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Economic Evaluation for Peak Shaving of Wind Power Integrated System

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Abstract

The variable and non-dispatchable output of wind farms brings great difficulty to the quantitative analysis of the economic operation for peak shaving of power system integrated with high penetration of wind power. For the random nature of wind power, the paper establishes a peak shaving capacity requirement model for wind power. Based on the peak shaving capacity requirement model for wind power, a model for economy evaluation of peak shaving of power system with a high penetration of wind power is proposed. The model makes it possible to quantitatively analyze the influences of wind power integration on the peak shaving capacity requirement and operation economy. The case studies were carried out for a system, and the results verified the effectiveness and accuracy of the presented model. Some conclusions are summarized about the economy evaluation method of peak shaving of systems integrated with significant wind.

Keywords: *economy evaluation of peak shaving, wind farm, peak shaving capacity requirement scenario, backward scenario reduction*

1. Introduction

The difference between peak load and valley load of power grid is growing year by year with the change of the structure of electricity demand, and the peak shaving of power system is increasingly difficult. In particular, with the quick development of renewable electricity generation such as wind power and solar power [1], especially the progress of wind power around the world is consistently impressive because of its low cost, mature technology, rich store and free pollution, the large-scale integration of wind power becomes a global trend of wind power development [2-3]. As a result, the large-scale integration of the stochastic and unpredictable power will create a much greater challenge for peak shaving of power system. Furthermore, the economic operation for peak shaving of power system occupies an important position in electricity production, and its impact on the economic benefits of the whole system is far more than 1/3, though the peak shaving period accounts for just 1/3 of the total operation period, and plays a decisive role in the operation economy of power system [4]. So it's important and necessary to study the characteristic of peak shaving capacity requirement of power system integrated with large-scale wind power and present the economy evaluation model of peak shaving.

In China, according to the national wind power planning, seven wind power bases with an installed wind power capacity up to ten million KW respectively will be built completely in 2020, and they are respectively located at Hami in Xinjiang province, Jiuquan in Gansu province, Hebei province, Jiangsu province, eastern inner Mongolia, and western inner Mongolia. The total installed wind power capacity of the seven wind bases will be up to 5808×10^4 KW in 2015, and 9017×10^4 KW in 2020. This large-scale and centrally explored wind power will greatly increase the difficulty of peak shaving of power system with wind power integrated.

In recent years, considerable research has been conducted on the integration of wind power [5-9], and there is a growing concern for the pressing issues facing peak shaving of power system integrated with large-scale wind power [10-15]. Reference [11] analyzed the characteristic of negative peak shaving of conventional generators and proposed a model to

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calculate the limit of capability of negative peak shaving based on the deterministic unit commitment and wind power output, ignoring the stochastic nature of wind power. Reference [12] presented a peak shaving scheme of thermal power for the integrated Jiuquan wind power base, combing its wind power characteristic. Reference [13] presented a method to calculate peak shaving ability of Northeast China power grid integrated with large-scale wind farms based on the feature of Northeast China power grid, and proposed a principle for peak shaving by coordinating hydro power and thermal power for wind farms. Reference [14] analyzed the peak shaving ability of Beijing-Tianjin-Tangsan power grid according to its load characteristic and power source composition, and provided the approximate capacity range of wind power integrated that the power grid can absorb. References [12-14] all analyzed the peak shaving ability the system can supply based on a specific system. Reference [15] evaluated the effect of wind power on the load peak-to-valley difference of power system integrated with large-scale wind power according to the variation of peak-to-valley of net load, based on chronological load time series and chronological time series of wind power output simulated by Weibull distribution function of wind speed. In fact, the peak shaving ability and operation economy of the power system integrated with wind power are closely related to the load characteristic, power source composition and wind power characteristic, only analyzing wind power characteristic or the peak shaving ability of the power system integrated with wind power is incomplete. Most of current literature analyzed the challenge brought by integrated wind power facing peak shaving of power system macroly and roughly, and there is a serious lack of a general method of quantitative analysis and modeling of operation economy of peak shaving. So there is urgent need for in-depth study on effects of stochastic nature of wind power on peak shaving and economy evaluation of peak shaving of power system integrated with high penetration wind power.

The peak shaving capacity requirement is the difference between the maximum load and minimum load during all the operation period, as a result, study on peak shaving of power system integrated with large-scale wind power needs coordinating the load characteristic and wind power output characteristic during the whole operation period. At the same time, the stochastic and unpredictable nature of wind power output makes the peak shaving capacity stochastic greatly, which is the key difference of peak shaving issue between traditional power system and one integrated with large-scale wind power.

For the stochastic nature of wind power, this paper presents a peak shaving capacity requirement model of power system integrated with large-scale wind power, combing the load characteristic, and chooses typical peak shaving capacity requirement scenarios to model its stochastic nature. Based on the peak shaving capacity requirement model, the paper proposes a economy evaluation model of peak shaving of power system integrated high penetration wind power. Taking into account the stochastic nature of wind power, the load shedding fee because of lack of positive peak shaving ability and penalty fees for wind spillage because of lack of negative peak shaving ability also become a part of the objective function of the model. Finally, the case studies were carried out for a system, and the results verified the effectiveness and accuracy of the presented model. Some conclusions are summarized about the economy evaluation method of peak shaving of systems integrated with significant wind.

This paper is divided into the following sections. Section III presents the peak shaving capacity requirement model of power system integrated with high penetration wind power. Section IV formulates the economy evaluation model of peak shaving. Section V illustrates the methodology using a test system. Section VI draws some relevant conclusions.

2. Peak Shaving Capacity Requirement Model

The peak shaving capacity requirement originates in variation of wind power output and the difference between peak load and valley load, and is closely related to their chronological correlation. To model the peak shaving capacity requirement of power system integrated with large-scale wind power, the paper uses the principle of choosing typical load curve for reference, according to statistical analysis on the peak-to-valley of net load and scenario reduction procedure, and obtains typical wind power output curves and corresponding probability for analysis on peak shaving of power system integrated with high penetration wind power.

2.1. Classification of Peak Shaving Capacity Requirement Scenarios

In operation simulation of power system integrated with large scale wind power, to absorb renewable energy prioritly, wind power is considered as a negative load and obtains the net load. The analysis on peak shaving capacity requirement is conducted based on the net load of power system integrated with large-scale wind power, which takes into account both the peak shaving of original load and variation of wind power, but also their correlation. The net load is formulated as follows:

$$L_{\mathrm{net}} = L - P_W \tag{1}$$

Where P_W and L are respectively wind power output and load of the whole operation period, and $P_W = \left[P_{W1}, \cdots, P_{Wt}, \cdots P_{WN_T}\right]^T$, $L = \left[L_1 \cdots, L_t, \cdots, L_{N_T}\right]^T$, P_{Wt} and L_t are respectively wind power output and load in period t, and t=1, 2, ……N_T.

The peak shaving capacity requirement of power system integrated with large-scale wind power is the difference between the maximum net load and minimum net load during all the operation period, that peak-to-valley of the net load. Due to the uncertain nature of wind power, there may are many scenarios of wind power output, so the net load obtained by formulation (1) also has many scenarios. The peak shaving capacity requirement of wind power output scenario i is formulated as follows:

$$P_{pv}^i = \max(L_{net}^i) - \min(L_{net}^i) \tag{2}$$

Where $L_{\mathrm{net}}^i = L - P_W^i$, P_W^i is the wind power output scenario i, and i=1,2,……N_s, P_{pv}^i and L_{net}^i are respectively peak shaving capacity requirement and net load of the wind power output scenario i, $\max(\cdot)$ and $\min(\cdot)$ are respectively the max function and min function.

From formulation (2), the set of peak shaving capacity requirement scenarios Ω_{pv}, can be obtained from the set of wind power output scenarios $\Omega_W = \left\{P_W^1, \cdots, P_W^i \cdots P_W^{Ns}\right\}$, and the probability of every scenario is $\Omega_{pro} = \{p_1, \cdots p_i, \cdots p_{Ns}\}$, and $\sum_{i=1}^{N_S} p_i = 1$, which is also the probably of the probability of corresponding wind power output scenario.

Using well-being analysis [16] for reference, the peak shaving capacity requirement scenarios can be divided into three groups Healthy, Marginal and Risk, according to the effects of wind power integration on the peak shaving of power system. Class Healthy represents that the peak shaving capacity requirement is less than that before wind power integration, L_{pv}, that is, wind power integration improves the peak shaving of power system. Class Risk represents that the peak shaving capacity requirement is greater than that the system can supply by other generators, C_{pv}, that is, the system can not meet the peak shaving capacity requirement of the power system integrated with wind power. So, class Marginal represents the scenarios except that of the two above classes, that is, wind power integration increases peak shaving pressure, but the C_{pv} can meet the peak shaving capacity requirement of the power system integrated with wind power. The classification represents three different effect situations of wind power integration on peak shaving, and distinguishes three different peak shaving states clearly.

Based on the above classification method, the set of peak shaving capacity requirement scenarios Ω_{pv} can be divided into three subsets, $\Omega_{H,pv}$, $\Omega_{M,pv}$ and $\Omega_{R,pv}$, and their scenarios and corresponding probability are respectively formulated as follows:

$$\begin{cases} \Omega_{H,pv} = \left\{P_{pv}^h \middle| P_{pv}^h \in \Omega_{pv} \cap \left[0, L_{pv}\right)\right\}, h = 1, 2, \cdots, N_H \\ \Omega_{M,pv} = \left\{P_{pv}^j \middle| P_{pv}^j \in \Omega_{pv} \cap \left[L_{pv}, C_{pv}\right]\right\}, j = 1, 2, \cdots, N_M \\ \Omega_{R,pv} = \left\{P_{pv}^k \middle| P_{pv}^k \in \Omega_{pv} \cap \left(C_{pv}, \propto\right)\right\}, k = 1, 2, \cdots, N_R \end{cases} \tag{3}$$

$$\begin{cases} p_H = \sum_{h=1}^{N_H} p_h \\ p_M = \sum_{j=1}^{N_M} p_j \\ p_R = \sum_{k=1}^{N_R} p_k \end{cases} \tag{4}$$

Where $\Omega_{H,pv}$, $\Omega_{M,pv}$ and $\Omega_{R,pv}$ represent the set of peak shaving capacity requirement of Healthy state, Marginal state and Risk state, respectively; P_{pv}^h, P_{pv}^j and P_{pv}^k represent scenario *h*, *j* and *k* of $\Omega_{H,pv}$, $\Omega_{M,pv}$ and $\Omega_{R,pv}$, respectively; N_H, N_M and N_R are respectively the total number of scenarios of $\Omega_{H,pv}$, $\Omega_{M,pv}$ and $\Omega_{R,pv}$.

2.2. Peak Shaving Capacity Requirement Model

For computational complexity, it's impossible to analyze and evaluate for every peak shaving capacity requirement scenario in detail, so backward scenario reduction technique based on Kantorovich distance, KD, [17] is applied to trim down the number of peak shaving capacity requirement scenarios, obtaining typical scenarios and corresponding probability while keeping most of stochastic information embedded in these scenarios. Backward scenario reduction technique based on KD is an optimal procedure, and eliminates the scenario which has the minimum probability distance until the stopping criterion has been met.

Based on the classification method of peak shaving capacity requirement scenario and scenario reduction technique described above, the peak shaving capacity requirement model is as follows:

$$\begin{cases} \Omega'_{lpv} = \left\{ P'_{pv,1}, \cdots P'_{pv,i_l}, \cdots P'_{pv,N_l} \right\} \\ \Omega'_{lW} = \left\{ P'_{lW,1}, \cdots P'_{lW,i_l}, \cdots P'_{lW,N_l} \right\} \\ \Omega'_{lpro} = \left\{ p'_{l,1}, \cdots p'_{l,i_l}, \cdots p'_{l,N_l} \right\} \cdot p_l \end{cases} \tag{5}$$

Where *l*=*H*, *M*, *R*, represents peak shaving capacity require state Healthy, Marginal, Risk, respectively, and it has the same meaning in the followings. Ω'_{lpv}, Ω'_{lW} and Ω'_{lpro} are respectively objective scenario sets of peak shaving capacity requirement, wind power output curve and corresponding probabilities of state L. P'_{lpv,i_l}, P'_{lW,i_l} and p'_{l,i_l} are respectively peak shaving capacity requirement, wind power output curve and corresponding probability of typical scenario il in objective scenario set of peak shaving state l.

The peak shaving capacity requirement model takes into account the stochastic nature of wind power according to choosing typical peak shaving capacity requirement scenarios, based on which the economy evaluation of peak shaving is conducted.

3. Economic Evaluation of Peak Shaving of Power System Integrated with Wind

3.1. Objective Function

The goal of study on peak shaving economy of power system integrated with high penetration wind power is to minimize the expected cost (F) in terms of absorbing wind power in priority and meet corresponding constraints. Taking into account the stochastic nature of wind power, the load shedding fee because of lack of positive peak shaving ability and penalty fees for wind spillage because of lack of negative peak shaving ability also become a part of the objective function of the model.

Base on the peak shaving capacity requirement model above, the objective function of the economic evaluation of peak shaving is formulated as follows:

$$MinF = \sum_{l}\sum_{i_l=1}^{N_l}\left(p'_{l,N_l} \cdot \sum_{t=1}^{N_T}\left[\sum_{u=1}^{N_u} f_{u,l,i_l}(t) + O_{l,i_l}(t) + C_{l,i_l}(t)\right]\right) \quad (6)$$

Where,

$$f_{u,l,i_l}(t) = f_{1u,l,i_l}(P_{u.t,l,i_l}) + S_{u,l,i_l}(t) + f_{2u,l,i_l}(NO_x.SO_2) \quad (7)$$

Where N_u is the number of conventional units, $f_{u,l,i_l}(t)$ is fuel cost of unit u in period t under the typical wind power output scenario P_{lW,i_l}, including operational cost $f_{1u,l,i_l}(P_{u.t,l,i_l})$, start-up cost $S_{u,l,i_l}(t)$ and emission cost of SO_2 and NO_x $f_{2u,l,i_l}(NO_x.SO_2)$, $P_{u.t,l,i_l}$ is power output of unit *i* in period *t* under the typical wind power output scenario P_{lW,i_l}, $O_{l,i_l}(t)$ and $C_{l,i_l}(t)$ are load shedding fee because of lack of positive peak shaving ability and penalty fees for wind spillage because of lack of negative peak shaving ability in period t under the typical wind power output scenario $P_{lW,i}$, respectively.

$O_{l,i_l}(t)$ and $C_{l,i_l}(t)$ are formulated as follows:

$$O_{l,i_l}(t) = E_{NSW.l,i_l}(t) \cdot \gamma \quad (8)$$

$$C_{l,i_l}(t) = E_{NAW.l,i_l}(t) \cdot \rho \quad (9)$$

Where γ is the cost per load shedding, ρ is the cost per wind power energy spillage, and $E_{NSW.l,i_l}(t)$, $E_{NAW.l,i_l}(t)$ are electricity not supplied, wind power energy spillage in period t under the typical wind power output scenario P_{lW,i_l}, respectively.

3.2. Constraints

For every typical wind power output scenario P_{lW,i_l}, the following constraints must be satisfied.

a) System operation constraints

1) Power balance constraint

$$\sum_{u=1}^{U} P_{u.t,l,i_l} + P'_{lW,i_l,t} - L_t - P_{L.t} = 0, (t = 1, 2, \cdots, N_T) \quad (10)$$

Where $P'_{lW,i,t}$ is wind power output in period t of the typical wind power output scenario $P_{lW,i}$, $P_{L.t}$ is net loss in period *t*.

2) Spinning reserve constraint

$$\sum_{u=1}^{U} P_{u.\max} \cdot x_{u,t} + P'_{lW,i_l,t} - P_{L.t} - L_t \geq R_t \quad (11)$$

Where $P_{u.\max}$ is rated capacity of unit *i*, R_t is spinning reserve in period t, $x_{u,t}$ is 0/1 variable which is equal to 1 if unit *i* is online in scenario *k* and period *t*.

b) Conventional units operation constraints

1) Generation limits

$$P_{u.\min} \leq P_{u.t,l,i} \leq P_{u.\max}, (t = 1, 2, \cdots, N_T) \quad (12)$$

Where $P_{u.\min}$ is minimum capacity of unit *i*.
2) Ramp rate limits

$$-D_u \le P_{u.t} - P_{u.t-1} \le U_u \tag{13}$$

Where U_u and D_u are, respectively, up and down ramp rate limit of unit *u*.
3) Minimum on and off time constraints

$$\begin{cases} t_{on.u}(t) \ge t_{on.u.\min} \\ t_{off.u}(t) \ge t_{off.u.\min} \end{cases} \tag{14}$$

c) Wind farm operation constraints
1) Generation limits

$$0 \le P'_{Wt} \le P_W^{total} \tag{15}$$

Where P_W^{total} is rated capacity of wind farm.
2) Wind power electricity constraints

$$E_W + E_{ENAW} = E_{\exp} \tag{16}$$

Where E_W and E_{ENAW} are wind energy absorbed and wind energy spillage, respectively. E_{exp} is expected electricity of wind farm.

4. Case Study

To analyze the impact of large-scale wind power on peak shaving capacity requirement and economy, the model is tested over a 24-h horizon on a real system with its load characteristics and generators of 2015. The data for generators and load are, respectively, listed as Table 1, Table 2 and Table 3. The maximum load is 87000MW, and the rated capacity of the wind farm integrated is assigned as 17400MW, which is 20% of the maximum load.

Table 1. Conventional Generator's Data

Pmax /MW	Pmin /MW	Number /台	Coal consumption at rated ouput /g/KWh	SO2 emission /g/Kg.Tce
1000	500	9	280	1.6
600	300	90	300	1.6
360	216	29	320	3.2
300	180	123	320	3.2
200	140	48	340	3.2
135	94.5	43	360	16
100	70	12	360	16
60	42	3	380	16
25	17.5	5	450	16

Table 2. Conventional Generator's Characteristic of Coal Consumption

Unit	Power Output Rate				
	[0.5,0.6)	[0.6,0.7)	[0.7,0.8)	[0.8,0.9)	[0.9,1)
1000	1.0556	1.037	1.0185	1.0074	1
600	1.063	1.046	1.029	1.012	1.006
360	/	1.026	1.015	1.003	1.002
300	/	1.026	1.015	1.003	1.002
200	/	/	1.024	1.013	1.006
135	/	/	1.044	1.032	1.016
100	/	/	1.044	1.032	1.016
60	/	/	1.088	1.044	1.02
25	/	/	1.088	1.044	1.02

Table 3. Load Data

t/h	Load/MW	t/h	Load/MW	t/h	Load/MW
1	0.758	9	0.852	17	0.946
2	0.743	10	0.903	18	0.897
3	0.734	11	1	19	0.912
4	0.727	12	0.926	20	0.986
5	0.725	13	0.928	21	0.958
6	0.741	14	0.949	22	0.899
7	0.74	15	0.963	23	0.839
8	0.779	16	0.952	24	0.787

4.1. Analysis on Peak Shaving Economy

Based on typical wind power output curves of the selected scenarios, the comparison of economic evaluation results of peak shaving between systems with wind power integrated and not is listed in Table 4.

From Table 4 it can be concluded that coal consumption, SO2 emission of the system both decrease after wind power integration. However, the coal consumption per thermal power generation increases for that the variation of wind power output increases peak shaving pressure of conventional units. This shows that wind power integrated saves operational cost of conventional units, at the same time, increases peak shaving cost for its variation. However, the operational cost saved is more than peak shaving cost increased by wind power integrated.

Table 4. Indices of Economic Operation for Peak shaving

indices	no wind power integrated	with wind power integrated
load shedding/MW	/	0
electricity not supplied/GWh	/	0
wind energy spillage/GWh	/	0.04
wind power absorption/%	/	99.97%
thermal power generation/GWh	1796	1673
coal consumption/104 t	56.10	52.29
thermal coal consumption/g/kWh	312.36	312.59
system coal consumption/g/kWh	312.36	291.13
SO2 emission/104 t	0.0172	0.0157
thermal SO2 emission/g/kWh	0.6530	0.6460
Peak shaving depth/%	36.1%	41.4%

4.2 Analysis on the ability to absorb wind power

To analyze the ability to absorb wind power of the system, the system with different wind power penetration (proportion of the maximum load) integrated is simulated based models presented above.

Table 5. Results of Economic Operation for Peak Shaving with Different Wind Power Penetration

wind penetration	thermal power generation /GWh	coal consumption /104 t	peak shaving depth/%	thermal coal consumption /g/KWh	wind power absorption /%
10%	1734	54.25	38.2%	312.80	100.0%
20%	1673	52.29	41.4%	312.59	99.4%
30%	1616	50.72	42.8%	313.82	96.7%
40%	1562	49.07	44.4%	314.18	94.5%
50%	1506	47.37	45.4%	314.56	93.6%
60%	1462	46.49	46.0%	317.89	89.7%
70%	1446	46.09	46.2%	318.73	80.6%
80%	1441	46.00	46.2%	319.15	71.5%

Table 5 presents results of economic operation for peak shaving with different wind power penetration. It can be seen that thermal power generation and coal consumption of the system decrease as wind power penetration increases, which shows that the system can absorb more wind power based on wind power penetration 20%, and the added wind power integrated saves thermal power generation but also coal consumption, but the amount of them replaced by the same added wind power decrease as wind power penetration increases. At the same time, the coal consumption per thermal power generation increases from wind power penetration 30%, and the reason is that the peak shaving pressure of thermal units increases when wind power penetration increases, and their power output rate decreases.

4.3. Accuracy Verification of the Model

To verify the accuracy of proposed models, all the wind power output scenarios are evaluated by enumeration method, and comparison of results of the two different methods is listed in Table 6.

From the comparison of results in Table 6, it can be seen that the calculation errors of operational indices of thermal power are small, and all are smaller than 1%, the largest one is peak shaving depth with an error 0.48%, in addition, thermal power generation, coal consumption, coal consumption per thermal power generation, SO_2 emission and SO_2 emission per thermal power generation are, respectively, 0%, -0.19%, -0.19%, -0.34% and -0.34%. Compared with operational indices of thermal power, the calculation errors of operational indices of wind power are greater. Though the calculation error of wind energy is slightly great, it's small as compared with the total wind energy the system absorbs, and the calculation error of the total wind energy the system absorbs is 0.01%.

Table 6. Comparison of Results of the Two Different Methods

indices	the proposed model	enumeration method
load shedding/MW	0	0
electricity not supplied/GWh	0	0
wind energy spillage/GWh	0.04	0.02
wind power absorption/%	99.97%	99.98%
thermal power generation/GWh	1673	1673
coal consumption/104 t	52.29	52.39
thermal coal consumption/g/kWh	312.59	313.19
system coal consumption/g/kWh	291.13	291.69
SO2 emission/104 t	0.1081	0.1084
thermal SO2 emission/g/kWh	0.6460	0.6482
Peak shaving depth/%	41.4%	41.2%

In a word, based on the three selected wind power output curves using the presented model, the calculation error is smaller than 1% from calculation errors of operational indices of thermal power and wind power. If increasing the number of typical scenarios, the calculation error will be smaller. In the practical work, the number of typical scenarios can be decided by the accuracy requirement.

5. Conclusion

The stochastic and unpredictable nature of wind power brings great challenge to peak shaving operation of power system integrated with large-scale wind power. This paper proposes a peak shaving capacity requirement model taking into account special characteristics of wind power, using KD scenarios reduction technique to choose typical peak shaving capacity scenarios. Based on the peak shaving capacity requirement model, the paper presents a method of economic evaluation of peak shaving. From the case study, some conclusions are summarized as follows: (1). Wind power integration can save operational cost of conventional units, at the same time, it increases the cost of peak shaving for that its variation stresses peak shaving pressure of the power system. (2). Thermal power generation and coal consumption of the system replaced by the same added wind power decrease as wind power penetration increases, and the coal consumption per thermal power generation increases. The optimal wind power capacity integrated should comprehensively consider operational cost of thermal power and wind power absorption indices and so on. (3). The presented model for economic evaluation of peak shaving of power system integrated high penetration wind power, which gives a high calculation accuracy, reduces the computational complexity greatly, what's more, it makes it convenient for power system planner to analyze the effect of wind power integration on the peak shaving capacity requirement and economy of power system intuitively and clearly on the whole, and can be easily applied to practical projects.

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