Evaluation Model for Smart Distribution Network Planning under Energy Interconnection

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Abstract. Due to the development of the energy interconnection, smart distribution networks (SDNs) should needs be transformed and upgraded to meet new demands. In order to assess the SDN planning, a new index system was conducted from the five attributes. The quantitative methods of all criteria were also defined. An evaluation model was proposed based on AHP weighting and TOPSIS methods. Empirical analysis was performed to verify the feasibility of the evaluation system.

1. Introduction
The global energy interconnection is a strong smart grid with UHV power grid as the backbone, clean energy as the leading factor and global interconnection. Electric power with the characteristics of clean, efficient, convenient transportation and distribution, can play a main role in the energy interconnection [1]. Distribution networks, as an important part of power grid, are not only the energy consumption terminal, but also the access carrier of distributed energy. There is an inevitable trend for the future power distribution system to adapt to the development of the global energy interconnection. Therefore, it is of great significance to promote the construction of smart distribution networks (SDNs). Due to the energy interconnection, SDNs should be the access of distributed power supply and energy storage equipment at any time and process information flows and energy flows [2]. It is important to construct an evaluation index system and relative model to assess a series of planning.

With the development of the energy interconnection technology, more and more distributed power supply planning based on clean energy and flexible load of electric vehicle and energy storage equipment will be widely connected to energy systems in China. Evaluation index for traditional distribution network planning, which only reflect total load forecast and power balance demand, cannot be used to judge the effectiveness of the planning scheme in the new situation. Moreover, due to the establishment of competitive power market pattern [3]. Thus, an operation mode of multilateral participation gradually replaces the vertical integration management for SDN planning. Then, it is essential to propose a comprehensive evaluation index system to promote the development of the SDN.

For the above reasons, a new evaluation index system was established for the assessment of SDN planning under energy interconnection. In Section 2, the impact of the development of energy interconnection on the SDN was analyzed. Section 3 established a preliminary index system to evaluate
the perform of SDN planning from the five perspectives of power quality, power supply reliability, operation sustainability, economic and environmental protection. In Section 4, important indicators were selected and an evaluation model were developed. An empirical analysis was performed in Section 5. The last section made the conclusions.

2. The Impact of Energy Interconnection on SDN Planning

Based on advanced intelligent information technology, energy interconnection takes electric power as the core and integrates a lot of energy storage, distributed energy resources and demand response into an interconnected platform, which can share energy flows, information flows and business flows widely. The interconnection can realize the optimization of the whole process from energy production to energy consumption, the adjustment of the structure of energy supply and demand and the improvement of the whole efficiency of energy utilization. A fully competitive energy market can form gradually to promote the interaction of demand-side energy load resources. Users can obtain more and more options to select energy suppliers and relative service [4]. The structure of the energy interconnection can be drawn, as is the figure 1.

For the development of the energy interconnection, the SDN should transform from a simple power distributor to a public platform with multiple roles. It can promote the absorption of new energy sources, integrate multi-source massive information to a data platform and attract multiple stakeholders to participate in market transactions. It can also provide basic services for interconnected energy sources for the construction of smart cities. Meanwhile, operational characteristics of SDNs need to be changed for massive penetration of intermittent distributed energy sources and demand response resources from end users.

Figure 1. The structure of the energy interconnection

3. An Evaluation Index System of SDN Planning

In view of the impact of the development of energy interconnection, a comprehensive evaluation index system should be established from the perspectives of power transmission quality, power supply reliability, operation sustainability, economy and environmental protection. It is vital to adopt a series of criteria into the evaluation index system to reflect the inherent characteristics of SDNs and ensure the safety of the whole electric power system [5]. The index system consists of three levels, namely target level, attribute level and criteria level, as shown in Figure 2.

(1). power supply reliability

Average self-healing ability of users and adequacy of power supply capacity are applied to reflect the power reliability. Average self-healing ability of users is the average number of fault self-healing rate for all users in a year, as is
\[ Rh = \frac{\sum_{n=1}^{N^{CB}} k_n^m}{M} \]  

(1)

where \( k_n^m \) is the number of users who successfully performed fault self-healing in the \( m \) blackout. \( N \) is the total number of the users affected by the blackout. \( M \) is the total number of the blackout.

Adequacy of power supply capacity can reflect the ability to supply electricity continuously and meet the needs of users completely. The indicator (Ap) is expressed as

\[ Ap = \frac{Q'_{\text{max}}}{q'_{\text{max}}} \]  

(2)

where \( Q'_{\text{max}} \) is the maximum demand load and \( q'_{\text{max}} \) is the maximum supply load. The larger the value of Ap, the weaker the power supply.

(2). Power supply quality

There are the following three indices to measure the attribute index. Customer average interruption frequency can reflect the average number of blackouts per outage user in a year, as is:

\[ Cv = \sum_{n=1}^{N^{CB}} \frac{C_n^{CB}}{N^{CB}} \]  

(3)

where \( C_n^{CB} \) is the number of blackouts outage user in a year, \( N^{CB} \) is the total number of the outage users.

Voltage qualified (Vq) rate is usually applied to the judgment of power supply quality, as is

\[ Vq = 1 - \frac{T^o}{T^r} \]  

(4)

where \( T^o \) is voltage overrun time, \( T^r \) is total running time.

Comprehensive voltage qualified (Vq) rate can be obtained to judge the performance of the voltage qualified, as is:

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**Figure 2.** The evaluation index system of SDN planning
where A represents 20kV, 10(6) kV busbar voltage of substations and power plants with regional power supply load, B represents power supply voltage of 35kV, 20kV dedicated line and 110 kV and above users. C represents power supply voltage of 35 kV and 20 kV non-dedicated lines and 10(6) kV subscriber terminals. And D represents 380/220V low voltage network and power supply voltage at user end.

Power supply stability rate (PR) reflect the ability of SDN to provide continuous power. It can be expressed as the percentage of the actual power supply time to the total power consumption time.

(3). Operation sustainability

The following three indicators can reflect the attribute of the operation sustainability. Line average load rate (La) means the ratio of the average active load to the maximum active load over a given period of time. The index can be applied to measure the difference between the average load and the maximum load, as is:

\[
La = \frac{AL_{\text{av}}}{AL_{\text{max}}} \quad (6)
\]

Where \( AL_{\text{av}} \) is the average active load, \( AL_{\text{max}} \) is the maximum active load.

Distribution transformer load rate (Dt) represents the ratio of the average apparent output of a distribution transformer to its rated capacity. It can reflect the load-carrying capacity of the transformer, as is:

\[
Dt = \frac{g_{\text{av}}}{g^r} \times 100\% \quad (7)
\]

Where \( g_{\text{av}} \) is the average apparent output and \( g^r \) is the rated capacity of the distribution transformer. Its optimum value is between 75 and 80%.

Distributed power supply permeability (\( DGp \)) means the percentage of total distributed generation (\( G^{DG} \)) in system power consumption (\( G^T \)) at a year, as is:

\[
DGp = \frac{G^{DG}}{G^T} \times 100\% \quad (8)
\]

(4). Economy

The economy attribute of the SDN planning can be reflected by the following four criteria. Construction investment cost (CI) can be obtained by summarizing the initial investment cost of all investors in the system. The index can be:

\[
CI = I^d + I^g + I^l \quad (9)
\]

Where \( I^d \), \( I^g \) and \( I^l \) represent the investment cost of the distributor, generator and load integrator, respectively.

Similarly, operation and maintenance cost (OC) can be calculated as:

\[
OC = O^d + O^g + O^l \quad (10)
\]

Where \( O^d \), \( O^g \) and \( O^l \) represent the operation and maintenance cost of the distributor, generator and load integrator, respectively.

Equipment depreciation can reflect the correct proportion of income and expenses during the period. Average limit method was applied to measure the equipment depreciation (ED), as is:

\[
ED = \frac{\sum_{i=1}^{EC} (EC_i - ER_i) / T^e}{T^e} \quad (11)
\]

Where \( EC_i \) is the original value of the ith equipment, \( ER_i \) is the residual value, \( T^e \) is the Time of depreciation.

Electricity sales revenue (Re) can reflect the income situation of SDNs, as is:
\[ R^* = Q^* \times (P^* + P^{p^e}) \]  

Where \( Q^* \) is the total power consumption, \( P^* \) is the transmission-distribution price determined by the distributor and \( P^{p^e} \) is the electricity price determined by the generator.

5. Environmental protection

Two criteria affiliated with the environmental protection attribute were selected to assess the performance of the SDN planning. CO\(_2\) reduction in the SDN system can be represented as the reduction of the CO\(_2\) emissions from the systems. Similarly, nitrogen oxide reduction in the SDN system was chosen to measure the reduction of the NO\(_x\) emissions from the systems.

4. The Framework of Proposed Evaluation Model

4.1. AHP Weighting Method

Analytic Hierarchy Process (AHP), proposed by Saaty, is an appropriate tool to clarify interdependent relationships among indicators expressed as a hierarchical structure and generates advantages in calculating the weights of different criteria [6]. Procedures of the weight determination using the AHP method:

Step1: Comparing the evaluation indexes and construct individual fuzzy comparison matrices of attribute layer and criteria layer in pairs, respectively. The pairwise comparative judgments should be expressed as linguistic variables based on the 0~9 scale method, as shown in Table 1.

| Linguistic Terms                  | Scaling | Meaning                                              |
|----------------------------------|---------|------------------------------------------------------|
| Equally important (EI)           | 1       | Criterion i is as important as criterion j           |
| Moderately more important (MI)   | 3       | Criterion i is moderately more important than criterion j |
| Strongly more important (SI)     | 5       | Criterion i is strongly more important than criterion j |
| Very strongly more important (VI)| 7       | Criterion i is very strongly more important than criterion j |
| Absolutely important (AI)        | 9       | Criterion i is absolutely more important than criterion j |
| Others                           | 2,4,6,8 | The median of two adjacent judgements                |

Step2: Test the consistency of the comparison matrices. Consistency ratio (CR) was usually applied to measure the deviation of the individual comparison matrix away from the consistency and is:

\[ CR = CI / RI \]  

Where RI is the random index and can be queried, CI is the consistency index and can be calculated as:

\[ CI = \frac{\lambda_{\text{max}} - n}{n - 1} \]  

Where \( \lambda_{\text{max}} \) is the largest eigenvalue of the matrix and \( n \) is the criteria number. Experiential threshold 0.1 is usually regarded as the upper limit for CR.

Step3: calculate the weights of attributes and criteria, as is:

\[ s = \left( \prod_{j=1}^{n} a_{ij} \right)^{1/n} \]  

\[ w_j = \frac{s_j}{\sum_{i=1}^{n} s_i} \]  

Where \( a_{ij} \) is an element in the comparison matrix.

4.2. TOPSIS Evaluating Method

The technique for order preference by similarity to an ideal solution (TOPSIS) has been employed to appraise SDN planning performance [7]. The method comprises:
Step 1: assemble initial decision matrix \( Z \) based on the comprehensive weights and standard matrix \( X \) integrated by the actual indicator data of the \( i \) alternatives, as is:
\[
Z = [w_i x_{ij}]_{m \times n}
\]  
(17)

Step 2: determine the positive ideal solution \( Z^+ \) and the negative ideal solution \( Z^- \), as are:
\[
Z^+ = \{\max(Z_{ij}), \max(Z_{ij}), \ldots, \max(Z_{ij})\}
\]  
(18)
\[
Z^- = \{\min(Z_{ij}), \min(Z_{ij}), \ldots, \min(Z_{ij})\}
\]  
(19)

Step 3: compute the distances \( d_i^+ \) and \( d_i^- \) of each alternative from \( Z^+ \) and \( Z^- \), respectively.
\[
d_i^+ = \sqrt{\sum_{j=1}^{n} (z_{ij} - z_{ij}^+)^2}
\]  
(20)
\[
d_i^- = \sqrt{\sum_{j=1}^{n} (z_{ij} - z_{ij}^-)^2}
\]  
(21)

Where \( z_{ij} \) is the element of the matrix \( Z \), and \( z_{ij}^+ \) and \( z_{ij}^- \) are belong to the \( Z^+ \) and \( Z^- \), respectively.

Step 4: calculate the closeness coefficient value (CV) of each alternative:
\[
CV = \frac{d_i^-}{d_i^+ + d_i^-}
\]  
(22)

Alternatives can be ordered based on the values of all closeness coefficient. The alternative with closest to \( Z^+ \) and farthest to \( Z^- \) should be regarded as the best one.

5. Empirical Analysis
An SDN planning in China are selected as the empirical analysis object. The proposed index system and evaluation model were used to access the performance of the planning.

5.1. Determining the weights
Based on the AHP method, five expert groups were asked to rate the indicators. According the ratings, the weights of all criteria and attributes can be calculated, as shown in Table2.

| Attributes | Local weights | Criteria | Local weights | Global weights |
|------------|---------------|----------|---------------|---------------|
| A1         | 0.210         | C1       | 0.75          | 0.157         |
|            |               | C2       | 0.25          | 0.052         |
| A2         | 0.194         | C3       | 0.423         | 0.082         |
|            |               | C4       | 0.214         | 0.042         |
|            |               | C5       | 0.363         | 0.07          |
| A3         | 0.263         | C6       | 0.243         | 0.064         |
|            |               | C7       | 0.392         | 0.103         |
|            |               | C8       | 0.358         | 0.094         |
| A4         | 0.146         | C9       | 0.243         | 0.036         |
|            |               | C10      | 0.272         | 0.04          |
|            |               | C11      | 0.296         | 0.043         |
|            |               | C12      | 0.209         | 0.031         |
| A5         | 0.187         | C13      | 0.5           | 0.093         |
|            |               | C14      | 0.5           | 0.093         |

5.2. Calculate the Preference of the SDN planning
The performance of all criteria was calculated by using the TOPSIS method. The results are shown in the Table 3. According to the equation (22), the CV values of the five attributes were 0.549, 0.344, 0.56,
0.515 and 0.49, respectively. The results can reflect that the SDN have poor performance in the attribute of “Power supply reliability” and represent general performance in other attributes.

### Table 3. The evaluation data and the performance of all index

| Attributes | Criteria | Global weights | Standardized values | The best values | The worst values | $d^+_r$ | $d^-_r$ |
|------------|----------|----------------|---------------------|----------------|-----------------|---------|---------|
| A1         | C1       | 0.157          | 0.63                | 0.8            | 0.4             | 0.0309  | 0.0376  |
|            | C2       | 0.052          | 0.7                 | 1              | 0.5             |         |         |
|            | C3       | 0.082          | 0.73                | 1              | 0.6             |         |         |
| A2         | C4       | 0.042          | 0.72                | 0.8            | 0.65            | 0.0226  | 0.0118  |
|            | C5       | 0.07           | 0.96                | 1              | 0.9             |         |         |
| A3         | C6       | 0.064          | 0.72                | 0.8            | 0.5             | 0.0235  | 0.0299  |
|            | C7       | 0.103          | 0.81                | 0.85           | 0.6             |         |         |
|            | C8       | 0.094          | 0.36                | 0.6            | 0.2             |         |         |
| A4         | C9       | 0.036          | 0.7                 | 0.85           | 0.65            | 0.0152  | 0.0162  |
|            | C10      | 0.04           | 0.6                 | 0.9            | 0.4             |         |         |
|            | C11      | 0.043          | 0.8                 | 0.95           | 0.5             |         |         |
|            | C12      | 0.031          | 0.87                | 1              | 0.7             |         |         |
| A5         | C13      | 0.093          | 0.56                | 0.7            | 0.3             | 0.0258  | 0.0248  |
|            | C14      | 0.093          | 0.36                | 0.6            | 0.3             |         |         |

### 6. Conclusion
The development of the energy interconnection puts forward new demands for SDNs. The impact of the demands on SDN planning was analyzed. Then the evaluation index system was established from the five attributes. Fourteen criteria were proposed in the system. Then, an evaluation model was developed based on the AHP and TOPSIS methods. Empirical analysis was applied to verify the practicality of the index system and the model.

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