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Quantitative model of peak regulation cost caused by wind power generation

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Abstract. With the integration of large-scale wind power plants (WPPs), there is more and more demand for peak regulation service, and the peak regulation cost is increasing too. Reasonable calculation of peak regulation service cost caused by wind power generation (WPG) is the premise of stimulating conventional units to provide peak regulation services. After introducing the concept of peak regulation service in China, the impact of WPG on peak regulation is analyzed, and a quantitative model of peak regulation cost caused by WPG is put forward form the view point of the value of unit output adjustment. An optimization model with paid peak regulation is established to analyze the impact of WPG on peak regulation costs. The proposed method is tested on a 10-thermal power units system with WPPs, and the results verify the effectiveness of the proposed method.

1. Introduction

With increasing levels of variable renewable energy, there is a growing need to study its impacts on power system operation [1]. Wind power as a promising alternative for power generation has gained great attention and WPG penetration levels are increasing rapidly around the world. This environmentally-friendly source of energy, however, owns an unpredictable and intermittent nature which in turn results some impacts on technical and financial aspects of power systems [2]. One typical aspect is that the integration burden due to wind variations is entirely put on the existing electric grid, it would become more difficult for the Independent System Operator (IOS) to perform peak regulation and optimal operation, and more reserve service is required. In China, the task of peak regulation is mainly undertaken by conventional units, the conventional units not only need to follow the load changes, but also balance the output fluctuation of WPG. However, the cost of peak regulation is mainly distributed within the conventional units, which is unfair to conventional ones [3].

To solve the problem of peak regulation cost caused by WPG, quantifying the peak regulation cost caused by WPG is needed. We firstly discuss the value of unit output adjustment, and then introduce concept of peak regulation service in China. The impact of WPG on peak regulation is analyzed, and a quantitative model of peak regulation cost caused by WPG is proposed. The scheduling model with paid peak regulation is established, and discrete particle swarm optimization algorithm is used to solve the model. Combined with the model proposed in this paper, the impact of WPG on the cost of depth peak regulation and start-stop peak regulation can be effectively estimated, while the impact of the total amount of WPG on the peak regulation cost can be effectively avoided. The proposed method is tested on a 10-thermal power units system with WPPs, and the results verify the effectiveness of the proposed method.

2. The value of generation unit output adjustment

In the single-sided electricity market, the relationship between unit price and electricity supply can be described by the supply curve, as shown in figure 1. All supply offers are submitted to and then ranked by the ISO in an increasing order; after that, the least expensive block offer will be accepted in order and this continues until all the demands are exactly satisfied [4]. The price of the last accepted unit is the system marginal price. When pay as bid, the electricity charge is the polygon area enclosed by the supply curve, the electricity demand, and the coordinate axis.

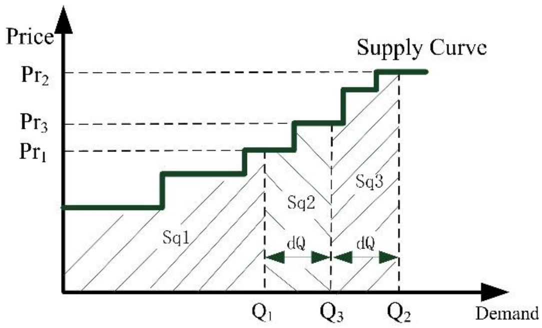

Figure 1. Illustration of supply curve.

As shown in figure 1, when the power demand in two certain hours are Q_1 and Q_2 respectively, the electricity cost for the two hours is the shadow area S_{q1} and (S_{q1}+S_{q2}+S_{q3}) respectively, then the total electricity cost C_{l1} is:

$$C_{l1}=2S_{q1}+S_{q2}+S_{q3} \tag{1}$$

When the electricity demand in the two hours are both (Q_1+ Q_2)/2, then the total electricity cost C_{l2} is:

$$C_{l2}=2S_{q1}+2S_{q2} \tag{2}$$

Thus, the total electricity cost difference ΔC_l of the two cases is:

$$\Delta C_l=S_{q3}-S_{q2}=dQ(P_{av3}-P_{av2}) \tag{3}$$

In the formula above, dQ shows the deviation from Q_1 or Q_2 to the average value Q_3, P_{av2} and P_{av3} represent the average prices of S_{q2} and S_{q3}, respectively. Since P_{av2} is less than P_{av3} and dQ is greater than 0, ΔC_l is greater than 0. According to the figure 1, under the condition that the amount of electricity is certain, the bigger dQ is, the smaller the P_{av2} is and the bigger the P_{av3} is. Combined with formula (3), we can conclude that the bigger the ΔC_l is in the discussion above.

The significance of equation (3) is that the fluctuation of the load over time will increase the electricity cost compared to when load was constant, and the greater the load fluctuated, the more the user would pay for the relative increment of the electricity cost. When some units are in the range of depth peak regulation, the cost of depth peak regulation will also be produced. For generating units, this increase in electricity revenue can be seen as the value generated by the units output adjustment.

3. The quantitative model

3.1 Peak regulation service

In China, peak regulation service is one of the main auxiliary services and it is divided into basic peak regulation service and paid peak regulation service [5]. Basic peak regulation service means that within the regulated output adjustment range (described as the basic peak regulation range in figure 2), generation units carry out planned output adjustments to track load changes, and the basic peak regulation basis is usually set at 50% or 60% of the rated capacity for conventional coal-fired units. Paid peak regulation means that generation units carry out peak regulation beyond the regulated peak regulation depth (described as the depth peak regulation range in figure 2), and thermal power generating units start or stop within the regulated time according to the requirements of the power dispatching and trading centres (this kind of peak regulation is named start-stop peak regulation in this paper), where the regulated time is set at 24h in most provinces in China.

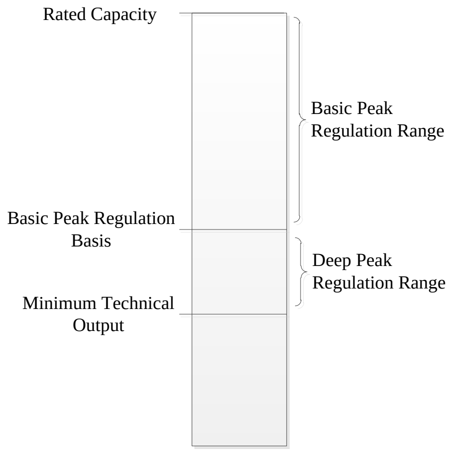

Figure 2. Illustration of coal-fired unit peak regulation characteristics.

Although the value of peak regulation is included in the basic peak regulation, depth peak regulation and start-stop peak regulation, only depth peak regulation and start-stop peak regulation are paid. And the cost of peak regulation service is allocated within generation units according to the proportion of a unit's power generation to the total power generation in many regional power grids.

3.2 Analysis of impact of WPG fluctuation on peak regulation service

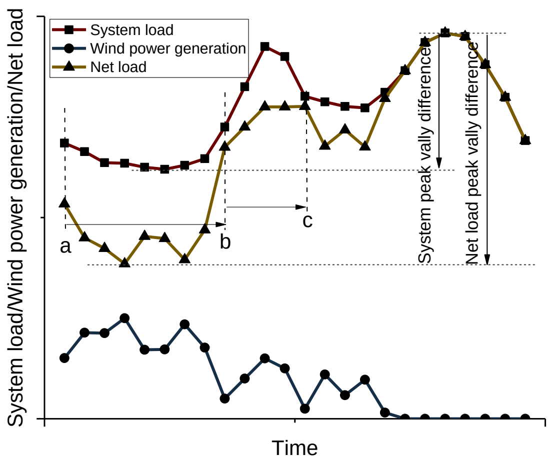

Figure 3. Illustration of impact of WPG on peak regulation.

The impact of WPG on peak regulation is illustrated in figure 3. The fluctuation of WPG within a few hours may stabilize the fluctuation of net load, or may aggravate the fluctuation of net load. In the period from a to b in figure 3, the fluctuation of the system load is gentle, the WPG obviously aggravates the fluctuation of net load, and this may lead to incremental cost of electricity as expressed in formula (3). In contrast, in the period from b to c, the fluctuation of the original load is strong, and the WPG stabilizes the fluctuation of the net load, which on the other hand plays a role of peak regulation, and this may lead to reduce the cost of electricity as expressed in formula (3). In addition, when the WPG fluctuates widely between the peak and valley periods, it may increase or decrease the peak valley difference, and show the characteristics of negative peak regulation or positive peak regulation [6]. In figure 3, the access of WPG significantly increases the peak valley difference of net load, which may depress the output of some conventional units and may even cause depth peak regulation or start-stop peak regulation. Combined with the above analysis, the WPG may affect the system basic peak regulation, depth peak regulation, and start-stop peak regulation.

3.3 Peak regulation cost caused by WPG

Although WPG affects three parts of peak regulation, only depth peak regulation and start-stop peak regulation are paid, thus this paper focuses on depth peak regulation and start-stop peak regulation cost caused by WPG. In order to achieve this goal, the formula (3) is extended to T (taking 24h in this paper) periods, and a quantitative model of peak regulation cost caused by WPG is presented:

$$\Delta C_w = C_w - C_{wm} \tag{4}$$

In the formula, ΔC_w represents the impact of WPG on paid peak regulation cost in the time range T, C_w represents the paid peak regulation cost under WPG scenario (hereinafter this scenario referred to as the original scenario); C_{wm} represents the paid peak regulation cost under the condition that the amount of WPG unchanged while only the output set at the average value of the WPG in original scenario (hereinafter this scenario referred to as the reference scenario). Due to the same amount of WPG in the original scenario and the reference scenario, the formula (4) effectively avoids the impact of the total amount of WPG on the paid peak regulation cost.

4. Dispatch model

In order to reflect the impact of WPG on paid peak regulation, this paper establishes a scheduling optimization model with paid peak regulation cost. We use this model because we want to directly observe the impact of WPG on peak regulation cost on the condition that the total system cost is minimum. Due to the current wind energy price being the benchmark electricity price and WPG fully guaranteed by the power grid enterprises, wind energy price is treated zero and its settlement is not included in the model. The objective function is expressed as follows.

Objective function:

$$F = \min(\sum_{t=1}^{T}\sum_{i=1}^{M}[p_i P_{i,t} u_{i,t} + p_{dr}\left(P_i^b - P_{i,t}\right)d_{i,t} + S_i U_{i,t}]) \tag{5}$$

Where: F means total dispatch cost; T means dispatch periods; M means the number of thermal units; p_i means the price of unit i; $P_{i,t}$ means the output of unit i at time t; $d_{i,t}$ means the depth peak regulation state of unit i at time t, 1 means in depth peak regulation, 0 means not in depth peak regulation; $u_{i,t}$ means the state of unit i at time t, 1 means on and 1 means off; p_{dr} means the price for depth peak regulation; S_i means the start-stop cost of unit i; $U_{i,t}$ means the start-stop peak regulation state of unit i at time t, 1 means in start-stop peak regulation and 0 means not in start-stop peak regulation; P_i^b means basic peak regulation basis of unit i. Some constraints are:

Power balance constraints with WPG:

$$\sum_{i=1}^{M} P_{i,t} u_{i,t} + W_t = L_t \tag{6}$$

Where W_t means WPG at time t.

Reserve constraints:

$$\sum_{i=1}^{N}\left(P_i^{max}\text{-}P_{i,t}\right)u_{i,t}\geq R_t \tag{7}$$

Where R_t means reserve requirement at time t.

Capacity constraints:

$$P_i^{min}\leq P_i\leq P_i^{max} \tag{8}$$

$$0\leq W_t\leq W^{max} \tag{9}$$

P_i^{min}/P_i^{max} mean the minimum/maximum output of unit i, W^{max} mean the maximum output of WPG.

Start-stop peak regulation state constraints:

$$U_{i,t}=\begin{cases}1,TUD_{i,t}\leq T_{SC}\\0,others\end{cases} \tag{10}$$

Where $TUD_{i,t}$ represents the time interval from the last stop to the current start of unit i at time t. T_{SC} means the regulated time of start-stop peak regulation.

Must run time and must down time constraints:

$$T_{i,j}{}^{on}\geq MUT_i\,,T_{i,j}{}^{off}\geq MDT_i \tag{11}$$

Where $T_{i,j}^{on/off}$ mean ON/OFF period of unit i at time j; MUT_i/MDT_i mean minimum up/down time of unit i.

5. Simulations

The numerical example is a 10-thermal units system with WPPs. The parameters of the thermal units are from Ref. [7] and some modifications are made, as shown in table 1, and p_{dr} is set at 100 Yuan / (MWh) as in Central China Grid. The original load curve and WPG curve are shown in figure 4.

In this paper, the load spinning reserve is set as 10% of system load, and the additional spinning reserve capacity is assumed to be 20% of the WPPs capacity [8]. Discrete particle swarm optimization algorithm [9-10] is adopted to solve the problem.

Table 1. Parameters of thermal units.

Units	P^{max}(MW)	P_b(MW)	P^{min}(MW)	p(￥/MWh)	S/￥	MUT/MDT(h)
1 (coal)	455	227.5	150	408.38	455000	8
2 (coal)	455	227.5	150	416.46	455000	8
3 (coal)	130	65	20	428.75	65000	5
4 (coal)	130	65	20	433.84	65000	5
5 (coal)	162	81	25	501.80	81000	6
6 (coal)	80	40	20	565.40	40000	3
7 (coal)	85	42.5	25	594.59	42500	3
8 (oil)	55	10	10	651.36	2750	1
9 (oil)	55	10	10	683.55	2750	1
10 (oil)	55	10	10	700.68	2750	1

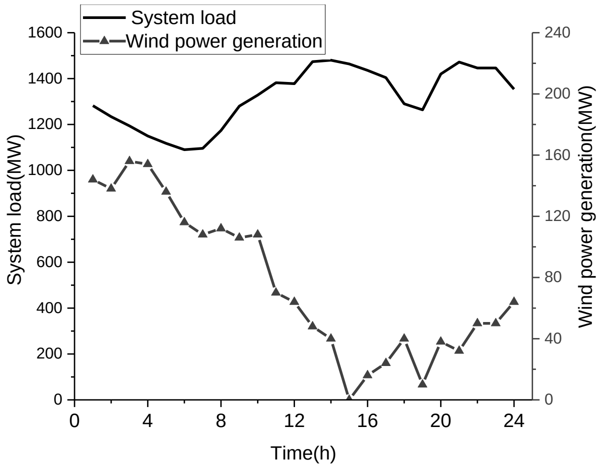

Figure 4. Original load and wind power generation curves.

Table 2. Simulation results.

Scenario	Peak (MW)	Valley (MW)	Peak valley difference (MW)	Start-stop peak regulation cost (￥)	Depth peak regulation cost (￥)	Total cost (￥)
Original scenario	1464	974	490	99000	9500	108500
Reference scenario	1404	1014	390	53500	32450	85950

Table 2 shows the simulation results of the original scenario and the reference scenario. As shown in table 2, due to the access of WPG, the peak valley difference increases from 390 MW in reference scenario to 490 MW in original scenario, and the peak regulation pressure is greatly increased. Compared to reference scenario, the access of WPG leaded to start-stop peak regulation services of unit 6 and 10, resulting in the start-stop cost increased by 45500 Yuan. Increased start-stop peak regulation in turn leaded to less depth peak regulation power, so the cost of depth peak regulation cost is reduced by 22950 Yuan. Thus the total increased peak regulation cost because of WPG fluctuation is 22550 Yuan, the WPG should bear the increased paid peak regulation cost 22550 Yuan under the principle of fairness.

In accordance with the current way of peak regulation cost allocation in China, the cost of peak regulation cost is allocated within generation units according to the proportion of a unit's power generation to the total power generation. In this case, total wind power generation is 1824 MWh which counts only 5.76% of total power generation (31656 MWh), thus the WPPs only need to share the peak regulation cost of 6252 Yuan which is only 28% of the cost quantified by the method in this paper, the thermal power units as a whole bears an additional peak regulation cost of 16298 Yuan. It can be seen that WPG will both affect start-stop peak regulation and depth peak regulation, the current peak regulation cost allocation way is unfair to conventional units, the method proposed in this paper can quantify the costs caused by WPPs.

6. Conclusions

In this paper, the impact of WPG on peak regulation is analyzed considering the large-scale WPPs integration, and a method of quantifying the peak regulation cost caused by WPG is proposed.

The simulation results show that the WPPs' integration affects both depth peak regulation and start-stop peak regulation. The method can quantify the peak regulation cost caused by WPG according to the time-varying characteristics of load and WPG. Under the new situation of large-scale WPPs integration, it is reasonable to quantify the peak regulation cost caused by WPG and effectively guide conventional units to provide peak regulation service for WPPs integration.

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