Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Optimal Peak Shaving Analysis of Power Demand Response Considering Unit Uncertainty

Optimal Peak Shaving Analysis of Power Demand Response Considering Unit Uncertainty

Yunhua Cong[1a], Feng Zuo[1b], Tongqing Li[1c], Miaozhao Shen[1d], Jin Li[1e], Lei Zhu[2f*]

[1]Economic and Technical Research Institute of Heilongjiang Electric Power Company Limited, Harbin City, Heilongjiang Province, 150036, China

[2]Power Construction Technical and Economic Consulting Center of China Electricity Council, Beijing City, 100053, China

[a]282183442@qq.com, [b]18103686793@139.com, [c]947088172@qq.com, [d]1021401348@qq.com, [e]374352912@qq.com, [f*]zhulei@org.cec.cn

Abstract-With the increasingly prominent environmental problems and the promotion of the “double carbon” goal, the participation of demand-side response resources in load peak shaving and valley filling is of great significance to the development of the power industry. In this paper, based on the background that demand-side response is being rapidly developed in China, we firstly consider the uncertainty of generating units and the operating constraints of power system and units, and construct the day-ahead output model of generating units by using stochastic production simulation and day-ahead optimal scheduling. Then, based on this model, we consider the impact of demand response on system peak shaving and build a demand response power system optimal scheduling model with unit uncertainty. Finally, the power supply and demand of the IEEE30 node system on two typical days of peak shaving considering demand response are analysed by MATLAB, and the minimum service cost of demand response and the amount of pull-out limit are derived, which clarify the important role of demand response in the process of power system peak shaving.

1. Introduction

With the economic development and improvement of people's living standard, the electric load requires higher and higher reliability of power supply, and short-time power outage may bring huge safety problems and property losses [1]. During the peak load period when electricity is tight, the demand side is utilized as a supplementary resource to the supply side electric energy, which can not only alleviate the tight situation of power supply and demand, but also reduce the consumption of primary energy. Demand response (DR) sends induced signals to power users to change their inherent electricity consumption patterns, reduce or push the load of a certain period of time and respond to the power supply to ensure grid stability and suppress the increase of electricity prices [2,3], and plays an important role in helping to maintain the stability of the power system and improve the grid's ability to consume renewable energy [4,5].

There is a large literature on the impact of demand response on system dispatch. The literature [6] proposed a model for measuring the effect of peak-valley tariff implementation, which measured the response effect in three aspects: customer benefit, grid benefit and environmental benefit. The literature [7] established a model for the interaction between the customer side and the higher-level grid through price-based demand response. In [8], a day-ahead optimal dispatch model of the power system considering price-based and incentive-based demand response in the power market environment is constructed. The above literature models do not mention the unit output uncertainty, and the units may be affected by various factors and shut down in actual engineering, so considering the random unit shutdown can make the dispatching model more realistic.

In this paper, on the basis of the day-ahead optimal dispatching model of power system with demand response, we further consider the influence of generator unit uncertainty on unit output, establish a probabilistic model for generator units based on time-series stochastic production simulation, and re-establish the probabilistic active output curve of units. Then, according to the relationship between the unit output curve and the load curve, the demand response resources are invested during the peak load period, so that there is no or minimal power restriction during the peak load period, and optimal peak shaving is realized. Finally, the accuracy of the model is verified by solving specific cases.

2. Power System Optimal Dispatching Strategy Considering Demand Response

This paper proposes to determine a unit output plan with the minimum power generation cost within a certain dispatching cycle, comply with constraints, such as system power balance, standby requirements, and unit operation, and establishes a power system optimal dispatching model with unit commitment (UC) [8]. Furthermore, in order to determine the impact on the dispatching and operation of the power system from demand response measures, it considers demand response resources in the UC model, and establishes a power system day-ahead optimal dispatching model considering demand response.

2.1 Objective function

Unit coal consumption and startup/shutdown cost are the main considerations in the current dispatching plan. However, the optimal dispatching model takes the minimization of system power generation cost as the optimization objective, whose function is as follows:

$$\min \sum_{i=1}^{N} \left(\sum_{t=1}^{T} C_i^f \left(P_{i,t} \right) + C_i^U + C_i^D \right) \tag{1}$$

where, T represents the research cycle; N represents the unit number; $P_{i,t}$ represents the active output of unit i in period t; C_i^f, C_i^U and C_i^D represent the coal consumption cost, startup cost, and shutdown cost of unit i.

Demand response takes the minimization of incentive cost and power restriction due to inadequate response capacity as the optimization objective.

(1)When the demand response capacity is able to achieve power balance during peak load periods, the minimization of the DR service cost is taken as the optimization objective, whose function is as follows:

$$\min \sum_{j=1}^{n} \sum_{t=1}^{T} D_{j,t} \omega_j \tag{2}$$

where, n represents the number of demand response resources; ω_j represents the incentive cost of j-th demand response resource; $D_{j,t}$ represents the load reduced of the demand response resource in period t.

(2)When the demand response capacity is unable to fully achieve power balance during peak load periods, the minimization of the orderly power management scale is taken as the optimization objective, whose function is as follows:

$$\min (\sum_{t=1}^{T} L_t - \sum_{j=1}^{n} \sum_{t=1}^{T} D_{j,t} - \sum_{t=1}^{T} P_t) \tag{3}$$

where, L_t represents the original load in period t; P_t represents the unit output in period t.

2.2 Constraints

The optimal dispatching model has two kinds of constraints, i.e., system operation constraint and generator unit operation constraint.

(1)Upper and lower output limit constraint.

$$u_{i,t}P_i^{min} \le P_{i,t} \le u_{i,t}P_i^{max} \tag{4}$$

(2)Unit ramp rate constraint.

$$P_{i,t-1} - r_{d,i} \le P_{i,t} \le P_{i,t-1} + r_{u,i} \tag{5}$$

(3)Minimum continuous startup time constraint.

$$(Y_{i,t-1}^{on} - T_i^{on})\left(u_{i,t-1} - u_{i,t}\right) \ge 0 \tag{6}$$

(4)Minimum continuous shutdown time constraint.

$$(Y_{i,t-1}^{off} - T_i^{off})\left(u_{i,t} - u_{i,t-1}\right) \ge 0 \tag{7}$$

(5)System power balance constraint.

$$\sum_{i=1}^{N} u_{i,t}P_{i,t} = L_t \tag{8}$$

(6)Rotation standby constraint.

$$\sum_{i=1}^{N} \min\left(u_{i,t}P_i^{max} - P_{i,t}, R_{i,t}^{max}\right) \ge R_t \tag{9}$$

where, u represents the startup/shutdown status of the unit; P_i^{max} and P_i^{min} represent the upper and lower output limits of unit i respectively; $r_{u,i}$ and $r_{d,i}$ represent the rise and decreasing rate per hour of unit i; $Y_{i,t}^{on}$ and $Y_{i,t}^{off}$ represent the continuous operation and shutdown time of unit i in period t; T_i^{on} andT_i^{off} represent the minimum startup and the minimum shutdown time of unit i respectively; L_t represents the load in period t; R_t represents the standby demand of the system in period t; $R_{i,t}^{max}$represents the maximum rotation standby capacity that can be provided by the unit.

In view that user response satisfaction needs to be considered during the implementation of demand response, energy response constraint and time response constraint are added.

(1)Energy response constraint

The load reduction energy of the demand response resource shall be lower than the maximum capacity that it can provide and higher than 0 (i.e. being in response status).

$$0 \le D_{j,t} \le a_{j,t}D_{j,t}^{max} \tag{10}$$

Where, $D_{j,t}^{max}$ represents the maximum load reduction of j-th demand response resource in period t; $a_{j,t}$ represents the energy transfer status in period t, in which 1 represents “being transferred”, and 0 represents “not being transferred”.

(2)Time response characteristic constraint

When receiving a dispatching order from the trading center, it is necessary to dispatch the demand response resources within the business area. The response time shall be limited to a certain range to make it convenient for users to adjust their production & living power consumption plans and take technical characteristics of all demand response resources into account.

$$T_j^{min} \le T_j^{on} \le T_j^{max} \tag{11}$$

Where, T_j represents the response time of j-th demand response resource within the dispatching cycle; T_j^{min} and T_j^{max} represent its minimum and maximum response time respectively within the dispatching cycle.

3. Demand Response Analysis Considering Unit Uncertainty

Stochastic production simulation of power systems can take into account load volatility and random unit failures, and calculate the generation capacity, generation cost, and system reliability index of each unit under optimal operation by optimizing the production of generating units. Currently, stochastic production simulation is widely used in cost analysis, development and operation planning, and reliability assessment of power systems [9-11]. To improve the computational accuracy and speed of stochastic production simulation algorithms, scholars from various countries have proposed a series of improved algorithms, including Fourier series method, segmented linear approximation method, semi-invariant method, equivalent power function method, etc. However, several of these algorithms are based on the equivalent continuous load curve to achieve the optimization of unit production situation, and the calculation process ignores the time-series related information and constraints, which makes it difficult to analyze the time-series characteristics of load and unit output [12,13].

3.1 Sequential Probabilistic Production Simulation

In order to obtain the time-varying undersupplied power in the system, so as to determine the starting time of demand response and response capacity, this paper uses a sequential probabilistic production simulation algorithm to optimize the production of generator units, i.e., to retain the sequential load curve, reflects the probabilistic unit shutdown and output fluctuations as the changes of system power supply capacity, calculates the reliability indicators of the system in periods, and then accumulates them to obtain the simulation results of the whole operation cycle [14].

Sequential probabilistic production simulation algorithm reflects unit output with probability density of available system capacity. Assuming the total unit capacity of N generator systems is P_z, and the greatest common divisor of the rated capacity of all units is α, then, the available capacity probability density function is generated by the following equation.

$$\begin{cases} F_i(M) = q_i F_{i-1}(M) + p_i F_{i-1}(M - M_i) \\ M_i = P_i / \alpha \end{cases} \tag{12}$$

where M=0, 1, 2 … P_z/α; q_i and p_i represent the forced outage rate and available rate of i-th unit respectively.

The initially available capacity probability density function value when the units in the system are not put into operation is F_0=[1 0 … 0]. F_0 is kept corrected based on equation (12) until all of n units are put into operation to obtain the available capacity probability density function diagram of n units, and contrastive analysis is performed between it and the system daily load curve on the power axis, as shown in Fig. 1.

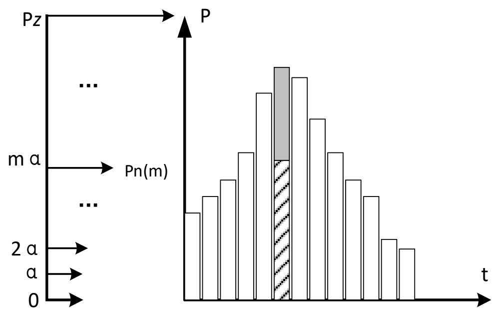

Fig.1 Schematic Diagram of Sequential Probabilistic Production Simulation

The gray part in Fig. 1 shows the load loss of the system at that moment corresponding to $m+1$-th status. When comparing load $P_{l,t}$ at a certain moment with the available capacity $M\alpha$one by one, if $P_{l,t}>M\alpha$, then it is believed that the system has load loss. In this case, the expected value of the system's power shortage at moment t is:

$$EENS_t = \sum_{M=0}^{D_{l,t}} (P_{l,t} - M\alpha) P_n(M) \tag{13}$$

Power shortage probability is:

$$LOLP_t = \sum_{M=0}^{D_{l,t}} P_n(M) \tag{14}$$

The expected value of the system's power shortage in the entire research cycle is:

$$EENS = \sum_{t=1}^{T} \sum_{M=0}^{D_{l,t}} (P_{l,t} - M\alpha) P_n(M) \tag{15}$$

where,

$$D_{l,t} = \begin{cases} INT(\dfrac{P_{l,t}}{\alpha}), \dfrac{P_{l,t}}{\alpha} \in Z \\ INT(\dfrac{P_{l,t}}{\alpha}) - 1, \dfrac{P_{l,t}}{\alpha} \notin Z \end{cases} \tag{16}$$

3.2 Demand Response Calculation Steps

To sum up, the analysis flow chart of the demand response considering unit uncertainty is as follows.

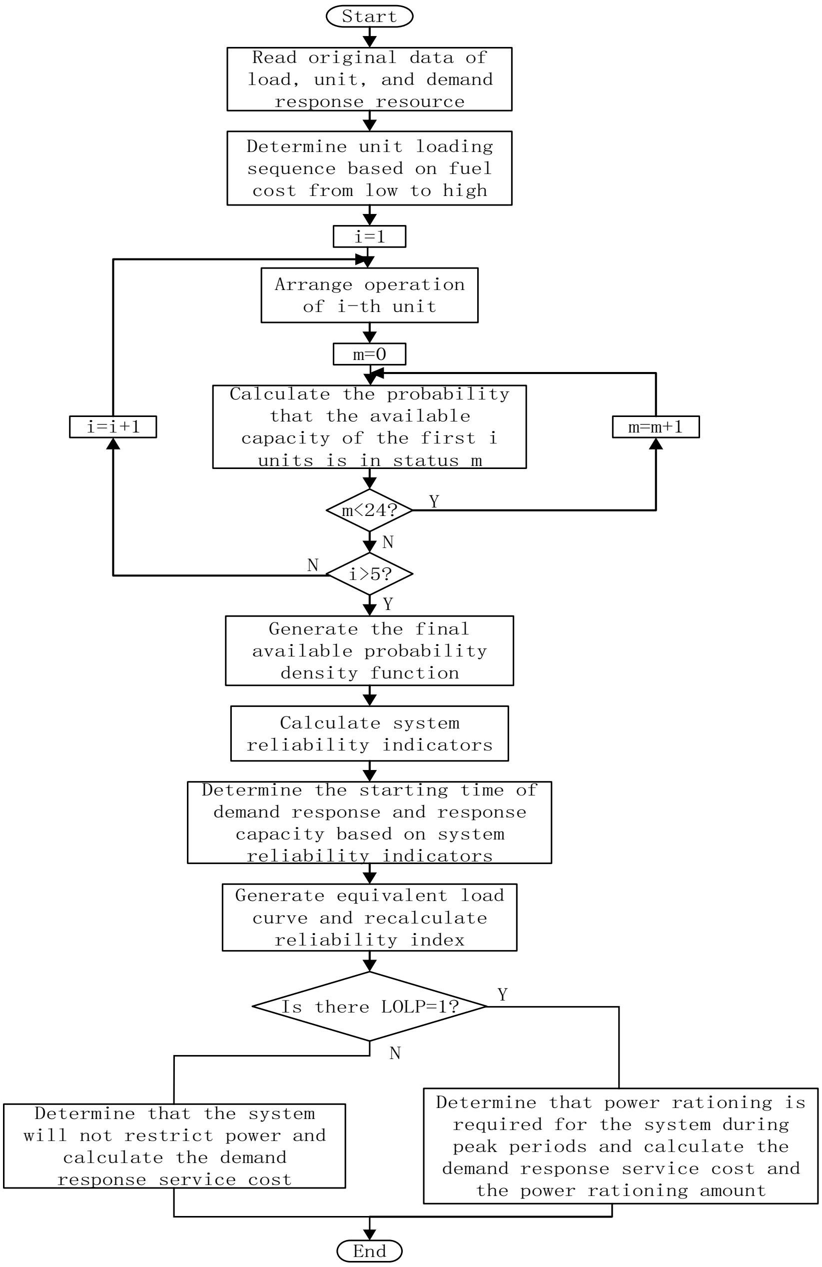

Fig.2 Algorithm flowchart

4. Test Results and Discussions

This paper takes two typical peak shaving scenarios of the IEEE30 node system for demand response analysis. The total installed capacity of the system is 480 MW, and the detailed parameters of the generator unit are shown in Table 1.

Tab.1 Parameters of Generator Unit

Unit model	**Capacity/MW**	**Forced outage rate *p***
1	160	0.04
2	100	0.026
3	60	0.017
4	80	0.02
5	40	0.01
6	40	0.01

The unit commissioning sequence is determined according to the fuel cost, and the available capacity probability density function of the system is generated based on the forced outage rate of the unit. The probability of the system operating in each available capacity status is shown in Table 2.

Tab.2 Probability Density of Available Capacity

Available capacity/MW	**Probability**	**Available capacity/MW**	**Probability**
0~200	0.0001	360	0.0003
220	0.001	380	0.0238
240	0.0006	400	0.0154
260	0.0008	420	0.018
280	0.0008	440	0.0178
300	0.0004	460	0.0001
320	0.0373	480	0.8828
340	0.0008		

The demand response resources that can be used for peak shaving in the system are as follows:
(1)Electric vehicle: Response capacity: 7.5 MW; duration: 2 h; incentive cost: CNY 0.4/kWh;
(2)Interruptible load: Response capacity: 0-15 MW; duration: 3 h; incentive cost: CNY 1/kWh.

4.1 Peak Shaving Scenario 1

The daily load data of Scenario 1 is shown in Fig. 3. Reliability indicators of Scenario 1 were figured out according to equations (13), (14), and (15).

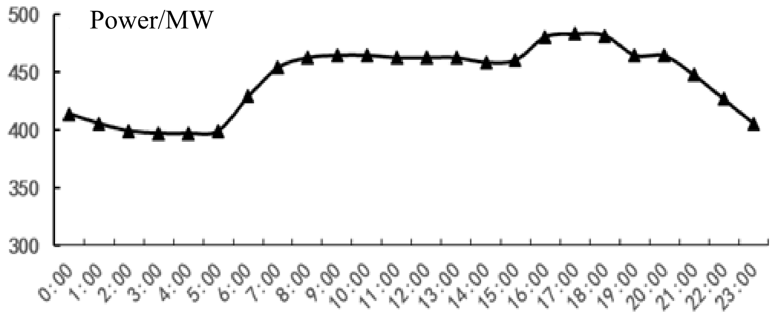

Fig. 3 Daily Load Curve of Scenario 1

According to Fig. 3, the load in 16:00~18:00 is greater than the maximum unit output, so load loss status must occur in this period, i.e., the probability of power shortage is 1. The load in other periods is small, and the power shortage probability considering unit output uncertainty is extremely small, so it can be deemed that the load in such periods can be balanced with the unit output. The demand response resource started response at 16:00, and its response results are shown in Fig. 4 and Table 3.

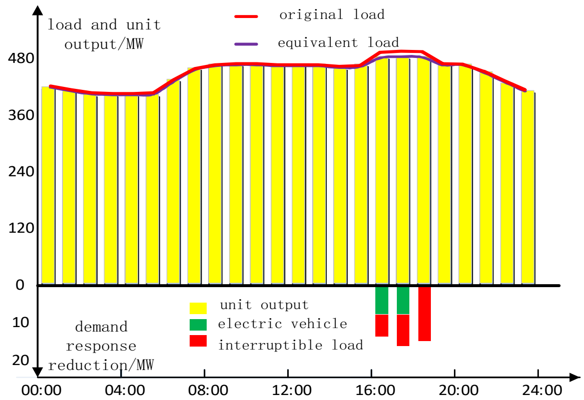

Fig. 4a System Operation Statuses before and after Demand Response

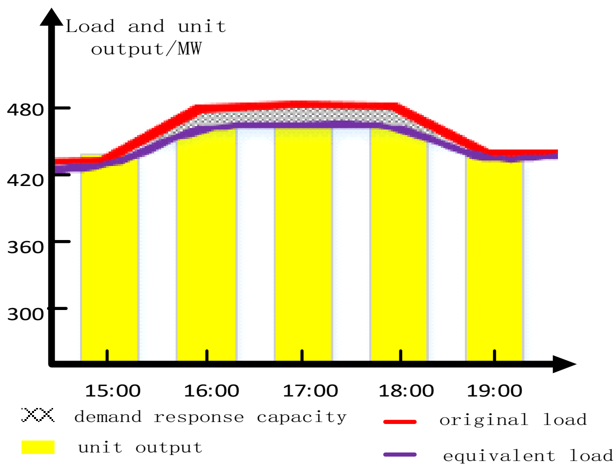

Fig. 4b Local System Operation Statuses before and after Demand Response

Fig. 4b shows a partial diagram of the demand response time period in Fig. 4a, and the shaded area is the system load reduction.

Tab.3 Power Shortage Probability

Time	LOLP after demand response	LOLP after demand response
16:00	1	0.1171
17:00	1	0.1171
18:00	1	0.1171

It can be learned from Fig. 4 and Table 3 that after the demand response in Scenario 1, the active output of the generator unit is basically able to meet the load demand. The power shortage probability during peak periods dropped to 0.1171 from 1, namely, it can be approximately regarded that the demand response enables Scenario 1 to achieve a balance between supply and demand even during peak load periods, so it is unnecessary to perform power rationing. The service cost on the peak shaving demand response side is CNY 34,480.

4.2 Peak Shaving Scenario 2

The daily load data of Scenario 2 is shown in Fig. 5. Reliability indicators of Scenario 2 were figured out according to equations (13), (14), and (15).

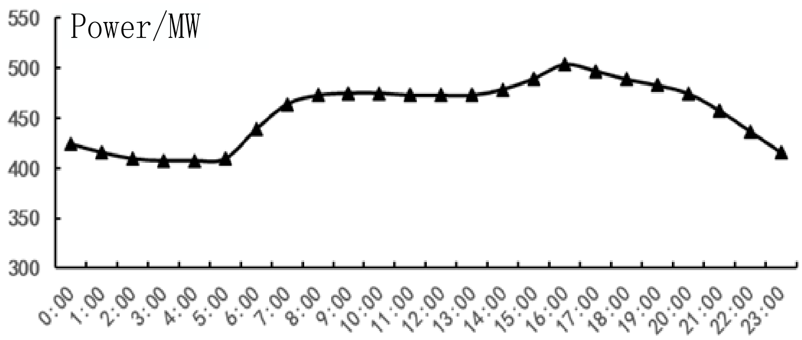

Fig. 5 Daily Load Curve of Scenario 2

According to Fig. 5, the load in 15:00~19:00 is greater than the maximum unit output, so load loss status must occur in this period, i.e., the probability of power shortage is 1. The load in other periods is small, and the power shortage probability considering unit output uncertainty is extremely small, so it can be deemed that the load in such periods can be balanced with the unit output. The demand response resource started response at 15:00, and its response results are shown in Fig. 6 and Table 4.

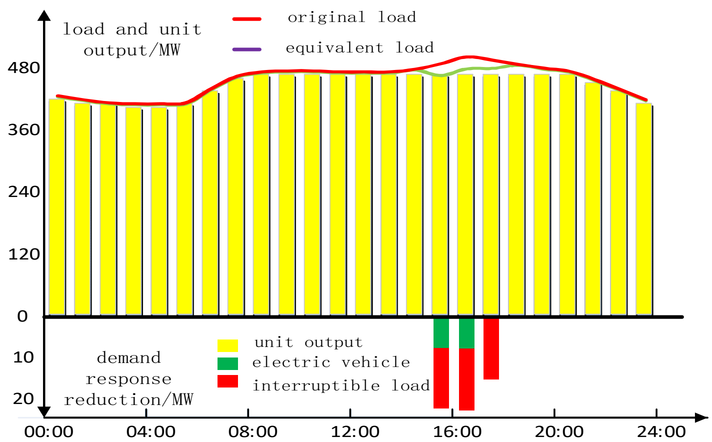

Fig. 6a System Operation Statuses before and after Demand Response

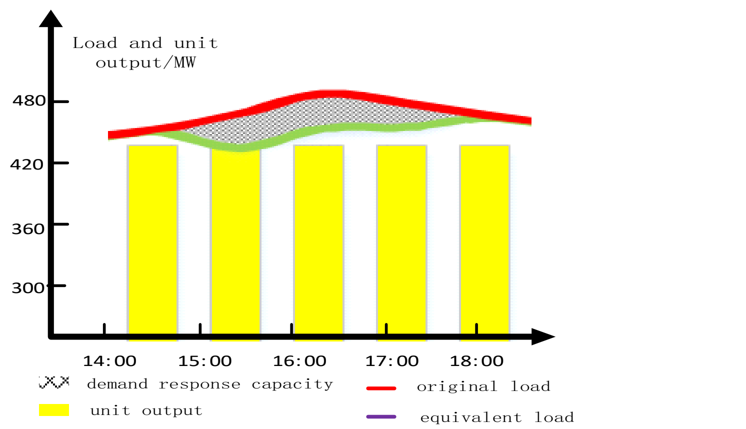

Fig. 6b Local System Operation Statuses before and after Demand Response

Fig. 6b shows a partial diagram of the demand response time period in Fig. 6a, and the shaded area is the system load reduction.

Tab.4 Power Shortage Probability

Time	LOLP after demand response	LOLP after demand response
15:00	1	0.1171
16:00	1	1
17:00	1	1

It can be learned from Fig. 6 and Table 4 that after demand response in Scenario 2, the generator unit still cannot always meet the load demand. Except for 15:00, when the power shortage probability dropped to 0.1171, the power shortage probability did not decrease significantly in other periods, i.e. it is still necessary to perform power rationing during peak periods to ensure system supply and demand balance. The service cost on the peak shaving demand response side is CNY 64,090. The power rationing amount before and after demand response is shown in Fig. 7.

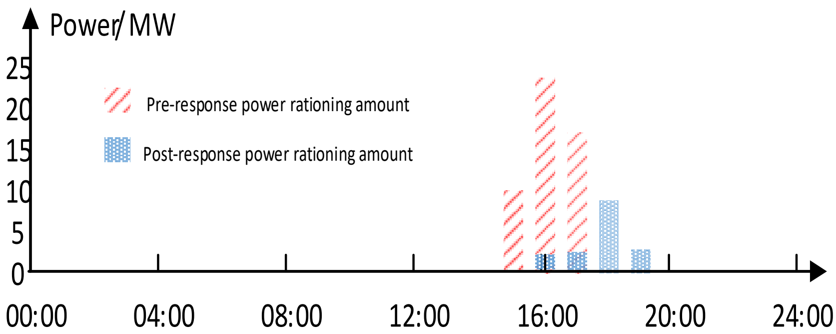

Fig. 7 Power Rationing Amount

Based on the comparison of power rationing amount before and after response, since the demand response resource is in response status during 15:00~17:00, the power rationing amount after response during this period in Fig. 7 dropped significantly compared with that before response, in which, the power rationing amount after a response at 15:00 is zero. Since no power rationing was performed during 18:00~19:00, the power rationing amount was not dropped. Therefore, demand response is able to narrow the power outage range of the system.

5. Conclusions

By research on optimal peak shaving analysis of power demand response considering unit uncertainty, this paper obtains the following conclusions:

(1) A demand-response power system optimization dispatch model that takes into account unit uncertainty is proposed to meet the peak load scenario peak shaving demand, alleviate power consumption tension and achieve optimal resource allocation.

(2) When the difference between the peak load and the maximum active output of the generating unit is not large, the demand response aims at the minimum response cost and participates in peak shaving in an economic order, so that the probability of power shortage during the peak load period is all reduced to a safe range, avoiding power pulling and restriction.

(3) When the difference between the peak load and the maximum active output of the generating unit is large and the electricity is tight, the demand response is aimed at the minimum power pulling limit, and the expected value of the system power shortage is greatly reduced after the response, which minimizes the power pulling limit and reduces the scale of orderly power consumption.

References

[1] Zheng J. Y., Hu M. Y., Hu Z. J. et al. Multi-objective planning model of distribution network considering reliability and demand response [J]. Journal of Electric Power Science and Technology, 2019, 34 (03):173-182.
[2] Guo M. X., Lv R., Fei W., et al. The scheduling strategy of multi-energy coupling system considering electric vehicles and demand response [J/OL]. Electric Power: 1-10 [2022-04-28]. http://kns.cnki.net/kcms/detail/11.3265.tm.20211210.1934.008.html.
[3] Li Z. J., Han A. Y., Zhou S. Q., et al. Optimization of an integrated energy system considering integrated demand response [J]. Power System Protection and Control, 2021, 49 (21):36-42.
[4] Li J. B. and Chen X. P. Analysis of demand-side response technology [J]. Sino-Global Energy, 2021, 26 (05):16-22.
[5] Wang B., Ye B., Zhu L. Z., et al. Practice and exploration of China's power demand response in electricity market [J]. Power Demand Side Management 2021, 23 (05):91-95.
[6] Dong M. M. Demand response effect evaluation considering time-of-use price [D]. Beijing: North China Electric Power University, 2014.
[7] Zhang Y. Q. Day ahead economic dispatch of integrated energy system considering price-based demand response [J]. Jilin Electric Power, 2020, 48 (03):20-23.
[8] Zhang Z. Study on day-ahead optimal scheduling model with demand response [D]. Beijing: North China Electric Power University (Beijing), 2016.
[9] Liu C., Qu J. X. and Shi W. H. Evaluating method of the ability to accommodate renewable energy based on probabilistic production simulation [J]. Proceedings of the CSEE, 2020, 40 (10):3134-3144.
[10] Wu S. L., Feng Y., Wu K. et al. Operation evaluation method of high proportion renewable energy power system based on exchange convolution [J]. Electric Power, 2019, 52 (04):25-31.
[11] An Z., Zhang Z. Z., Chen Z., et al. Stochastic production simulation study of power system with photothermal-photovoltaic combined power generation [J]. Renewable Energy Resources, 2019, 37 (11):1603-1610.
[12] Zhu R., Hu B., Xie K. G., et al. Sequential probabilistic production simulation of multi-energy power system with wind power, photovoltaics, concentrated solar power, cascading hydropower, thermal power, and battery energy storage [J]. Power System Technology, 2020, 44 (09):3246-3253.
[13] Wang L. G., Zhu Y. F., Wu X. D. et al. Assessment on the capacity value of wind power based on probabilistic chronological production cost simulation [J]. Proceedings of the CSU-EPSA, 2018, 30 (11):114-119.
[14] Liao Q. L., Xie K. G. and Hu B. Sequential probabilistic production simulation of power systems with wind power and energy storage [J]. Power System Technology, 2017, 41 (09):2769-2776.