Method for Electricity Distribution Network Expansion Planning Considering Opening Incremental Distribution Network

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Abstract. Market-oriented electricity reform will enable social capital to participate in the investment in incremental distribution grid through market competition and to build or even operate and sell electricity service. The liberalization of incremental distribution network will affect the planning of traditional distribution network. First of all, summarizes the characteristics of incremental distribution network and its impact on the distribution network planning, puts forward the factors that need to be considered in distribution network planning after the incremental distribution network service is released, put forward the distribution network planning and modeling method adapted to the liberalization of incremental distribution network business. Finally, the validity of the proposed planning method is verified by an example of a park.

Key words: AIP Proceedings; Title Here; International Conference; Research Center of Engineering and Science.

1. Introduction

In October 2016, the National Development and Reform Commission and the National Energy Administration issued the “Management Measures for the Orderly Release of Distribution Network Business”, proposing the concept of incremental distribution network, which represents the distribution network to be constructed corresponding to the stock distribution network assets with voltage levels below 220kV, in order to encourage social capital to orderly invest and operate incremental networks which can result in the promotion of the development and the improvement of the efficiency of distribution network. At the end of November 2016, the “Notice on Standardizing the Pilot Reform of Incremental Distribution Business” was issued, and the first 105 pilot projects were identified. In December of the same year, the State Grid announced the key reform initiatives such as managing the investment of incremental distribution network in the form of mixed ownership and relatively independent operation of trading institutions. The critical points are as follows: (1) Support of the government for opening of the investment on incremental power distribution business. (2) Grid-connecting services for pilot project owners. (3) Multi-win for cooperative partners. Subsequently, each provincial power company, as an investment entity, actively participated in the competition, cooperated
with qualified social capital to establish a hybrid ownership power supply company, and managed to become a pilot project owner by participating in marketization such as bidding and etc. [1].

Incremental distribution network differs from traditional one in the business pattern. The former one has clear scope of power supply and there is only one company for one power supply area that has operation right. Its business pattern is more flexible and can include value-added services such as comprehensive energy services, user intelligence, and user contract energy management services [2]. Its return on investment will become an important factor in social capital considerations [3]. Based on the characteristics, incremental distribution network planning needs more considerations on its business pattern and more accuracy of load forecast. As the profit of incremental distribution network mainly comes from the wheeling cost [4], power and electricity balance have important guiding significance for the analysis of investment efficiency of incremental distribution network and verification of distribution price. In addition, the incremental distribution network will reflect the characteristics of differentiated power supply services, thereby reducing the construction cost of distribution networks and improving the reliability of power supply for important users [5].

The opening of incremental distribution network market has changed the pattern of unified planning, construction and operation of power supply companies in the past. From the aspects of planning, construction, operation and management of distribution network, it will have an impact on traditional power supply companies [6-7]. The current research on distribution network planning mainly focus on the conventional network. It still refers to the principles of traditional network planning and there is little research on incremental distribution network planning in the background of current business. In order to ensure the safe and orderly development of the distribution network and reduce the impact on the expansion of the distribution network business on the traditional power supply company business, and improve the management of these companies under the new situation, it is necessary to conduct this research on the planning method that is suitable for the opening incremental distribution network.

2. Impact on the Network Planning

2.1. Characteristics of the incremental distribution network

According to the “Management Measures for the Orderly Release of Distribution Network Business”, the incremental distributional network has the following characteristics.

2.1.1. Changes in Planning and Investment Decision-making Models. The traditional distribution network is invested and constructed by the public power grid to solve the problem of land use for power grids such as substations and lines in the future. Local governments will prepare special plans for electricity, but such power special plans often combine with the public power grid company’s own needs. The “Management Measures for the Orderly Release of Distribution Network Business” has pointed out that the incremental distribution network project should be included in the distribution network planning prepared by the local government's energy management department. The qualified market entities shall apply to the local government energy management department as the owner of the incremental distribution network project according to the plan. The incremental distribution business form has changed the development model of distribution network planning and investment in the past, and as a result, the planning of distribution network is getting more important.

2.1.2. The Contradiction between Multi-Agent Investment Operation and Coordinated Scheduling. Incremental distribution network allows investment from social capital. At present, power generation groups and private enterprises are actively involved in the incremental distribution network market. The experience of these enterprises in developing and operating distribution networks differ widely, which will have a greater impact on the coordinated dispatching and safe operation of the distribution network. Different investment owners will have an impact on the management and dispatch of the incremental distribution network. It is advisable to consider the impact of multiple types of investment operations from the planning stage of the distribution network.
2.1.3. Changes in the Economic Assessment Model. The construction of traditional distribution network is social nonprofit nature. At the same time, due to cross-subsidization and unclear transmission and distribution costs, there is almost no requirement for the investment return of the distribution network. However, for incremental distribution networks, social capital is involved, and return on investment will be an important factor in social capital considerations.

2.1.4. First-mover Advantage of Business Model Innovation. In addition to the basic power supply and electricity sales services, the incremental distribution network operators are encouraged to innovate in business models, and their service models can also include services such as user power usage planning, energy saving, safe use of electricity, alternative power supply, optimized power consumption and demand response, user contract energy management services, user electrical equipment operation and maintenance, multi-energy supply and optimized combination plan[11]. The incremental distribution network has a first-mover advantage in terms of policy, timing and feasibility.

2.2. Considerations After Opening Business

2.2.1. Balance between Safety, Reliability and Economic. Traditional distribution networks often regard safety and reliability as the only considerations for network planning, and even lead to serious redundancy in distribution networks[12]. Incremental distribution network will release social capital investment, and the return on investment will be a key consideration for social capital. It is necessary to meet basic investment income. Therefore, the safety and reliability of power supply should be considered with investment economy.

2.2.2. Changes in Load Rate and Capacity-load Ratio. Reasonable capacity-load ratio combined with the grid structure can ensure the orderly transfer of load during faults, ensure power supply reliability, and meet the demand for load growth[13]. For a large power grids, the value is generally taken in accordance with the range of the empirical load value. However, the general distribution area of the incremental distribution network is small. The planning of the actual grid structure of the incremental distribution network should be considered and optimized with load ratio from the aspects of satisfying load growth and mutual supply. Otherwise, the unreasonable capacity-load ratio will have a greater impact on the economic future of the grid.

2.2.3. Topology of the Incremental Distribution Network. The distribution network structure mainly refers to the topology form of the distribution network. For the 110kV ~ 35kV distribution network, the structure is generally selected according to the load level, power supply reliability requirements and development goals, and there are chain, T-connection, ring network, radiation and other structures. For the 10kV distribution network, the structure should be concise and clear, which helps the implementation of distribution automation. Specifically, for 10kV overhead line network, the structure can be multi-segmented together with moderate connection, or single connection, or single radiation and other structures. As for the 10kV cable network, double-ring type, single-ring type, double-shot type, opposite-beam type, or n-supply-1-backup (n ≥ 2) structure can be adopted. Distribution network structure is important for the economic and reliability of the distribution network and as a result, the topology of the incremental distribution network should be designed with fully consideration of the power supply security, reliability, economy, and distribution energy connection.

2.2.4. Uncertainty Impact of Multi-Agent Participation. Incremental distribution networks are social capital investment projects, and their economics are of great importance. The incremental power distribution business is opened and private capital is encouraged to participate in the construction of the distribution network. For the planning and construction of the distribution network in the incremental area, there will be a situation shared by multiple enterprises, and the cooperation between the various
parties. Including construction progress, construction standards, etc., will bring uncertainty to the implementation of the plan.

3. Distribution network planning adapted to the Opening of incremental distribution network business

3.1. Overview of the Planning Procedure

The incremental distribution network business has changed the development strategy of traditional distribution network investment. The State Grid Corporation invests in traditional distribution networks using corporate financing methods, while using project financing methods such as PPP and BOT for incremental distribution networks. The biggest characteristic of its financing mode is that the financing amount and cost structure are closely related to the future cash flow and asset value of the project. Different from the traditional distribution network, planning of the incremental distribution network must focus on the investment income. It should be combined with the incremental distribution price mechanism to take the power supply safety and reliability as constraints, with the maximization of investment income as the optimization aim. The basic procedure is as Fig.1.

![Applicative Planning Procedure of Incremental Distribution Network](image)

Figure 1. Applicative Planning Procedure of Incremental Distribution Network

3.2. Planning Model for Incremental Distribution Network

The distribution network optimization model adapted to the incremental distribution network should be classified according to the price regulation target, and consider various security constraints, reliability constraints, and policy constraints. Its pricing regulations are not clearly documented currently and as a result, two price regulation models are discussed in this paper: (1) Income cap or fixed price model. (2) Permitted cost + permitted revenue model. For the income cap or fixed electricity price model, it should be considered in combination with the minimum operating investment cost; the permitted cost + permitted income model should be considered in conjunction with the financial net present value objective.
3.2.1. **Objective Function.** (1) Income cap or fixed price model

The incremental distribution network optimization planning model under the income ceiling or fixed electricity price model should be based on the minimum annual operating investment cost. The annual operating investment cost includes the annual investment cost of the grid construction, the network loss cost, and the annual maintenance cost of the distribution network, and considers the basic constraints of the incremental distribution network.

\[
\min F_{\text{inv}} = F_{\text{inv}} + F_{\text{loss}} + F_{\text{YW}} 
\]

\[
F_{\text{inv}} = C_{\text{line}} \cdot L_{\text{line}} \cdot \frac{r(1+r)^n}{(1+r)^n - 1} 
\]

\[
F_{\text{loss}} = \rho \cdot E_{\text{loss}} 
\]

\[
F_{\text{YW}} = b_{\text{YW}} \cdot E_{\text{YW}} 
\]

In (1), \(F_{\text{inv}}\) is the annual investment of the distribution grid construction, \(F_{\text{loss}}\) is the annual net loss cost, \(F_{\text{YW}}\) is the annual operation and maintenance cost. \(C_{\text{line}}\) is the unit length of the distribution network line; \(L_{\text{line}}\) is the total length of the line; \(r\) is the discount rate, taking 10%; \(n\) is the economic life of the line, taking 40 years; \(E_{\text{loss}}\) is the annual network loss; \(E_{\text{DG}}\) is for the annual distribution network, the total network power; \(b_{\text{YW}}\) is the operation and maintenance cost required for one unit power.

(2) Permitted cost + permitted revenue model

Financial Net Present Value (FNPV) is a dominant indicator for evaluating the profitability of a planning program. Under the permitted cost + permitted income model background, the objective function of incremental distribution network planning is to maximize the financial net present value.

\[
\max \text{FNPV} = \sum_{t=0}^{n}(B_t - C_t)(1+i)^{-t} 
\]

\[
C_t = C_{\text{op},t} + C_{\text{sal},t} + C_{\text{buy},t} + C_{\text{loss},t} 
\]

\[
C_{\text{buy},t} = c_{\text{NET}} \left( P_{\text{load},t} - \sum_{i \in \text{DG}} P_{i,DG}^{\text{DG}} \right) + c_{\text{DT}} S_{\text{trans}} 
\]

\[
C_{\text{loss},t} = \lambda_t P_{\text{load},t} 
\]

Among them, \(C_t\) is the incremental distribution network operation and maintenance cost, \(B_t\) is the distribution service operation income, and \(n\) represents the calculation period of the project investment plan. \(i\) is the set project's benchmark rate of return. The operation and maintenance cost of the incremental distribution network includes the operation and maintenance cost \(C_{\text{op},t}\), employee compensation \(C_{\text{sal},t}\), purchase cost \(C_{\text{buy},t}\), network loss cost \(C_{\text{loss},t}\), \(\lambda_t\) is the network loss rate. \(P_{\text{load},t}\) is the total load, \(c_{\text{NET}}\) is the sum of the electricity price of the power grid and the power transmission and distribution power of the power plant, \(c_{\text{DT}}\) is the basic electricity price of the transmission transformer capacity, and \(P_{i,DG}^{\text{DG}}\) is the output power of the \(i\)-th distributed power generation, and \(S_{\text{trans}}\) is the capacity of the transmission transformer.

3.2.2. **Constraints.** The common constraints of the model under the two objectives are as follows.

(1) Reliability Constraints

The reliability constraint is taken as the expectation of loss of power after failure occurs.
\[ E_r = \sum_{j=1}^{m} \sum_{i=1}^{n} E_{ij}^0 > E_{giv} \]  

(9)

\( E_{giv} \) is the reliability constraint required by the national standard (or the requirements of the local power regulatory authority); \( E_{ij}^0 \) is the insufficient power supply at node \( i \) when the \( j \)-th line fails; \( p_j \) is the probability of the \( j \)-th line failure.

\[ E_{ij}^0 = 8760P_{si} \]  

(10)

In (10), \( P_{si} \) is the power shortage of node \( i \): When node \( i \) is not connected to the power supply, \( P_{si} \) is the power of the load carried by node \( i \); when node \( i \) is connected to the power supply, \( P_{si} = 0 \).

(2) Radial Operating Constraints
The radial network should satisfy the following equation.

\[ n = m+1 \]  

(11)

Where \( n \) is the number of network nodes and \( m \) is the number of branches.

(3) Power Flow Constraints
The power flow constraints is the power balance at each node.

\[ P_{Gi} + P_{DGi} - P_{Li} = V_i \sum_{j=1}^{N} V_j (G_{ij} \cos \theta_j + B_{ij} \sin \theta_j) \]  

(12)

\[ Q_{Gi} + Q_{DGi} - Q_{Li} = V_i \sum_{j=1}^{N} V_j (G_{ij} \sin \theta_j - B_{ij} \cos \theta_j) \]  

(13)

where \( P_{Gi} \) and \( Q_{Gi} \) are the active and reactive power of the power input at node \( i \); \( P_{DGi} \) and \( Q_{DGi} \) are the active and reactive power injected into the distributed power supply at node \( i \) respectively; \( P_{Li} \) and \( Q_{Li} \) are the active and non-active at node \( i \) respectively. The work load; \( G_{ij} \) and \( B_{ij} \) are the real and imaginary parts of the admittance matrix element corresponding to the line between the node \( i \) and the node \( j \).

(4) Node Voltage Constraints
The voltage of each node should be within its limit.

\[ V_{\text{min}} \leq V_i \leq V_{\text{max}} \]  

(14)

(5) Financial Net Present Value Constraint
The financial net present value should be positive.

\[ FNPV > 0 \]  

(15)

3.2.3. Solve Method. For the income upper limit or fixed electricity price mode, the mathematical model is a mixed integer programming (MIP) model. The existing commercial solving software is mature, and the internal branch and bound method is used to complete the planning and calculation tasks. In theory, the optimized maximum or minimum can be attained and is suitable for solving incremental distribution networks planning model.

4. Case Study
The actual planned area of an actual industrial park is 14 square kilometers, the already built part of which is about 8 square kilometers. The future is positioned as an production area, with a focus on the core infrastructure development base. During the current situation and planning period, there is no public and self-powered power supply in the pilot area. In 2016, the maximum load of the whole society in the park was 9.2 MW, and the electricity sold was 408 million kWh, mainly due to the industrial and general industrial and commercial load of 10 kilovolts. At present, the road network of the park has basically formed, and about 45 companies have settled in the enterprise.
As shown in Fig. 2, the park’s sources mainly consist of a 220kV power station A, a 110kV power station B, and a 35kV power station C. Three of which locate outside the park and there is no power station at the level of 35kV or higher voltage.

Table 1. Existence Substation Properties

| Number | Power Station Name | Voltage Level | Capacity | Owner  |
|--------|-------------------|---------------|----------|--------|
| 1      | A                 | 220kV         | 180+180  | Public |
| 2      | B                 | 110kV         | 50+50    | Public |
| 3      | C                 | 35kV          | 10+10    | Public |

The four 10 kV main extension lines and the branch lines for enterprises in the park have been constructed, with a total length of 30.8 km, of which the cable length is 8.36 km. In February 2017, it has invested in the construction of two 10 kV lines with a length of 4.95 km.

According to the planning procedure of Fig. 1, the load forecasting has been made. The method is Load Density Index Method combined with correction from other methods. The coverage capacity of local blocks and their margins has been prepared according to development and construction time schedule.

When the load density index method is used for load forecasting, the reference index of the power load density for each type of load is determined. In order to make the load density index representative of future development, the load density of the same type of load in large and medium-sized cities that have been fully developed is investigated, and these load density indicators are used as the main basis for setting the load density index of the park.

Meanwhile, some classifications with obvious regional characteristics, such as industry and residence, are combined with local actual conditions. The development orientation of different types of land in the park is different, which leads to different load density indicators. Therefore, it is necessary to conduct detailed investigation and analysis on the power consumption indicators of various loads and finally
determine the selection results. For near-term load forecasting, the forecast is based on the comprehensive forecasting method of natural growth load + large load. The natural growth load is constructed by a two-stage model; the large user load is obtained through the investigation and analysis of the construction of major projects during the planning period and the customer’s report loading situation. The final park load forecasting results are shown in Table 2.

| Year      | 2016 (Actual) | 2018     | 2019     | 2020     | 2025     | Annual Growth (2016-2020) | Annual Growth (2021-2020) |
|-----------|----------------|----------|----------|----------|----------|---------------------------|---------------------------|
| Load      | 0.92           | 1.64     | 2.39     | 3.58     | 7.63     | 40.45                     | 16.34                     |
| Power Usage | 0.48          | 0.84     | 1.23     | 1.83     | 4.09     | 39.45                     | 17.45                     |

According to the incremental distribution network planning model under the permitted cost + permitted income model, the mathematical model is established and solved, and the following planning results are obtained: a high-voltage distribution network in the park will construct a 110kV substation D, and its grid-connected scheme should be coordinated with the 220kV grid. According to the overall planning of the park, the D substation’s connection scheme is: the #2 incoming line is directly connected to the 220kV transformer. The summarized plan is as follows.

| Name                        | Branch Line (km) | All Investment (10^4 Yuan) | Finish Time |
|-----------------------------|------------------|----------------------------|-------------|
| Line 2                      | 12               | 324                        | 2018        |
| D substation 10kV out project (West) | 8             | 216                        | 2019        |
| D substation 10kV out project (East) | 8             | 216                        | 2019        |
| Line 3                      | 12               | 348                        | 2020        |
| Line 4                      | 6                | 174                        | 2020        |
| Total                       | 62               | 1710                       | --          |

According to the financial evaluation of the distribution price at 0.03 yuan / kWh, the financial internal rate of return on project investment is 4.04% (after tax, the same below), the internal financial return rate of capital is 11.46%, and the investment recovery period is 17.74 years. The rate of return in total is 5.3%, and the net profit margin of project capital is 12.54%. The project internal financial internal rate of return (11.46%) is higher than the capital base benchmark rate (7%), which verifies the effectiveness of the project plan.

5. Conclusion

This paper analyzes the characteristics of the incremental distribution network, the impact on the distribution network planning after the business is released, and the factors that need to be considered during the planning. Combined with the different incremental distribution service price supervision mechanism, the incremental power distribution planning models which meet the corresponding needs are proposed. The income upper limit or fixed electricity price mode and the permitted cost + the permitted revenue mode are discussed and different optimization models are developed correspondingly. Based on an actual industrial park, the permitted cost + the permitted revenue model is applied in its planning of the incremental distribution network. The financial evaluation verifies the planning method, meaning the proposed planning method can be applied to the planning of incremental distribution network. Future work includes more detailed modelling on the transactions between the users inside the park and the impact of renewable energy on incremental planning.

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