Long-term transmission-grid network in China adapting to clean energy and prospect of adaptive planning methods

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Abstract. The energy strategy and development direction of advanced power grid have prompted future development of China's transmission-grid to a new model. In order to solve the problem of the deficiency in overall and the lack of adaptability to renewable energy in the long-term transmission-grid network (LTTGN), China's LTTGN and adaptive planning methods which have not been comprehensively studied are worth exploring. This paper firstly summarizes European and American power grids as reference and predicts the three stages of China's balance between power supply and demand by different geographical locations. Then on this basis, this paper puts forward a kind of China's long-term transmission-grid network and points out its characteristics, which builds a national interconnected long-term target grid through the super-connected “sending-end network” and complex “receiving-end network”. Furthermore, in order to solve the current situation that the current grid planning method is not suitable for the LTTGN, this paper proposes a grid planning method based on grid evolution and explores its implementation based on the characteristics of low-carbon, structural-complexity and time-space diversity in LTTGN. All work in this paper aims to provide reference for follow-up research and development direction in related fields.

1. Introduction
In response to environmental pollution, countries around the world are constantly seeking new ways to transform development model of power grid. Europe and the United States have proposed their grid plans to adapt to changes in various factors, which have certain reference significance for China. In the reality of reverse distribution of energy and load, China has proposed a power grid development model oriented to optimization of energy in wide-area, which includes the ultimate high voltage (UHV) power grids as backbone. Therefore, the research on the adaptability of long-term transmission-grid network (LTTGN) in China needs to be further studied. Scholars have carried out preliminary explorations on network structure and development model of LTTGN in China[1,2], proposing the concept of the LTTGN. However, the existing researches in this field has the following shortcomings.

Firstly, there is no overall perspective on the future structure of transmission-grid in China, and insufficient consideration have been given to the situation that may arise during the long-term phase. Secondly, the existing idea of LTTGN can realize the long-distance power transmission, but wide-area “super-connection” of receiving-end and sending-end has not been considered, which means achieving extremely complex connections of all energy bases or load node among nationwide. Thirdly, while the LTTGN exhibits strong characteristics such as low-carbon, wide-area and structural-complexity, it also brings much incompatibility of grid planning method adapting to the above characteristics.
Therefore, it’s of great significance to construct LTTGN in China and explore grid planning method adapting to LTTGN, which isn’t carried out in current indication.

The research of this paper is carried out under the above background. Firstly, it summarizes the methodology of power grids development plan in Europe and America and uses them as a reference. From the perspective of power load and energy resources development, it predicts the balance between power supply and demand (BPSD) in China, and it is divided into 3 stages. Then, based on forecast of BPSD, and aiming at adapting to large-scale consumption of renewable energy, the super-connected “sending-end network”(SeN) and “receiving-end network”(ReN) are constructed, which (SeN and ReN) are combined and then lead to LTTGN in China. LTTGN has significant characteristics of low-carbon, wide-area and structural-complexity. Last but not least, the research status of power grid planning and power grid evolution were summarized, and then, a grid planning method based on grid evolution is proposed, which realizes the preliminary exploration of related fields at the level of idea.

2. World advanced grid development ideas and forecast of power supply/demand in China

2.1. European and American power grid development plan and its long-term grid Conceive

Driven by the global energy crisis and the demand for grid development, the United States and Europe have proposed grid development plans respectively of “Grid 2030” and “Super Grid”.

The “Grid 2030” plan was based on the upgrading of power grid equipment and construction of the interconnected grid, which was subsequently given a new position to absorb renewable energy sources in large scale[3]. The “Grid 2030” plan proposes to link American east coast, American west coast, Canadian grids and Mexican grids by building a national backbone network, which can expand the balance range of power supply and demand, and finally form a backbone network covering the whole America and interconnecting North America with a “pentagon” structure.

From the “European Maritime Super Grid Plan” to the “North Sea Countries Offshore Wind Power Plan”, the specific roadmap of the “Super Grid” plan in European Union was officially born[4]. By 2050, Europe will form a super grid with the optimization and integration of resources such as wind power, solar power and hydropower as its goal, connecting the clean energy from the North Sea and other European countries. In future, large-scale interconnected grids covering Europe, North Africa and the Middle East will have a balance of renewable energy in an extremely wide range[4].

Although the motivations of the “Grid 2030” and “Super Grid” are different, they show similarities in demand positioning and technology integration. The similarity has reference significance for China. For this purpose, we summarized the ideas of grid in Europe and America, as shown in Table 1.

| Energy strategy | Maximize the use of clean energy and enable energy wide-area optimization |
|-----------------|-------------------------------------------------------------------------|
| Power supply    | Build long-distance transmission mode and while reduce the potential risk of grid |
| Grid structure  | Achieve large-scale interconnection in wide-area while avoid casual interconnection |

2.2. Forecast of balance between power supply and demand by geographical locations in China

The spatial distribution of energy and load in China is extremely uneven, and this characteristics of reverse distribution cannot be changed in the short term. This paper believes that the load in the east will continue to grow in the future, but it will slow down and eventually stabilize, while the central and western load of China will still have rapid growth potential for a certain period of time.

Therefore, BPSD in China will shift in time and space under the contradiction between energy distribution and load distribution. This paper predicts the future BPSD in China, and believes that it will go through 3 stages shown in Figure 1. ①Phase I: Due to the development of renewable energy and the continued increase of load in the eastern region, the imbalance between supply and demand will continue to increase. ②Phase II: When the development of hydropower bases peaks and the load growth rate in developed regions slows down, the BPSD in China appears to be relatively stable, and...
this phase will last for a substantial period. ③Phase III: Economic gap between east and west will narrow. The distributed power capacity in eastern region is increasing and nuclear power in southeast coast is following up. Then the reverse distribution of power supply and demand will be changed.

3. Long-term transmission-grid network in China and its characteristics

3.1. Construction of long-term transmission-grid network in China

Integrating renewable energy and meeting load demand will still be the main target of China’s LTTGN, but there are some characteristics of super-connection and wide-area, which is reflected in Europe and America. Therefore, China's power grid can build its LTTGN in accordance with national conditions. This paper proposes LTTGN in China based on SeN for connections between all energy bases and the ReN for connections between distributed grid resources, which includes the UHV grids as its backbone. This paper believes that development of China's UHV grid is closely related to the stage of BPSD. In Phase I and II, the main function of the UHV grid is to transfer electrical energy from energy base to the load center. With the arrival of Phase III, the UHV grid will take into account the dual role of regional power inter-supply and long-distance transmission. In ultra-long-term phase, BPSD in China may undergo fundamental changes, and large-capacity energy transmission will be constrained. In this phase, the UHV grid has the possibility of step-down operation to a certain extent.

![Figure 1. Stage for BPSD.](image1)

![Figure 2. Long-term transmission-grid network in China.](image2)

In the long-term phase, large-scale energy bases are connected through “sending-end network”. SeN is positioned by 2 parts. Firstly, the energy in renewable energy base is combined and sent out as the whole, forming a “renewable energy network”, which will initially integrate renewable energy sources across the whole country and achieve reliable and stable delivery of renewable energy. Secondly, the large-scale coal energy bases are directly connected to form a “traditional energy network”, which interconnected with “renewable energy network” through the UHV line and then form SeN. The SeN can realize complementary and secondary integration of wide-area energy, reducing energy storage devices and eliminating uncertainty in renewable energy transmission.

In long-term stage, traditional main-network will cooperate with the UHV grid to achieve dense connection by strengthening the transmission lines, which constitutes the wide-area “receiving-end network” of China's LTTGN. The “SanHua” grid, which is composed of North China, Central China
and East China, is connected to northeast and northwestern power grids to form a large ReN. Distributed energy power stations (including traditional power stations and new energy power stations) will continue to realize its function and deliver electricity in local consumption. Such power stations are “scattered” in the center of load, accessing the ReN in the nearest way, or accessing the ReN after local integration between them in a short-distance manner. This paper believes that the construction of LTTGN consists of 3 development stages. Firstly, develop UHV grids and optimize configuration of wide-area energy, achieving dense connection of receiving-end. Secondly, UHV is used to connect large energy bases and SeN is built. Thirdly, long-term network fusion between SeN and ReN is realizing. Overall, the concept of LTTGN is based on UHV grid as backbone, with wide-area connection between sending-end as the new form, as shown in Figure 2. We can see that all energy bases are connected by SeN from Northwest, Southwest, Northeast of China and all receiving grids are connected complexly with distributed power supply.

3.2. Characteristics and execution effect of long-term transmission-grid network

Characteristics of LTTGN are as follows.  
①Low-carbon characteristic[5-6], which are reflected in 2 aspects. Firstly, it’s SeN and complementary balance of large-scale renewable energy. Secondly, it’s low-carbon of UHV grid and superconducting transmission technology.  
②Connection in wide-area and hierarchical partitioning. The SeN and ReN are integrated and UHV as the backbone network will be further improved while the hierarchical partition will not change as basic structure.  
③Structural-complexity. Modern power systems have been proven to be typical complex networks[7,8], and large blackouts have advanced the study on complex attributes of grids[9]. Many grids, such as regional grid in North America and Italian grid, exhibit complex attributes and the structural-complexity is caused by increasing connectivity of grid. China's regional power grids were confirmed to have significant complex attributes[10] while the structural-complexity is constantly increasing[8]. It is not difficult to predict that LTTGN will exhibit strong structural-complexity.  
④Accident risk characteristic. Recent studies have shown that the larger synchronization of power grid lead to the greater risk of accidents[8]. In the future, China will merge through SeN and ReN to form a super-connected network.

In order to verify the adaptability of China's LTTGN to renewable energy, the LTTGN proposed in this paper was compared with the traditional transmission-grid without SeN and ReN. The power generation discard rate of renewable energy (mainly including solar energy and wind power), the proportion of traditional coal energy generation and the N-2 pass rate (probability that grid can operate normally when any 2 faults occur on the line) of the main grid line are evaluated for the long-term stage. The evaluation results are shown in Table 2.

It can be seen that the LTTGN proposed in this paper can reduce the abandoned rate of renewable energy and the proportion of traditional coal energy, while increasing the renewable energy consumption ratio and N-2 pass rate. According to the reduction of traditional coal ratio from 30% to 15%, it can reduce carbon-emissions by about a half. Therefore, LGGTN has good adaptability.

4. Prospect of grid planning method for adapting to long-term transmission-grid network

4.1. Research status on power grid planning and power grid evolution

For a long time, power grid planning has been the focus of research in field of power systems[11-13]. Then, planning of smart distribution grids and Energy Internet also became a hot spot[14,15]. This article does not go into details for grid planning, and a review of grid planning can be found in reference [11].

We focus on the research status of power grid evolution. The development of power grid is a gradual evolution process, and the research on grid evolution has been gradually deepened under expansion of traditional grid planning research[16-21]. Reference [16] proposes an evolutionary model that can simulate the evolution of power networks based on the dual factors of local world evolution and stochastic evolution. Reference [17] proposes an evolutionary model that can simulate the
evolution of power networks based on the dual factors of local world evolution and stochastic evolution. Reference [18] considers many factors of power plant and substation construction in grid growth model, and proves that the small world feature is the result of the grid structure optimization. Reference [19] starts from its own evolution mechanism and proposes an evolution model, which redefine “neighborhood” with the geographic area and determine how to access a new site. The development of the three generations of power grids has made a macro interpretation on grid evolution to a certain extent. Based on the research of the three generations of power grids[20], Reference [21] proposed a grid evolution model from the physical level of the grid structure to reproduce the evolution process of the three generations of power grids.

|                | Abandoned rate of renewable energy (energy base) | Abandoned rate of renewable energy (distributed generation) | The proportion of traditional coal energy generation | N-2 pass rate of main grid |
|----------------|-----------------------------------------------|----------------------------------------------------------|---------------------------------------------------|---------------------------|
| LTTGN          | About 2%                                      | Less than 5%                                             | About 15%                                         | 100%                      |
| Traditional grid | About 15%~20%                                | About 5%~8%                                              | About 30%                                         | 90%~97%                   |

4.2. A new planning method of transmission grid based on grid evolution

4.2.1. New power grid planning ideas based on evolution. For China's LTTGN, the limitations of traditional planning methods are prominent, mainly in the following four aspects. Firstly, the characteristics of wide-area connections lead to diversification of planning boundary conditions. Secondly, low-carbon characteristic leads to complication of various energy in planning. Thirdly, the structural-complexity puts an urgent need on complex network theory and grid evolution method. Fourthly, in order to adapt to long-term development, grid planning should be guided by the LTTGN.

Considering the above 4 points, the paper proposes a grid planning method based on grid evolution. In grid planning, the construction of power lines and stations, as well as the transformation of transmission lines, will cause changes in the power grid structure over time. The multi-temporal power evolution model proposed in this paper is established comprehensively through requirements of traditional grid planning principles, long-term target network and characteristics of low-carbon and wide-area. At the same time, the established grid evolution model can return to support the grid planning on a single time section, which has strong objectivity and adaptability to the long-term network. There is no relevant exploration and research on the planning method based on evolution.

4.2.2. Process of grid planning method based on grid evolution. Decision-making elements of grid planning include two aspects which are site and capacity of substation and accessing-system mode. At the same time, grid planning must involve two major boundary conditions which are load forecasting and power planning. According to grid structure evolution, this paper divides the decision-making elements into three according to new idea, that is, node growth position, node growth capacity, and line growth mode, which are respectively representing site selection of substation, capacity of substation and accessing-system mode of substation.

Grid planning method based on grid evolution in this paper proposes as shown in Figure 3 for details. It can be seen from the figure that the future wide-area characteristic are fully considered because boundary conditions of load forecasting and power planning are determined. In the establishment of the grid evolution model, the new requirements of the target attributes and low-carbon characteristic in LTTGN are fully considered. Further can be seen, in grid planning method based on evolution, it is the key to establish grid evolution model that considers the adaptability of LTTGN comprehensively, such as low-carbon characteristic, target attribute and so on.
4.2.3. Ideas for establishing a grid evolution model. The grid evolution model considering the long-term transmission-grid network involves multiple variables in the time and space dimensions. The historical evolution law and future evolution law of grid should be considered separately and fully integrated. This paper proposes to establish the evolution model using space-time multi-scene fitting method through various grid structure in a single space-time section. However, the planning principles at a particular stage, the target network of power grid and the development of renewable energy will all affect the way of grid evolution. The implementation framework of space-time multi-scene fitting method is given in this paper. ①Step.1: The variable elements in a single scene should be determined. Secondly, those elements should be decoupled in time and space. ②Step.2: The fitting of single elements should be executed by traditional fitting method in their respective dimension. ③Step.3: The fitting of the individual features are fused.

4.2.4. Simple verification power grid planning method based on grid evolution. A city-level small grid for a simple argument is conducted and the conclusions are as follows. The node growth result of the planning year using grid planning method in this paper is consistent with the idea of LTTGN frame, which is better than the node growth results using traditional method.

5. Summary
In the background of new type of energy strategy and advanced power grid construction, China's LTTGN urgently needs to meet the overall and adaptability of renewable energy. However, there is no comprehensive and adaptive implementation idea of LTTGN and current planning methods are not adaptable to LTTGN and its characteristics such as low-carbon and structural-complexity. In order to solve the above problems, this paper focuses on two aspects of work. Firstly, drawing on the development ideas of European and American grids, it predicts the 3 stages of LPSD in China, and propose super-connected "sending-end network" and complex "receiving-end network" to build a LTTGN in China which can achieve optimal energy allocation across the country. And then, it analyzes new characteristics of this LTTGN. Secondly, adapting to the construction of LTTGN and its characteristics, it puts forward the idea of using the grid evolution to reverse the guidance of power...
grid planning for the first time. A grid planning method based on grid evolution was proposed and preliminary exploration of the key issue in this planning method was conducted. The research work in this paper aims to provide reference for follow-up work on China's transmission-grid development. Future research should pay more attention to the changes in influencing factors of the LTTGN in China and explore the specific issues involved in the adaptive planning method.

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