PAPER • OPEN ACCESS

Adaptability Planning of Transmission Grid with Integration of High-proportion Renewable Energy

View the article online for updates and enhancements.

IOP ebooks™

Bringing you innovative digital publishing with leading voices to create your essential collection of books in STEM research.

Start exploring the collection - download the first chapter of every title for free.

Adaptability Planning of Transmission Grid with Integration of High-proportion Renewable Energy

Li Huaqiang[1], Wang Ziyao[1], Fan Jinzhu[1,a], Liu Wanyu[1]

[1]Intelligent Electric Power Grid Key Laboratory of Sichuan Province (Sichuan University), Chengdu 610065, China

[a]fjzscu@163.com

Abstract. The large-scale integration of renewable energy to power grid is an important feature of future power system development, but renewable energy has strong fluctuation and high uncertainty, which will have a strong impact on power grid. In order to ensure the safe, efficient and reliable operation of power system, improve the acceptability of renewable energy in power grid planning, it is urgent to evaluate the adaptability of power grid structure to the strong fluctuation and uncertainty of renewable energy. Considering that the adaptability of power grid has a broad meaning and is difficult to quantify, this paper analyses the characteristics and actual operation state of the high-penetration renewable energy system and establishes an adaptability index series of power gird structure considering operation safety, efficiency and stability. Based on the adaptability indexes, a multi-objective transmission planning model is put forward. The improved chaotic crossover genetic algorithm and the nonlinear PCA method are used to solve the planning model. Finally, the simulation of Gaver-18 bus system demonstrates the feasibility and effectiveness of the adaptability indexes and planning model.

1. Introduction

With the depletion of fossil energy and the deterioration of global environment, renewable energy has become an important choice for sustainable development of human beings. Large-scale integration of renewable energy to power grid will be an important feature of future power system. However, renewable energy has strong volatility and uncertainty, which will have a strong impact on the power system. The influence is manifested by decentralization and complication of power grid operation, probability of electricity and power balance, scarcity of flexible resources [1]. In this context, grid structure constraints will largely restrict the adaptability of power systems to renewable energy integration. Therefore, in order to meet the development trend of large-scale renewable energy access to the power grid, it is urgent to strengthen the power grid construction, planning and building a highly adaptable power grid structure.

At present, there are a lot of studies on transmission grid planning considering renewable energy integration at home and abroad. Different grid planning models are established from the perspective of renewable energy absorption, to optimize the grid structure and make the planning scheme applicable to various uncertain scenarios. However, most of the studies use the abandonment cost of renewable energy to measure the adaptability of the planning scheme to renewable energy, and the evaluation index is relatively single, which cannot fully reflect the impact of renewable energy integration on the power system in many aspects.

Power system adaptability evaluation includes power grid security, economy, reliability and other aspects. Its application in power grid planning can more comprehensively reflect the capacity of power grid construction to accept renewable energy. Traditional power system adaptability research mainly focuses on the security adaptability analysis of power grid structure. Based on the homogeneity theory and complex network theory, W.Y.Liu [2] establishes the united weighted entropy index reflecting the self-organize criticality of power grid to analyze the adaptability of power grid structure and operation state to cascading failure. G.Qu [3] puts forward the index of generation capacity adaptability and guides power grid planning to improve the adaptability of planning scheme to different output modes of power plants. However, the above studies are based on low-random scenarios. After considering renewable energy integration, adaptability studies are mostly based on flexibility theory. Lannoye E [4][5] summarizes the research status of power system flexibility. Z.X.Lu [6] elaborates on the mechanism of flexibility balance and the ways to improve the flexibility of the system. However, the flexibility theory mainly evaluates the adaptability of power system to renewable energy from the perspective of power balance, lacking consideration of the operation status of power grid. Therefore, it is of great significance to study and improve the adaptability index series and apply it to power grid planning for realizing the integration of high proportion renewable energy to grid.

In view of the above shortcomings, this paper proposes a set of grid structure adaptability evaluation indexes to measure the adaptability of grid structure to renewable energy integration from the perspective of actual operation safety, efficiency and stability of the grid. Then, based on the adaptability index, considering the construction cost, renewable energy abandonment cost and operation constraints, a multi-objective power grid planning model is established. The improved non-linear principal component analysis method is used to make comprehensive decision on the planning scheme in order to obtain the optimal scheme. Finally, an example of Garver-18 bus system is given to verify the rationality and validity of the proposed index and planning model.

2. Adaptability of power grid structure and evaluation index

2.1. Adaptability of power grid structure
The randomness of renewable energy leads to the decentralization and complication of power grid operation mode, which not only increases the risk of operation, but also reduces the utilization efficiency of some transmission equipments. Under the background of high proportion renewable energy integration, this paper defines the adaptability of power grid structure as: facing the strong fluctuation and multi-temporal distribution characteristics of high proportion renewable energy, power grid relies on its own topological structure to suppress uncertain disturbances, and always maintains the ability of safe, efficient and stable operation. According to the above definition, the evaluation of grid structure adaptability includes three aspects.

1) Safety adaptability: refers to the uniformity of power flow distribution. The theory of uniformity points out that, at the same load level, the more uniform the power distribution of each line is, the stronger the bearing capacity of the power grid structure to uncertain factors, the lower the probability of large-scale cascading failures, and the higher the security level of the power grid.

2) Efficiency adaptability: refers to the maximization of power grid utilization. Under the premise of satisfying the security constraints such as power capacity constraints of normal and N-1 operation, if the average operation efficiency of each line is at a high level, over-construction of power grid can be avoided.

3) Fluctuation adaptability: refers to the high inertia of power flow. In the face of random disturbances, the smaller the actual power fluctuation range of each line is, the more stable the system operation state is, and the power grid structure has better suppression ability of power fluctuation.

2.2. Adaptability indexes of power grid structure
This paper evaluates the adaptability of power grid structure to renewable energy integration by analyzing the operation status of power grid. Because the power fluctuation of renewable energy will

transfer the power flow of power grid, the actual operation state of the system is always in dynamic change.

Therefore, this paper first defines the average load rate η and power fluctuation rate B of the line to represent the actual operation status of each single line. Combining with the content of grid structure adaptability evaluation in Section 2.1, the grid structure adaptability index of the whole grid is established to evaluate the multi-adaptability of the power grid structure in the dynamic operation process.

The average load rate η of each line is defined as the average of the actual load rate, which reflects the average load level of a single line in a random scenario.

$$\eta_i = \frac{E(P_{i,s,t})}{S_{i,max}} \tag{1}$$

Where: η_i represents the average load rate of line i; $P_{i,s,t}$ represents the actual transmission power of line i; s represents typical scenes; t represents every moment of typical scenes; $E(P_{i,s,t})$ represents the average value of transmission power of line i; $S_{i,max}$ represents the maximum transmission capacity of line i.

The power fluctuation rate B of each line is defined as the ratio of line actual power fluctuation to line power fluctuation capacity, which reflects the fluctuation range of actual power of a single line in actual operation.

$$B_i = \frac{\sqrt{E(P_{i,s,t}^2) - E(P_{i,s,t})^2}}{\min\left\{\left|S_{i,max} - E(P_{i,s,t})\right|, \left|E(P_{i,s,t})\right|\right\}} \tag{2}$$

Where: B_i represents the power fluctuation rate ofline i; $E(P_{i,s,t}^2)$ represents the average value of the square value of transmission power of line i; $\min\left\{\left|S_{i,max} - E(P_{i,s,t})\right|, \left|E(P_{i.s.t})\right|\right\}$ represents the fluctuation capacity of transmission power of line i; $\sqrt{E(P_{i,s,t}^2) - E(P_{i,s,t})^2}$ represents the actual transmission power fluctuation of line i.

Based on the average load rate η and the power fluctuation rate B of each line, considering the whole power grid, the adaptability indexes of power grid structure is established as follows.

1) Safety adaptability index: refers to the standard deviation of the average load rate of all lines, which reflects the uniformity of power flow distribution in average operation state.

$$f_{SA} = \sqrt{\frac{\sum_{i=1}^{N}(\eta_i - \eta_{ave})^2}{N-1}} \tag{3}$$

Where: N represents the total number of main grid lines; η_{ave} represents the average value of η_i.

2) Efficiency adaptability index: refers to the weighted average value of η_i, which reflects the efficiency of power grid operation under the average operation state. The bigger the index, the better the comprehensive utilization efficiency of power grid.

$$f_{EA} = \sum_{i=1}^{N} \alpha_i \eta_i \quad \alpha_i = \frac{(1-\eta_i)}{\sum_{i=1}^{N}(1-\eta_i)} \tag{4}$$

Where: α_i is the efficiency weight factor of line i, which can highlight the impact of low utilization line on the whole grid operation efficiency, and avoid data masking caused by using only average value.

3) Fluctuation adaptability index: refers to the weighted average value of B_i, which reflects the fluctuation range of line power in actual operation. The smaller the index is, the closer the actual operation state of the power grid is to the average operation state. The power grid can suppress the power flow transfer caused by the fluctuation of renewable energy power to the greatest extent, and

always maintain a safe and efficient operation state. The power grid structure has strong anti-disturbance ability.

$$f_{FA} = \sum_{i=1}^{N} \beta_i B_i \quad \beta_i = \frac{B_i}{\sum_{i=1}^{N} B_i} \tag{5}$$

Where: β_i is the power fluctuation weight factor of line i, which can highlight the impact of lines with large power fluctuation on the power flow stabilization performance of the grid, and avoid data masking caused by using only average value.

In summary, the safety and efficiency adaptability indexes reflect the characteristics of the average operating state of the grid under uncertain operating conditions. The fluctuation adaptability index reflects the ability of the power grid to maintain the efficiency and security of the average operation state in actual operation. Using the above indexes to evaluate the target grid structure comprehensively is conducive to the construction of a multi-adaptable grid structure. What needs to be added is that the power fluctuation range of renewable energy transmission lines is large, and these lines mainly focus on transmission capacity to ensure the absorption of renewable energy. Therefore, the above indicators only consider the main grid lines except the renewable energy transmission lines. For renewable energy transmission lines, capacity constraints are added to ensure renewable energy delivery.

3. Transmission grid planning model based on adaptability index
This paper establishes a multi-objective planning model based on adaptability index, and takes the location and capacity of transmission line construction as decision variables. The planning scheme is simulated in typical scenarios to extract the operation status of power grid, which is used to calculate the adaptability indexes and verify the constraints of safe operation. Then, the investment cost of power grid, the abandonment cost of renewable energy and the adaptability index are considered to optimize the power grid structure. The above process reflects the interaction between power grid planning and operation.

3.1. The objective functions
The objective functions of the model are total investment cost C, renewable energy abandonment cost D and adaptability index f. The specific planning model is as follows:

$$F = \min\{F_1, F_2, F_3, F_4\} \tag{6}$$

Where: F represents the comprehensive evaluation value of the planning scheme; F_1 represents the total investment cost and renewable energy abandonment cost; F_2, F_3 and F_4 represents the adaptability indexes of safety, efficiency and fluctuation.

3.2. Total investment cost and renewable energy abandonment cost

$$F_1 = C + D \tag{7}$$

$$C = (k_1 + k_2) \sum_{i \in \Omega_l} c l_i x_i \tag{8}$$

Where: $k_1 = r(1+r)^n / [(1+r)^n - 1]$ represents the capital recovery coefficient; r represents the discount rate; n represents the economic life of engineering; k_2 represents the fixed operating rate of engineering; Ω_l represents the new line set; c represents the unit length cost of transmission lines; l_i represents the length of line i; x_i represents the number of new lines i.

When the outgoing power of renewable energy is bigger than the line capacity, the renewable energy will be abandoned due to the overload of the transmission line. Therefore, the abandonment cost D of renewable energy is calculated as follows:

$$D = \begin{cases} k_1 c_r \sum_s (P_{r,s,t} - S_{r,max}) \Delta t & P_{r,s,t} > S_{r,max} \quad P_{r,s,t} > S_{r,max} \\ 0 & P_{r,s,t} < S_{r,max} \end{cases} \tag{9}$$

where: c_r represents the price of renewable energy; $P_{r,s,t}$ represents the power generated by renewable energy sources at time t in scene s; $S_{r,max}$ represents the capacity of transmission line for renewable energy; Δt represents the time scale.

3.3. Adaptability indexes

$$F_2(f_{SA}) = f_{SA} \tag{10}$$

$$F_3(f_{EA}) = -f_{EA} \tag{11}$$

$$F_4(f_{FA}) = f_{FA} \tag{12}$$

The above expressions are safety, efficiency and fluctuation adaptability indexes.

3.4. Constraints

The constraints including the number constraints of new transmission lines and the security constraints of power grid operation in different operating status are as follows:

$$\begin{cases} x_i^{\min} \leq x_i \leq x_i^{\max} \\ \quad i \in \Omega_l \\ \quad x_i \in \mathbf{Z} \end{cases} \tag{13}$$

$$\begin{cases} -\mathbf{B\theta} + \mathbf{P}_g + \mathbf{P}_{REG} = \mathbf{P}_L \\ |P_i| \leq S_{i,\max} \quad i \in \Omega_L \end{cases} \tag{14}$$

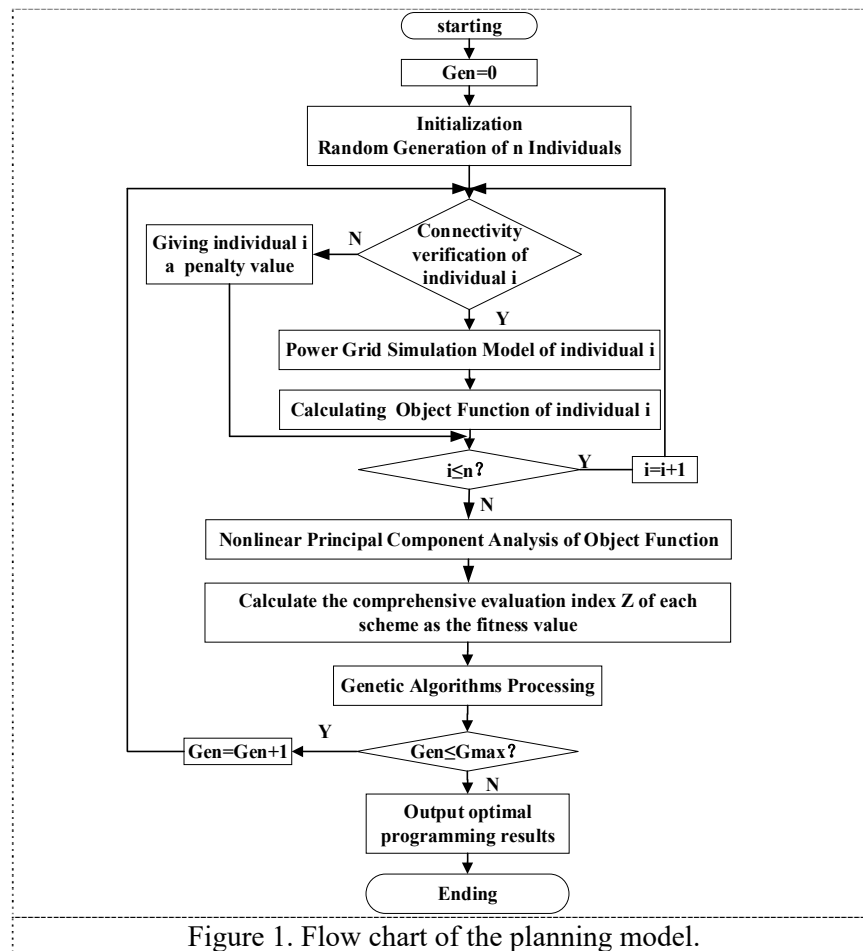$$\begin{cases} -\mathbf{B}^{N-1}\mathbf{\theta}^{N-1} + \mathbf{P}_g^{N-1} + \mathbf{P}_{REG}^{N-1} = \mathbf{P}_L^{N-1} \\ \left|P_i^{N-1}\right| \leq S_{i,\max} \quad i \in \Omega_L^{N-1} \end{cases} \tag{15}$$

$$\begin{cases} -\mathbf{B}^{s,t}\mathbf{\theta}^{s,t} + \mathbf{P}_g^{s,t} + \mathbf{P}_{REG}^{s,t} = \mathbf{P}_L^{s,t} \\ \left|P_{i,s,t}\right| \leq S_{i,\max} \end{cases} \quad s \in \Omega_s \tag{16}$$

Where: $x_i^{\max}$, $x_i^{\min}$ are the maximum and minimum number of lines to be built; x_i is the number of new lines i; Ω_L is the set of all lines; $\mathbf{B}$, $\mathbf{\theta}$, $\mathbf{P}_g$, $\mathbf{P}_{REG}$ and $\mathbf{P}_L$ are system node admittance matrix, node voltage phase angle vector, system node conventional generator output vector, renewable energy output vector and load power vector; superscript "N-1" means the N-1 operating status; superscript "s,t" means the typical scenarios; Ω_s is the set of all typical scenarios.

4. Example simulation

In this paper, the chaotic genetic algorithm and the non-linear principal component analysis are used to solve the multi-objective planning model of power grid. The non-linear principal component analysis method is applied to calculate the comprehensive evaluation value of the objective function and realize the comprehensive decision-making of power grid planning schemes. The flow chart is shown below.

Figure 1. Flow chart of the planning model.

4.1. Parameters

Based on the historical data of a wind farm, this paper uses K-means clustering method to form 4 typical wind power scenarios, as shown in figure A1 appendix A. This paper uses Garver-18 node system as an example to carry out simulation and node 16 is set as a wind farm with a capacity of 500 MW. The remaining specific parameters are set as follows: the voltage reference value is 220 kV and the power reference value is 100 MVA.

4.2. Analysis of planning scheme

According to the simulation calculation, the results of grid planning are shown in Figure 2. The dotted lines in the graph represent the newly built lines.
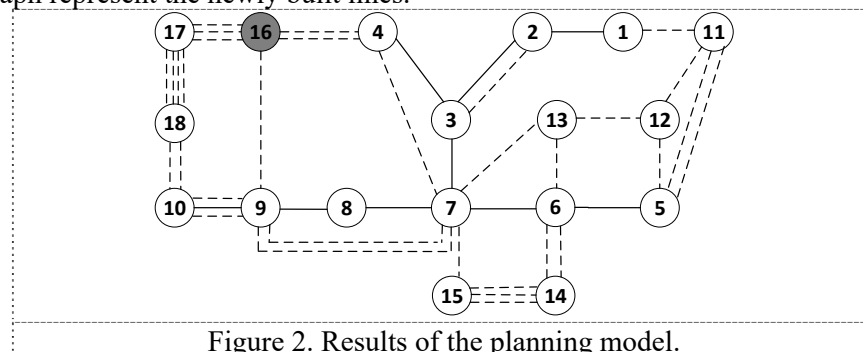

Figure 2. Results of the planning model.

To verify the validity and superiority of the model in this paper, we compare it with the existing economic plan [7]. The data is shown in Table 1.

Table 1 Planning Results of Garver-18 Node System

	scheme 1	scheme 2
Expansion line and its quantity	1-11(1),2-3(1),4-7(1), 4-16(2),5-11(2),5-12(1), 6-13(1),6-14(2), 7-9(2), 7-13(1),7-15(1), 9-10(2), 9-16(1),10-18(2), 11-12(1), 12-13(1),14-15(3), 16-17(3),17-18(4)	1-2(1),1-11(2),4-16(1), 5-12(1),6-13(1),6-14(2), 7-8(2),7-13(2),7-15(1), 8-9(2),9-10(2),10-18(1), 11-12(1),14-15(2),16-17(2), 17-18(1)
Construction cost (USD·10^4)	8025.9	5776.2
Normal penalty fee (USD·10^4)	0	1.26
N-1 penalty fee (USD·10^4)	0	74.6
Efficiency adaptability index	0.3342	0.4702
Safety adaptability index	0.2154	0.4218
Fluctuation adaptability index	0.1863	0.2553

Scheme 2 aims at economic optimization, with fewer new lines, lower costs and higher operational efficiency than scheme 1. However, in the context of renewable energy integration, due to the lack of transmission capacity, scheme 2 will appear line overload and N-1 overload, which cannot guarantee the safety and reliability of the power system. Through the optimization of adaptability indexes, scheme 1 adds 9-16 and 16-17 renewable energy transmission lines and forms more loop network structure inside the power grid. Although scheme 1 sacrifices part of the economy and the efficiency of power grid operation, it improves the power transmission capacity of the power grid and the power grid topology is more reasonable, which can effectively resist the disturbance of renewable energy on the system operation status. The simulation results show that the power grid in scheme 1 satisfies the N-1 security constraints and the operation state is more balanced and stable. To sum up, grid planning based on adaptability index can improve the system's adaptability to renewable energy from different aspects, and meet the development trend of renewable energy integration.

4.3. Impact of Renewable Energy Capacity on Adaptability Indexes

In order to verify the effectiveness of the adaptability index, the planning scheme is simulated under different renewable energy integration capacity. The variation of each adaptation index with the increasing of renewable energy penetration is shown in Figure. 3.

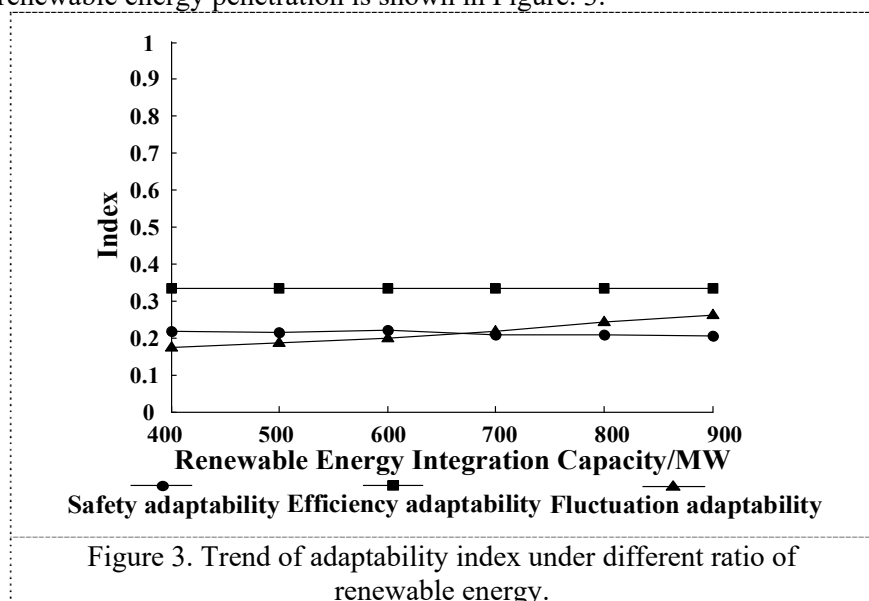Figure 3. Trend of adaptability index under different ratio of renewable energy.

Figure. 3 shows that the randomness of renewable energy will have a greater impact on the system when the proportion of renewable energy increases. The main performance is that the fluctuation adaptability index shows an upward trend, which indicates that the fluctuation range of power of each line is enlarged and the stability of operation state is gradually reduced.

In conclusion, with the increase of renewable energy penetration, the randomness of renewable energy has more obvious impact on the system. It is necessary to strengthen the construction of power grid to improve the system's acceptance of renewable energy.

5. Conclusion

In order to meet the large-scale integration of renewable energy and improve the adaptability of power grid planning scheme, this paper establishes a grid structure adaptability index to quantitatively evaluate the grid's receptivity to renewable energy. The indexes, which take into account the operation efficiency, safety status and fluctuation stabilization ability of the grid, is used to guide transmission grid planning. Compared with the traditional planning method, the planning model in this paper can not only ensure the safe, stable and efficient operation of the system, but also enhance the system's receptivity to renewable energy, which meets the needs of practical engineering applications.

References

[1]   Z. X. Lu, H. Huang, B. G. Shan, Y. H. Wang, S. H. Du, J. H. Li, "Morphological evolution model and power forecasting prospect of future electric power systems with high proportion of renewable energy," *Automation of Electric Power Systems*, vol. 41, no. 9, pp. 12-18, May. 2017.

[2]   W. Y. Liu, W. T. Cai, N. Zhang, Y. Q. Dan, C. Liang, W. Z. Wang, C. Liang, "Evolution of self-organizing of grid critical state based on united weighted entropy theory," *Proceedings of the Csee*, vol. 35, no. 6, pp. 1363-1370, Mar. 2015.

[3]   G. Qu, H. Z. Cheng, Z. L. Ma, Z. L. Zhu, J. P. Zhang, L. Z. Yao, "Multi-objective transmission expansion planning considering generation capacity adaptability," *Automation of Electric Power Systems*, vol. 33, no. 23, pp. 19-23, Dec. 2009.

[4]   Lannoye E, Flynn D, O'Malley M, "Evaluation of power system flexibility," *IEEE Transactions on Power Systems*, vol. 27, no. 2, pp. 922-931, May. 2012.

[5]   Lannoye E, Flynn D, O'Malley M, "The role of power system flexibility in generation planning," in *2011 IEEE Int. Conf. on Power and Energy Society*, pp.1-6.

[6]   Z. X. Lu, H. B. Li, Y. Qiao, "Flexibility evaluation and supply/demand balance principle of power system with high-penetration renewable electricity," *Proceedings of the CSEE*, vol. 37, no. 1, pp. 9-19, Jan. 2017.

[7]   Y. X. Jin, C. M. Wang, Power grid planning foundation and application, China Electric Power Press, 2011.