Comprehensive Evaluation for Differentiated Development of Disaster Resistant Power Grid Based on Essential Security

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Abstract. The occurrence of natural disasters and accidents can pose a great threat to the safe and stable operation of power grid. It is of great significance to promote the differentiated development of disaster-resistant power grid. A comprehensive evaluation system should be proposed to assess the differentiated development quality of the disaster-resistant power grid based on the essential security. First, an evaluation index system should be built from many perspectives. Then, an integrated evaluation framework were designed based on the AHP and DEMATEL approaches. Finally, an empirical analysis was performed to demonstrate the feasibility of the evaluation system.

Keywords: disaster-resistant power grid, comprehensive evaluation, AHP, DEMATEL, differentiated development

1. Introduction

Power grid security is the basis of the foundation of electric power industry reform and development. It is related to economic development and social stability [1]. Essential security reflects the ability of power grid to prevent and resist accident risk in extremely harsh environments [2]. It requires the unification of core elements such as team construction, power grid structure, equipment quality and management system.

Due to the difference of construction processes, load levels and grid structures in different areas, it is necessary to carry out differentiated construction for some regional power grids [3]. A series of measures should be implemented to guarantee the load power supply capacity in disaster situations and ensure the essential security of power grid, including local optimization of grid structure, the improvement of the design standards of key power transmission and transformation equipment etc. Thus, it is necessary to promote the balance of power grids in different regions and enhance the ability of continuous safe power supply. And a differentiated development way of regional power grids based on essential security will be widely adopted [4].

In order to ensure the performance of the differentiated development way according to essential security, an evaluation system for power grid quality should be proposed. First, an evaluation indexes system should be established to reflect the characteristics of differentiated development of power grid based on the premise of essential security. Then, a comprehensive weight method can be developed
based on Analytic Hierarchy Process (AHP) and Decision Making Trial Evaluation Laboratory (DEMATEL) methods to determine the weights of evaluation indicators. A series of indicator data can be normalized and weighted summation is performed to form a complete evaluation system. Finally, an empirical analysis should be performed to prove the practicality of the evaluation system.

2. Differentiated Development Evaluation Indicators for Disaster Resistant Power Grid

A comprehensive evaluation index system should be built first to reflect the characteristics of differentiated development of disaster resistant power grid. Meanwhile, essential security should be considered to ensure the construction quality of the power grid. Thus, the evaluation index system can be designed from the five perspectives of economic benefit, equipment safety, structure safety, disaster resistance and external environment safety. A series of indicators can be grouped into three levels, namely target level, attribute level and criteria level, as shown in Figure 1.

![Figure 1. The index system of differentiated development of disaster resistant power grid](image)

(1) Economic Benefit

Average annual cost and annual economic return can be estimated from the perspective of life cycle management based on the project feasibility report. These indicators can reflect the economy of disaster resistant power grid development.

(2) Equipment Safety

Capacity-load ratio (CV) can reflect the rationality of power grid planning, as is:

\[ CV = \frac{Sc}{\bar{L}} \]  

where \( Sc \) is the total substation capacity and \( \bar{L} \) is the largest load in regional power grid.

Transformer average load rate can be obtained as the following:

\[ Tal = \frac{\bar{A}p}{Rp} \times 100\% \]  

where \( \bar{A}p \) is average of actual output power of transformer and \( Rp \) is the rated power.

Line average load rate (Lal) can be computed as:
\[
Lal = \bar{At}/Rt \times 100\% 
\]

Where \( \bar{At} \) is average of actual transmission power of line and \( Rt \) is the rate transmission power.

Insulation rate can be used to reflect the safety performance of the whole line, as is:

\[
IR = LL/SL \times 100\% 
\]

Where LL is insulated line length and SL is statistical line length.

(3) Structure Safety

N-1 passage rate for lines (NL) and N-1 passage rate for transformer (Nnm) are reflect that if a line or a transformer fails, the other part of the power grid can be return to operation and provide continuous electricity to users. They are:

\[
NL = L_{iz}/L^T \times 100\% 
\]

\[
Nnm = M_{iz}/M^T \times 100\% 
\]

where \( L_{iz} \) and \( M_{iz} \) are the numbers of all lines and transformer satisfying N-1 conditions, \( L^T \) and \( M^T \) are the total numbers of all lines and transformer.

Underload transformer ratio (UT) and overload transformer ratio (OT) can be used to reflect the operational status of the transformer. They are:

\[
UT = \text{NUT}/\text{NT} \times 100\% 
\]

\[
OT = \text{NOT}/\text{NT} \times 100\% 
\]

where \( \text{NUT} \) is the number of transformers with peak load rate less than 30%, \( \text{NT} \) is the total number of transformers and \( \text{NOT} \) is the number of transformers with peak load rate more than 90%.

(4) Disaster Resistance

Super load refers to the user load that must be guaranteed after the disaster, including hospital, communication center, fire center, transportation hub etc. Super load rate (SL) is defined as:

\[
SL = SLL/TOL \times 100\% 
\]

where \( SLL \) is the super load and \( TOL \) is the total load.

Self-provided emergency power can be used to quickly restore power after a disaster. Qualification rate of self-provided emergency power supply configuration (SE) can be reflected to the ability of restoring power, as is:

\[
SE = NQE/NCE \times 100\% 
\]

where \( NQE \) is the number of the qualified self-provided emergency power supply and \( NCE \) is the number of the self-provided emergency power supply that should be configured.

Supporting power supply should be reasonably allocated in disaster-prone administrative centers to meet the base load requirements. The ratio of supporting power to load in the core area (RS) is adopted, as is:

\[
RS = \sum (q_\lambda)/P_g \times 100\% 
\]

Where \( q_\lambda \) is installed capacity of supporting power supply, \( \lambda \) is output coefficient of support power supply and \( P_g \) is the base load requirements.

(5) External Environment Safety

Incidence of natural disaster risk (IN) and incidence of external damage risk (IE) can reflect the impact from external environment on the safe operation of power grid, as are:
\[ \text{IN} = \frac{\text{INN}}{\text{ITN}} \times 100\% \quad (12) \]

\[ \text{IE} = \frac{\text{IEN}}{\text{ITN}} \times 100\% \quad (13) \]

where \( \text{INN} \) is the number of natural disaster accidences, \( \text{IEN} \) is the number of external damage accidences and \( \text{ITN} \) is the total number of all accidences.

3. The framework of the evaluation model

3.1. AHP Method

Analytic Hierarchy Process (AHP), proposed by Saaty [5], is used to build a hierarchical structure to reflect interdependent relationships among indicators. The structure can be applied to calculate the criteria weights. Procedures of the AHP method:

Step1: Comparing the evaluation indexes in pairs and establish all individual comparison judgment matrices for attribute layer and criteria layer respectively. The pairwise comparative judgments can be described as linguistic variables, 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: Check the consistency of all comparison judgment matrices. Consistency ratio (CR) can be used to understand the deviation of the individual comparison judgment matrix away from the consistency. It is:

\[ CR = \frac{CI}{RI} \quad (14) \]

where RI is the random index and can be consulted, CI is the consistency index and can be:

\[ CI = \frac{\lambda_{\text{max}} - n}{n-1} \quad (15) \]

where \( \lambda_{\text{max}} \) is the largest eigenvalue of the matrix and \( n \) is the criteria number. Threshold 0.1 is considered as the upper limit of CR.

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

\[ g_i = \left( \prod_{j=1}^{n} a_{ij} \right)^{1/n} \quad (16) \]

\[ w_i = g_i / \sum_{i=1}^{n} g_i \quad (17) \]

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

3.2. DEMATEL model

For AHP method, the relations of the system factors are regarded as independent. In fact, these factors are related rather than independent. Decision making trial and evaluation laboratory (DEMATEL), proposed by Gabus and Fontela [6] in 1972, is employed to analyze the relationship between system factors based on graph theory and matrix tool. The method can be applied to establish a series of direct relation matrixes and measure the degree of these relationship. The steps of the method are:

Step 1: Determine the direct relation matrix \( Y \):
\[ Y = (y_{ij})_{n \times n} \]  

(18)

where \( y_{ij} \) represents the influence degree of criterion \( i \) on criterion \( j \), and \( y_{ij} = 0, 1, 2, 3, 4 \). \( y_{ij} = 0 \) indicates there is no relation. \( y_{ij} = 1 \) indicates that the influence is very lower. \( y_{ij} = 2 \) indicates that the influence is slightly lower. \( y_{ij} = 3 \) indicates that the influence is slightly higher. \( y_{ij} = 4 \) indicates that the influence is very higher.

Step 2: Normalize the direct relation matrix \( Z \):

\[
Z = (z_{ij})_{n \times n} = \frac{y_{ij}}{\max \sum_y y_{ij}}
\]

(19)

Step 3: Build the comprehensive relation matrix \( H \):

\[
H = (h_{ij}) = Z(1-Z)^{-1}
\]

(20)

Step 4: Compute the degree of influence (\( R \)) and the degree of being influenced (\( D \)) by the sum of rows and columns of \( H \) as are:

\[
R = (r_{i})_{n \times n} = \left( \sum_{j=1}^{n} h_{ij} \right)_{n \times n}
\]

(21)

\[
D = (d_{i})_{n \times n} = \left( \sum_{j=1}^{n} h_{ij} \right)_{n \times n}
\]

(22)

Where \( r_{i} \) is the comprehensive influence of criterion \( i \) on other criteria, \( d_{i} \) is the comprehensive influence of other criteria on the criteria \( j \).

Step 5: calculate the centrality value and causality value. The centrality value (\( U \)) can reflect the important degree of criterion \( i \) in the system, as is:

\[
U = R + D
\]

(23)

The causality value (\( V \)) can reflect the intensity of the logical relations between criteria, as is:

\[
V = R - D
\]

(24)

If the value of \( V \) is greater than zero, the criterion belongs to a cause group. Otherwise, it belongs to a result group.

3.3. The proposed research framework

In order to evaluating the differentiated development of disaster resistant power grid, a comprehensive framework is proposed as:

Phase 1: A combined weight can be obtained as the following based on the AHP and DEMATEL.

\[
w'_{j} = \left( u_{j} \times w_{j} \right) / \sum_{j} \left( u_{j} \times w_{j} \right)
\]

(25)

Where \( w'_{j} \) is the combined weight, \( u_{j} \) is the element of the matrix \( U \).

Phase 2: Normalize the initial data of all criteria. In general, the data can be divided into benefit-type indicators and cost-type indicators. For benefit-type indicators, the process of the normalization is:

\[
f_{p} = x_{p} / \max_{r} x_{r}
\]

(26)

For cost-type indicators, the process of the normalization is:

\[
f_{p} = \min_{r} x_{r} / x_{p}
\]

(27)
Where $x_{jr}$ is the initial data for the criterion j of alternative r

Phase 3: establish a comprehensive evaluation index (CE) for each alternative, as is:

$$CE = \sum_{j=1}^{n} w_j \times f_j$$

(28)

4. Empirical Analysis
Taking the disaster-resistant distribution network planning scheme in a region with high typhoon incidence as an example, the method proposed in this paper is used to evaluate the differential construction level of the distribution network. The maximum load in the region will reach 950 MW after three years. Three planning schemes of the disaster-resistant distribution network are designed to meet the needs of differential development of power grids, as shown in table 2.

| Table 2. Planning schemes of the disaster-resistant distribution network |
|-----------------|-----------------|-----------------|-----------------|
| New 220 kV Substation | New 110 kV Substation | New 10 kV Line | Total capacity (MVA) |
| scheme 1 | 1 | 4 | 160 | 1700 |
| scheme 2 | 2 | 6 | 180 | 2100 |
| scheme 3 | 3 | 7 | 200 | 2440 |

First, some experts were invited to rate the criteria according to the Table 1. Some comparison judgment matrices were assembled based on the average of the criterion scores. Software yaahp can be applied to determine criteria weights based on the AHP method. All comparison judgment matrices have the CR values less than 0.1 and is consistent. All weights of attributes and criteria can be calculated as the Table 2. Then, according to the DEMATEL model, the direct relation between criteria can be rated by the experts. The judgments from the experts can be combined as the direct relation matrix based on arithmetic mean method. The normalized matrix and the centrality value can be computed according to the equation (18) to (22). The combined weights can be obtained, as shown in the table 3.

| Table 3. The calculation process and the final results based on the AHP and DEMATEL method |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Attribute | Weights | Criteria | Weights | R | D | U | Combined weight |
| A1 | 0.274 | C1 | 0.156 | 0.017 | 0.04 | 0.058 | 0.037 | 0.347 |
| | | C2 | 0.052 | 0.051 | 0.038 | 0.089 | 0.053 |
| | | C3 | 0.206 | 0.108 | 0.04 | 0.148 | 0.04 |
| | | C4 | 0.088 | 0.069 | 0.042 | 0.112 | 0.017 |
| | | C5 | 0.075 | 0.04 | 0.044 | 0.084 | 0.072 |
| | | C6 | 0.031 | 0.022 | 0.033 | 0.054 | 0.019 |
| A2 | 0.400 | C7 | 0.097 | 0.041 | 0.05 | 0.091 | 0.01 |
| | | C8 | 0.109 | 0.025 | 0.034 | 0.059 | 0.073 |
| | | C9 | 0.05 | 0.038 | 0.03 | 0.069 | 0.039 |
| | | C10 | 0.018 | 0.036 | 0.027 | 0.063 | 0.013 |
| | | C11 | 0.017 | 0.031 | 0.026 | 0.058 | 0.011 |
| A3 | 0.055 | C12 | 0.032 | 0.02 | 0.026 | 0.046 | 0.017 |
| | | C13 | 0.006 | 0.04 | 0.022 | 0.061 | 0.004 |
| | | C14 | 0.047 | 0.006 | 0.044 | 0.05 | 0.027 |
| | | C15 | 0.016 | 0.004 | 0.052 | 0.056 | 0.01 |
| A4 | 0.063 | C16 | 0.047 | 0.006 | 0.044 | 0.05 | 0.027 |
| | | C17 | 0.016 | 0.004 | 0.052 | 0.056 | 0.01 |

Then, the values of the criteria were collected and normalized based on the equation (25) and (26), and the comprehensive index can be computed according to the equation (27). The calculation results were shown in the Table 4. And the scheme 3 have the best performance. Thus, the scheme 3 is the best option and should be performed to promote the differential construction level of the disaster resistant distribution network.

| Table 4. The calculation results of the comprehensive evaluation index |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Indicator | A1 | A2 | A3 | A4 | A5 | CE |
| scheme 1 | 0.143 | 0.405 | 0.211 | 0.026 | 0.037 | 0.822 |
| scheme 2 | 0.148 | 0.474 | 0.214 | 0.032 | 0.034 | 0.902 |
| scheme 3 | 0.122 | 0.544 | 0.225 | 0.030 | 0.034 | 0.955 |
5. Conclusion
In the paper, a comprehensive evaluation system was developed to evaluation the differentiated development of disaster resistant power grid effectively. First, an evaluation index system was developed from the perspectives of economic benefit, equipment safety, structure safety, disaster resistance and external environment safety to ensure the essential security of power grid. Then, a framework of the evaluation model was established based on the AHP and DEMATEL methods. Finally, the framework was performed by the empirical analysis to verify the role of promoting the differentiated development of disaster resistant power grid.

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