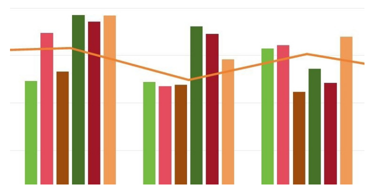
Comprehensive evaluation method for distribution grids based on combination weighting and modified TOPSIS



Método de evaluación integral para redes de distribución basado en la ponderación combinada y el TOPSIS modificado

Zhen Lu, Jiang Qian, Jian Zhang, Yong Yao and Xiaopeng Zhang
State Grid Shanxi Electric Power Company Yuncheng Power Supply Company, Hedong East Str., Yanhu District - Yuncheng City (China).

DOI: https://doi.org/10.52152/D11394 | Received: 26/dec/2024 • Reviewing: 26/dec/2024 • Accepted: 25/mar/2025

To cite this article: LU, Zhen; QIAN, Jiang; ZHANG, Jian; YAO, Yong; ZHANG, Xiaopeng. COMPREHENSIVE EVALUATION METHOD FOR DISTRIBUTION GRIDS BASED ON COMBINATION WEIGHTING AND MODIFIED TOPSIS. *DYNA* July August 2025, vol. 100, n.4, pp. 341-349. DOI: https://doi.org/10.52152/D11394

FUNDING
This work was financially supported by the Science and Technology Project of State Grid Shanxi Electric Power Company (Grant No. 5205M0230002).

RESUMEN

- La planificación de redes se ha convertido en un método nuevo e importante. En el proceso de implementación de la planificación de redes para una red de distribución, la evaluación precisa del rendimiento y las ventajas de cada red y la identificación de sus debilidades son requisitos previos para una planificación de redes científica, razonable y práctica. Por lo tanto, este estudio introduce un enfoque de evaluación para la construcción de una red de distribución con el fin de realizar una planificación de inversiones precisa para la misma. En primer lugar, se estableció un sistema de índices de una red de distribución. En segundo lugar, se introdujeron el método de ponderación antientropía (a-EWM) y el método mejor-peor (BWM) para calcular las ponderaciones subjetivas y objetivas, respectivamente, y se obtuvieron las ponderaciones combinadas utilizando la teoría de juegos. Por último, se modificó la técnica del método de orden de preferencia por similitud a la solución ideal (TOPSIS) utilizando la similitud del coseno y el análisis relacional gris (GRA). Los resultados indican que (1) los índices de primer nivel en el sistema de índices de evaluación aquí pueden utilizarse para reflejar la situación general de construcción de cada cuadrícula, y los índices de segundo nivel pueden emplearse para representar las debilidades dentro de cada cuadrícula. (2) El método de ponderación combinada basado en la teoría de juegos puede combinar las ventajas de los métodos de ponderación subjetiva y objetiva y reflejar con precisión la importancia de varios índices de evaluación. (3) Los inconvenientes del método TOPSIS tradicional, en el que no se puede considerar la correlación de los índices y solo se calcula la distancia relativa, lo que da lugar a una evaluación inexacta, pueden evitarse mediante el método TOPSIS modificado, en el que se adoptan la similitud del coseno y el análisis relacional gris. Por lo tanto, el uso de la ponderación combinada y el método TOPSIS modificado pueden hacer más práctico el valor de evaluación integral de una red de distribución. El método aquí puede utilizarse para demostrar el statu quo general y las demandas de desarrollo futuro de las redes de distribución y compensar los defectos del método de evaluación tradicional.
- **Palabras clave:** Red de distribución, Evaluación integral, Ponderación combinada, TOPSIS.

ABSTRACT

Grid planning has become a new and important method. In the process of implementing the grid planning for a distribution network, accurately evaluating the performance and advantages of each grid and identifying its weaknesses are prerequisites for a scientific, reasonable, and practical grid planning. Hence, this study introduces an evaluation approach for the construction of a distribution grid to make a pointed investment planning for it. First, an index system of a distribution grid was established. Second, the anti-entropy weight method (a-EWM) and the best-worst method (BWM) were introduced to compute the subjective and objective weights, respectively, and the combination weights were obtained using game theory. Finally, the technique for order preference by similarity to ideal solution (TOPSIS) method was modified using cosine similarity and gray relational analysis (GRA). Results indicate that, (1) The first-level indexes in the evaluation index system here can be used to reflect the overall construction situation of each grid, and the second-level indexes can be employed to represent the weaknesses within each grid. (2) The combination weighting method based on game theory can combine the advantages of subjective and objective weighting methods and reflect the importance of various evaluation indexes accurately. (3) The drawbacks of the traditional TOPSIS method, where index correlation cannot be considered and only relative distance is calculated, resulting in inaccurate evaluation, can be avoided by the modified TOPSIS method, in which cosine similarity and gray relational analysis are adopted. Therefore, the use of combination weighting and the modified TOPSIS method can make the comprehensive evaluation value of a distribution grid more practical. The method here can be utilized to demonstrate the overall status quo and future development demands of distribution grids and compensate for the defects of the traditional evaluation method.

Keywords: Distribution grid, Comprehensive evaluation, Combination weighting, TOPSIS.

1. INTRODUCTION

As the construction of new power systems advances and the energy structure transforms in China, distribution networks are facing a series of new development requirements, such as enhancing their reliability, flexibility, level of intelligence, and proportion of green energy consumption, in order to adapt to the diversified demands of future power markets. In the context of the "dual carbon" targets, distribution networks must support the low-carbon transition and accelerate the application of green energy. With the rapid development of distributed renewable energy, distribution networks need to possess greater carrying capacity to meet the demands of large-scale renewable energy integration and consumption. At the same time, distribution networks must fully support the construction of electric vehicle charging infrastructure and promote the diversified development of new energy storage to comprehensively advance the green and low-carbon transformation of energy. Additionally, distribution networks must enhance their level of intelligence and achieve digital transformation. In this context, grid segmentation of distribution networks has become an important solution.

The development of grid in distribution networks stems from the pursuit of refined management of power systems. By dividing a vast distribution network into several relatively independent and easily managed grids, precise division and efficient management of power supply areas can be achieved. This division method not only helps optimize the allocation of power resources and improve energy utilization efficiency, but also effectively addresses the challenges posed by load growth and the integration of distributed energy.

In the context of grid in distribution networks, the evaluation of distribution grids becomes particularly important. Evaluation work is not only a test of the implementation effects of existing grid plans, but also a guide for the future development direction of distribution networks. Through comprehensive and objective evaluations of distribution grids, existing problems and deficiencies can be promptly identified, providing a basis for subsequent improvements and optimizations. At the same time, the evaluation of distribution grids is also an important means to promote energy transformation and green development. Through evaluation work, distribution networks can be guided to develop in a more intelligent and green direction, contributing to the construction of a clean, low-carbon, safe, and efficient energy system.

In summary, the development of grids in distribution networks reflects the inevitable and new trend of modernized management in power systems, so the evaluation of distribution grids is an important guarantee to ensure the smooth advancement of this trend.

Present studies of assessing distribution grids focus primarily on the evaluation index system and the approach for comprehensive evaluation. The number of first-level indexes in most evaluation systems, such as grid power supply reliability [1], operating efficiency [2], power supply capacity [3], economy [4], or power quality [5], is less than 3 and is obviously too limited to show the overall situation of distribution grids. Studies of the comprehensive evaluation of grids rely mainly on traditional evaluation methods for distribution networks, including the technique for order preference by similarity to ideal solution (TOPSIS) method [6] and the fuzzy evaluation method [7]-[9]. Although the rough situation of power grids can be reflected using these methods, accurate evaluation of distribution grids and identification of their weaknesses cannot be realized. Simultaneously, the current evaluation methods focus only on a single distribution grid and cannot take into account the overall planning of multiple distribution grids, resulting in insufficient consideration of the balance of their overall development.

In order to address the aforementioned issues, this study introduces a comprehensive evaluation method for distribution grids on the basis of combination weighting and the modified TOPSIS method. In accordance with operational guidelines and experts' experiences, an index system is established, game theory is used for combination weighting, and cosine similarity and gray relation are adopted to modify the TOPSIS method to realize a comprehensive evaluation of distribution grids, identify the weaknesses of distribution grids, guide the follow-up investment accurately, and enhance the investment efficiency.

2. STATE OF THE ART

A comprehensive evaluation of grids mainly includes an evaluation system, index weighting, and an evaluation method [10]-[12]. Wang et al. [13] created an index system from the perspectives of reliability, economy, adaptability, and cleanness. Niu et al. [14] created an index system for assessing investment benefit of distribution networks by finding the influencing factors of each effect index using the fish bone method. The study of comprehensive evaluation index systems for distribution networks encompasses economic operation, smart development, and investment benefit [15]-[17]. Few studies exist on the establishment of comprehensive evaluation index systems with a distribution grid as an evaluation object. The methods for index weighting mainly comprise subjective, objective, and combination methods. In the first method, such as the analytic hierarchy process (AHP) [18]-[19], sequential relationship analysis, and Delphi methods, the calculation of index weights primarily depends on the decision-makers' subjective attention to the indexes. Rezaei [20] put forward the the best-worst method (BWM), by which the number of comparisons between indexes could be effectively reduced to simplify the comparison process considerably. However, judgments are made by decision-makers based on their experiences, which causes strong subjective randomness easily. In objective weighting methods, including entropy weight [21]-[22], critical and standard deviation methods, index weights are calculated using a mathematical approach, considering the correlation between the original and objective data of indexes. Majumder et al. [23] determined the objective weights of indexes in a low-carbon operation evaluation index system for distribution networks through the anti-entropy weight method (a-EWM). In fact, the results of this method often deviate from actual situations because decision-makers' subjective intentions and wishes are not considered. In combination weighting methods, the information of objective data is fully utilized, and the subjective opinions of decision-makers can be considered. Wang et al. [24] and Lu et al. [25] discussed the applications of game theory to combination weighting in detail. Jia et al. [26] used game theory to combine the weights obtained from AHP and EWM.

Gray relational analysis (GRA) [27]-[28] and TOPSIS [29]-[31] are widely applied to evaluation. Zhao et al. [32] used GRA in TOPSIS, and evaluated power quality using a modified gray-Euclidean distance measure, however, they didn't consider the problem that the calculation results were biased when the indexes were correlated. Zhang et al. [33] used a distance measure in TOPSIS based on cosine similarity, and developed an algorithm.

On the basis of the related studies, this study used distribution grids as evaluation objects to establish an index system. A combination weighting approach for calculating the combination weights of indexes by using a-EWM, BWM, and game theory was presented. Moreover, a modified TOPSIS based on cosine similarity and GRA for carrying out the comprehensive evaluation of distribution grids was proposed.

The remainder of this paper is outlined below: The third part presents the approach for developing a comprehensive evaluation index system and gives the approach for calculating combination weights and modifying the traditional TOPSIS. The fourth part analyzes the application of combination weights and the modified TOPSIS to the comprehensive evaluation of distribution grids through numerical examples, and the practicality of the method here is verified. The fifth part summarizes the results and presents the corresponding conclusions.

3. METHODOLOGY

3.1. COMPREHENSIVE EVALUATION INDEX SYSTEM

Distribution grids are the smallest units for distribution network planning, project management, and operation and maintenance. Therefore, accurate evaluation of their operation condition is necessary to provide auxiliary support for the meticulous planning and precise investment of distribution networks. The traditional evaluation indexes for distribution networks only focus on power supply reliability, grid structure, and other aspects, while the distribution grid under the new power system not only needs to ensure power supply reliability, but also needs to have a certain level of intelligence and digitization, while ensuring the economic operation of the power grid. All of these require further improvement of the grid based evaluation index system. The evaluation indexs for the distribution grid under the new power system proposed in this paper contain a wider range of content and involve some new indexs and concepts compared to traditional distribution network evaluation indexs. To achieve comprehensive and refined decision-making for distribution networks, this study uses distribution grids as evaluation units and selects key indexes on the basis of relevant guidelines and expert judgments to build an index system. The second-level indexes of the system include power supply capacity, grid structure, equipment level, service level, smartness and friendliness, and economic operation. A total of 24 third-level indexes are mainly used to reflect the reliability and cost-effectiveness of the distribution grids. The index system is elucidated in Table 1. The power supply capacity reflects distribution networks' capacity for bearing electrical loads and meeting the needs of users under the premise of safe operation, and it can be analyzed from the average power outage time for users, average distribution transformer capacity per household, and heavy load. The grid structure reflects the grid of distribution networks and can be analyzed from the standardized connection for lines, power radius, and line contact. The equipment level is used to evaluate the service life of equipment and line insulation. The service level is used to evaluate the capacity for serving users from the aspects of users' complaints, faults, and emergency repairs. Smartness and friendliness are used to evaluate distribution automation construction and its practicability. Economic operation is used to assess the financial returns, including the passing rate of integrated voltage, the proportion of low-voltage users, and combined line loss rate.

3.2. WEIGHTING METHOD

(1) A-EWM

The objective weights are often determined by the EWM. The principle of the EWM is based on the concept of information entropy, which is used to measure the uncertainty or degree of dispersion of information. In the EWM, if the data of a certain index has large variations, indicating a high degree of dispersion in information distribution, then this index provides more information and its weight is correspondingly higher; conversely, if the data of an index has small variations, indicating a more concentrated information distribution, then this indicator provides less information and its weight is lower. Therefore, the EWM determines the weights of indexes by calculating their information entropy, achieving objective weighting. This method avoids the interference of subjective factors and can more scientifically reflect the impact of data on evaluation results. However, extreme weights may come from the EWM because of its high sensitivity to the degree of disorder of indexes. In the a-EWM, an index with a higher anti-entropy indicates a greater degree of disorder, which in turn results in a more pronounced effect on the final evaluation result. Accordingly, the index should be assigned a greater weight. The detailed procedures for the a-EWM are outlined below:

1) Preprocessing index data

Given that the dimensions of each index are not consistent, the index data cannot be directly used for analysis and comparison. Thus, they need to be preprocessed by using Eqs. (1), (2), and (3). The index system in this study includes benefit-, cost-, and interval-oriented indexes. The benefit-oriented index indicates that

Table 1. Index system for distribution grids

First-level index	Second-level index	Third-level index
Comprehensive evaluation	Power supply capacity (B1)	average power outage time for users (C1), average distribution transformer capacity per household (C2), heavy load rate for a line (C3), heavy load rate for a distribution transformer (C4)
	Grid structure (B2)	passing rate of line N-1 (C5), standardized connection rate (C6), passing rate of power radius (C7), line connection rate (C8)
	Equipment level (B3)	average service life of a line (C9), average service life of a distribution transformer (C10), line insulation rate (C11)
	Service level (B4)	complaint rate of 10,000 households (C12), line failure outage rate (C13), outage rate of a distribution transformer (C14), average repair time of distribution network fault (C15),
	Smartness and friendliness (B5)	effective coverage of line distribution automation (C16), intelligent fusion terminal coverage (C17), participation rate of FA failure handling (C18)
	Economic operation (B6)	passing rate of integrated voltage (C19), proportion of low-voltage users (C20), combined line loss rate (C21), unit investment to increase power supply (C22)

a larger value is more favorable; the cost-oriented index suggests that a smaller value is more advantageous; the interval-oriented index implies that the optimal value lies within a specific range.

The benefit-oriented index data that need to be made dimensionless are calculated as:

$$y_{ij} = \left(x_{ij} - x_j^{\min}\right) / \left(x_j^{\max} - x_j^{\min}\right) \tag{1}$$

where x_{ij} is the jth index data of the ith object; $x_j^{\min}$ and $x_j^{\max}$ are the minimum and maximum values of the jth index, respectively. The cost-oriented index data that need to be made dimensionless are calculated as:

$$y_{ij} = 1 - \left(x_{ij} - x_j^{\min}\right) / \left(x_j^{\max} - x_j^{\min}\right) \tag{2}$$

The interval-oriented index data that need to be made dimensionless are calculated as:

$$y_{ij} = \begin{cases} 0 & h_j^{\min} \geq x_{ij} \\ 1 - (h_j^{best} - x_{ij}) / (h_j^{best} - h_j^{\min}) & h_j^{\min} \leq x_{ij} \leq h_j^{best} \\ 1 - (x_{ij} - h_j^{best}) / (h_j^{\max} - h_j^{best}) & h_j^{best} < x_{ij} \leq h_j^{\max} \\ 0 & h_j^{\max} \leq x_{ij} \end{cases} \tag{3}$$

where $h_j^{\min}$, $h_j^{\max}$, and h_j^{best} are the lower and upper boundary of the interval value, as well as the optimal value of the jth index, respectively.

2) Determining the anti-entropy of indexes

Due to the fact that entropy directly reflects the amount of information contained in an index, the larger the entropy and the more information it contains, the greater the importance of the index. The anti-entropy e_j of the jth index data that have been preprocessed is computed as:

$$e_j = -\sum_{i=1}^{m} p_{ij} \ln(1 - p_{ij}) \tag{4}$$

where m represents the quantity of objects, and p_{ij} is calculated as:

$$p_{ij} = y_{ij} \Big/ \sum_{i=1}^{m} y_{ij} \tag{5}$$

3) Determining the objective weights of indexes

Normalizing the anti-entropy e_j yields the weight w_j^{obj} of the jth index, that is:

$$w_j^{obj} = e_j \Big/ \sum_{j=1}^{n} e_j \tag{6}$$

where n represents the quantity of indexes.

(2) BWM

The BWM is a method used to determine weights in multi-criteria decision-making. The core idea of this method is based on comparisons between the "best" and "worst" factors. Firstly, decision-makers select the best and worst indexes from the evaluation criteria, and then compare the best index with all other indexes to construct a comparison vector for the best index. Similarly, the worst index is compared with all other indexes to construct a comparison vector for the worst index. Finally, through mathematical programming, the weights of each index are obtained. The number of comparisons between indexes is effectively reduced, the comparison process is simplified, the mistakes in decision-making made by experts when dealing with large volumes of data are reduced, and thus, more reliable subjective weights are obtained. The detailed procedures of BWM are outlined below:

1) Selecting the best and worst indexes

The best and worst indexes are chosen in accordance with the subjective opinions of experts, and the bth and wth indexes are considered the best and worst indexes, respectively.

2) Constructing a comparison vector

A comparison is made between the best index and other indexes, and the best comparison vector $\boldsymbol{C}_b = (C_{b1}, C_{b2}, \cdots, C_{bj}, \cdots, C_{bn})^T$ is constructed from the scores of the degree of importance of other indexes relative to the best one, which are given by experts using a 1–9 scale. A score of 1 signifies that the best index holds equal importance compared to the index, whereas a score of 9 denotes that the best index is of utmost importance in relation to the index. Similarly, a comparison is made between other indexes and the worst index, and the worst comparison vector $\boldsymbol{C}_w = (C_{1w}, C_{2w}, \cdots, C_{jw}, \cdots, C_{nw})^T$ is constructed.

3) Solving for the subjective weights of indexes

The planning model for the subjective weights $\boldsymbol{W}^{sub} = (w_1^{sub}, w_2^{sub}, \cdots, w_j^{sub}, \cdots, w_n^{sub})^T$ of indexes is:

$$\begin{cases} \min \max\limits_{j} \left\{ \left| w_b^{sub} / w_j^{sub} - C_{bj} \right|, \left| w_j^{sub} / w_w^{sub} - C_{jw} \right| \right\} \\ s.t.\ \sum\limits_{j=1}^{n} w_j^{sub} = 1 \\ \qquad w_j^{sub} \geq 0 \end{cases} \tag{7}$$

where w_b^{sub} and w_w^{sub} are the weights assigned to the best and worst indexes, respectively. $j = 1, 2, \cdots, n$.

For the convenience of solution, letting $k = \max\limits_{j} \left\{ \left| w_b^{sub} / w_j^{sub} - C_{bj} \right|, \left| w_j^{sub} / w_w^{sub} - C_{jw} \right| \right\}$, Eq. (7) is changed into:

$$\begin{cases} \min k \\ s.t.\ \left| w_b^{sub} / w_j^{sub} - C_{bj} \right| \leq k, \quad \left| w_j^{sub} / w_w^{sub} - C_{jw} \right| \leq k \\ \qquad \sum\limits_{j=1}^{n} w_j^{sub} = 1 \\ \qquad w_j^{sub} \geq 0 \end{cases} \tag{8}$$

4) Conducting consistency testing

After the subjective weights of indexes are obtained, the consistency ratio CR should be calculated to test the consistency between the best and worst comparison vectors. CR is calculated as:

$$CR = k^* / CI \tag{9}$$

where k^* is the optimal value of k from Eq. (8), and CI is the value determined by C_{bw}, as shown in Table 2. A lower value of CR signifies a higher degree of consistency, In this study, $CR < 0.1$ means that consistency testing is passed.

Table 2. CI values

C_{bw}	1	2	3	4	5	6	7	8	9
CI	0	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

(3) Combination weighting method

The objective and subjective weights of indexes here are calculated using the a-EWM and BWM, respectively. The former includes the information of index data themselves, and the latter incorporates the subjective judgments of experts. Calculating combination weights containing subjective and objective information is necessary to make the weights in this study more reliable and reasonable.

With the Nash equilibrium as the optimization objective to coordinate the subjective and objective weights, this study introduces game theory into comprehensive evaluation to solve for the combination weights of indexes. The idea of this method is that an equilibrium point between the objective and subjective weights is found to reduce the discrepancy between the combined weights and the two weights; thus, relatively reasonable and equilibrious combination weights can be obtained. The detailed procedures are outlined below:

1) Determining the combination weight vector

This study assumes that l weighting methods are used in evaluation. A set of basic weight vector $(\boldsymbol{g}_1, \boldsymbol{g}_2, \cdots, \boldsymbol{g}_j, \cdots, \boldsymbol{g}_l)$ is established, where $\boldsymbol{g}_j (j = 1,2,\cdots,l)$ is the weight vector of the *jth* weighting method, and the combination weight vector is:

$$\boldsymbol{g} = \sum_{j=1}^{l} \eta_j \boldsymbol{g}_j \tag{10}$$

where ς_j is the linear combination coefficient of the *jth* basic weight.

2) Calculating the optimal linear combination coefficient

For determining the optimal combination weight vector $\boldsymbol{g}^*$, the linear combination coefficient ς_j is optimized using game theory, The optimization model is deduced as:

$$\min \sum_{i=1}^{l} \left\| \sum_{j=1}^{l} \eta_j \boldsymbol{g}_j - \boldsymbol{g}_i \right\|_2 (i = 1,2,\cdots, l) \tag{11}$$

Essentially, Eq. (11) is a planning model for crossing combinations of multiple weight vectors, and its first-order derivative condition for optimization is derived from matrix differential properties as:

$$\begin{bmatrix} \boldsymbol{g}_1^T \boldsymbol{g}_1 & \cdots & \boldsymbol{g}_1^T \boldsymbol{g}_l \\ \vdots & & \vdots \\ \boldsymbol{g}_l^T \boldsymbol{g}_1 & \cdots & \boldsymbol{g}_l^T \boldsymbol{g}_l \end{bmatrix} \begin{bmatrix} \eta_1 \\ \vdots \\ \eta_l \end{bmatrix} = \begin{bmatrix} \boldsymbol{g}_1^T \boldsymbol{g}_1 \\ \vdots \\ \boldsymbol{g}_l^T \boldsymbol{g}_l \end{bmatrix} \tag{12}$$

Normalizing the solution η_j from Eq. (12) yields the optimal linear combination coefficient η_j^*, that is:

$$\eta_j^* = \eta_j \Big/ \sum_{j=1}^{l} \eta_j \, (j = 1,2,\cdots,l) \tag{13}$$

3) Determining the combination weight

The optimal vector $\boldsymbol{g}^*$ is calculated as:

$$\boldsymbol{g}^* = \sum_{j=1}^{l} \eta_j^* \boldsymbol{g}_j \tag{14}$$

Because the two basic weights in this study are from the a-EWM and BWM, $l = 2$.

3.3. MODIFIED TOPSIS AND A COMPREHENSIVE EVALUATION METHOD

TOPSIS is a multi-attribute decision-making method aimed at selecting the best decision by calculating the similarity of alternatives to the ideal solution. Its basic principle involves ranking evaluation objects based on their distances to the optimal solution and the worst solution. Specifically, this method first determines the positive ideal solution and the negative ideal solution, which represent the best and worst solutions, respectively. Then, by calculating the distance of each alternative to these two solutions, the closeness of each alternative is obtained. Finally, sorting is done based on the closeness to determine the best decision.

TOPSIS has two main problems: 1) The relative distance is calculated, but the curve trend is ignored, making the final evaluation results different from the actual situations. 2) If a correlation exists between the indexes, then the Euclidean distance may lead to deviations in calculation results. Therefore, GRA and cosine similarity are used to modify TOPSIS to Improve the precision of the evaluation approach presented in this study.

(1) GRA and cosine similarity

1) GRA

In GRA, the relation and order of the objects to be evaluated are well described by the gray relational degree. The relations between sequence curves are measured by comparing their geometric shape similarity. The gray relational coefficient g_{ij} is calculated as:

$$g_{ij} = \frac{\min_i \min_j |z_{0j} - z_{ij}| + \rho \max_i \max_j |z_{0j} - z_{ij}|}{|z_{0j} - z_{ij}| + \rho \max_i \max_j |z_{0j} - z_{ij}|} \tag{15}$$

where z_{0j} is the *jth* value of the reference sequence, z_{ij} is the *jth* value of the *ith* comparison sequence, and $\rho \in [0,1]$ is the identification coefficient.

The gray relational degree can be obtained by calculating the mean of the relational coefficients for each point. For GRA, sample size does not need to be required strictly, and the proximity between different objects can be reflected by the similarity of curve shapes. Therefore, the problem of not reflecting the reality accurately enough in TOPSIS caused by ignoring the trends of curves is solved.

2) Cosine similarity

The basic content of cosine similarity is that the cosine of the angle included between two vectors is calculated to evaluate the similarity between them. With the cosine similarity applied to TOPSIS, the smaller the included angle between two vectors, the greater the similarity, and the nearer the distance between them. Likewise, the closer the object being evaluated is to the ideal solution, the smaller the distance between them. [34].

The cosine similarity between $\boldsymbol{O} = (o_1, o_2, \cdots, o_n)$ and $\boldsymbol{Q} = (q_1, q_2, \cdots, q_n)$ is calculated as:

$$\cos(\theta) = sim(\boldsymbol{O}, \boldsymbol{Q}) = \frac{\boldsymbol{O} \cdot \boldsymbol{Q}}{\|\boldsymbol{O}\| \|\boldsymbol{Q}\|} = \frac{\sum_{i=1}^{n} o_i \times q_i}{\sqrt{\sum_{i=1}^{n} (o_i)^2} \times \sqrt{\sum_{i=1}^{n} (q_i)^2}} \tag{16}$$

For cosine similarity to be applied to TOPSIS and for the difference in relative closeness between objects to be evaluated to be better shown to obtain more accurate evaluation results, the cosine similarity needs to be modified to develop the expression for distance calculation based on it [14]. The distance based on cosine similarity is calculated as:

$$D = \log_{0.5}\left(\frac{sim(\boldsymbol{O},\boldsymbol{Q})+1}{2}\right) \tag{17}$$

The value of distance obtained from Eq. (17) is positive; the smaller the similarity, the farther the distance. In addition, the difference between objects to be evaluated is enlarged.

(2) Evaluation method based on the modified TOPSIS

The modified TOPSIS based on GRA and cosine similarity can cure some defects in TOPSIS, such as the biased calculation results in case of the correlation of indexes. The evaluation method here involves the following procedures:

1) Developing a weighted and standardized matrix

The quantity of evaluation objects and indexes is assumed to be m and n, respectively. The index data are preprocessed using Eqs. (1)–(3) to obtain a standardized matrix, then the data in the standardized matrix are assigned weights by using the optimal combination weight vector $\boldsymbol{g}^* = (g_1^*, g_2^*, \cdots, g_j^* \cdots, g_n^*)$ to develop a weighted and standardized matrix as:

$$\boldsymbol{Z} = \begin{bmatrix} z_{11} & z_{12} & \cdots & z_{1n} \\ z_{21} & z_{22} & \cdots & z_{2n} \\ \vdots & \vdots & & \vdots \\ z_{m1} & z_{m2} & \cdots & z_{mn} \end{bmatrix} \tag{18}$$

where the jth index data z_{ij} for the ith object are calculated as:

$$z_{ij} = y_{ij} \times g_j^* \tag{19}$$

2) Determining the positive and negative ideal solutions

Using the data from the weighted and standardized matrix $\boldsymbol{Z}$, this study calculates the positive ideal solution vector $\boldsymbol{Z}^+$ and negative ideal solution vector $\boldsymbol{Z}^-$ as:

$$\boldsymbol{Z}^+ = (z_1^+, z_2^+, \cdots, z_j^+, \cdots, z_n^+) = (\max\{\boldsymbol{z}_1\}, \max\{\boldsymbol{z}_2\}, \cdots, \max\{\boldsymbol{z}_j\}, \cdots, \max\{\boldsymbol{z}_n\}) \tag{20}$$

$$\boldsymbol{Z}^- = (z_1^-, z_2^-, \cdots, z_j^-, \cdots, z_n^-) = (\min\{\boldsymbol{z}_1\}, \min\{\boldsymbol{z}_2\}, \cdots, \min\{\boldsymbol{z}_j\}, \cdots, \min\{\boldsymbol{z}_n\}) \tag{21}$$

where $\boldsymbol{z}_j$ is a column vector representing the value of the m objects under the jth index, i.e. $\boldsymbol{z}_j = [z_{1j}, z_{2j}, \cdots, z_{ij}, \cdots, z_{mj}]$; max $\{\cdot\}$; max $\{\cdot\}$ and min $\{\cdot\}$ are respectively represented as the maximum and minimum values in the column vector.

3) Calculating the distance based on cosine similarity

Given that the angle included between two vectors may be smaller, the distance of the object to be evaluated from the positive and negative ideal solutions is closer, and the comparative proximity or similarity degree is lower, an average is subtracted from the values in all dimensions to enlarge the differences in the degrees of closeness. The distances of cosine similarity of the ith object to be evaluated from positive and negative ideal solutions are calculated as:

$$D_i^+ = \log_{0.5}\left(\frac{sim(\boldsymbol{Z}_i - \boldsymbol{Z}^{avg}, \boldsymbol{Z}^+ - \boldsymbol{Z}^{avg})+1}{2}\right) \tag{22}$$

$$D_i^- = \log_{0.5}\left(\frac{sim(\boldsymbol{Z}_i - \boldsymbol{Z}^{avg}, \boldsymbol{Z}^- - \boldsymbol{Z}^{avg})+1}{2}\right) \tag{23}$$

where:

$$sim(\boldsymbol{Z}_i - \boldsymbol{Z}^{avg}, \boldsymbol{Z}^+ - \boldsymbol{Z}^{avg}) = \frac{\sum_{i=1}^{n}(z_{ij} - z_j^{avg}) \times (z_j^+ - z_j^{avg})}{\sqrt{\sum_{i=1}^{n}(z_{ij} - z_j^{avg})^2} \times \sqrt{\sum_{i=1}^{n}(z_j^+ - z_j^{avg})^2}} \tag{24}$$

$$sim(\boldsymbol{Z}_i - \boldsymbol{Z}^{avg}, \boldsymbol{Z}^- - \boldsymbol{Z}^{avg}) = \frac{\sum_{i=1}^{n}(z_{ij} - z_j^{avg}) \times (z_j^- - z_j^{avg})}{\sqrt{\sum_{i=1}^{n}(z_{ij} - z_j^{avg})^2} \times \sqrt{\sum_{i=1}^{n}(z_j^- - z_j^{avg})^2}} \tag{25}$$

where $\boldsymbol{Z}^{avg} = (z_1^{avg}, z_2^{avg}, \cdots, z_j^{avg}, \cdots, z_n^{avg})$, $z_j^{avg} = 0.5 \times (z_j^+ + z_j^-)$.

4) Calculating gray relational coefficients

The gray relational coefficients g_{ij}^+ and g_{ij}^- relating the jth index data z_{ij} for the ith object to be evaluated to the positive ideal solution z_{ij}^+ and the negative ideal solution z_{ij}^- are calculated as:

$$g_{ij}^+ = \frac{\min_i\min_j\left|z_{ij} - z_j^+\right| + \rho\max_i\max_j\left|z_{ij} - z_j^+\right|}{\left|z_{ij} - z_j^+\right| + \rho\max_i\max_j\left|z_{ij} - z_j^+\right|} \tag{26}$$

$$g_{ij}^- = \frac{\min_i\min_j\left|z_{ij} - z_j^-\right| + \rho\max_i\max_j\left|z_{ij} - z_j^-\right|}{\left|z_{ij} - z_j^-\right| + \rho\max_i\max_j\left|z_{ij} - z_j^-\right|} \tag{27}$$

where $\rho = 0.5$ in this study.

5) Calculating gray relational degree

The gray relational degrees R_i^+ and R_i^- are calculated as:

$$R_i^+ = \frac{1}{n}\sum_{j=1}^{n} g_{ij}^+ \tag{28}$$

$$R_i^- = \frac{1}{n}\sum_{j=1}^{n} g_{ij}^- \tag{29}$$

The greater the gray correlation between the evaluation object and the positive ideal solution, and the greater the cosine similarity with the negative ideal solution, the closer it is to the optimal object.

6) Performing dimensionless processing

The calculation formulas for dimensionless processing are as follows:

$$\begin{cases} d_i^+ = D_i^+ \big/ \max_i D_i^+, d_i^- = D_i^- \big/ \max_i D_i^-, \\ r_i^+ = R_i^+ \big/ \max_i R_i^+, r_i^- = R_i^- \big/ \max_i R_i^- \end{cases} \tag{30}$$

7) Establishing the gray relation–cosine similarity distance

Combining the gray relation degree and the distance based on cosine similarity yields the gray relation–cosine similarity distance S_i^+ and S_i^-, as shown below:

$$S_i^+ = \delta d_i^- + (1-\delta) r_i^+ \quad (31)$$

$$S_i^- = \delta d_i^+ + (1-\delta) r_i^- \quad (32)$$

where δ represents the degree of preference, that is, $\delta = 0.5$ here. The greater d_i^- and r_i^+, the shorter the distance of the gray relation degree–cosine similarity of the object to be evaluated from the positive ideal solution; the greater d_i^+ and r_i^-, the longer the distance of the gray relation degree–cosine similarity of each evaluation object from the positive ideal solution.

8) Calculating the comprehensive evaluation value

The evaluation value of the *ith* object is computed as:

$$C_i = S_i^+ / \left(S_i^+ + S_i^-\right) \quad (33)$$

In summary, the process of the comprehensive evaluation method for the distribution grid constructed in this paper is shown in Fig. 1 (see section: supplementary material).

4. RESULT ANALYSIS AND DISCUSSION

Five grids in a regional distribution network in China are used to verify the efficacy of the method suggested in this study. An evaluation of them is carried out on the basis of the evaluation index system for grids in Table 1.

The data under each index are preprocessed, then the objective and subjective weights of the index data are computed using the a-EWM and BWM, respectively. The combination weights of the index data are determined via the combination weighting approach based on game theory, as shown in Table 3.

Table 3. Objective, subjective and combination weights of 22 indexes.

Index \ Weight	Objective weight	Subjective weight	Combination weight
C1	0.0438	0.2051	0.1879
C2	0.0397	0.1192	0.1107
C3	0.0556	0.0341	0.0364
C4	0.0538	0.0191	0.0228
C5	0.0399	0.1381	0.1277
C6	0.0372	0.0239	0.0253
C7	0.0463	0.0121	0.0157
C8	0.0378	0.0557	0.0538
C9	0.0339	0.0025	0.0058
C10	0.0455	0.0042	0.0086
C11	0.0565	0.0261	0.0293
C12	0.0570	0.0710	0.0695
C13	0.0419	0.0207	0.0230
C14	0.0404	0.0166	0.0191
C15	0.0474	0.0066	0.0109
C16	0.0472	0.0664	0.0644
C17	0.0533	0.0061	0.0111
C18	0.0472	0.0194	0.0224
C19	0.0370	0.0914	0.0856
C20	0.0351	0.0355	0.0355
C21	0.0413	0.0178	0.0203
C22	0.0623	0.0085	0.0142

Table 4. Values of S_i^+, S_i^-, and C_i of the five grids.

Values \ Grids	A	B	C	D	E
S_i^+	1.000	0.985	0.941	0.939	0.917
S_i^-	0.621	0.574	0.951	0.609	0.836
C_i	0.617	0.632	0.497	0.607	0.523

The assessment values under the first-level index can reflect the overall construction situation of each grid, and they can be used to make a comparison between grids.

The data under 22 third-level indexes are standardized and assigned the weights to obtain a 5×22 weighted and standardized matrix. The positive and negative ideal solutions are identified using Eqs. (20) and (21), the gray relation–cosine similarity distance S_i^+ and S_i^- are obtained using Eqs. (22)–(32), and the assessment values under the first-level index of the five grids are acquired using Eq. (33), as shown in Table 4.

The assessment values under the first-level index are shown in Fig. 2. The evaluation values of distribution grids C and E are obviously smaller than those of other distribution grids. This result shows that the general situation of these two grids is relatively bad. Additional investment should be allocated to them, rather than to other distribution grids, to improve the development balance of the overall distribution network.

The assessment values under the second-level indexes of the five grids can reflect the weaknesses in each grid and can be calculated using the comprehensive evaluation method here. The calculation under power supply capacity is taken as an example.

The data under the four third-level indexes C_1£ C_2¬ C_3, and C_4 are standardized and assigned the weights to obtain a 5×4 weighted and standardized matrix. In accordance with the procedure in 4.1, the evaluation values under the index power supply capacity of the five grids are obtained using Eqs. (20)–(33), as shown in Fig. 3. The power supply capacity of grid D is greater than those of other distribution grids. In terms of power supply capacity, the performance of grids B and C is poor, much lower than that of other distribution grids. Therefore, more investment amount should be allocated to them to improve their power supply capacities.

Similarly, the assessment values under the remaining five second-level indexes of the five grids are obtained. The evaluation values under all second-level indexes are shown in Table 5.

The assessment values under the first-level and the six second-level indexes of the five grids are illustrated in Fig. 4. A comparison of the construction situation under the second-level indexes of the same grid can be made to identify the weaknesses in the development of each grid, make clear investment emphases, and improve the follow-up investment benefits.

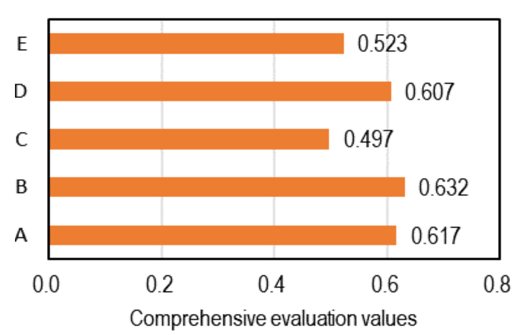


Fig. 2. Assessment values of the five grids.

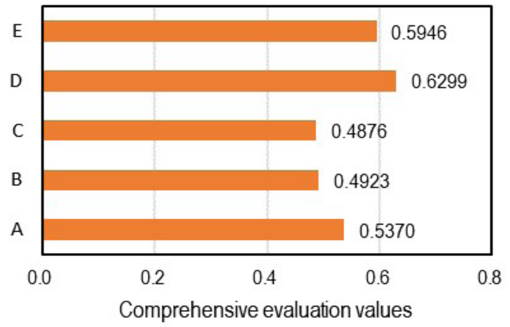


Fig. 3. The assessment values of the five grids under the index power supply capacity.

Table 5. Assessment values under all the second-level indexes of the five grids.

Grid / Index	A	B	C	D	E
B1	0.537	0.492	0.488	0.630	0.595
B2	0.756	0.695	0.470	0.643	0.518
B3	0.751	0.533	0.477	0.446	0.557
B4	0.621	0.771	0.722	0.543	0.443
B5	0.782	0.742	0.690	0.484	0.438
B6	0.707	0.769	0.584	0.679	0.445

From Fig. 4, owing to its relatively serious problems with line overload and distribution transformer overload, the development in power supply capacity of grid A lags slightly behind. Hence, the construction emphasis should be placed on the improvement of equipment loads. Nevertheless, the development in other aspects of grid A is good, relatively balanced, and reasonable, with its comprehensive evaluation values in the second place among the five grids. The power supply capability and equipment level of grid B lag relatively behind, but there is still much room for improvement. The construction emphasis should be placed on improving the line insulation rate and reducing the average lifespan of equipment. Nevertheless, the overall status quo of grid B is relatively better, with its comprehensive evaluation score in the first place among the five grids. The balance of development of grid C is poor, that is, the service level, smartness and friendliness, and economic operation are better, but the power supply capacity, grid structure, and equipment level are not good enough. The main reason is that the lines are severely overloaded, and the principle N-1 is not well met. Consequently, the construction emphasis should be placed on raising the N-1 passing rate and reducing line load rate to improve the safety and reliability. Grid D is weak in equipment level and smartness and friendliness. The main problem is the high proportion of old equipment and insufficient automation construction, so the construction emphasis should be placed on enhancing the smart automation level. The general development of grid E lags behind in comparison with that of other grids, but the power supply capability is great owing to the better situation of the lines and distribution transformer loads in this region.

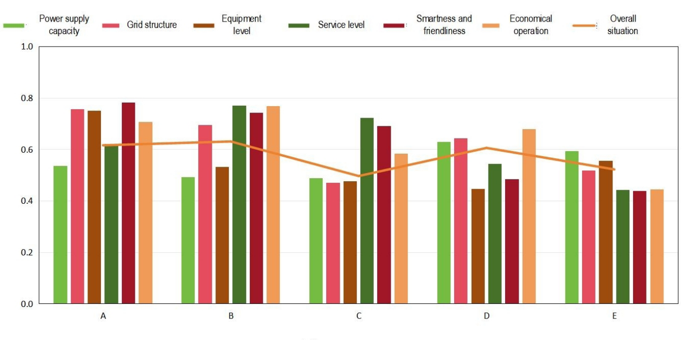


Fig. 4. Assessment values under the first-level and the six second-level indexes of the five grids.

To illustrate the implementation process, accuracy, and universality of the method proposed in this paper, a representative distribution grid from a typical region was selected as the analysis. Therefore, the applicability of the method presented here is not limited and possesses certain generalizability. The specific reasons are as follows: 1) A combination weighting method based on game theory is adopted, which can avoid subjective biases in the evaluation process due to experts' differences in familiarity with distribution grids in different regions, making the evaluation results more accurate and objective. 2) The limitations of the traditional TOPSIS method are further overcome, thereby preventing issues that information redundancy among the selected index attributes can affect the accuracy of evaluation results when the distribution grids of different regions are evaluated. Because of these improvements, the evaluation method proposed in this paper is highly suitable for the application to distribution grids of different regions. When applying it to the distribution grids in some special regions, only minor adjustments to the data types and variables are needed based on their specific characteristics.

5. CONCLUSIONS

This study develops a systematic evaluation index system for distribution grids, which is used to reflect their overall status quo and development needs. The evaluation approach here compensates for the defects of the TOPSIS method and improves the calculation precision. The key findings are summarized as follows:

1) Selecting the indexes from as many aspects as possible, such as power supply capacity, grid structure, equipment level, service level, smartness and friendliness, and economic operation, can establish a scientific, reasonable, practical, and comprehensive evaluation index system for a distribution grid.

2) The combination weighting approach based on game theory can combine the advantages of subjective and objective weighting methods and remedy the defects of traditional weighting methods. The use of cosine similarity can avoid potential bias in calculation results when indexes are correlated, and the use of GRA can offset the deficiency of the TOPSIS method in ignoring curve trends. The use of the combination weighting method and the improved TOPSIS method can make the comprehensive evaluation values of distribution grids more accurate and practical.

3) With a horizontal comparison between different distribution grids and a vertical comparison between various indexes within a single grid, identifying relatively lagging distribution grids and their own weaknesses and assigning a priority in investment are feasible.

This study establishes an evaluation index system for distribution grids and proposes an evaluation approach for them, but it still lacks a connection with the future development goals of distribution grids. The follow-up study will focus on the correlation analysis between investment projects and distribution grid indexes, determine the investment strategies for distribution grids, and achieve the expected goals of distribution grid construction.

REFERENCES

[1]Li J, Deng J, Jiang S, Wang Y, Li P, Fan X. "A distribution network optimization planning method based on differential reliability demand". Power System and Clean Energy. May 2021. Vol. 37-5. p. 74-82.

[2] Pan X, Shao J, Liu S, Pan X, Chen J, Hu F, Wang J. "Accurate investment strategy for urban distribution network based on grid planning". Smart Power. February 2022. Vol. 50-2. p. 1-8.

[3] Li H, Sun B, Wang X. "Power grid planning method and its application". Proceedings of the CSU-EPSA. December 2015. Vol. 27-S1. p. 33-37.

[4] Wang X, Kang Q, Guo L, Liang Z, Gao J, Liu W. "Economic evaluation for 5G planning of distribution network considering transmission loss and vulnerability". Sustainable Energy. Grids and Networks. December 2023. Vol. 36. p. ID 101231. DOI: https://doi.org/10.1016/j.segan.2023.101231

[5] Shi H, Li Y, Jiang Z, Zhang J. "Comprehensive power quality evaluation method of microgrid with dynamic weighting based on CRITIC". Measurement and Control. May 2021. Vol. 54-5-6. p. 1097-1104. DOI: https://doi.org/10.1177/00202940211016092

[6] Xu B, Ma J, Chen Q, Ligao J, Hu P. "Research on comprehensive evaluation index system and investment strategy of economic development zone distribution network based on improved AHP-TOPSIS method". Power System Protection and Control. November 2019. Vol. 47-22. p. 35-44. DOI: https://link.cnki.net/doi/10.19783/j.cnki.pspc.181585

[7] Ma L, Zhang X. "Economic operation evaluation of active distribution network based on fuzzy borda method". IEEE Access. February 2020. Vol. 8. p. 29508-29517. DOI: https://doi.org/10.1109/ACCESS.2020.2972015

[8] Liang H, Liu Z. "Comprehensive benefit evaluation of smart distribution network based on analytic hierarchy process entropy method-fuzzy comprehensive analysis". Journal of North China Electric Power University (Natural Science Edition). September 2023. Vol. 50-1. p. 48–55. DOI: https://link.cnki.net/urlid/13.1212.TM.20210914.1444.002

[9] Lu J, Lin W, Dabić M. "Coevolution analysis of the sustainable development systems of energy firms from a strategic philanthropy perspective". IEEE Transactions on Engineering Management. March 2023. Vol. 71. p. 6887-6902. DOI: https://doi.org/10.1109/TEM.2023.3244500

[10] Zhang J, Gao C, Wang T, Duan Y, Xu M, Guo Z, "A dynamic evaluation method for high-permeability new energy distribution network planning considering multistage development trends". Frontiers in Energy Research. August 2022. Vol. 10. p. ID 958892. DOI: https://doi.org/10.3389/fenrg.2022.958892

[11] Sun X, Sheng Y, Wu C, Cai Q, Lai X. "Comprehensive evaluation of interval equalization of power quality in active distribution network based on CVAE-TS". Journal of Electrical Engineering & Technology. August 2023. Vol. 19-1. p. 83-95. DOI: https://doi.org/10.1007/s42835-023-01584-y

[12] Zheng W, Zou B, "Evaluation of intermittent-distributed-generation hosting capability of a distribution system with integrated energy-storage systems". Global Energy Interconnection. August 2021. Vol. 4-4. p. 415-424. DOI: https://doi.org/10.1016/j.gloei.2021.09.003

[13] Wang Y, Ge L, Zhang N. "Hybrid evaluation method for dispatching control level of smart distribution network". Journal of Electrical Engineering and Technology. August 2019. Vol. 14-6. p. 2263-2275. DOI: https://doi.org/10.1007/s42835-019-00267-x

[14] Niu D, Song Z, Wang M, Xiao L. "Improved TOPSIS method for power distribution network investment decision-making based on benefit evaluation index system". International Journal of Energy Sector Management. September 2017. Vol. 11-4. p. 595-608. DOI: https://doi.org/10.1108/IJESM-05-2017-0005

[15] Wang C, Yang L, Zhang X, Liang R, Li H, Wang Y, "Optimisation analysis of distribution network planning based on the IVIF-AHP method". Applied Mathematics and Nonlinear Sciences. April 2023. Vol. 8-2. p. 1105-1116. DOI: https://doi.org/10.2478/amns.2021.2.00229

[16] Ma X, Wang Y, Liu Z, Feng X. "Comprehensive evaluation of 5G+ smart distribution network based on combined weighting method-cloud model". Glob. Energy Interconnection. December 2022. Vol. 5-6. p. 675-691. DOI: https://doi.org/10.1016/j.gloei.2022.12.009

[17] Xu J, Li W, Song B, Wang F, Wang X, Yang S. "Adaptability evaluation of distributed photovoltaic access distribution network". [EB/OL]. Retrieved from http://kns.cnki.net/kcms/detail/23.1202.TH.20220602.1656.006.html, 2022-06-06/2024-12-08.

[18] Zhang M, Sun Q, Yang X. "Research on the assessment of the capacity of urban distribution networks to accept electric vehicles based on the improved TOPSIS method". IET Generation, Transmission and Distribution. June 2021. Vol. 15-19. p. 2804-2818. DOI: https://doi.org/10.1049/gtd2.12216

[19] Liu Z, Xie Q, Dai L, Wang H, Deng L, Wang C, Zhang Y, Zhou X, Yang C, Xiang C, Qin S. "Research on comprehensive evaluation method of distribution network based on AHP-entropy weighting method". Frontiers in Energy Research. August 2022. Vol. 10. p. ID 975462. DOI: https://doi.org/10.3389/fenrg.2022.975462

[20] Rezaei J. "Best-worst multi-criteria decision-making method". Omega. June 2015. Vol. 53. p. 49-57. DOI: https://doi.org/10.1016/j.omega.2014.11.009.

[21] Chen J. "Fault prediction of a transformer bushing based on entropy weight TOPSIS and gray theory". Computing in Science and Engineering. November-October 2019. Vol. 21-6. p. 55-62. DOI: https://doi.org/10.1109/MCSE.2018.2882357

[22] Zhu H, Li J, Liu X, Wang H, Cui Z, Dong F. "Multidimensional evaluation method for the operational status of photovoltaic arrays in large-scale pv power stations". IEEE Journal of Photovoltaics. July 2024. Vol. 14-4. p. 679-690. DOI: https://doi.org/10.1109/JPHOTOV.2024.3384913

[23] Majumder P, Balas V E, Paul A, Baidya D. "Application of improved fuzzy best worst analytic hierarchy process on renewable energy". PeerJ Computer Science. April 2021. Vol. 7-1. p. ID e453. DOI: https://doi.org/10.7717/peerj-cs.453

[24] Wang D, SunH, Ge Y, Cheng J, Li G, Cao Y, Liu W, Meng J. "Operation effect evaluation of grid side energy storage power station based on combined weight TOPSIS model". Energy Reports. June 2024. Vol. 11. p. 1993-2002. DOI: https://doi.org/10.1016/j.egyr.2024.01.056

[25] Lu D, Xu C, Zhang L, Wang L, Sun Y. "Comprehensive risk assessment method of power grid based on grey relational weight game theory". In: 2019 5th international conference on green materials and environmental engineering, Guangzhou, China: IOP, 2020. Vol. 453-1. p. ID 012068. DOI: https://doi.org/10.1088/1755-1315/453/1/012068

[26] Jia M, Li M, Song H, Li Q. "Research on rural power system comprehensive evaluation system based on game theory combination weights". Journal of Electric Power Science and Technology. March 2020. Vol. 35-2. p. 69-75. DOI: https://link.cnki.net/doi/10.19781/j.issn.1673-9140.2020.02.009

[27] Xiang Y, Lin Y, Zhang Y, Lan J, Hao M, Wang L, Wang J, Qin L. "A grid-wide comprehensive evaluation method of power quality based on complex network theory". Energies. June 2024. Vol. 17. p. ID 3193. DOI: https://doi.org/10.3390/en17133193.

[28] Zhang Q, Ma W, Li G, Xie M, Shao Q. "Partition fault diagnosis of power grids based on improved PNN and GRA". IEEJ Transactions on Electrical and Electronic Engineering. October 2020. Vol. 16-1. p.57-66. DOI: https://doi.org/10.1002/tee.23268

[29] Maccarty N A, Bryden K M. "An integrated system model for energy services in rural developing communities". Energy. October 2016. Vol. 113. p. 536-557. DOI: https://doi.org/10.1016/j.energy.2016.06.145

[30] Tan W, Ge Y, Chen B, Ding J, Luo X, Lin Z, Qiu W, Lin Z. "Gaussian cloud and TOPSIS based power supply quality evaluation method". Energy Reports. November 2022. Vol. 8. p. 377-384. DOI: https://doi.org\10.1016/j.egyr.2022.10.093

[31] Jiang E, Zhang W, Xue A, Lin S, Mi Y, Li D. "Vulnerable node identification method for distribution networks based on complex networks and improved TOPSIS theory". IET Generation Transmission & Distribution. October 2023. Vol. 17-22. p. 4991-5002. DOI: https://doi.org/10.1049/gtd2.13011

[32] Zhao H, Li J, Mi Z, Pu L, Cui Y. "Grading evaluation of power quality based on CRITIC and improved Grey-TOPSIS". Power System Protection and Control. February 2022. Vol. 50-3. p. 1-8. DOI: https://link.cnki.net/doi/10.19783/j.cnki.pspc.210386

[33] Zhang L, Xia P, Li F. "A method based on cosine similarity in supplier selection". Journal of Shandong University (Engineering Science). September 2017. Vol. 47-1. p. 1-6. DOI: https://link.cnki.net/urlid/37.1391.t.20160929.1021.002

[34] Rana S C, Patel J N. "Selection of best location for small hydro power project using AHP, WPM and TOPSIS methods". ISH Journal of Hydraulic Engineering. May 2018. Vol. 26-2. p. 173-178. DOI: https://doi.org/10.1080/09715010.2018.1468827

SUPPLEMENTARY MATERIAL

https://www.revistadyna.com/documentos/pdfs/_adic/11394-1_en.pdf