Evaluating Comprehensive Development Quality of a Regional Power Grid by Using an Integrated Multi-criteria Decision-Making Methodology

Xiaodong Zhang¹, Kaiming Qin¹, Ruihua Si¹ and Xianjun Ge²,*

¹ State Grid Henan Electric Power Company, Zhengzhou, 450018, China
² State Key Laboratory of Power System and Power Generation Equipment Control and Simulation, Department of Electrical Engineering, Tsinghua University, Haidian, Beijing, 100084, China

*Corresponding author e-mail: gexj2010@163.com

Abstract. Due to the economic situation changes and the continuous expansion of new energy power in China, a new evaluation methodology based on multi-criteria decision making (MCDM) should be proposed to promote the comprehensive development of the new regional power grid. Some criteria were selected to constitute an indicator system from the perspectives of the safety reliability, network structure and economic benefit. Then, an integrated evaluation model was proposed based on fuzzy AHP method and VIKOR method was applied to calculate a series of comprehensive evaluation indexes. A regional power grid was chosen as an empirical analysis to demonstrate the feasibility of the evaluation system.

Keywords: power grid development quality, comprehensive evaluation, fuzzy AHP, VIKOR, power grid structure

1. Introduction
The power industry is a basis of the economic-society development. Safe and stable operation of power grids is closely related to economic sustainable development and social stability. In order to meet the needs of economic and social in China, power grids should further strengthen the infrastructure construction, optimize the layout and improve the stability of power supply[1].

China is gradually promoting UHV transmission technology to reinforce power grid construction. Power supply reliability and loss rate improve increasingly. However, due to the of the uneven economic development between the east and west of China and the differences between urban and rural, there a significant gap between urban and rural power grids. Some regional grid structure should be strengthened further[2]. The imbalance of power grid construction may affect the high-quality development of economy and society in turn[3]. And lagging power grid construction in some regions will influence on urbanization and clear energy absorption[4]. Thus, it is essential to promote the balanced construction of regional power grids and improve the development of the quality of the regional grid.
In order to the comprehensive quality of the power grid should be fully grasp. Considering the complexity and dynamics of power grids and energy structure adjustment, an evaluation system for the comprehensive development quality should be developed to reflect overall level of regional power grids. An evaluation index system should be established from the four perspectives of safety reliability, grid structure, equipment and facilities and economic benefits. Fuzzy Analytic Hierarchy Process (AHP) was introduced to calculate criteria weights. And an evaluation index of the comprehensive quality of the regional power grids was obtained by using VIKOR method. Then, the above evaluation model was applied to a specific regional power grids in order to demonstrate its practicability in the empirical analysis section.

2. An index system of evaluating power grid quality
A comprehensive evaluation index should be constructed to reflect the impact of safety reliability, grid structure, equipment and facilities and economic benefits on the overall development quality of regional power grids. The index system involves three levels, namely target level, attribute level and criteria level.

![The index system of evaluating power grid quality](image)

Figure 1. The index system of evaluating power grid quality

(1) safety reliability
There are five criteria to reflect the safety reliability of regional power grid. Comprehensive voltage qualification rate ($\bar{V}$) involves four types of voltage qualification rate, as is:

$$\bar{V} = 0.5v_d + 0.5 \times \frac{v_b + v_c + v_2}{3}$$  \hspace{1cm} (1)

where $v_d$ is the voltage qualification rate of 10kV bus, $v_b$ is the voltage qualification rate of 35kV, 66kV dedicated line voltage and customer terminal voltage of 110 kV and above, $v_c$ is the voltage qualification rate of terminal voltage of 10 kV line, and $v_2$ is the voltage qualification rate of low voltage distribution network[5].

Power supply reliability ($P$) is used to reflect the ability of continuous power supply of the regional power grid, as is:

$$P = 1 - \frac{T^r}{T^v}$$  \hspace{1cm} (2)

where $T^v$ is voltage overrun time, $T^r$ is total running time.
Capacity-load ratio (CV) can reflect the rationality of power grid planning, as is:

\[
CV = \frac{Sc}{L}
\]  \hspace{1cm} (3)

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

Heavy load ratio for line (HL) indicates the load condition of power grid equipment, as is:

\[
HL = \frac{Li^2}{Li^T} \times 100\%
\]  \hspace{1cm} (4)

where \( Li^2 \) is the number of overloaded lines, \( Li^T \) is the total number of all lines.

(2) network structure

There are three criteria to reflect the attribute of network structure. N-1 passage rate for lines (Nl) and N-1 passage rate for main transformer (Nm) are reflect that if a line or a main transformer of the power grid fails, the power grid can maintain normal and continuous power supply to users. They are:

\[
Nl = \frac{Li^{ind}}{Li^T} \times 100\%
\]  \hspace{1cm} (5)

\[
Nm = \frac{Mt^{ind}}{Mt^T} \times 100\%
\]  \hspace{1cm} (6)

where \( Li^{ind} \) and \( Mt^{ind} \) are the numbers of lines and main transformer satisfying N-1 conditions.

The connection rate of lines (CR) can measure the flexibility of grid structure [6], as is:

\[
CR = (1 - \frac{Ns}{Nv}) \times 100\%
\]  \hspace{1cm} (7)

where \( Ns \) is the number of single radiation lines, and \( Nv \) is the number of medium voltage lines.

(3) equipment and facilities

Three criteria are selected to declare the level of equipment and facilities. Operated life for lines (OL) and for main transformers (OM) can be defined as the proportion of line and main transformers with a service life of more than 20 years, as are:

\[
OL = \frac{MOL}{Li^T} \times 100\%
\]  \hspace{1cm} (8)

\[
OM = \frac{MOM}{Mt^T} \times 100\%
\]  \hspace{1cm} (9)

where \( MOL \) is the number of the lines with a service life of more than 20 years, and \( MOM \) is the number of the main transformers with a service life of more than 20 years. These criteria can reflect the probability of relative equipment failure.

Proportion of smart substations (Ps) and overage of distribution automation (Od) can reflect the intelligent level of regional power grid. The criteria can be:

\[
Ps = \frac{SSU}{SU} \times 100\%
\]  \hspace{1cm} (10)

\[
Od = \frac{ALO}{Li^T} \times 100\%
\]  \hspace{1cm} (11)

where \( SSU \) is the number of smart substations, \( SU \) is the total number of the whole substations. And \( ALO \) is the number of the lines with distribution automation.

(4) economic benefits

There are three criteria to reflect the economic benefits of regional power grids, involving composite line loss rate, increase power supply per unit of grid investment and increased electricity sales per unit of grid assets.

Composite line loss rate (CL) can reflect the level of power grid planning and operation and be defined as:

\[
CL = \frac{IP}{OP} \times 100\%
\]  \hspace{1cm} (12)

where \( IP \) is the electricity input to power grid, and \( OP \) is the electric output of power grids.
Increase power supply per unit of grid investment (II) is the power added by the investment of power grid in a certain period, as is:

\[ II = \frac{ES}{EB} \times 100\% \]  

(13)

where \( ES \) is electricity sales in statistical period, \( EB \) is electricity sales in base period.

Increased electricity sales per unit of grid assets (IA) is the electricity sales added by the power grid assets in a certain period, as is:

\[ IA = \frac{IE}{TF} \times 100\% \]  

(14)

where \( IE \) is the income from electricity sales, \( TF \) is the total fixed assets of the power grids.

3. The framework of evaluation model

3.1. Fuzzy AHP weighting method

Considering the uncertainty of comparisons of criteria from decision makers, fuzzy AHP was proposed to determine the weights [7]. Step 1: integrate a set of pairwise comparisons from a group of experts into a fuzzy comparison matrix \( W^k \). The comparisons are based on Table 1.

| Linguistic Terms       | TFNs          | Reciprocal TFNs | Meaning                                                   |
|------------------------|---------------|-----------------|-----------------------------------------------------------|
| Equally important (EI) | (1/2,1,3/2)   | (2/3,1,2)       | Criterion \( i \) is as important as criterion \( j \)      |
| Moderately more        | (1,3/2,2)     | (1/2,2/3,1)     | Criterion \( i \) is moderately more important than criterion \( j \) |
| important (MI)         |               |                 |                                                           |
| Strongly more          | (3/2,2,5/2)   | (2/5,1/2,2/3)   | Criterion \( i \) is strongly more important than criterion \( j \) |
| important (SI)         |               |                 |                                                           |
| Very strongly more     | (2,5/2,3)     | (1,3/2,5,1/2)   | Criterion \( i \) is very strongly more important than criterion \( j \) |
| important (VI)         |               |                 |                                                           |
| Absolutely important   | (5/2,3,7/2)   | (2/7,1/3,2/5)   | Criterion \( i \) is absolutely more important than criterion \( j \) |
| (AI)                   |               |                 |                                                           |

Step 2: Aggregate all matrices into an integrated matrix to determine comprehensive importance for the criteria, as are:

\[ \tilde{a}_y = (a^L_y, a^M_y, a^R_y) = (\frac{1}{U} \sum_{k=1}^{U} a^L_y, \frac{1}{U} \sum_{k=1}^{U} a^M_y, \frac{1}{U} \sum_{k=1}^{U} a^R_y) \]  

(15)

\[ \tilde{W} = (\tilde{a}_y)_{nxn} \]  

(16)

Where the triangular fuzzy number \( \tilde{a}_y = (a^L_y, a^M_y, a^R_y) \) is a member of the integrated matrix \( \tilde{W} \). \( U \) is the total number of all experts.

Step 3: compute and transform the values of fuzzy synthetic extent by summing the row vectors of the aggregated fuzzy comparison matrices, as are:

\[ HH = (h^L, h^M, h^R) = \sqrt[3]{\prod_j a^L_j} \]  

(17)

\[ HT = (h^L + 4h^M + h^R) / 6 \]  

(18)

Where fuzzy synthetic extent HH includes \( h^L = \sqrt[3]{\prod_j a^L_j} \), \( h^M = \sqrt[3]{\prod_j a^M_j} \), \( h^R = \sqrt[3]{\prod_j a^R_j} \), the transformed synthetic extent HT can be obtained by the GMIR method.
Step 4: Calculate the criteria weights \( w \) at the attribute level and the criteria level according to the hierarchy structure, as is:

\[
w = HT \times (\sum HT)^{-1}
\]  

### 3.2. VIKOR method

Vlsekriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method, put forward by Opricovic S. firstly \[8\], has been regarded as a compensatory aggregation approach to handle discrete MCDM issues. The method is applied to conduct the comprehensive evaluation indexes for the power grid development, the procedures of the approach are:

**Step 1:** build an initial decision matrix and standardize the matrix based on the followings:

For a benefit-type criterion:

\[
\bar{y}_i = \frac{x_{ij}}{u^+_j}, \quad u^+_j = \max\{x_{ij}\}
\]  

(20)

For a cost-type criterion:

\[
\bar{y}_i = \frac{x_{ij}}{u^-_j}, \quad u^-_j = \min\{x_{ij}\}
\]  

(21)

where \( x_{ij} \) is the element of the initial matrix, and \( \bar{y}_i \) is the element of the standardized matrix.

**Step 2:** Determine the positive ideal solutions and negative ideal solutions for all criteria.

**Step 3:** Compute whole benefits \( S_i \), individual regret \( R_i \) and the compromise index \( Q_i \) for each alternative, as are:

\[
S_i = \sum_{j=1}^{n} w_j \left[ \frac{\max(y_j) - y_{ij}}{\max(y_j) - \min(y_j)} \right]
\]  

(22)

\[
R_i = \max\left\{ w_j \left[ \frac{\max(y_j) - y_{ij}}{\max(y_j) - \min(y_j)} \right] \right\}
\]  

(23)

\[
Q_i = \eta \frac{S_i - S_{\text{min}}}{S_{\text{max}} - S_{\text{min}}} + (1 - \eta) \frac{R_i - R_{\text{min}}}{R_{\text{max}} - R_{\text{min}}}
\]  

(24)

where \( \eta \) denotes the weight of the strategy of the maximum whole benefits.

**Step 4:** Sort the alternatives by comparing \( S_i, R_i \) and \( Q_i \). The lower the \( Q_i \) value is, the more optimal the related alternative is. The ordering method was shown in the reference [9].

### 4. Empirical Analysis

Three regional power grids in China are chosen as the empirical analysis object, and indicated as U1, U2 and U3. The proposed index system and evaluation model were used to access the performance of the development of the grid.

First, the weights of all criteria can be calculated by using the fuzzy AHP method. Four groups of experts give the criteria importance based on Table 1. These TFNs can be assembled some fuzzy comparison matrices based on a layer-by-layer analysis. Their consistencies were confirmed by computing a series of CR values, which are all below 0.2 and are the judgments are credible. The results are shown in Table 2
### Table 2. The fuzzy synthetic extent values and the weights of the evaluation criteria.

| Main criteria | Local weights | Sub-criteria | HH   | Local weights | Global weights |
|---------------|---------------|--------------|------|---------------|----------------|
| A1            | (0.05, 0.18, 0.48) | C1           | (0.19, 0.63, 1.53) | 0.392 | 0.041 |
|               |               | C2           | (0.13, 0.41, 1.35) | 0.315 | 0.033 |
|               |               | C3           | (0.05, 0.13, 0.37) | 0.093 | 0.011 |
|               |               | C4           | (0.11, 0.28, 0.81) | 0.200 | 0.021 |
| A2            | (0.26, 0.72, 1.56) | C5           | (0.15, 0.33, 0.59) | 0.167 | 0.063 |
|               |               | C6           | (0.06, 0.09, 0.19) | 0.052 | 0.02  |
|               |               | C7           | (0.94, 1.56, 2.5)  | 0.781 | 0.295 |
| A3            | (0.09, 0.25, 0.89) | C8           | (0.44, 1.11, 2.35) | 0.557 | 0.102 |
|               |               | C9           | (0.07, 0.22, 0.71) | 0.142 | 0.026 |
|               |               | C10          | (0.05, 0.13, 0.35) | 0.076 | 0.014 |
|               |               | C11          | (0.15, 0.41, 1.03) | 0.225 | 0.041 |
| A4            | (0.27, 0.61, 1.36) | C12          | (0.27, 0.65, 1.2)  | 0.432 | 0.144 |
|               |               | C13          | (0.11, 0.18, 0.33) | 0.126 | 0.042 |
|               |               | C14          | (0.28, 0.55, 1.33) | 0.441 | 0.147 |

Then, the criteria values were collected to assemble the initial evaluation matrix. The matrix can be standardized by using the equation (21) and (22). The positive ideal solutions and negative ideal solutions for all criteria can be determined. And the $S_i$, $R_i$, and $Q_i$ can be obtained based on the equation (23)-(25). The evaluation processes and calculate results were shown in the Table 3. According Table 3 and the conditions of “Acceptable advantage” and “Acceptable stability” of the VIKOR, the final priority order is U2 > U1 > U3. Thus, the U2 has the best performance in the comprehensive development quality of the regional power grid. U1 is the second. And U3 has the worst performance.

### Table 3. The evaluation processes and results of all alternatives

| Criteria | U1  | U2  | U3  |
|----------|-----|-----|-----|
| C1       | 1   | 0   | 0.54|
| C2       | 0.11| 0.04| 0   |
| C3       | 4.01| 12.04| 0   |
| C4       | 13.86| 23.46| 0   |
| C5       | 10.4| 0   | 13.86|
| C6       | 21.78| 0   | 13.31|
| C7       | 0   | 8.02| 60.18|
| C8       | 0   | 19.84| 40.44|
| C9       | 52.32| 0   | 44.96|
| C10      | 16.03| 0   | 30.1 |
| C11      | 17.94| 0   | 40.36|
| C12      | 7.6 | 0   | 2.68 |
| C13      | 25.41| 0   | 11.29|
| C14      | 19.33| 5.37| 0   |
| Si       | 8.79| 5.81| 27.14|
| Ri       | 2.84| 2.37| 17.75|
| Qi       | 0.085| 0   | 1   |

5. Conclusion

A hybrid framework for evaluating the comprehensive development quality of regional power grids was developed in this paper to efficiently promote the balanced development of regional power grids. First,
an index system was established at the angles of safety reliability, grid structure, equipment and facilities and economic benefits. Then, a comprehensive model based on MCDM was proposed based on the weighting method of the fuzzy AHP and the appraisement approach of the VIKOR. Finally, empirical analysis was performed to demonstrate the practicality of the hybrid evaluation framework.

Acknowledgments
This study is supported by the Science and Technology Project of State Grid Corporation of China: Research on Topological Structure Characteristics and Preventive Planning Technology of Large Power Grid.

References
[1] F. Zhu, Y. Zheng, X. Guo, et al, Environmental impacts and benefits of regional power grid interconnections for China, Energy Policy, 33(2005), 1797-1805.
[2] X. Xu, D. Niu, J. Qiu, et al, Comprehensive evaluation of coordination development for regional power grid and renewable energy power supply based on improved matter element extension and TOPSIS method for sustainability, Sustainability. 8(2016) 143.
[3] Y. Liu, Y. Xu, X. Xiao, Analysis of new method on power quality comprehensive evaluation for regional grid, Proceedings of the CSEE. 28(2008) 130-136.
[4] S. Jinwei, J. Yu, Z. Jiayi, et al, Construction method of green power index model in regional power grid, 2016 IEEE International Conference on Power and Renewable Energy (ICPRE), IEEE, 2016, pp. 420-423.
[5] P. Zhang, Y. Wang, W. Xiao, et al, Reliability evaluation of grid-connected photovoltaic power systems, IEEE transactions on sustainable energy, 3(2012), 379-389.
[6] J. Zhengyuan, W. Chunmei, H. Zhiwei, et al, Evaluation research of regional power grid companies’ operation capacity based on entropy weight fuzzy comprehensive model, Procedia Engineering. 15(2011) 4626-4630.
[7] F. T. Bozbura, A. Beskese, C. Kahraman, Prioritization of human capital measurement indicators using fuzzy AHP, Expert Systems with Applications, 32(2007), 1100-1112.
[8] S. K. Patil, R. Kant, A hybrid approach based on fuzzy DEMATEL and FMCDM to predict success of knowledge management adoption in supply chain, Appl. Soft Comput, 18(2014), 126-135.
[9] J. Dong, H. Huo, D. Liu, et al, Evaluating the comprehensive performance of demand response for commercial customers by applying combination weighting techniques and fuzzy VIKOR approach, Sustainability. 9(2017) 1332.