Extension Hierarchical Assessment Method for Low-Carbon Efficient Operation of New-Energy Distribution Networks (Postprint)

Authors: Yan Haoran, Wu Jiekang, Yan Hanting, Liu Xiangdong

Date: 2018-06-15T00:00:00+00:00

Abstract

This paper establishes a comprehensive evaluation index system for new energy distribution networks based on traditional distribution network evaluation models. The index system provides a relatively comprehensive assessment of new energy distribution networks from five aspects: equipment operation status, power supply reliability, power quality, economic efficiency, and environmental protection, thereby highlighting the distinguishing characteristics of new energy distribution networks compared to traditional ones. Additionally, a comprehensive evaluation method based on the extension analytic hierarchy process is proposed; this method incorporates the fuzziness of human judgment on the foundation of the traditional analytic hierarchy process and more readily satisfies the consistency requirements of the judgment matrix. Finally, case study analysis is employed to verify the comprehensiveness of the index system and the adaptability of the evaluation method.

Full Text

Preamble

DOI: 10.11985/2018.02.003

Extension Hierarchy Analytical Method for Low-Carbon and High-Efficiency Operation of Distribution Grids With Renewable Energy

Yan Haoran[1], Wu Jiekang[1], Yan Hanting[2], Liu Xiangdong[1]
[1]. School of Automation, Guangdong University of Technology, Guangzhou 510006, China
[2]. Jinan Power Supply Bureau, Jinan 250000, China

Biographies:
Yan Haoran (male, born 1991) is a master’ s student whose research focuses on

power system operation and control.
Wu Jiekang (male, born 1965) is a professor and doctoral supervisor whose research focuses on power system operation.

Abstract

This paper establishes a comprehensive evaluation index system for distribution grids with renewable energy based on traditional distribution grid assessment models. The index system provides a holistic evaluation from five dimensions: equipment operational condition, power supply reliability, power quality, economic efficiency, and environmental protection, highlighting the distinguishing characteristics of renewable energy distribution grids compared to conventional ones. Additionally, a comprehensive evaluation method based on the extension analytic hierarchy process (EAHP) is proposed. This method accounts for the fuzziness inherent in human judgment while more readily satisfying consistency requirements for judgment matrices. Finally, case studies verify the comprehensiveness of the index system and the adaptability of the evaluation method.

Keywords: Distribution grid with renewable energy; low-carbon and high-efficiency operation; extension hierarchy analytical method

---

1 Introduction

In recent years, massive consumption of traditional fossil fuels has exacerbated environmental challenges, making the integration of renewable distributed generation—characterized by safety, cleanliness, and flexibility—into conventional distribution grids a prominent research focus. Additionally, as electric vehicle technology matures, EVs are becoming significant loads for distribution networks. However, most existing distribution grid assessments target traditional networks, necessitating a dedicated evaluation index system for renewable energy distribution grids. Such a system enables scientific, rational, and comprehensive analysis to guide the construction and upgrading of these grids toward low-carbon, high-efficiency operation.

Current research has extensively studied traditional distribution grid evaluation, but assessments for renewable energy grids remain limited. Reference [1] established an index system for conventional distribution grids covering security, economy, flexibility, reliability, and coordination, but it is unsuitable for comprehensive renewable energy grid evaluation. References [2-3] developed reliability and security index systems specifically for traditional grids. Reference [4] created a cleanliness evaluation system for smart distribution grids. Reference [5] assessed reliability for distribution networks with distributed generation, but with an insufficient and non-specific indicator set. Reference [6] evaluated distribution grids with distributed generation without considering the environmental benefits of grid integration. References [7-8] applied analytic hierarchy process (AHP) for comprehensive evaluation, yet failed to address AHP' s inability to model the fuzziness of human judgment.

To address these gaps, this paper establishes an index system that incorporates new core requirements for distribution grids and employs the extension hierarchy evaluation method.

---

2 Extension Hierarchy Evaluation Method

The critical step in hierarchy evaluation is constructing the judgment matrix, which requires combining quantitative and qualitative analysis. Traditional AHP uses a 1-9 scale and its reciprocals to assign fixed values when comparing two indicators relative to a higher-level criterion. While straightforward, this approach ignores the fuzziness of human judgment—for instance, experts often cannot determine the precise relative importance between two indicators, instead providing an interval rather than a fixed value. The extension hierarchy fuzzy analysis method using extension interval number matrices effectively addresses this limitation.

Furthermore, judgment matrices from traditional AHP often fail to meet consistency requirements when many indicators are present, requiring multiple adjustments. The final adjusted matrix may not accurately reflect true relative importance. The extension analytic hierarchy process proposed in this paper resolves this issue effectively.

2.1 Extension Interval Number Judgment Matrix

Definition 1: Let R be the set of all extension sets on a given domain. If $a = [a^-, a^+] \in R$ and $a = [a^-, a^+] = \{x \mid 0 < a^- < x < a^+\}$, then a is called an extension interval number. The distance from 0 to point a is defined as $L_0(a) = a^- + a^+$.

Definition 2: Let matrix $A = [a_{ij}]_{n\times n}$. If for all $i, j = 1, 2, \dots, n$:
$a_{ij} = [a_{ij}^-, a_{ij}^+]$, with $1/9 \le a_{ij}^- \le a_{ij}^+ \le 9$;
$a_{ij} = 1/a_{ji}$,
then matrix A is called an extension interval number judgment matrix.

Theorem 1: Let $A = [A^-, A^+]$ be an extension interval number matrix. If λ^- and λ^+ are the maximum eigenvalues of A^- and A^+, respectively, then:
(1) $\lambda = [\lambda^-, \lambda^+]$ is the maximum eigenvalue of matrix A.
(2) $X = [kx^-, mx^+]$ represents all eigenvectors of matrix A corresponding to the maximum eigenvalue λ, where x^- and x^+ are the normalized positive eigenvectors of A^- and A^+, respectively, and k and m are positive real numbers satisfying $0 < kx^- \le mx^+$.

Theorem 2: If matrix A is an extension interval number judgment matrix, then the eigenvector satisfying consistency requirements is $\omega = [kx^-, mx^+] = (\omega_1, \omega_2, \dots, \omega_n)^T$.

Let A be an indicator at layer $k-1$ in the hierarchy structure, with n_k factors at layer k related to indicator A. When T experts conduct pairwise weight comparisons of these n_k factors relative to indicator A, the inherent fuzziness of judgment yields extension interval numbers. The extension interval number judgment matrix derived from expert t is $A_t = [a^t_{ij}]_{n_k \times n_k}$, where $a^t_{ij} = [a^{t-}_{ij}, a^{t+}_{ij}]$ represents expert t' s assessment of the relative importance between factor i and factor j regarding indicator A, with $t = 1, 2, \dots, T$.

Integrating opinions from all T experts yields the comprehensive extension interval number judgment matrix for indicator A:

$$A = [a_{ij}]_{n_k \times n_k}, \quad a_{ij} = [a^-_{ij}, a^+_{ij}]$$

where $a_{ij} = [a^-_{ij}, a^+_{ij}]$ represents the combined expert opinion on the relative importance between factors i and j regarding indicator A.

Based on the comprehensive extension interval number judgment matrix $A = [A^-, A^+]$, the steps to obtain the weight vector for the n_k factors at layer k relative to indicator A at layer $k-1$ are:

(1) Compute the normalized positive eigenvectors x^- and x^+ corresponding to the maximum eigenvalues of matrices A^- and A^+.

(2) Determine values of k and m using equations (3) and (4) to obtain the consistency-satisfying extension interval number weight vector:

$$\omega_A = (\omega_{A1}, \omega_{A2}, \dots, \omega_{An_k})^T = [kx^-, mx^+]$$

where $\omega_{Ai} = [\omega^-_{Ai}, \omega^+_{Ai}]$ $(i = 1, 2, \dots, n_k)$ represents the extension interval number weight of factor i relative to indicator A.

2.2 Solution of Extension Interval Numbers

In traditional AHP, the weight vector of a judgment matrix is the normalized eigenvector corresponding to the maximum eigenvalue. In extension AHP, the judgment matrix is an extension interval number matrix, and the normalized eigenvector obtained is the extension interval number weight vector in equation (8). This vector must be converted to a real number weight vector.

According to Definition 1, the distance from 0 to each element in the consistency-satisfying extension interval number weight vector is:

$$L_0(\omega_{Ai}) = \omega^-_{Ai} + \omega^+_{Ai}$$

where $L_0(\omega_{Ai})$ represents the single-level ranking of factor i at layer k related to indicator A. After normalization:

$$L_0(A) = (L_{A1}, L_{A2}, \dots, L_{An_k})^T$$

2.3 Comprehensive Weight Vector and Comprehensive Evaluation Value

Using a three-layer hierarchy as an example, we calculate the comprehensive weight vector and evaluation value. [Figure 1: see original paper] illustrates the three-tier structure of the extension analytic hierarchy process. The first layer is the objective layer, reflecting the final system evaluation; the second is the criterion layer, representing major categories; the third is the index layer, representing specific evaluation metrics.

Assume the criterion layer contains n criteria, with m_i indices related to criterion A_i. The single-level weight vector of these indices relative to criterion A_i can be derived from the extension interval number judgment matrix as:

$$L_0(A_i) = (L(B_{i1}), L(B_{i2}), \dots, L(B_{im_i}))^T$$

where $L(B_{ij})$ $(i = 1, 2, \dots, n;\ j = 1, 2, \dots, m_i)$ represents the weight value of index B_{ij} relative to criterion A_i.

From the criterion layer' s extension interval number judgment matrix regarding the objective layer, the single-level weight vector of all criteria relative to the objective layer is:

$$L_0(G) = (L(A_1), L(A_2), \dots, L(A_n))^T$$

where $L(A_i)$ $(i = 1, 2, \dots, n)$ represents the weight of criterion A_i relative to the objective layer.

The comprehensive ranking weight vector of the m_i indices related to criterion A_i relative to the objective layer is:

$$P_i(G) = (P(B_{i1}), P(B_{i2}), \dots, P(B_{im_i}))^T = L(A_i) \cdot L_0(A_i)$$

where $P(B_{ij})$ represents the comprehensive weight value of index B_{ij} relative to the objective layer.

If the index value vector for the m_i indices related to criterion A_i is $W_i = (w_{i1}, w_{i2}, \dots, w_{im_i})$, then the comprehensive evaluation value of the assessed system is:

$$\sum_{i=1}^{n}[W_i \cdot P_i(G)] = \sum_{i=1}^{n}[W_i \cdot L(A_i) \cdot L_0(A_i)]$$

---

3 Grid Low-Carbon High-Efficiency Operation Evaluation Indicators

When establishing a comprehensive index system for renewable energy distribution grids, principles of systematicity, scientific rigor, independence, adaptability, and comparability must be followed. This paper constructs a three-layer hierarchical evaluation model from five criteria: equipment operational condition, power supply reliability, power quality, economic efficiency, and environmental protection, as shown in [Figure 2: see original paper].

3.1 Equipment Operation Indicators

Distribution grids comprise distribution lines, transformers, and numerous power electronic components whose operational condition directly affects grid performance. This paper selects the following indicators:

(1) **Equipment Service Life Index (B_{11}):** Equipment failure probability increases exponentially after reaching a certain service life. The index is calculated as:

$$B_{11} = \frac{N_1 - N_2}{N_1}$$

where N_1 is the total number of devices, and N_2 is the number of devices exceeding 60% of their rated service life.

(2) **Equipment Maintenance Level Index (B_{12}):** This parameter reflects equipment condition:

$$B_{12} = \frac{\sum_{i=1}^{N_1} M_i}{N_1}$$

where M_i represents the maintenance level of device i (1 = good, 0.5 = average, 0 = substandard).

(3) **Equipment Failure-Free Rate Index (B_{13}):** This reflects equipment reliability:

$$B_{13} = \frac{T_D}{T}$$

where T is the total statistical period duration, and T_D is the operating time without any equipment failures.

(4) **Equipment Overload Rate Index (B_{14}):** Overloading increases failure probability and indicates structural issues:

$$B_{14} = \frac{N_{\text{over}}}{N_1}$$

where N_{over} is the total number of overloaded devices during the statistical period.

3.2 Reliability Indicators

Power supply reliability measures a distribution system' s ability to provide continuous, adequate power during a given period. Five indicators are selected:

(1) **Power Supply Reliability Rate (B_{21}):** Quantifies reliability according to the "Power Supply System User Power Supply Reliability Evaluation Regulations," excluding external grid failures:

$$B_{21} = \left(1 - \frac{\text{Total user-hours of power outage}}{\text{Total user-hours of power supply}}\right) \times 100\%$$

(2) **Average Customer Interruption Duration Index (B_{22}):** Average hours of outage per user:

$$B_{22} = \frac{\sum T_{Di}}{N}$$

where T_{Di} is the outage duration per user per incident, and N is the total number of users.

(3) **Average Customer Interruption Frequency Index (B_{23}):** Average number of outages per user annually:

$$B_{23} = \frac{\sum N_{Di}}{N}$$

where N_{Di} is the number of users affected per outage incident.

(4) **Load Transfer Capability Between Lines (B_{24}):** Reflects "N-1" reliability:

$$B_{24} = \frac{1}{N_L} \sum_{i=1}^{N_L} \frac{P_{i,\text{need}}}{P_{i,\text{oth}}}$$

where N_L is the total number of lines, $P_{i,\text{need}}$ is the transferable load when line i fails, and $P_{i,\text{oth}}$ is the required transferred load.

(5) **Line Non-Full Load Rate Index (B_{25}):** Lines exceeding 0.8 load factor are considered fully loaded:

$$B_{25} = \frac{N_L - N_{LO}}{N_L}$$

where N_{LO} is the number of fully loaded lines.

3.3 Power Quality Indicators

Providing quality power is a primary responsibility. Renewable generation and EVs transform passive networks into active ones, introducing challenges from generation volatility, random EV charging, and power electronic harmonics. Five power quality indicators are assessed using measured electrical parameters and membership functions:

(1) **Voltage Deviation Membership Function:**

$$f(\Delta U) = \begin{cases} e^{-\Delta U^2/2\sigma^2} & \Delta U \in [0, U_1] \\ \Delta U/U_2 & \Delta U \in [U_1, U_2] \\ 1 & \Delta U \in [U_2, +\infty] \end{cases}$$

where ΔU is the percentage voltage deviation, and δ, U_1, U_2 are constants.

(2) **Voltage Fluctuation and Flicker Membership Function:** (Similar structure to voltage deviation)

Frequency deviation, grid harmonics, and three-phase imbalance use similar membership functions.

3.4 Economic Indicators

Economic assessment must consider both loss reduction from distributed generation and its investment costs. Three indicators are included:

(1) **Line Loss Rate Index (B_{41}):** Statistical line loss rate:

$$B_{41} = \frac{W_1 - W_2}{W_1} \times 100\%$$

where W_1 and W_2 are power supply and sales quantities.

(2) **Power Supply per Unit Asset Index (B_{42}):** Reflects asset efficiency:

$$B_{42} = \frac{W_1}{Y}$$

where Y is total grid assets.

(3) **Input-Output Ratio Index (B_{43}):** Reflects investment return:

$$B_{43} = \frac{Y_1 - Y_2 - Y_3}{Y} \times 100\%$$

where Y_1, Y_2, and Y_3 are sales revenue, power purchase cost, and O&M cost.

3.5 Environmental Indicators

Distributed generation and EVs reduce losses, fossil fuel consumption, and pollutant emissions. Four indicators are established:

(1) **Clean Energy Grid Integration Rate (B_{51}):** Percentage of actual clean energy integrated versus available:

$$B_{51} = \frac{\sum_{i \in \Omega} P_i T_i}{\sum_{i \in \Omega} W_i} \times 100\%$$

where Ω is the set of clean energy units, P_i is active power output, T_i is grid connection duration, and W_i is total generation.

(2) **Clean Energy Generation Proportion (B_{52}):**

$$B_{52} = \frac{\sum_{i \in \Omega} W_i}{W} \times 100\%$$

where W is total grid generation.

(3) **CO , SO , and NOx Emission Reduction:** Assuming non-clean energy comes from coal plants, CO reduction from clean energy is:

$$C_{DG} = W_{DG} \cdot a_2$$

where W_{DG} is clean energy generation and a_2 is coal’ s CO emission factor.

EVs replacing fuel vehicles also reduce CO :

$$C_{EV} = W_{EV} \cdot \frac{k_2}{k_1} \cdot a_3$$

where W_{EV} is EV charging energy, k_1 and k_2 are EV and fuel vehicle consumption rates, and a_3 is oil’ s CO factor.

The CO reduction index (B_{53}) is the ratio of reduced CO to total emissions from coal:

$$B_{53} = \frac{C_{DG} + C_{EV}}{W \cdot a_2}$$

SO (B_{54}) and NOx (B_{55}) reduction indices use similar formulas with respective emission coefficients b_2, b_3, c_2, c_3.

---

4 Case Study

4.1 Example and Data

A distribution grid in Guangdong Province is analyzed to validate the method. Assuming EV charging power of 45 kW, EV consumption of 15 kWh/100km, and fuel vehicle consumption of 7 L/100km, index values are calculated using the formulas from Section 3. Scores are then assigned on a 100-point scale based on evaluation criteria, with results shown in .

4.2 Comprehensive Weights from Extension AHP

Two expert groups (grid dispatchers and O&M personnel) provided pairwise comparisons of criterion layer elements, yielding relative importance values shown in . In the table, A_1 through A_5 represent equipment condition, reliability, power quality, economy, and environmental protection.

Combining both expert groups' data using equations (6) and (7) yields the comprehensive judgment matrix. The eigenvectors corresponding to the maximum eigenvalues of matrices A^- and A^+ are:

$$x^- = [0.0978, 0.3554, 0.2397, 0.1313, 0.1757]^T x^+ = [0.1128, 0.3552, 0.2340, 0.1225, 0.1755]^T$$

From equations (3) and (4), $k = 1.04$ and $m = 0.84$, yielding the extension interval weight vector via equation (8). Using equations (9) and (10), the criterion layer weight vector relative to the objective layer is:

$$L_0(A) = [0.1045, 0.3553, 0.2372, 0.1274, 0.1756]^T$$

The same method calculates index layer weights relative to each criterion, with comprehensive weights obtained via equation (14). presents single-level and comprehensive weights.

4.3 Comprehensive Evaluation and Analysis

Comprehensive evaluation values for five grid districts are calculated using equation (14) and shown in .

District D achieves the highest comprehensive score, indicating optimal overall performance, though its economic score is lower than other districts—suggesting economic improvements could enhance performance. District B' s low score stems from lacking clean distributed generation, resulting in zero environmental indicators. District C' s equipment condition score is slightly lower, indicating maintenance improvements would be beneficial.

---

5 Conclusion

This paper establishes a comprehensive evaluation model for renewable energy distribution grids covering equipment condition, reliability, power quality, economy, and environmental protection. Compared to traditional grid evaluation models, this approach incorporates environmental criteria unique to renewable energy contexts, using five performance indicators including clean energy integration rate and CO emission reduction. The extension hierarchy evaluation method better captures human judgment fuzziness than conventional deterministic AHP.

Case study results demonstrate the method's comprehensiveness and practicality for renewable energy distribution grids. The approach provides not only comprehensive evaluation values but also identifies weak links, offering references for future planning and operational optimization.

References

[1] Fang Huanhuan, Cheng Haozhong, Xin Jieqing, et al. Indices system of distribution network planning evaluation[J]. Proceedings of CSU-EPSA, 2013, 25: 106-111.

[2] Li Xiaohui, Xu Jing, Li Da, et al. Index system of reliability evaluation for distribution network based on analytic hierarchy process[J]. Proceedings of CSU-EPSA, 2009, 21(3): 69-74.

[3] Liu Ruoxi, Zhang Jianhua, Wu Di, et al. Research on static security index of distribution network based on risk theory[J]. Power System Protection and Control, 2011, 39(15): 89-95.

[4] Wang Xiaojing, Chen Xingying, Chen Kai, et al. Research on cleaning evaluation indices of smart distribution grid[J]. Proceedings of the CSEE, 2013, 33(31): 43-50, 5.

[5] Lu Jingjing, Zhao Yuan, Zhao Yongshuai, et al. A point estimation method for reliability evaluation of distribution network with distributed generation[J]. Power System Technology, 2013, 37(8): 2250-2257.

[6] Chen Chiye, Wen Yafeng, Liu Zifa, et al. Comprehensive evaluation method of distribution network including various types of distributed generation[J]. Electric Power Construction, 2015(1): 128-135.

[7] Cao Yang, Meng Hanhui, Zhao Li, et al. A comprehensive evaluation method of new rural low-voltage distribution networks based on analytic hierarchy process[J]. Power System Technology, 2007, 31(8): 68-72.

[8] Yang Xiaobin, Li Heming, Yin Zhongdong, et al. Energy efficiency index system for distribution network based on analytic hierarchy process[J]. Automation of Electric Power Systems, 2013, 37(21): 146-150, 195.

[9] Wang Guiping, Jia Yazhou, Zhou Guangwen, et al. Evaluation method and application of CNC machine tool' s green degree[J]. Journal of Mechanical Engineering, 2010, 46(3): 141-147.

[10] Zhang Xinjie, Ge Shaoyun, Liu Hong, et al. Comprehensive assessment system and method of smart distribution grid[J]. Power System Technology, 2014, 38(1): 4-7.

[11] Wang Bin, He Guangyu, Mei Shengwei, et al. Construction method of smart grid' s assessment index system[J]. Automation of Electric Power Systems, 2011, 35(23): 146-150, 195.

[12] Gao Wei, Zhang Qingpu, Dun Xiaobiao, et al. Comprehensive assessment of advanced military aerospace technologies based on improved EAHP and dynamic weighting[J]. Systems Engineering and Electronics, 2016, 38(1): 102-109.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.