Analytics of high-penetration renewable energy accommodation using power system operation simulation

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Abstract: In recent years, China’s renewable energy has developed rapidly. The installed capacity of wind power and photovoltaic power has ranked first in the world. While at the same time, China is also facing a serious problem of curtailment of wind and photovoltaic energy. In this study, the statistical characteristics of high-penetration renewable energy accommodation were analysed using power system operation simulation. The sensitivity of the bottleneck is quantified based on the operation simulation results. The contribution degrees of peak regulation and transmission capacity are analysed using the proposed metrics. Finally, the proposed methods are used to analyse the characteristics of renewable energy accommodation in a provincial power grid of China in the scenario of 2020.

1 Introduction

In recent years, the installed capacity of renewable energy in China has maintained a rapid growth. By the end of 2017, the installed capacity of wind power in China has reached 164 GW and photovoltaic has reached 130 GW [1]. At the same time, due to various limiting factors, some areas have experienced serious problems of renewable energy curtailment. It is estimated that the opportunity cost of wind power curtailment in China exceed $1.2 billion from 2010 to 2016 [2]. With the national average curtailment ratio in 2016 at 17% for wind and 10% for solar [3], the problem of renewable energy curtailment in China is prominent in the world and urgent to be solved. It is necessary to study the characteristics of renewable energy accommodation at the planning and operation levels. By analysing the limiting factors affecting the consumption of renewable energy, the weaknesses of renewable energy accommodation can be identified. Several existing literatures have discussed the problem of renewable energy curtailment in China. According to the analysis of wind power operation data over the years, it is pointed out in [4] that the phenomenon of the abandoning wind energy in China is a result of a combination of factors. Some literatures focus on ways to increase the consumption capacity of renewable energy. Shi et al. [5] proposed policies and market mechanisms to promote the consumption of renewable energy in China. The effect of using heat storage technology, electric boilers and pumped storage to improve wind power consumption capacity was quantitatively analysed in [6, 7]. The effect of demand-side response on wind power consumption was studied in [8]. Zhu et al. [9] calculated the wind power consumption capacity based on the multi-scenario method in which a variety of constraints was considered in detail.

Power system operation simulation is generally used for the evaluation of generation expansion planning and transmission network planning [10, 11]. In recent years, this technology has also been used in studies related to renewable energy consumption [7, 12]. The power system operation simulation methods can be classified as deterministic and uncertain models. The deterministic models are mainly used for testing and analysis to evaluate power supply planning. Some temporal and spatial constraints can be considered in the deterministic models. However, the accidents of the unit are usually simulated under a certain reserve capacity, resulting in a lack of flexibility of reliability analysis. The uncertain models compensate for the shortcomings of the deterministic models. Nevertheless, they have poor suitability due to the large amount of calculations performing under the sequential load curve. The uncertainty models can be further divided into stochastic and probabilistic models, as shown in Table 1.

The methods proposed in the current studies to improve the consumption of renewable energy mainly include energy storage technology, cross-regional power transmission, multi-energy complementarity, and demand-side response [26–31]. These studies mainly demonstrate the feasibility of these methods from the perspectives of economic theory, technical solutions, and policies.

Curtailment of wind and photovoltaic energy is caused by a variety of factors [32, 33]. The existing researches qualitatively analyse the causes of renewable energy curtailment and quantitatively calculate the total amount of curtailment. Quantitative analysis of the renewable energy curtailment causing by specific limiting factor is an unsolved problem. The essence of the problem lies in the fact that the curtailment of wind and photovoltaic energy is the result of many factors, and the relationship between various factors is not a simple linear superposition. Therefore, we need to quantify the relationship of the limiting factors affecting renewable energy consumption based on power system operation simulation.

This paper presents an analytic method of renewable energy accommodation characteristics based on power system operation simulation, which can provide quantitative results for the characteristic analysis of renewable energy accommodation. The sensitivity of renewable energy accommodation to the change of limiting factors and the contribution degree of limiting factors are studied. Using the proposed method, this paper analyses the renewable energy accommodation in a provincial power grid of China in 2020.

Table 1 Uncertainty power system operation simulation models

| Type              | Methods                        | Literatures |
|-------------------|--------------------------------|-------------|
| stochastic models | Monte Carlo                    | [13–15]     |
|                   | Markov                         | [16, 17]    |
| probabilistic     | piecewise linear approximation  | [18, 19]    |
|                   | blocking method                | [20, 21]    |
|                   | equivalent energy function     | [22–24]     |
|                   | cumulative method              | [24, 25]    |
2 Characteristic analysis of renewable energy accommodation based on power system operation simulation

2.1 Power system operation simulation

The power system operation simulation simulates the power system operation over a period of time by choosing a certain optimisation target. The simulation runs under a series of operational constraints and within the system boundary based on data such as generation expansion planning, transmission network planning, and load forecasting. In other words, the power system operation simulation is a multi-period unit commitment and economic dispatch problem with security constraints.

The simulation function of power system operation in global optimization planning tool for power system (GOPT) software, which is developed by Tsinghua University, can realise quantitative analysis of renewable energy accommodation. The GOPT software can generate chronological sequences of wind power and photovoltaic power. Also its sequential simulation function can contain multiple factors, such as the operation characteristics of the unit, the operation state of the system, the peak regulation capacity of the unit, the transmission capacity of the line and so on. The fluctuation and uncertainty of wind power and photovoltaic power can be fully considered through the long period operation simulation. The accurate curtailment of renewable energy can be obtained, which provides the databases for the characteristic analysis of renewable energy accommodation.

2.2 Characteristic analysis of renewable energy accommodation

For the power system with high penetration of renewable energy, the generation and operation mode of renewable energy have significant influence on the generation mix, operation form, and energy efficiency. The study of the accommodation characteristics of high-penetration renewable energy can identify the key factors that restrict the accommodation of high-penetration renewable energy. By changing the boundary conditions of the power system operation simulation, the curtailment under different factors can be calculated. The accommodation characteristics can be described through analysis of curtailment electricity under different boundaries. The framework of characteristic analysis of renewable energy accommodation is shown in Fig. 1.

2.3 Evaluation method of limiting factors

Renewable energy accommodation is affected by various factors. The contribution degree can be used to describe the impact of different factors on renewable energy accommodation. The contribution degree is defined as the ratio of electricity curtailment caused by a certain factor to the total electricity curtailment. The value of the contribution degree indicates the percentage of electricity curtailment that can be reduced by improving the limit of a certain factor. Therefore, it is possible to quantify the importance of factors that influence renewable energy accommodation.

For the factor \( X \) affecting renewable energy accommodation, its contribution degree is defined as follows:

\[
C_x = \frac{Q_{c0} - Q_{cX}}{Q_{c0}} \times 100\% 
\]  

(1)

where \( Q_{c0} \) is the electricity curtailment of the original grid with limit on \( X \), and \( Q_{cX} \) is the electricity curtailment of the grid when \( X \) is not limited.

For the factors \( X \) and \( Y \) affecting renewable energy accommodation at the same time, the total contribution degree is defined as follows:

\[
C_{x\oplus y} = \frac{Q_{c0} - Q_{cXY}}{Q_{c0}} \times 100\% 
\]  

(2)

where \( Q_{cXY} \) is the electricity curtailment of the grid when both \( X \) and \( Y \) are not limited.

Due to the interaction between multiple factors, the total contribution degree of the two factors is not equal to the sum of the two contribution degrees. The synergy factor \( C_{x\oplus y} \) is defined to characterise the differences:

\[
C_{x\oplus y} = C_{x\oplus y} - (C_x + C_y) 
\]  

(3)

When the synergy factor is >0, it is reflected that the renewable energy curtailment when \( X \) and \( Y \) work together is greater than the sum of the curtailment of the two factors. In other words, \( X \) and \( Y \) have a synergistic effect. When the synergy factor is <0, it means that the renewable energy curtailment when \( X \) and \( Y \) work together is less than the sum of the curtailment when the two factors are acting alone. In other words, there is a negative synergy between \( X \) and \( Y \).

The contribution degree quantitatively describes the influence of various factors on the renewable energy accommodation, and its calculation depends on the electricity curtailment of the grid under various constraints. With GOPT software, the contribution degree analysis process based on power system operation simulation is established, as shown in Fig. 2.

3 Results and analysis

In this paper, we selected a grid in one of the provinces in China under the scenario of 2020 planning and conducted detailed modelling of 330 kV and above lines in this region. In this power system, the installed capacity of thermal power is 63.1 GW, wind power is 23 GW, photovoltaic power is 17 GW, hydropower is 24.9 GW, and the maximum load is 70.8 GW. With the proposed characteristic analysis method of renewable energy accommodation...
based on power system operation simulation, we analyse the accommodation characteristics of renewable energy and the contribution degree of limiting factors.

3.1 Characteristic analysis of renewable energy accommodation

3.1.1 Accommodation capacity of renewable energy without external power transmission: Various types of power output and renewable energy accommodation are obtained through the simulation of renewable energy operation, as shown in Tables 2 and 3. The average external power transmission is set to zero in the basic boundary conditions. Through power system operation simulation, the output of various types of power and renewable energy accommodation are obtained, as shown in Table 4.

Without external power transmission, the amount of renewable energy accommodation of this provincial grid will be around 22 billion kWh. The curtailment of wind power and photovoltaic power is about 16.3 billion kWh, as shown in Table 5.

3.1.2 Impact of external electricity on renewable energy accommodation capacity: This case examines the relationship between external electricity supply and the incremental consumption of renewable energy. The average external power transmission is gradually increased during the operation simulation, as shown in Table 6. Through the power system operation simulation, the continuous output of various types of units can be obtained. For a specific period of time, such as January 1st to January 14th, the load curve and output curve can indicate the system operation conditions, as shown in Fig. 3(B2), Fig. 4(B4) and Fig. 5(B6). The incremental consumption of renewable energy and peak load electricity of thermal power are obtained, as shown in Fig. 6.

Table 2 Simulation of wind power

| Capacity (MW) | Annual utilisation hours | Simulation output (billion kWh) |
|---------------|--------------------------|-------------------------------|
| 12772.1       | 2180.68                  | 27.85                         |

Table 3 Simulation of photovoltaic power

| Capacity (MW) | Annual utilisation hours | Simulation output (billion kWh) |
|---------------|--------------------------|-------------------------------|
| 6501.94       | 1628.38                  | 10.59                         |

Table 4 Renewable energy accommodation capacity of the original grid

| Index name                        | Value/billion, kWh |
|-----------------------------------|--------------------|
| external electricity consumption  | 0                  |
| wind power consumption            | 13.89              |
| photovoltaic power consumption    | 8.13               |
| thermal power generation          | 36.75              |
| hydropower generation             | 37.73              |
| renewable energy consumption      | 22.02              |

Table 5 Renewable energy curtailment

| Wind power | Curtailment rate | Photovoltaic power | Curtailment rate |
|------------|------------------|--------------------|------------------|
| 13.96 billion, kWh | 50.13% | 2.46 billion, kWh | 23.23% |

Table 6 Simulation scenario settings

| Scenario | Average external power (MW) | External electricity (billion kWh) |
|----------|-----------------------------|-----------------------------------|
| B1       | 500                         | 4.38                              |
| B2       | 1000                        | 8.76                              |
| B3       | 1500                        | 13.14                             |
| B4       | 2000                        | 17.52                             |
| B5       | 3000                        | 26.28                             |
| B6       | 4000                        | 35.04                             |
| B7       | 6000                        | 52.56                             |

Fig. 2 Flow chart of evaluation method of contribution degree...
external power exceeds 4000 MW and <6000 MW, the ratio is $\sim 3: 2$.

3.1.3 Impact of generation right trade of the autonomous power plant: This case examines the relationship between generation right trade of the autonomous power plant and the incremental consumption of renewable energy. The trade capacity of the autonomous power plant is gradually increased, as shown in Table 7, and the increment of renewable energy consumption is simulated through operation simulation, as shown in Fig. 7.

Through the power system operation simulation, the continuous output of various types of units can be obtained. For a specific
period of time, such as January 1st to January 14th, the load curve and output curve can indicate the system operation conditions, as shown in Fig. 8(C2), Fig. 9(C4) and Fig. 10(C6). When the trade capacity is 300 MW, the incremental renewable energy consumption is about 75.4% of the replacement electricity. With the increase capacity, the incremental consumption of renewable energy is gradually saturated. When the trade capacity is increased to 2040 MW, the increase of renewable energy consumption is reduced to 49.9%.

### 3.1.4 Impact of the market trading Cap of a single renewable energy power plant:

This case is used to study the impact of the market trading cap that a single wind farm can participate in on the overall renewable energy accommodation and other renewable power stations. The trading cap of all the renewable energy power plants that participate in the electricity market is cancelled, and the power generation of those renewable energy power plants not participating in the electricity market is fixed according to the historical data. This case includes three sub-programs, i.e. three wind farm with market trading cap, and each sub-program contains five different scenarios, as shown in Table 8. Under this condition, the market trading cap of each renewable energy power plant is obtained (annually and monthly). By comparing the total renewable energy accommodation with or without the market trading caps, the effect of the trading cap on the overall renewable

| Scenario | Trade capacity, MW | Substitution electricity/billion, kWh |
|----------|--------------------|---------------------------------------|
| C1       | 300                | 1.37                                  |
| C2       | 600                | 2.73                                  |
| C3       | 900                | 4.10                                  |
| C4       | 1300               | 6.34                                  |
| C5       | 1740               | 8.40                                  |
| C6       | 2040               | 9.81                                  |

Fig. 7  Incremental renewable energy consumption with increasing generation right trade

Fig. 8  Operation analysis of scenario C2 from January 1 to January 14

Fig. 9  Operation analysis of scenario C4 from January 1 to January 14
energy accommodation and the renewable energy power plants is analysed, as shown in Fig. 11.

The total amount of renewable energy accommodation is saturated faster with the market trading caps. When the trade capacity is low, the increment of the renewable energy consumption with the market trading caps is not significantly different from unconstrained consumption. When the trading capacity reaches 1500 MW, since only a part of the power plants participating in the electricity market can increase the power, the overall renewable energy accommodation is saturated very quickly. At 3000 MW, the increment with the market trading caps is only half of the total unconstrained increment, and even significantly lower than the original wind power accommodation increment. Therefore, increasing the number of renewable energy power plants participating in electricity market is very important for the fair accommodation of renewable energy and the reduction of renewable energy curtailment.

3.1.5 Evaluation of contribution degree: This section uses the proposed evaluation method to analyse the contribution degree of limiting factors. The total amount of renewable energy curtailment of the provincial grid in 2020 was calculated by the power system operation simulation, as shown in Table 9.

The contribution degree can be calculated according to the above results, as shown in Table 10. The main factor affecting renewable energy accommodation is the line transmission capacity, which contribution degree is 89%. Due to the high proportion of hydropower in the system, the peak regulation capacity has less impact on renewable energy accommodation with contribution degree of 7%. The synergy factor is 1.7%. The positive value shows that the common contribution of the two factors is slightly greater than the sum of the two contributions, but the synergistic effect is not obvious.
Table 10 Contribution degree of limiting factors in 2020

| Factors                                    | Contribution degree, % |
|--------------------------------------------|------------------------|
| Total                                      | 97.7                   |
| Peak regulation capacity                   | 7.0                    |
| Line transmission capacity                 | 89.0                   |
| Synergy factor                             | 1.7                    |

Fig. 12 Contribution degree of renewable energy accommodation at different hours

Due to the different output characteristics of renewable power at different time periods, the contribution degrees of limiting factors at different time period are different. In this section, based on the results of the power system operation simulation, the contribution degree for each hour is calculated, as the curve shown in Fig. 12.

In the whole period, the line transmission capacity is the main factor constraining the renewable energy accommodation. The impact of peak regulation capacity is small. As the photovoltaic power output is low in the morning and evening, the contribution degree of the line transmission capacity is close to 100%. When the photovoltaic power output is high at noon, the contribution degree of the peak regulation capacity and the changing trend of the synergy factor rise slightly.

4 Conclusions

At present, the renewable energy curtailment in some areas of China is serious. The renewable energy installed capacity has exceeded the accommodation capacity of the grid. It is of great significance for the planning and operation of the power grid to study the bottleneck of renewable energy accommodation.

In this paper, the concept of contribution degree is proposed to quantitatively describe the influence of various limiting factors on renewable energy accommodation. With the proposed analytic method based on power system operation simulation, the renewable energy curtailment under different constraints can be obtained. The contribution degree of different limiting factors can also be calculated and analysed on the basis of power system operation simulation.

A case study of the planning power grid of a province in China in 2020 shows that the main factor restricting the renewable energy accommodation is the line transmission capacity. The results of the contribution degree at different time periods show that when the photovoltaic power output is high at noon, the contribution degree of the line transmission capacity decreases slightly. While the contribution degrees of the peak regulation capacity and the synergy factor have opposite trends.

5 References

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