{U_t}}{P_{\text{net},t+1} - P_{\text{net},t}} \quad (1)$$

$$R_{U_t} = \min\left(\sum_{i=1}^{N_G} (P_{G_i,t} - P_{G_i}^{\min}), \sum_{i=1}^{N_G} R_{u_i} \Delta T\right) \quad (2)$$

Where R_{U_t} represents capacity that can be up-regulated at time t , $P_{\text{net},t+1}$ and $P_{\text{net},t}$ represent the net load at time $t+1$ and t respectively. $P_{G_i}^{\max}$ and $P_{G_i,t}$ represent maximum output of coal-fired power generating unit i and actual output of unit i at time t . R_{u_i} represents the rate of increasing power of unit i , ΔT represents dispatching interval which is set as 1 hour, N_G represents the number of conventional generating units.

When the net load of power system decreases, down-regulated flexibility coefficient K_d is defined as follows:

$$K_d = \frac{R_{D_t}}{P_{\text{net},t} - P_{\text{net},t+1}} \quad (3)$$

$$R_{D_t} = \min\left(\sum_{i=1}^{N_G} (P_{G_i,t} - P_{G_i}^{\min}), \sum_{i=1}^{N_G} R_{d_i} \Delta T\right) \quad (4)$$

Where R_{D_t} represents capacity that can be down-regulated at time t , $P_{G_i}^{\min}$ represents minimum output of coal-fired power generating unit i , R_{d_i} represents the rate of reducing power of generating unit i .

It's worth noting that the flexibility coefficient at each dispatching period is one of up-regulated flexibility coefficient and down-regulated flexibility coefficient, which depending on the increase or decrease of the net load in the next dispatching period.

B. The objective function

The conventional dispatching model takes the thermal operation cost as the objective function. However, its dispatching results don't take the flexibility of each dispatching period into account. Therefore, in order to increase available regulated capacity of power system under the condition of insufficient flexibility, this paper introduces the wind power deviation cost into the objective function. In summary, the objective function of the modified model includes thermal power operation cost and wind power deviation cost.

The thermal power operation cost is defined as follows:

$$F_G = \sum_{t=1}^T \sum_{i=1}^{N_G} (aP_{G_i,t}^2 + bP_{G_i,t} + c) \quad (5)$$

The wind power deviation cost is defined as follows:

$$F_W = \sum_{j=1}^{N_W} Q_{\text{cost}} K_u T_1 (P_{W_j,t} - P_{W_j,t}^{\text{pred}}) + \sum_{j=1}^{N_W} Q_{\text{cost}} K_d T_2 (P_{W_j,t}^{\text{pred}} - P_{W_j,t}) \quad (6)$$

$$\begin{cases} P_{W_j,t} - P_{W_j,t}^{\text{pred}} > 0, T_1 = 1, T_2 = 0 \\ P_{W_j,t} - P_{W_j,t}^{\text{pred}} < 0, T_1 = 0, T_2 = 1 \end{cases} \quad (7)$$

The objective function is defined as follows:

$$F = F_G + F_W \quad (8)$$

Where T represents total number of dispatching periods. N_G represents the number of conventional generating units. a , b and c are fuel cost factors. $P_{Wj,t}$ and $P_{Wj,t}^{\text{pred}}$ represent dispatching value and predicted value of wind power farm respectively. K_u and K_d represent up-regulated and down-regulated flexibility coefficient respectively. N_W represents the number of wind power farm. Q_{cost} represents benchmark price which can be adjusted according to actual demand, in this paper, Q_{cost} is set to a value which is close to the fuel cost factor b . The purpose of this setting is to make the flexibility coefficients play a crucial role in the objective function.

C. The Constraint Conditions

1) Active power balance constraint

$$\sum_{i=1}^{N_G} P_{Gi,t} + \sum_{j=1}^{N_W} P_{Wj,t} = P_{D,t} \quad (9)$$

2) Output restraint of thermal power units

$$P_{Gi}^{\min} < P_{Gi,t} < P_{Gi}^{\max} \quad (10)$$

3) Output restraint of wind power units

$$P_{Wj}^{\min} < P_{Wj,t} < P_{Wj}^{\max} \quad (11)$$

4) Constraint on climbing rate of thermal power units

$$-r_{Gi}^{\text{down}} < P_{Gi,t} - P_{Gi,t-1} < r_{Gi}^{\text{up}} \quad (12)$$

5) positive and negative reserve capacity constraint

$$\sum_{i=1}^{N_G} (P_{Gi}^{\max} - P_{Gi,t}) + \sum_{j=1}^{N_W} P_{Wj,t} \geq C_{\text{up}}^{\text{need}} \quad (13)$$

$$\sum_{i=1}^{N_G} (P_{Gi,t} - P_{Gi}^{\min}) + \sum_{j=1}^{N_W} P_{Wj,t} \geq C_{\text{down}}^{\text{need}} \quad (14)$$

Where $P_{D,t}$ represents total load at time t . P_{Wj}^{\min} and P_{Wj}^{\max} represent minimum output and maximum output of wind power farm respectively. r_{Gi}^{down} and r_{Gi}^{up} represent the maximum increased and reduced power of thermal power unit i in a dispatching period respectively. $C_{\text{up}}^{\text{need}}$ is positive reserve capacity of power system, and $C_{\text{down}}^{\text{need}}$ is negative reserve capacity of power system.

It should be noted that in the conventional dispatching model, the dispatching value of wind power is a fixed value, which is the predicted power. However, in this modified model, the wind power dispatching value will be limited to different interval ranges. The radius of these dispatching interval ranges depend on different peak-valley time horizons, installed capacity, history prediction and actual data of different wind farms. The day will be divided into 5 different time horizons according to characteristics of peak-valley load. They are time horizon of valley-load before dawn, time horizon of peak-load in the forenoon, time horizon of valley-load in the afternoon, time horizon of peak-load in the evening and other time horizon. The specific time horizon division method is as follows. Taking

Hebei Province as an example, firstly, the time points corresponding to the peak and valley values of the annual daily load curve are selected. Then the time points with the most occurrence times are taken as the central time points of the peak or valley time horizons. Finally, through consulting experts, the specific length of the peak and valley time horizons are determined to be 2 hours. To be specific, time horizon of valley-load before dawn is 03:00~05:00, time horizon of peak-load in the forenoon is 09:00~11:00, time horizon of valley-load in the afternoon is 12:00~14:00, time horizon of peak-load in the evening is 17:00~19:00 and remaining periods belong to other time horizon.

Fig.2 shows the weighted RMSE value of wind farms used in the case study in five different time horizons. The weight is determined according to the installed capacity of wind farms. In this picture, Time horizon I represents the time horizon of valley-load before dawn, Time horizon II represents the time horizon of peak-load in the forenoon, Time horizon III represents the time horizon of valley-load in the afternoon, Time horizon IV represents the time horizon of peak-load in the evening and Time horizon V represents other time horizon.

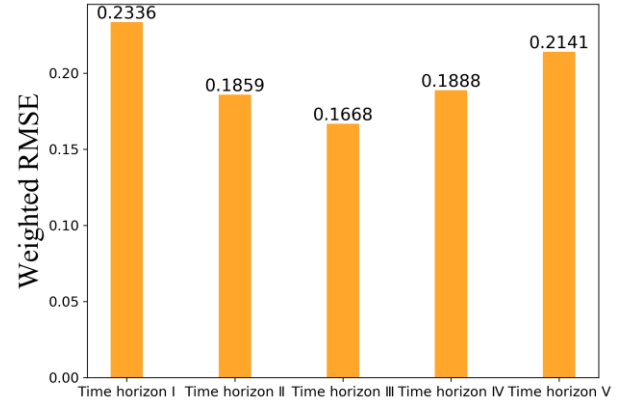


Fig. 2. Weighted RMSE of wind farms in five different time horizons

In next case study, the radius of wind power dispatching interval will be determined by the product of RMSE and the prediction value.

III. CASE STUDY

Our research relies on the IEEE 30-bus system which contains a total of 30 nodes. There are 4 thermal power nodes (node 1, node 2, node 5 and node 8) and 2 wind power nodes (node 11 and node 13) in this system.

There are a total of 4 thermal power units and two wind power farms will be connected to this system. Thermal power unit 1, 2, 3, 4 and wind power farm 1 and 2 will be connected to node 1, node 2, node 5, node 8, node 11 and node 13 respectively. The predicted load curve of a region and the predicted power of two wind farms in Hebei Province are shown in Fig.3 and Fig.4 respectively.

In this section, two economic dispatching model will be constructed for comparative verification. One is the conventional economic dispatching model which thinks predicted wind power as fixed value to dispatch conventional

units. The other is a modified dispatching model considering the flexibility of power system.

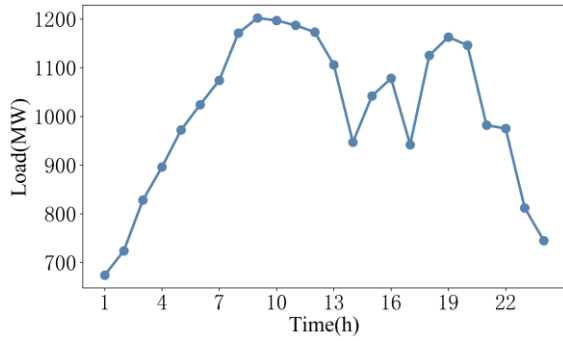


Fig. 3. Load of power system

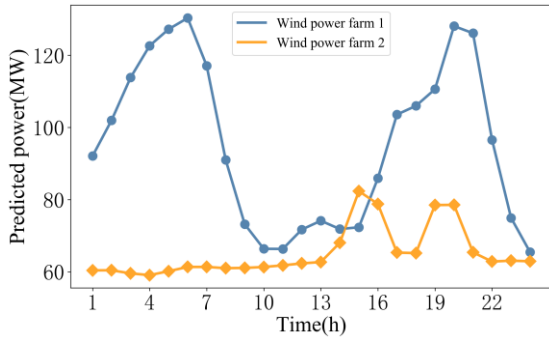


Fig. 4. Predicted power of wind power farms

The parameters of four conventional units used in the case study are also shown in Table I.

TABLE I. THE PARAMETERS OF THERMAL POWER UNITS

Unit number	P_{max} /(MW)	P_{min} /(MW)	r_G^{up} or r_G^{down} /(MWh)
G_1	320	150	50
G_2	360	135	50
G_3	300	73	50
G_4	200	60	35

Unit number	a /(¥/MW ² h)	b /(¥/MWh)	c /¥
G_1	0.009	164.7	20613
G_2	0.014	152.9	28258
G_3	0.016	150.7	13014
G_4	0.015	156.1	10145

Then, Two evaluation items will be carried out. One is comparing economic cost of two dispatching models, the lower economic cost reflects the better performance. The other is comparing the influence of two models on the flexibility of power system. To be more specific, when the net load is increasing or decreasing, The model which can increase regulated capacity in need is more beneficial to improve the flexibility of power system.

The economic cost comparison between the proposed and conventional model is shown in Table II. Compared with conventional model, the cost of the proposed model decreases by 67382 yuan, accounting for 1.36% of original cost. The simulation results demonstrate that the modified model can effectively reduce the economic cost of power system.

TABLE II. THE ECONOMIC COST OF TWO DISPATCHING MODELS

The modified model	The conventional model	Percentage decline
4881508 ¥	4948890 ¥	1.36%

The other evaluation item is to compare the influence of two models on the flexibility of power system. It is worth noting that in each dispatching period, either up-regulated capacity or down-regulated capacity will always be more important, which depends on the net load increasing or decreasing in the next period. Specifically, when the net load increases rapidly in the next period, up-regulated capacity of power system will be the focus of attention. Similarly, when the net load is decreasing rapidly in the next period, down-regulated capacity is the key to maintaining flexibility.

The net load of the system is shown in Fig.5. Meanwhile, for dispatch periods that are about to face the net load increase, the comparison of available up-regulated capacity of two dispatching models and the improvement effects of the modified model are shown in Fig. 6 and Fig. 7 respectively. Similarly, for dispatch periods that are about to face the net load decrease, the comparison of available down-regulated capacity of two dispatching models and the improvement effects of the modified model are shown in Fig. 8 and Fig. 9 respectively.

As can be seen from Fig. 6 and Fig. 7, in dispatch periods that are about to face the net load increase, available up-regulated capacity of modified model is generally higher than or equal to that of conventional model. This result shows that when the net load is about to increase, modified model will have more up-regulated capacity than the conventional model to cope with possible crisis of lack of flexibility. Similarly, in dispatch periods that are about to face the net load decrease, modified model also has better performance than conventional model.

It is worth noting that the modified model shows obvious improvement effects on increasing regulated capacity of power system only when the net load changes sharply. To be specific, when the net load is about to increase or decrease rapidly, the up-regulated capacity or down-regulated capacity is higher than before respectively. When the net load fluctuates relatively stable, the optimization results of modified model are consistent with the previous regulated capacity.

In conclusion, in the case of rapid increase or decrease of net load, the modified model shows a good performance than conventional model in improving the regulated capacity to enhance the flexibility of power system.

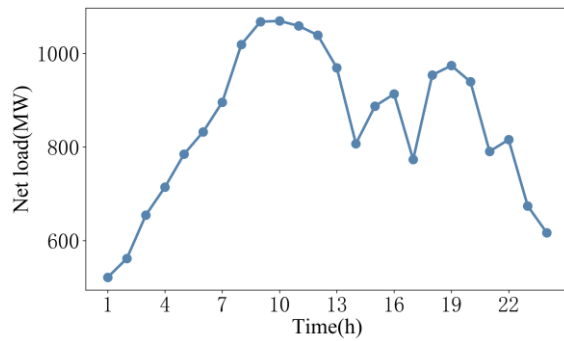


Fig. 5. Net load of power system

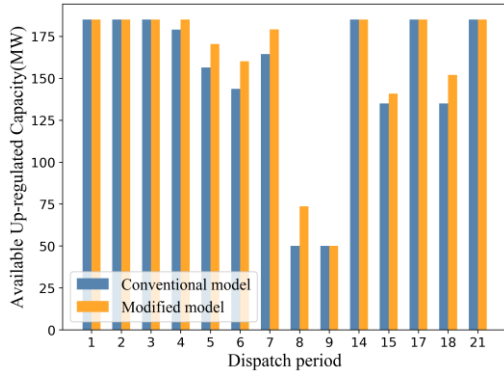


Fig. 6. Comparison of available up-regulated capacity of two dispatching models in dispatch periods that are about to face the net load increase

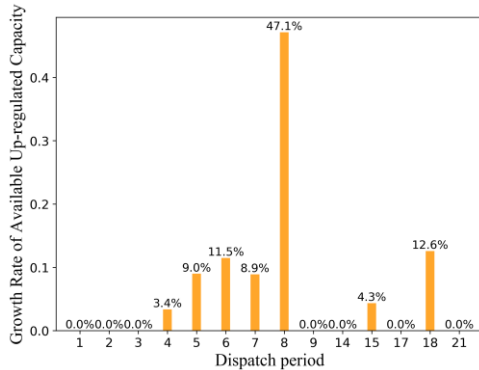


Fig. 7. Growth rate of available up-regulated capacity of modified model in dispatch periods that are about to face the net load increase

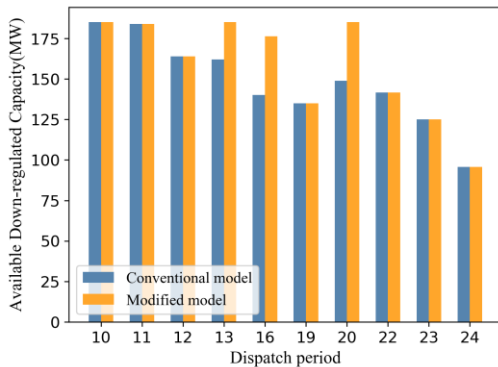


Fig. 8. Comparison of available down-regulated capacity of two dispatching models in dispatch periods that are about to face the net load decrease

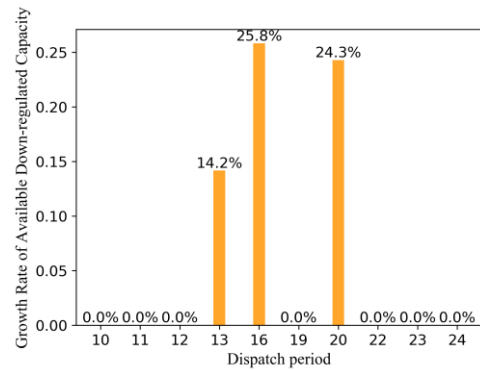


Fig. 9. Growth rate of available down-regulated capacity of modified model in dispatch periods that are about to face the net load decrease

IV. CONCLUSION

In this paper, the factor of flexibility of power system is described by defining up-regulated flexibility coefficient and down-regulated flexibility coefficient. Then, these parameters will be used to construct the wind power deviation cost in the objective function which is used to increase available up-regulated or down-regulated capacity of power system. Simulation results demonstrate that, compared with conventional dispatching models, the proposed modified dispatching model can not only reduce the economic cost, but also increase available regulated capacity to enhance the flexibility of power system.

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