Extension Hierarchy Evaluation Method for Low-Carbon Efficient Operation of Renewable Energy Distribution Networks (Postprint)

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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 dimensions: 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 (EAHP) is proposed, which incorporates the fuzziness of human judgment on the basis 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

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

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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 distinctive characteristics of renewable energy distribution grids compared to conventional ones. Additionally, a comprehensive evaluation method based on the extension hierarchy analytical process is proposed. This method accounts for the fuzziness inherent in human judgment and more readily satisfies consistency requirements for judgment matrices compared to traditional analytic hierarchy processes. Finally, case study analysis verifies 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, the massive consumption of traditional fossil fuels has exacerbated environmental problems, making the integration of renewable distributed generation into conventional distribution grids a prominent research focus due to its safety, cleanliness, and flexibility. Additionally, with the maturation of electric vehicle technology, EVs will become significant loads for distribution grids. However, current distribution grid assessments primarily target traditional networks, necessitating the establishment of a comprehensive evaluation index system specifically for renewable energy distribution grids. Such a system enables scientific and rational analysis to guide the construction and renovation of these grids toward low-carbon, high-efficiency operation.

Existing research on traditional distribution grid evaluation is extensive, but studies on grids with renewable energy remain limited. Reference [?] established an index system for traditional distribution grids covering security, economy, flexibility, reliability, and coordination, but it is unsuitable for comprehensive evaluation of renewable energy grids. References [?] developed index systems for reliability and security in traditional distribution networks. Reference [?] created a cleanliness evaluation index system for smart distribution grids. Reference [?] evaluated reliability for distribution networks with distributed generation, but the indicator set was too limited and lacked specificity. Reference [?] conducted comprehensive evaluation of distribution grids with distributed generation without considering the environmental benefits of grid integration. References [?] employed analytic hierarchy process for comprehensive evaluation but failed to address the limitation that traditional AHP cannot simulate the fuzziness of human judgment.

To address these gaps, this paper establishes an index system for renewable energy distribution grids that incorporates core requirements of modern grids and employs the extension hierarchy analytical method for comprehensive evaluation.

2 Extension Hierarchy Assessment Method

The critical step in hierarchy assessment methods is forming judgment matrices, which requires combining quantitative and qualitative analysis. Traditional AHP uses a 1-9 scale and its reciprocals when comparing two indicators relative to a higher-level criterion, assigning a fixed value. While straightforward, this approach ignores the fuzziness of human judgment. For instance, when experts assess the relative importance of indicator 1 versus indicator 2, they often cannot be completely certain and provide an interval rather than a fixed value. Extension hierarchy fuzzy analysis using extension interval number matrices effectively addresses this fuzziness.

Furthermore, judgment matrices formed by traditional AHP often fail to satisfy consistency requirements initially, particularly with many indicators, requiring multiple adjustments. The final adjusted matrix may not accurately reflect true relative importance. The extension hierarchy analytical method 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 $a = [a^-, a^+] = \{x | 0 < a^- < x < a^+\}$, 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 $i, j = 1, 2, \dots, n$, the following hold: (1) $a_{ij} = [a_{ij}^-, a_{ij}^+]$ and $1/9 \le a_{ij}^- \le a_{ij}^+ \le 9$; (2) $a_{ij} = 1/a_{ji}$, 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 $\omega = [kx^-, mx^+] = (\omega_1, \omega_2, \dots, \omega_n)^T$.

Consider A as an indicator at level $k-1$ in the hierarchy structure, with n_k factors at level k related to indicator A. When T experts conduct pairwise weight comparisons of these n_k factors relative to indicator A, the fuzziness of judgment leads them to provide extension interval numbers. The extension interval number judgment matrix derived by expert t is $A_t = [a_{ij}^t]_{n_k \times n_k}$, where $a_{ij}^t = [a_{ij}^{t-}, a_{ij}^{t+}]$ 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 $A = [a_{ij}]_{n_k \times n_k}$, where $a_{ij} = [a_{ij}^-, a_{ij}^+]$ represents the relative importance between factors i and j regarding indicator A based on all expert opinions.

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

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

(2) Determine the 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 Solving Extension Interval Numbers

In traditional AHP, the weight vector of a judgment matrix is the normalized eigenvector corresponding to the maximum eigenvalue. In extension hierarchy analysis, 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 related to indicator A at level k. After normalization, we obtain $L_0(A) = (L_{A1}, L_{A2}, \dots, L_{An_k})^T$, where $L_0(A)$ represents the single-level weight vector of the n_k factors at level k relative to indicator A at level $k-1$.

2.3 Comprehensive Weight Vector and Comprehensive Assessment Value

Using a three-level hierarchy structure as an example, we calculate the comprehensive weight vector and assessment value. [Figure 1: see original paper] shows the three-level structure of the extension hierarchy analytical method. The first level is the goal layer, reflecting the final system evaluation; the second is the criterion layer, representing major categories; the third is the indicator layer, representing specific metrics.

Assume the criterion layer has n criteria, with m_i indicators related to criterion A_i. The single-level weight vector of these indicators relative to criterion A_i can be derived from the indicator layer' s 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 indicator B_{ij} relative to criterion A_i.

From the criterion layer' s extension interval number judgment matrix regarding the goal layer, we obtain the single-level weight vector of all criteria relative to the goal layer: $L_0(G) = (L(A_1), L(A_2), \dots, L(A_n))^T$, where $L(A_i)$ $(i = 1, 2, \dots, n)$ represents the weight value of criterion A_i relative to the goal layer.

The comprehensive ranking weight vector of the m_i indicators related to criterion A_i for the goal 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 indicator B_{ij} relative to the goal layer.

If the indicator value vector for the m_i indicators related to criterion A_i is $W_i = (w_{i1}, w_{i2}, \dots, w_{im_i})$, then the comprehensive assessment value of the evaluated system is $[W_i P_i(G)] = [W_i \cdot L(A_i) \cdot L_0(A_i)]$.

3 Assessment Indicators for Low-Carbon and High-Efficiency Operation of Power Grids

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-level hierarchical model for distribution grid comprehensive assessment 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 consist of distribution lines, transformers, and numerous power electronic components whose operational conditions directly affect grid performance. This paper selects the following indicators to reflect equipment operation:

(1) **Equipment Service Life Indicator (B_{11}):** Equipment condition is closely related to service life. Failure probability increases exponentially after a certain operational period. The calculation is $B_{11} = N_1/N_2$, where N_1 is the total number of grid equipment and N_2 is the number of equipment exceeding 60% of rated service life.

(2) **Equipment Maintenance Level Indicator (B_{12}):** This parameter affects equipment condition, calculated as $B_{12} = \sum_{i=1}^{N_1} M_i/N_1$, where M_i represents the maintenance level of equipment i (1 for good, 0.5 for average, 0 for substandard).

(3) **Equipment Failure-Free Rate Indicator (B_{13}):** This reflects equipment reliability to some extent: $B_{13} = T_D/T$, where T is the statistical period duration and T_D is the grid' s operational time with all equipment failure-free.

(4) **Equipment Overload Rate Indicator (B_{14}):** Overloading increases failure probability and indicates unreasonable network structure if widespread. The indicator is $B_{14} = 1/N_{\text{over}}$, where N_{over} is the total number of overloaded equipment during the statistical period.

3.2 Reliability Indicators

Power supply reliability measures a distribution system' s ability to maintain continuous, adequate power supply. This paper selects five indicators:

(1) **Power Supply Reliability Rate (B_{21}):** Quantifies reliability based on the "Power Supply System User Power Supply Reliability Evaluation Regulations," excluding outages from external grid faults: $B_{21} = 1 - \frac{\sum T_{\text{out}}}{T} \times 100\%$, where T_{out} is outage time and T is the statistical period.

(2) **Average Customer Interruption Duration (B_{22}):** Defined as average outage hours per customer: $B_{22} = \frac{\sum T_{Di}}{N} \times 100\%$, where T_{Di} is outage duration per customer and N is total users.

(3) **Average Customer Interruption Frequency (B_{23}):** Average annual outages per customer: $B_{23} = \frac{\sum N_{Di}}{N}$, where N_{Di} is number of interrupted customers per outage.

(4) **Load Transfer Capability Between Lines (B_{24}):** Relates to "N-1" reliability. When a line fails, its load must transfer to other lines. Stronger transfer capability indicates higher reliability: $B_{24} = \sum_{i=1}^{N_L} \frac{P_i^{\text{need}}}{P_i^{\text{oth}}}$, where N_L is total lines, P_i^{need} is transferable load, and P_i^{oth} is required transferred load.

(5) **Line Non-Full Load Rate (B_{25}):** Lines exceeding 0.8 load factor are considered fully loaded. Excessive full-load lines weaken structural resilience: $B_{25} = N_L - N_{LO}$, where N_{LO} is number of fully loaded lines.

3.3 Power Quality Indicators

Providing quality power is essential. Renewable generation and EVs transform passive networks into active ones, introducing volatility and randomness that adversely affect power quality. Power electronic interfaces also introduce harmonics. This paper selects five indicators calculated via membership functions:

(1) **Voltage Deviation Membership Function:** $f(\Delta U) = \exp(-\Delta U^2/2\sigma^2)$, where ΔU is voltage deviation percentage and σ is a constant.

(2) **Voltage Fluctuation and Flicker Membership Function:** Similar functional forms apply for frequency deviation, harmonics, and three-phase unbalance.

3.4 Economic Indicators

Economic assessment must consider both loss reduction from distributed generation and investment costs. This paper includes three indicators:

(1) **Line Loss Rate (B_{41}):** Uses 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 (B_{42}):** Reflects return on net assets: $B_{42} = \frac{\sum_{i=1}^{N_1} P_i}{Y}$, where Y is total grid assets.

(3) **Input-Output Ratio (B_{43}):** Measures investment return: $B_{43} = \frac{Y_1 - Y_2 - Y_3}{\sum Y} \times 100\%$, where Y_1, Y_2, and Y_3 are sales revenue, power purchase cost, and O&M cost.

3.5 Environmental Indicators

Renewable generation and EVs reduce losses, fossil fuel consumption, and emissions. The environmental criterion includes:

(1) **Clean Energy Grid-Connected Rate (B_{51}):** Percentage of actual clean energy integrated: $B_{51} = \frac{\sum_{i\in\Omega} P_i T_i}{\sum_{i\in\Omega} W_i} \times 100\%$, where Ω is the clean energy unit set.

(2) **Clean Energy Generation Proportion (B_{52}):** Ratio of clean energy to total generation: $B_{52} = \frac{\sum_{i\in\Omega} W_i}{W} \times 100\%$.

(3) **Emission Reduction Indicators (B_{53}-B_{55}):** For CO , SO , and nitrogen oxides. Assuming non-renewable generation comes from coal: $C_{DG} = \sum_{i\in\Omega} W_i k_2 a_2$, where k_2 is coal emission coefficient. EVs also reduce emissions: $C_{EV} = W_{EV}\frac{k_2 a_3}{k_1}$, where W_{EV} is EV charging energy. The CO reduction ratio is $B_{53} = \frac{C_{DG} + C_{EV}}{W k_2 a_2}$. Similar formulas apply for SO and nitrogen oxides using coefficients b_2, b_3, c_2, c_3.

4 Case Study

4.1 Example and Data

A distribution grid in Guangdong province validates the method. Assuming EV charging power of 45 kW, consumption of 15 kWh/100km, and fuel vehicle consumption of 7 L/100km, indicator values are calculated using the formulas from Section 3. Scores are then assigned on a 100-point scale, with results shown in .

4.2 Comprehensive Weights Using Extension Hierarchy Analysis

Two expert groups (grid dispatchers and O&M personnel) provided pairwise comparisons of criteria importance, shown in , where A_1-A_5 represent equipment condition, reliability, power quality, economy, and environmental protection. Integrating both 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 is: $L_0(A) = [0.1045, 0.3553, 0.2372, 0.1274, 0.1756]^T$

The same method calculates indicator-level single-level weights, and equation (14) yields comprehensive weights. shows single-level and comprehensive weights.

4.3 Comprehensive Assessment and Analysis

Equation (14) produces comprehensive assessment values for five supply districts, shown in . District D has the highest score (optimal performance) but lower economy than others, suggesting economic improvements. District B scores lowest due to zero clean energy integration, making its environmental indicator zero. District C' s equipment condition is slightly lower, indicating need for improved maintenance.

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 models, it emphasizes environmental criteria using five performance indicators including clean energy grid-connected rate and CO emissions. The extension hierarchy method better simulates human judgment fuzziness than conventional AHP.

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

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