Prospects for Power Systems with High Proportion of Renewable Energy Considering the Coordination of Source-grid

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Abstract. In the future, the spatiotemporal distribution of a high proportion of renewable energy will bring unprecedented challenges to power system, and the basic form and operation of power system will have great changes. On the basis of investigating the research status in China and abroad, this paper expounds the scientific problems faced by the planning of Power Systems with High Proportion of Renewable Energy (PSHPRE) considering the coordination of source-grid, and put forward the basic ideas and framework of research from four aspects: overview of the development of PSHPRE, power planning in PSHPRE and coordinated planning of source-grid in PSHPRE. Finally, the prospects for Power Systems with High Proportion of Renewable Energy considering the coordination of source-grid are presented.

1. Introduction

In order to cope with climate change and environmental pollution, power systems of major countries in the world are in a period of the transformation of clean, low-carbon and intelligent. Building a green, low-carbon, and clean power system with renewable energy as the mainstay is an energy strategic for China and the world. The data shows that the total installed capacity of renewable energy worldwide in 2020 has reached 2536.853 GW, which has increased of 175.792 GW year-on-year; and the total installed capacity of renewable energy in China has reached 905.124 GW, of which wind power and photovoltaic installed capacity are both close to 300 GW [1]. As of the end of 2020, China's installed renewable energy power generation capacity accounted for approximately 41.13% of all electricity installed capacity, and the replacement role of renewable energy has become increasingly prominent.

According to the "China Renewable Energy Outlook 2019", by 2050, China's wind power (44%) and photovoltaic (27%) will dominate the supply of renewable energy in 2050 [2]. By 2050, non-fossil energy may account for 70% of electricity consumption [3].

This article will introduce in detail the overview of the development of Power Systems with High Proportion of Renewable Energy (PSHPRE), power planning in PSHPRE and coordinated planning of source-grid in PSHPRE, and make an outlook of the PSHPRE considering the coordination of source-grid in China.
2. Overview of the development of PSHPRE

2.1. Distribution of Source and Load in China
Table 1 shows the load and resource comparisons of three typical provinces in northwest, central and eastern China [4], respectively, expressed in terms of load utilization hours and power generation utilization hours. $T_L$, $T_W$, $T_S$ are the ratio of the province’s annual total electricity, wind power generation and photovoltaic generation to the annual maximum load.

| Table 1. Annual utilization hours of the system load and renewable energy. |
|-----------------------------|------------------|------------------|------------------|
|                             | Northwest | Central | Eastern |
| System Load                 | 6628      | 6117    | 5683    |
| Wind Power                  | 2037      | 2063    | 1987    |
| Solar Power                 | 1710      | 918     | 890     |

The annual utilization hours of the system load are between 5300h and 7000h, showing the characteristics of low in the central and eastern part, high in the west, and small peak-valley difference. The annual utilization hours of wind power are between 1700h and 2000h, the north-western region has relatively abundant wind resources, but from the perspective of the whole China, there is little difference in the annual utilization hours of wind power. The annual utilization hours of photovoltaics are between 900h and 1700h, and the central and eastern regions are significantly lower than those in the northwest, which indicates that China’s photovoltaic resources are mainly concentrated in the northwest. Analysing relevant data, we can draw the following conclusions: China's load and renewable energy resources basically show reverse distribution characteristics, and a large number of wind power and photovoltaic resources in the north-western region have problems with the consumption.

2.2. Overview of the Development of PSHPRE
Table 2 shows the installed capacity of renewable energy units when renewable power generation accounts for 30%, 50%, and 100%. This set of data uses the typical annual maximum load $L_{max}$ of a province in Northwest China [5] as the base value to calculate the installed scale of new energy.

| Table 2. The Installed Capacity of Renewable Energy Units. |
|-----------------------------|------------------|------------------|------------------|
|                             | $\alpha = 30\%$ | $\alpha = 50\%$ | $\alpha = 100\%$ |
| Sum                         | 1.07              | 1.78             | 3.55             |
| Wind Power                  | 0.49              | 0.81             | 1.62             |
| Solar Power                 | 0.58              | 0.97             | 1.93             |

When $\alpha = 30\%$, the installed capacity of renewable energy will exceed the maximum annual load of the system, reaching $1.07L_{max}$. When $\alpha = 50\%$, the installed capacity of renewable energy will reach $1.78L_{max}$, the photovoltaic installed capacity will be calculated to $L_{max}$ at this time. When $\alpha = 100\%$, the installed capacity of renewable energy will far exceed the maximum load of the system.

2.3. Evolution of Source-Load Characteristics of PSHPRE
Figure 1. Source-Load Characteristics of PSHPRE in Different Periods.

Figure 1 shows the source-load characteristics of PSHPRE in the prophase (20%), early (30%), mid-term (50%), and late-term (100%) periods [6][7]. Among them, the histogram represents the daily load
curve of the maximum load day, the minimum load day, and the average load day. The line graphs respectively represent the upper and lower envelopes and average curves of renewable energy output. From the analysis of Figure 1, the following conclusions can be drawn. ① In the prophase stage of PSHPRE, the envelope of renewable energy output is lower than the minimum daily load, the depth peak load cycling of thermal power can solve the problem of renewable energy consumption. ② In the early stage of PSHPRE, the envelope of new energy output is higher than the maximum daily load, which shows that the difficulty of renewable energy has increased significantly. At this time, it needs to increase system energy storage capacity to solve the problem of high proportion of renewable energy consumption. ③ In the mid-term of PSHPRE, the capacity and energy demand of system energy storage will increase sharply, and new technologies and methods must be adopted. ④ In the later stage of PSHPRE, the daily average power generation curve of new energy will be much higher than the daily load of the system. At this time, it is necessary to rely on the leapfrog development of energy storage technology to absorb so much new energy power.

3. Power planning in PSHPRE

3.1. Demand for the Consumption of Renewable Energy: Energy Storage

In the context of a high proportion of renewable energy connected to the grid, the installed capacity of thermal power is constantly being replaced by wind power and photovoltaic power generation, and the development of hydropower is limited by natural resources [8]. Considering the increasing imbalance of power and electricity in the power system, energy storage will become the mainstay flexibility to adjust resources. Energy storage methods such as electrochemical energy storage used in traditional power systems mainly provide services such as intraday peak shaving, frequency modulation, and hill climbing for the power system, which are used to smooth short-term (second, minute, hour) power fluctuations, and it is difficult to deal with the problem of electricity imbalance between renewable energy output and load demand on a long-term (weekly, monthly, and yearly) scale. In the middle and later stages of the development of a high-proportion renewable energy power system, in order to achieve long-term energy translation, smooth out days, weeks, and even seasonal power fluctuations, and participate in the monthly, quarterly, annual, and even multi-year adjustment process, it is necessary to adopt Long-term, large-capacity energy storage technology.

![Figure 2. Net Load and Energy Storage Curve.](image)

The figure 2 and figure 3 respectively represent the typical daily (weekly) net load curve and the energy storage curve for the early (30%) and mid-term (50%) of PSHPR. It can be seen that development of PSHPRE needs for generalized energy storage. When $\alpha = 30\%$, the power system requires daily regulation capability for energy storage, energy storage needs to have a charging capacity of 4-6h. At this time, pumped storage power stations with daily regulation capability can meet the dispatch requirements. When $\alpha = 50\%$, the requirement of the power system for energy storage is to have the ability to regulate weekly, and at this time, the energy storage system needs to have a charging capacity
of more than 10h. It can be inferred that when $\alpha = 100\%$, that is, when a 100\% renewable energy power system is realized, conventional energy storage can no longer meet the requirements, and rapid development of battery energy storage and hydrogen energy storage technology is required.

### 3.2. Demands for Power Balance: Capacity Benefits of Energy Storage

The following two figures respectively show the energy storage capacity benefits of the high-proportion of renewable energy in the early (30\%) and mid-term (50\%) stages. The red curve in the figure is the typical daily (weekly) net load curve of the system, the green area represents energy storage charging, the blue area represents energy storage discharge, and the yellow dotted line represents the system net load curve after considering the effect of energy storage capacity. Through the above two figures, it can be seen that the ability of the system energy storage to change the net load curve reflects the ability of energy storage to reduce the load pressure of the thermal power unit.

![Energy Storage Capacity Benefits of PSHPRE.](image)

It can be seen from the figure that in the early stage of PSHPRE, daily operation optimization can achieve the maximum benefit of energy storage capacity. At this time, energy storage has a higher capacity benefit, which can reach 96.7\%. Due to the existence of energy storage, the capacity requirement of conventional power supply is reduced to 76\% of the maximum load of the system.

### 3.3. System Flexibility Resource Requirements: Peak Shaving & Ramping

| $\alpha$      | Energy Storage ($*L_{\text{max}}$) | Ramping Demand ($*L_{\text{max}}$) |
|---------------|------------------------------------|-------------------------------------|
| Early (30\%)  | 0.24                               | 0.50                                |
| Mid-term (50\%) | 0.86                              | 0.84                                |
| Later         | 2.41                               | 1.69                                |

It can be seen from the Table 3 that with the gradual increase in the development process of high proportion of renewable energy, the maximum ramping demand of the system gradually increases. The flexibility resource demand is higher than the demand for power consumption in the early stage of PSHPRE.
4. Coordinated planning of source-grid in PSHPRE

4.1. Power Grid Planning of the Sending End in Mid or Late Term of PSHPRE
The sending end of the multi-terminal HVDC transmission system mainly has two forms: the one is that the DC line directly falls on the large AC grid at the sending end, and the electricity generated by the new energy base is sent through the AC grid at the sending end through the converter station, which is called a strong connection form; the other is that the DC line is connected to a large new energy base, not directly connected to the AC grid, and can be used to transmit power to the AC grid through an AC tie line, which is called a weak connection form. Figure 4 and Figure 5 are schematic diagrams of strong connection form and weak connection form. In the middle and later stages of PSHPRE, the weak connection form is more conducive to the operation and control of PSHPRE.

![Figure 4. Strong Connection Form.](image1)
![Figure 5. Weak Connection Form.](image2)

4.2. Power Grid Planning of the Receiving End in Mid or Late Term of PSHPRE
In PSHPRE, the receiving end of the multi-terminal HVDC transmission system mainly has two forms: the one is that the DC drop point is connected to a large AC power grid at the receiving end, and then connected to other regional power grids through the AC transmission network at the receiving end, which is called centralized form; the other is that the DC line is dispersed into multiple distribution lines at the receiving end and connected to power grids, which is called distributed form. Figure 6 and Figure 7 are schematic diagrams of centralized form and distributed form. In the middle and later stages of PSHPRE, the distributed form is more conducive to the operation and control of PSHPRE.

![Figure 6. Centralized Form.](image3)
![Figure 7. Distributed Form.](image4)
5. Conclusion
The inclusion of a high proportion of renewable energy is the basic feature of power system in the future. However, renewable energy has high level uncertainty, its high proportion of access will have a strong impact on power system. Therefore, in order to meet the development of PSHPRE, it is urgent to strengthen the construction of source and grid, and plan to build a highly adaptable power system.

6. References
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