Analysis of Flexibility Demand with Regional Power Grid

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Abstract. Improving the flexibility of regional power grid is an important means to solve the problem of energy abandonment. Quantitative calculation of flexibility demand is the premise of unit transformation and optimal allocation of flexible resources. This study analyzed the definition of flexibility demand, and established the model of flexibility demand. In this paper, random variables are introduced to describe the flexibility demand, and the sequence operation theory is used to solve the model. A case study is given to verify the proposed method. The results prove that the proposed method can calculate the probability distribution of flexibility demand in the planning year without detail information of units. It can provide a reference for the capacity transformation of units and the optimal allocation of flexible resources.

Keywords: Renewable energy; Flexibility demand; Sequence Operation Theory (SOT); Random variable.

1. Introduction

Large scale renewable energy source (RES) integration is the main trend of energy development at present. It is also the main characteristics of electric power grid in China. The installed capacity of RES accounted for 38% of the total installed capacity of China, of which wind and solar energy sources accounted for 21% in 2019 [1]. Due to large-scale fluctuating power sources are connected to the electric power grid, the peak-valley difference becomes larger. It is difficult to adjust the peak of the electric power grid, which resulting in a large number of wind and solar curtailment [2-3]. Since the heating units need to operate determined by heat in winter, there is basically no space for downward peak load regulation in power grid [4]. Lack of flexibility of regional power grid is the key factor. The flexibility of regional power grid can be improved by transforming coal-fired power plants. However, it is difficult to accurately determine the flexibility demand which is depend on the fluctuation quantities of load and RES. Unites transforming has an impact on transformation cost, transaction cost of peak load regulation, loss cost of electricity sales, generation cost of peak load regulation and electricity abandonment cost. Therefore, it is urgent to quantitative calculate the power system flexibility demand, so as to scientifically plan and arrange the flexibility transformation and flexible resources to prevent the waste of resources caused by excessive investment [5].

In recent years, scholars have done some research on power system flexibility, mainly focusing on the establishment, evaluation and optimal dispatching. Based on the sequential method, Ge [6] established the index of flexibility demand, which measures the insufficient climbing power caused by the strong fluctuation of renewable energy. Li [7] quantitatively analyzed the flexibility of power system from the view of power balance. Huang [8] established a quantitative model of demand and supply of flexibility based on sequential data. Heggarty [9] studies flexibility remand of power grid system in different time...
scales based on the method of frequency spectrum. Reference [10-12] analyzed the mechanism of power system flexibility balance from the perspective of stochastic production simulation, and established flexibility evaluation index. Reference [6-9] studies the flexibility demand from the perspective of time series simulation. Although this method can be used for specific operation guidance, it needs large amount of calculating, and this method requires a lot of detailed information of the unit, which is not easy to obtain.

In this study, the method proposed is quantitative analysis and calculation of flexibility demand from perspective of stochastic production simulation. The paper makes a comparative analysis of flexibility demand under different time scales. The structure of the study is arranged as below. Section 2 introduces the definition and modeling of flexibility demand. Section 3 introduces the sequence operation theory. Section 4 is calculated an example. Section 5 draws the conclusions.

2. Analysis of Flexibility Demand

2.1. Definition of Flexibility Demand

With the extensive development of RES, electric vehicles and intelligent household appliances, the energy generation side and load side of renewable electric power grid have strong random volatility and uncertainty compared with traditional power system. When the power grid fluctuates, it is necessary to deploy flexibility resources to stabilize, so as to ensure the balance of power and electricity. The flexibility demand refers to the minimum active power regulation capability of electric power system to stabilize the fluctuation of uncertain net load in a certain time scale. When the flexibility demand is positive, it means that the power system needs to allocate flexibility resources to increase output power to reduce load shedding accidents. When the flexibility demand is negative, the power system needs to allocate flexibility resources to reduce output to reduce the power abandonment. The flexibility demand are generated by the fluctuation of RES and load and the prediction error between RES and load.

2.2. Flexibility Demand Model

The net load of the system is the difference between the load and the renewable energy. Similarly, the flexibility demand is the difference between the flexibility demand generated by the original load and the flexibility demand generated by the renewable energy. The load flexibility demand is mainly caused by load fluctuation and prediction error. The flexibility demand of renewable energy is mainly generated by the fluctuation of renewable energy and prediction error [10]. This paper introduces random variables to describe the system flexibility demand. The flexibility demand generated by load is the addition-type-convolution (ATC) between random variables of load fluctuation quantities and prediction error. The flexibility demand of renewable energy is the addition-type-convolution between random variables of renewable energy fluctuation quantities and prediction error. The system flexibility demand is the subtraction-type-convolution (STC) between the flexibility demand of load and renewable energy. The expressions are shown in equation (1-3).

\[ P_{\text{load}} = P_{\text{load}}^{\text{vol}} \oplus P_{\text{load}}^{\text{err}} \]  
\[ P_{\text{re}} = P_{\text{re}}^{\text{vol}} \oplus P_{\text{re}}^{\text{err}} \]  
\[ P_{\text{sys}} = P_{\text{load}} \ominus P_{\text{re}} \]

Where, \( P_{\text{sys}} \) is the random variables of flexibility demand of regional power grid, MW, \( P_{\text{load}} \) is the random variables of flexibility demand generated by load, MW, \( P_{\text{re}} \) is the random variables of flexibility demand generated by RES, MW, \( P_{\text{load}}^{\text{vol}} \) is the random variables of fluctuating quantity generated by load, MW, \( P_{\text{re}}^{\text{vol}} \) is the random variables of prediction error generated by load, MW, \( P_{\text{re}}^{\text{err}} \) is the random
variables of fluctuating quantity generated by RES, MW, $P_{re}^{err}$ is the random variables of prediction error generated by RES, MW, $\oplus / \Theta$ are the symbols of ATC and STC.

3. Sequence Operation Theory

Sequence operation theory (SOT) is an effective algorithm to solve stochastic production simulation problems, which can effectively solve a class of stochastic and uncertain problems in power system. In this section, the flexibility demand model is calculated based on the SOT [13], and the addition and subtraction method of random variables is calculated through ATC and STC [9].

$p(m)$ and $q(n)$ are two discrete sequences defined on nonnegative interval, where $m=0,1\ldots L_m, n =0,1\ldots L_n$, $L_m$ and $L_n$ are the length of the two sequences respectively. The operation principle of addition-type-convolution and subtraction-type-convolution difference operation are shown in equations (4) - (6).

(1) Let $L_s = L_m + L_n$, then

$$s(j) = \sum_{m+n=j} p(m) \cdot q(n), \quad j = 0, 1\ldots L_s$$

(4)

Where, $0 \leq m \leq L_m, 0 \leq n \leq L_n$, the operation defined by formula (5) is named addition-type-convolution. $s(j)$ is the addition-type-convolution of $p(m)$ and $q(n)$, $L_s$ is the length of the sequence.

$$s(j) = p(m) \oplus q(n)$$

(5)

(2) Let $L_d = L_m$, then

$$d(j) = \begin{cases} \sum_{m+n=j} p(m) \cdot q(n) & 0 \leq j \leq L_d \\ \sum_{m+n=j} p(m) \cdot q(n) & j = 0 \end{cases}$$

(6)

Where, $0 \leq m \leq L_m, 0 \leq n \leq L_n$, the operation defined by formula (7) is named subtraction-type-convolution. $d(j)$ is the subtraction-type-convolution of $p(m)$ and $q(n)$, $L_d$ is the length of the sequence.

$$d(j) = p(m) \Theta q(n)$$

(7)

In this paper, the fluctuation quantities and prediction error of the load and wind energy are expressed by probability series. The operation principle of probability series is shown in reference [14].

4. Case Study

The data used in the case study come from the data of regional power grid in North China. The data include wind farm operation data and load of power grid. Four typical scenarios are set up in this section, which are spring, summer, autumn and winter. There are three different time scales, which are 15 minutes, 1 hour and 4 hours.

Taking the winter scenario as an example. The historical operation data of load and wind farm from January to March are taken, as shown in figure 1 and figure 2. From the figure, you can see that the probability of wind power generation less than 50 MW is the highest, and the probability of load less than 2000 MW is about 85%.

The proposed methodology can be used in calculating the probability distribution of flexibility demand in medium and long-term scenarios. The probability distribution of flexibility demand generated by load on 15 minutes time scale is described in figure3. Figure 4 shows the probability distribution of flexibility demand generated by load and wind energy on 15 minutes time scale. Comparison with the two figures,
the system flexibility demand increases due to the strong random fluctuation of wind energy. The scope of the downward flexibility demand increases from 350 MW to 675 MW and the scope of upward flexibility demand increases from 300 MW to 575 MW. According to figure 4, flexibility demand is mainly distributed between 0 and 50 MW, with a probability of 53%.

Assuming that the thermal power generation capacity of power grid is 500 MW, and the climbing rate is 1% of rated capacity per minute. Then the climbing capacity of power system in 15 minutes is 75 MW. We can draw a conclusion from figure 4 that flexibility demand of climbing capacity greater than
75 MW cannot be met. If the climbing rate is increased to 2% of rated capacity per minute, which is transformed by flexibility, the climbing capacity of system is 150 MW within 15 minutes, and 92% of the probability of climbing flexibility demand can be satisfied, which is 30% higher than that when the climbing rate is 1% of rated capacity per minute. In addition, it can also be used to reduce the system flexibility demand with demand response, energy storage system and renewable energy control. Figure 5 shows the probability distribution of flexibility demand in spring, summer, autumn and winter on 15 minutes time scale. The range of climbing flexibility demand of the system varies greatly in winter is obvious from the calculation. When the climbing capacity is 75 MW, it can meet more than 90% of the climbing flexibility demand in spring, summer and autumn, but only 62% in winter. We can draw a conclusion that wind power consumption is reduced because of heating supply in winter. Therefore, the system needs to improve system flexibility or provide flexible resources to accept more wind energy. Probability distribution of flexibility demand in different time scales under the same scenario is described in figure 6. The probability distribution range of flexibility demand varies with time scales. The larger the time scale, the greater the scope of flexibility demand. On the 4 hours scheduling range, the frequency modulation and climbing flexibility demand increase of the time scale. Therefore, flexibility resources can be optimally allocated on different time scales to meet the demand of system flexibility balance.

**Figure 5.** Probability distribution of flexibility demand in different scenarios under the same time scale.  
**Figure 6.** Probability distribution of power system flexibility demand in different time scales.

5. Conclusions
In this work, the model of flexibility demand is established, and random variables are introduced to describe the flexibility demand. The model can find the solution by probabilistic sequence operation theory. The results of this work describe the probability distribution of the demand for flexible resources in the regional power grid. It can provide a certain reference for the capacity transformation of thermal power units in the power system. The advantage of the method presented in this study is that the detailed information of the unit is not needed in the calculation process. However, the method proposed in this study has some limitations. It cannot reflect the specific operation information, but only illustrate the probability distribution of the demand for flexible resources within the study period from the perspective of probability.

(1) This paper compared the changes of system flexibility demand before and after wind power integration. The results show that the system flexibility demand increases due to the strong volatility of wind power.
(2) This paper analyzed the probability distribution of flexibility demand in different scenarios under the same time scale. The result shows that the system flexibility demand of winter in northern China is higher. In this case, the optimal allocation of flexibility resources can be done well in advance.

(3) In the same scenario, the flexibility demand of frequency adjustment and climbing increases with the increase of time scale.

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References
[1] China Electricity Council List of national power industry statistical express data in 2019 https://cec.org.cn/detail/index.html?3-277095
[2] Wang, Y., Ji, Q., Shi, X., & Kazmerski, L. 2020 Regional renewable energy development in China: a multidimensional assessment. Renewable and Sustainable Energy Reviews, 124
[3] Tang N, Zhang Y, Niu Y and Du X 2018 Solar energy curtailment in China: Status quo, reasons and solutions Renew. Sustain. Energy Rev. 97 509–28
[4] Yuan G, Wang L and Wang B 2017 Optimal dispatch of heat-power load and economy benefit analysis based on decoupling of heat and power of virtual power plant Proceedings of the CSEE 37(17):4974-4985
[5] Xu H, Jin Q, Jiang J, Lu Z, Qiao Y 2020 Capacity optimal plan of thermal power flexibility transformation based on probabilistic production simulation Journal of Global Energy Interconnection 3(4):393-403
[6] GeZ, Zhang Q, Qi X, et al. 2018 Index system for renewable energy output characteristics considering flexible demand Proceedings of the CSU-EPSA, 30(7):30-37
[7] Li Z, Chen L, Lu X, et al. 2017 Assessment of renewable energy accommodation based on system flexibility analysis Power System Technology 41(7):143-150.
[8] Huang P, Zhou Y, Xu F, Cui D, Ge W, Chen X, Li T and Jiang F Source-load-storage coordinated rolling dispatch for wind-turbine-integrated power system based on flexibility margin Electric power http://kns.cnki.net/kcms/detail/11.3265.TM.20200513.1929.006.html
[9] Heggarty, T., Bourmaud, J. Y., Girard, R., & Kariniotakis, G.. 2019 Multi-temporal assessment of power system flexibility requirement. Applied Energy, 238(MAR.15), 1327-36.
[10] Lu Z, Li H and Qiao Y 2017 Flexibility evaluation and supply/demand balance principle of power system with high-penetration renewable Electricity Proceedings of the CSEE 37(1):9-19
[11] Li H, Lu Z, Qiao Y, et al. 2015 Assessment on operational flexibility of power grid with grid-connected large-scale wind farms Power System Technology 39(6):1672-1678
[12] Li H, Lu Z and Qiao Y 2015 Evaluation method of wind power accommodation capacity based on non-sequential production simulation Electric Power Construction 36(10):129-137
[13] Kang C, Xia Q, Xiang N, et al. 2002 Sequence operation theory and its application Automation of Electric Power Systems 26(17):6-11
[14] Kong C,Bai L, Xia Q, et al. 2003 Probabilistic sequences and operation theory J Tsinghua Univ ( Sci & Tech ) 43(3):35-38