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Analysis and comprehensive assessment method of power quality in advanced distribution networks based on complex network theory

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Introduction: As China continues to develop the advanced power systems, the network structure of distribution networks is becoming increasingly complex. The integration of numerous power electronic devices has caused growing severity of power quality issues in present-day distribution networks. Moreover, the complexity of the networks has resulted in a significant increase in the volume of power quality data, posing greater challenges in data processing and power quality assessment.

Methods: This paper investigates a novel method for comprehensive assessment of power quality in advanced distribution networks (ADN) grounded in complex network theory. First, the influencing factors of power quality in advanced distribution networks are analyzed, and based on this analysis, the power quality evaluation indicators for advanced distribution networks are determined. Then a node characteristic matrix of the distribution network is constructed based on complex network theory which is used to generate the significance of each node within the network. Moreover, the sequential relationship analysis method (G1) and criteria importance though intercrieria correlation (CRITIC) method are leveraged to determine the subjective and objective weights of each indicator. These weights are then combined to calculate the comprehensive weight, which is further optimized using a two-stage method to increase the rationality. Furthermore, a fuzzy comprehensive evaluation method is applied to quantitatively assess the power quality within ADN. Finally, the proposed method is validated using measurement data from a specific ADN.

Results and discussion: The findings demonstrate the rationality and effectiveness of the proposed method, providing valuable insights for optimizing power quality of advanced distribution systems.

KEYWORDS

advanced distribution network, complex network, power quality, comprehensive weight, two-stage method, fuzzy comprehensive assessment

1 Introduction

In 2021, the Ninth Meeting of the Central Committee for Financial and Economic Affairs provided clarity on the implementation of the renewable energy substitution initiative. It also deepened the reform of the power system and built an advanced power system centered around renewable energy sources. The overarching aim was to achieve the dual carbon goals. With the development of the new system, more and more distributed resources will be integrated into the new distribution network. The proliferation of distributed new energy sources, such as distributed photovoltaics and decentralized wind power, within the ADN will serve to augment the generation capacity and output of new energy, which will bolster the preeminent role of new energy in the new power system. However, the growing integration of distributed power sources, coupled with the application of nonlinear devices, has made the power quality of the network increasingly complex and acute (Vannoy et al., 2007; Wang H. et al., 2022). Moreover, with technological advancements, the increasing use of power quality-sensitive appliances raises the demand for power quality on the user side. In addition, the integration of more distributed new energy sources into the new distribution network further complicates the network structure, and the impact of complex networks on the new distribution system cannot be ignored. Accurate assessment of power quality in distribution networks is conducive to targeted improvement of power quality issues (Liu B. et al., 2018; Liu K. et al., 2020). Therefore, the evaluation of power quality in the ADN has high research value.

In the context of energy conservation and emission reduction, the ADN serves as a platform for accommodating large-scale distributed new energy, flexible regulation resources, and energy consumption. In order to ensure power supply quality and improve user electricity experience, it is necessary to enhance power quality. Therefore, from both technological and economic perspectives, the assessment and analysis of power quality are particularly important (Huang et al., 2023). A study detailed in reference (Dong et al., 2021) analyzed the characteristics of the new distribution system under the "dual carbon" background and the main challenges it faces. The new distribution system is characterized by diversified power supply and the large-scale application of power electronic equipment, indicating that the problem of deteriorating power supply quality is significant due to the large-scale access of power electronic equipment. In terms of the mechanism and governance of power quality issues, references (Naderi et al., 2018; Ghorbani and Mokhtari, 2015; Liang, 2016) studied the impact of distributed power generation grid connection and the access of power electronic devices on the power quality of distribution networks, and proposed corresponding detection and governance methods.

The comprehensive assessment of power quality is the process of evaluating and comparing various indicators of power quality with their standard grades after obtaining basic data by actual measurement of electrical operating parameters in power systems or using modeling and simulation (Liu Y. et al., 2020). Regarding the assessment of power quality, existing methods for weighting power quality assessment indicators can mainly be split into subjective, objective, and subjective-objective integrated weighting methods. Reference (Bajaj et al., 2022) proposes a power quality assessment method for distributed generation systems based on analytic hierarchy process (AHP). AHP is one of the subjective weighting methods, relying on expert experience for subjective weighting, which may lead to deviation of evaluation results from the actual situation due to excessive subjectivity. Moreover, when considering a large number of indicators, AHP may encounter problems of inconsistency in judgment matrices. Reference (Zhao et al., 2022) proposes the use of CRITIC weighting method to calculate indicator weights. CRITIC weighting approach takes into account the comprehensively correlation and differences among indicators, making it an objective weighting method. Objective weighting methods require a sufficient amount of sample data, and the resulting indicator weights are highly objective. However, CRITIC method may not adequately reflect the decision-maker's preference for different indicators during the evaluation. References (Zaninelli et al., 2013; Zhang et al., 2021) propose a power quality assessment method based on data envelopment analysis, which can objectively evaluate the power quality of distribution networks. However, the accuracy of the evaluation results of this method is generally lower when objective data is scarce. References (Jia et al., 2000; Cheng et al., 2020) respectively adopt fuzzy pattern recognition methods, set pair analysis, and variable fuzzy set methods for power quality assessment. These methods are of significant value for power quality evaluation. However, the power quality indicators used in the above evaluation methods are not optimized based on the characteristics of ADN, there may be issues such as high computational complexity and discrepancies between the evaluation results and the actual situation of the distribution network when applied to power quality evaluation in the distribution network. Reference (Li et al., 2020) adopts a subjective-objective integrated weighting method based on an improved AHP and the coefficient of variation method for power quality assessment. The improved AHP and coefficient of variation method are used to determine the subjective and objective weights of each power quality indicator, respectively. Subsequently, the least squares method is employed to obtain the comprehensive weight values of each indicator. All the evaluation methods mentioned above determine the weights of indicators through a single weighting method, which lacks consideration for the preference orientation of each evaluation scheme. Even in the integrated weighting method, there may be unreasonable discrepancies between subjective and objective weights, leading to unreasonable final weights obtained through integrated weighting.

In response to the shortcomings of aforementioned methods and taking into account the network structure of ADN, this paper firstly conducts an importance assessment of nodes in ADN based on the complex network theory, and proposes incorporating node importance into the comprehensive evaluation of power quality indicators. Subsequently, this paper designs a novel method for power quality assessment in the distribution network by employing the G1 method and the CRITIC method, along with a two-stage approach. The G1 method addresses the drawbacks of AHP, while the two-stage approach, which is based on optimization theory, initially determines the weights of indicators. After considering decision-makers' subjective preferences and differences among evaluation schemes, in the second stage, it utilizes an optimization model to adjust the original indicator weights based

on the initial weights. This enables a more comprehensive consideration of subjective and objective weighting methods, thereby avoiding instances of "unfair weighting" (Jing and Hu, 2013). In the first stage, the G1 and CRITIC methods are employed to calculate subjective and objective weights respectively, which are then amalgamated to determine the comprehensive weights, reducing information loss during the weighting process. In the subsequent second stage, a least squares method is utilized to establish an optimization model for the indicator weights, determining the optimal weights. Finally, the effectiveness of the proposed method in assessing power quality in the new distribution network is validated through case studies using data from several power quality monitoring points.

2 The indicator framework for evaluating power quality in ADN

2.1 Power quality evaluation indicators

Power quality refers to the quality of alternating current supplied to the user side of the power grid. In general terms, power quality refers to the provision of high-quality power (Li et al., 2019). Ideally, electrical power is a perfectly symmetrical sine wave with a phase difference of 120°. However, in actual systems, deviations in waveform, frequency, and amplitude occur due to the growth of nonlinear loads such as air conditioning, the application of power electronic devices, issues such as electricity theft, etc., These deviations lead to deterioration in power quality, which in turn affects the safety of power supply and utilization.

The power quality standard is a fundamental set of criteria for electrical power established from the perspectives of the safe operation of the power grid and normal user utilization. Based on nationally issued power quality indicators combined with indicators proposed during the application process, there are dozens of power quality assessment indicators. Among them, temporary overvoltage and transient overvoltage are categorized as event-based power quality phenomena and are contingent in nature, making them difficult to measure in practical engineering. The commonly utilized power quality assessment indicators, as depicted in Figure 1, are organized across three principal dimensions: voltage, frequency, and waveform.

In addition, other commonly used power quality indicators include supply reliability, service indicators, user satisfaction, and non-national standard indicators. The operating environment, constituent devices, and existing issues vary among different systems, resulting in differences in the importance of power quality indicators. Therefore, when evaluating the power quality of different systems, power quality evaluation indicators should be selected based on their characteristics, which can make the evaluation results more closely aligned with the actual situation.

2.2 Analysis of factors affecting power quality in advanced distribution systems

Distribution network is an electricity grid that distributes electric power from transmission networks or power plants to various types of users through distribution facilities. In the context of the construction of a advanced power system, compared to traditional distribution networks, advanced distribution systems allow for the integration of distributed energy resources. The application of various communication and power electronics technologies enables active distribution networks to effectively manage various energy sources, efficiently incorporate clean energy, and achieve low-carbon operation. However, the increasing integration of distributed energy resources and power electronic devices can have a certain impact on the power quality of active distribution networks. The main influences include the following aspects:

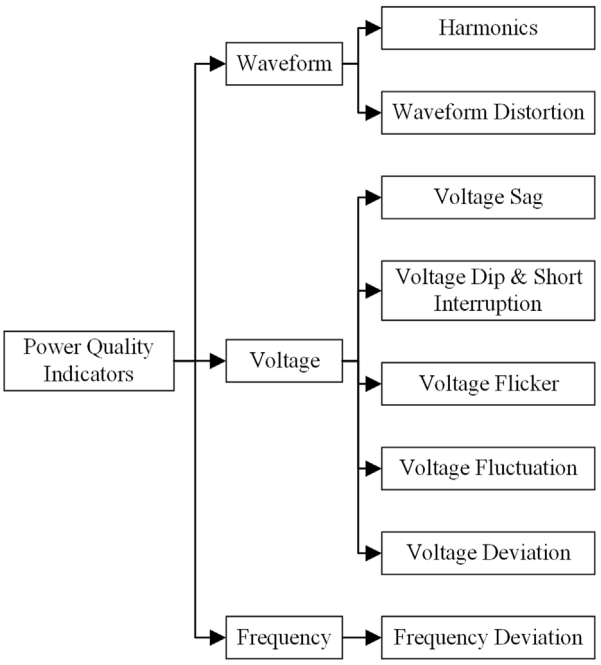

FIGURE 1
General power quality assessment indicator system.

- The fluctuating, stochastic, and intermittent characteristics of distributed energy sources such as wind power and photovoltaics can cause power imbalances between sources and loads in active distribution networks. During the process of connecting and disconnecting distributed energy sources from active distribution networks, surplus or deficient capacity may lead to voltage fluctuations, voltage sag, and other issues (Liang et al., 2003).
- Distributed energy sources typically connect to the distribution grid through power electronic devices, which inject a large amount of harmonic currents into the distribution grid. Moreover, when external environmental factors change significantly, such as fluctuations in photovoltaic generation, it can also lead to a sharp increase in the harmonic content injected into the grid (Hu et al., 2015).
- Nonlinear loads such as transformers, generators, and air conditioners, due to their nonlinear, impulsive, and unbalanced electrical characteristics, cause voltage distortion or voltage fluctuations and flicker in the power

grid (Luo et al., 2016; Hadi et al., 2023). Additionally, they contribute to harmonic and three-phase imbalance issues. Furthermore, the reactive power imbalance caused by nonlinear loads can also lead to voltage deviations and other problems (Li et al., 2023).

- The phenomenon of electricity theft in certain areas can lead to voltage dips and short interruptions in the distribution network.
- The complex topology of the advanced distribution system implies that fluctuations in power quality at one node may cause issues at several associated nodes. Therefore, nodes with higher importance should receive greater attention regarding their power quality issues.

2.3 Power quality evaluation indicators for advanced distribution system

Considering the factors affecting power quality in the advanced distribution system, the selected power quality evaluation indicators are as follows:

1) Node Importance: For different complex network models, studying the characteristics of complex network model properties using newly defined or existing complex network topology attributes is one of the hotspots in network science research. In power networks, considering directed flow with the flow of power, the power network can be considered as a directed network. For directed networks, node modeling can be achieved by calculating the node degree parameters, and then node importance can be obtained through certain algorithms. Nodes with higher importance are the ones that need to be emphasized in power quality management.
2) Voltage deviation: the main cause of voltage deviation is the imbalance of reactive power in the system. For example, appliances like air conditioners consume a large amount of reactive power, resulting in an imbalance between active and reactive power, which in turn leads to a decrease in grid voltage and voltage deviation. Excessive voltage deviation can pose a threat to the stable operation of the power system, and electrical equipment may also be damaged due to overvoltage.
3) Voltage fluctuation: the integration of a high proportion of distributed energy sources such as wind power and photovoltaics into advanced distribution networks often exhibits significant randomness, variability, and intermittency. Large-scale integration may lead to voltage fluctuations in the active distribution network, resulting in voltage flicker phenomena. Voltage fluctuations can accelerate the aging of equipment insulation, shorten equipment lifespan, increase grid losses, and undermine the safety of grid operation.
4) Voltage sag: voltage sag is a short-term disturbance phenomenon that occurs in advanced distribution networks, primarily due to sudden large currents. Line and bus short-circuit faults, no-load excitation of large transformers, and large load switching can all lead to this issue. Additionally, voltage sag can be caused by switching issues in certain areas.
5) Three-phase voltage imbalance: nonlinear loads in the power system inject a large amount of harmonic currents into the active distribution network, resulting in three-phase imbalance issues. Three-phase imbalance increases line and distribution transformer losses, leading to severe transformer heating. For users, three-phase imbalance issues can easily cause electrical equipment connected to the phase with high voltage to burn out, while electrical equipment connected to the phase with low voltage may not be useable, significantly affecting the safe use of electrical equipment. Therefore, considering three-phase imbalance issues is essential.
6) Harmonics: with the informatization and intelligence of active distribution networks, the operation of active distribution networks requires the participation of power electronic devices. The integration of nonlinear devices such as power electronic devices can lead to significant harmonic issues. Harmonics can result in increased transmission line losses, overheating of electrical equipment, increased additional losses, and reduced efficiency and durability of equipment.
7) Frequency deviation: the frequency of the power system remains constant only when the total active power output of all generators equals the total active load. For advanced distribution systems, the proportion of renewable energy on the power source side is high, and the output is fluctuating. Meanwhile, the load varies in real-time, resulting in an imbalance in the total system power and causing frequency fluctuations. Excessive frequency fluctuations can threaten the safety of user appliances, cause new energy sources such as wind power to operate abnormally or even disconnect from the grid, thereby leading to other cascade failures in the advanced distribution network.

Due to the rare occurrence of issues such as waveform distortion in advanced distribution networks, they are not considered in the power quality assessment process for advanced distribution networks. Therefore, the power quality assessment indicators adopted in this paper are voltage deviation, voltage fluctuation, voltage sag, three-phase imbalance, harmonics, frequency deviation, and node importance.

2.4 Framework of power quality assessment for ADN

This article first proposes a calculation method for complex network parameters and node importance parameters, and proposes to combine node importance parameters with power quality indicators as the power quality evaluation index matrix. Subsequently, the comprehensive assessment method of power quality was introduced: firstly, the power quality data was standardized, and the subjective and objective weights were calculated using G1 method and CRITIC method respectively. Then, the combined weighting method was used to obtain the comprehensive weight, and the final weight was optimized using a two-stage method with the comprehensive weight as the initial weight. The overall framework of this paper is depicted in Figure 2.

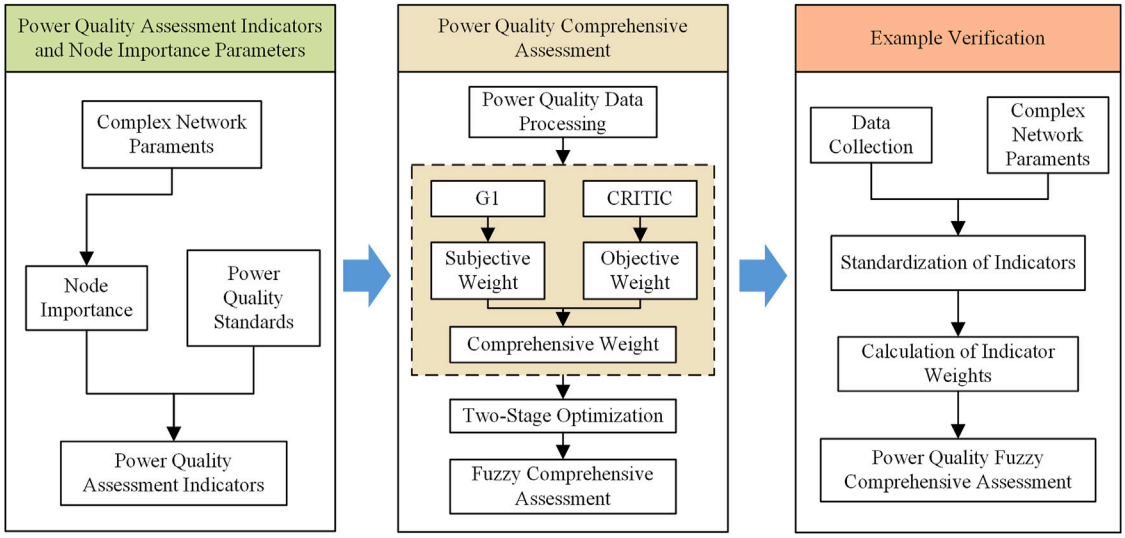

FIGURE 2
The schematic diagram of two-stage comprehensive assessment framework for power quality in ADN based on complex network theory.

3 Evaluation of node importance in power networks based on complex network theory

In the power network, nodes mainly consist of power plants, substations, and converter stations, among other facilities, while the lines between two nodes represent the power lines connecting them. For a given power network model, the complex network characteristics of the power network can be analyzed based on complex network theory, and a matrix describing the characteristic indicators of each node in the power network can be established. The CRITIC weighting method is used to calculate the comprehensive decision values of the importance of each node in the power network, which are then involved in the process of comprehensive assessment of power quality.

3.1 Calculation of power network node parameters based on complex network theory

Complex networks are a perspective and method for studying complex systems. Therefore, analyzing the properties, functions, and relationships of nodes in a power network through node degree centrality, betweenness centrality, and eigenvector centrality reflects the characteristics of various nodes in the system. The specific calculation methods are as follows (Liu W. et al., 2018):

1) Degree Centrality (Degree): The degree of a node in a power network is denoted as $d_g^+(v_i^p)$, indicating the number of nodes directly connected to a certain node. Considering the directed nature of power flow in the power network, the degree of directed network nodes can be divided into out-degree and in-degree. The number of links starting from node v_i^p is defined as the out-degree $d_g^+(v_i^p)$, and the number of links ending at the node v_i^p is defined as the in-degree $d_g^-(v_i^p)$. The centrality degree of nodes in a power network is defined as Equation 1:

$$d_g(v_i^p) = \frac{1}{2} \times \left(d_g^+(v_i^p) + d_g^-(v_i^p)\right) \tag{1}$$

2) Betweenness Centrality: To accurately characterize the influence and utilization of nodes in the network, the calculation method for node betweenness centrality is as Equation 2:

$$B_i = \sum_{j \neq k} \frac{\delta_{jk}(i)}{\delta_{jk}} \tag{2}$$

where δ_{jk} represents the number of shortest paths from node v_j to node v_k in the network using the shortest path algorithm, while $\delta_{jk}(i)$ represents the number of paths passing through node v_i in δ_{jk}. For a directed power network, the calculation of out-degree and in-degree is completed based on the Dijkstra algorithm.

3) Eigenvector Centrality: The importance of nodes in a power network depends not only on their own degrees but also on the importance of their neighboring nodes. In a power grid, the more edges that lead to a node, the higher its importance. Therefore, this node will pass on higher importance to its neighboring nodes connected by directed edges. The eigenvector centrality in a directed network can be calculated using the PageRank algorithm, and its calculation formula is shown in Equation 3:

$$E_C(v_i^p) = (1-d) + d \sum_{v_j^p \in T_i} \left(E_C(v_j^p) \Big/ d_g^+(v_j^p)\right) \tag{3}$$

where T_i is the set of all nodes in the directed network that have directed edges pointing to node i; $d_g^+(v_j^p)$ is the out-degree of node j; d is the damping coefficient, generally taken as 0.85.

According to the above formula, for any node in a power grid with a known topology, its characteristic matrix can be constructed.

The set of samples $S = \{S_i\}(i = 1, 2, \cdots, m)$ consists of m samples from the electric power quality monitoring points, and the set $G = \{g_j\}(j = 1, 2, \cdots, n)$ consists of n complex network node parameter indicators. In this paper, n is set to 3, and each node sample corresponds to n complex network node parameters. The matrix $\Psi_{m\times n}$ of node characteristic indicators for a power network with m nodes can be obtained with Equation 4:

$$\Psi_{m\times n} = \begin{bmatrix} \psi_1^1 & \cdots & \psi_1^j \\ \vdots & \ddots & \vdots \\ \psi_i^1 & \cdots & \psi_i^j \end{bmatrix} \tag{4}$$

where ψ_i^j is the jth node importance characteristic value of the ith monitoring point.

This node characteristic indicator matrix will serve as the evaluation parameter for the importance of power network nodes and will be involved in the calculation of certain assessment indicators (Wang Z. et al., 2022).

3.2 Calculation of node importance in power networks

The node indicator matrix Ψ reflects the network characteristics of various nodes in the power network. Considering that the importance of nodes is determined by their position in the network, the CRITIC method is adopted to assess the node importance to reflect its objectivity. The CRITIC method is an objective weighting method based on the comparison strength of evaluation indicators and the conflict between indicators to comprehensively measure the weights of indicators. The CRITIC method can eliminate the influence between indicators with strong correlation, reduce the redundancy of information between indicators, and obtain more scientifically credible evaluation results. The specific steps are outlined below:

1) Data Standardization: For a power network with m nodes in its network topology, node parameter calculations are performed, resulting in the node indicator matrix $\Psi_{m\times n}$. The initial data is processed using Equation 5 to uniformly process the initial data matrix, resulting in the standardized node characteristic indicator matrix $Y = (y_{ij})_{m\times n}$ shown in Equation 6.

$$y_{ij} = \frac{\psi_{ij}}{max\,\psi_j} \tag{5}$$

$$Y = \begin{bmatrix} y_{11} & \cdots & y_{1n} \\ \vdots & \ddots & \vdots \\ y_{m1} & \cdots & y_{mn} \end{bmatrix} \tag{6}$$

where ψ_{ij} is the jth node importance feature value of the ith node object, where $i = 1, \cdots, m$, $j = 1, 2, 3$, m represents the quantity of evaluation objects, $max(\psi_j)$, $min(\psi_j)$ are respectively the highest and lowest values of different node feature data under the same node feature indicator. y_{ij} is the standardized data value after processing the jth node feature indicator of the ith evaluation object.

2) Indicator Coefficient of Variation: The coefficient of variation quantitatively displays contrast strength of indicators. The procedure to compute the coefficient of variation v_j is shown in Equations 7–9:

$$v_j = \frac{s_j}{\bar{y}_j} \tag{7}$$

$$\bar{y}_j = \frac{1}{m}\sum_{i=1}^{m} y_{ij} \tag{8}$$

$$s_j = \sqrt{\frac{\sum_{i=1}^{m}\left(y_{ij} - \bar{y}_j\right)^2}{m-1}} \tag{9}$$

where s_j is the standard deviation of the jth feature indicator, and $\bar{y}_j$ is the mean value of the jth feature indicator.

3) Conflict Measurement of Indicators: Based on the standardized matrix $Y = (y_{ij})_{m\times n}$, calculate the correlation coefficient r_{ij} between the ith and jth indicators using Equation 10, then calculate the quantified conflict value A_j as shown in Equation 11:

$$A_j = \sum_{i=1}^{n}\left(1 - r_{ij}\right) \tag{10}$$

$$r_{ij} = \frac{Cov\left(y_i^*, y_j^*\right)}{S_i S_j}, i, j = 1, 2, \cdots, n \tag{11}$$

where y_i^*, y_j^* are the covariance for the ith and jth columns of $Y = (y_{ij})_{m\times n}$.

4) Information Quantity Calculation: employ Equation 12 to evaluate the information quantity E_j:

$$E_j = v_j \times A_j \tag{12}$$

5) Objective Weighting of Feature Indicators: Standardize the information quantity to derive the weight θ_j^* of the jth indicator as shown in Equation 13:

$$\theta_j^* = \frac{E_j}{\sum_{j=1}^{n} E_j} \tag{13}$$

According to the above calculations, the set of node importance indicator weights is denoted as θ^*. The node importance decision value for each node can be calculated using Equation 14:

$$F_i = \sum_{j=1}^{n} \theta_j^* y_{ij} i = 1, 2, \cdots, m \tag{14}$$

Where F_i represents the node importance decision value of the ith node

4 Method for comprehensive weight calculation of power quality indicators in advanced distribution networks based on two-stage approach

The current common method for assigning weights to power quality data indicators is the subjective-objective integrated

TABLE 1 The relative importance ratio r_k between evaluation indicators.

r_k	Scale significance
1.0	x^*_{k-1} is equally important as x^*_k
1.2	x^*_{k-1} is slightly more important than x^*_k
1.4	x^*_{k-1} is more important than x^*_k
1.6	x^*_{k-1} is significantly more important than x^*_k
1.8	x^*_{k-1} is extremely more important than x^*_k
1.1, 1.3, 1.5, 1.7	The intermediate value of the aforementioned adjacent judgments

weighting method. Building upon this, the paper adopts the two-stage approach for assigning weights to power quality indicators. This chapter will commence by utilizing the G1 method and CRITIC method to arrive at the subjective, objective, along with integrated weights. Subsequently, the principle of the two-stage weighting method will be introduced.

4.1 First-stage indicator weighting

4.1.1 Subjective weights calculation based on G1 method

The commonly used method for subjective weighting is AHP, but this method is prone to issues with judgment matrices not meeting consistency requirements. Therefore, this paper adopts an improved AHP method—the G1 method—to circumvent the shortcomings of the AHP. The G1 method relies on expert subjective experience to determine the weight of each indicator based on its importance. Experts can rank and quantify the importance of indicators based on the characteristics and knowledge of active distribution networks. The detailed steps for computing subjective weights using the G1 method are as follows:

1) Determining the sequence relationship of evaluation indicators: The evaluation set $X = \{x_1, x_2, ..., x_n\}$ consists of n power quality evaluation indicators. In the case where the significance of evaluation indicator x_i exceeds that of x_j, it is denoted as $x_i > x_j$. Rearrange the indicators in descending order of significance to establish the sequence relationship of the indicators as $x^*_1 > x^*_2 > x^*_3 > \cdots > x^*_n$, where x^*_i represents the ith indicator after sorting by importance.
2) Determining the relative importance ratio between evaluation indicators as shown in Equation 15: Rational judgment ratios r_k between adjacent indicators x^*_{k-1} and x^*_k based on their importance are determined according to Table 1.

$$r_k = w^*_{k-1} / w^*_k (k = n, n-1, \cdots, 3, 2) \tag{15}$$

where w^*_{k-1} and w^*_k respectively represent the weighting coefficients of indicators x^*_{k-1} and x^*_k, and the value of r_k is determined as shown in Table 1.

3) Calculating the subjective weights of evaluation indicators: Based on the determined r_k, use Equation 16 to calculate the weight of the nth evaluation indicator.

$$w^*_n = \left[1 + \sum_{k=2}^{n} \left(\prod_{i=k}^{n} r_i \right) \right]^{-1} \tag{16}$$

The weight of the *(k-1)*-th indicator is shown in Equation 17:

$$w^*_{k-1} = r_k w^*_k, k = n, n-1, \ldots, 3, 2 \tag{17}$$

4.1.2 Objective weight calculation based on CRITIC method

The procedure for determining objective weights using CRITIC method is detailed in Section 2.2.

4.1.3 Integrated weight calculation

To mitigate the potential over-reliance on expert opinions stemming from single subjective weighting approach, as well as the excessive focus on quantitative analysis of sample data and neglect of subjective qualitative analysis, this paper adopts a combined weighting method. This integrated method leverages both subjective weighting (G1) and objective weighting (CRITIC) to compute the comprehensive weight λ, as shown in Equation 18:

$$\lambda = \left[\frac{\sqrt{\theta_1 \omega_1}}{\sum_{j=1}^{n} \sqrt{\theta_j \omega_j}} \quad \frac{\sqrt{\theta_2 \omega_2}}{\sum_{j=1}^{n} \sqrt{\theta_j \omega_j}} \cdots \frac{\sqrt{\theta_n \omega_n}}{\sum_{j=1}^{n} \sqrt{\theta_j \omega_j}} \right] \tag{18}$$

where ω represents the subjective weight calculated using G1 method, and θ denotes the objective weight derived from CRITIC method.

4.2 Two-stage weighting

The two-stage optimization method can more effectively handle the relationship between multidimensional data and indicators through the optimization calculation process, thereby improving the accuracy and reliability of overall evaluation. By obtaining the expected weight value of this scheme based on the given initial weight, and then optimizing the calculation with the goal of minimizing the deviation, it can avoid the situation where the subjective and objective deviation values of certain indicators are too large during the comprehensive weighting process, resulting in unreasonable weighting.

In the first stage, corresponding sets of indicator weights are obtained through subjective weighting, objective weighting, and comprehensive weighting methods. Referring to the two-stage optimization method in reference (Jing and Hu, 2013), the weights obtained from any weighting method as initial weights x_j are used to calculate the expected weight value ω_j of the jth indicator at the ith monitoring point by using Equation 19:

$$\omega_j^{(i)} = \frac{x_j y_{ij}}{\sum_{j=1}^{n} x_j y_{ij}} \tag{19}$$

The comprehensive decision value of the evaluation object S_i is calculated using a weighting method and obtained as Equation 20

$$f_i = \sum_{j=1}^{n} \omega_j^{(i)} y_{ij} \tag{20}$$

According to the purpose of the two-stage method, assuming that there exists a weight ω_j for the final evaluation indicators that minimizes the difference between the comprehensive decision values and the sum of all comprehensive values f_i for all samples, as expressed in Equation 21:

$$\min \sum_{i=1}^{m} \sum_{j=1}^{n} \omega_j y_{ij} - \sum_{i=1}^{m} f_i \tag{21}$$

An optimization model for indicator weights is established using the least squares method as Equation 22:

$$\begin{aligned} \min & \sum_{i=1}^{m} \sum_{j=1}^{n} \left(\omega_j - \omega_j^{(i)}\right)^2 y_{ij}^2 \\ \text{s.t.} & \sum_{j=1}^{n} \omega_j = 1 \\ & \omega_j \geq 0 \end{aligned} \tag{22}$$

The final solution obtained is $W = [\omega_1, \omega_2, \cdots, \omega_n]$, which represents the optimal weight values for each indicator sought.

5 Quantitative evaluation and fuzzy comprehensive judgment of power quality data in advanced distribution networks

5.1 Quantification of power quality evaluation indicators

Commencing a fuzzy comprehensive judgment necessitates, as the primary step, specifying the factor set T and the evaluation set V. Through analysis, the power quality evaluation indicators selected in this study are voltage deviation, voltage fluctuation, voltage sag, three-phase imbalance, harmonics, frequency deviation, and the comprehensive decision value of node importance, which constitute the factor set T:{T_1 (voltage deviation), T_2 (voltage fluctuation), T_3 (voltage sag), T_4 (three-phase imbalance), T_5 (harmonics), T_6 (frequency deviation), T_7 (comprehensive decision value of node importance)}.

This paper defines five distinct levels of power quality, thereby establishing a five-level fuzzy judgment set V: {V_1 (excellent power quality), V_2 (good power quality), V_3 (average power quality), V_4 (poor power quality), V_5 (very poor power quality)}.

Quantitative grading results of the quality of electrical energy in the new distribution network are obtained through the fuzzy judgment set of evaluation indicators, as shown in Table 2.

The evaluation set V obtained from the above table is shown as Equation 23:

$$\begin{aligned} V &= [\text{excellent good average poor very} - \text{poor}] \\ &= [9\,5\,8\,0\,7\,0\,5\;\;4\,0] \end{aligned} \tag{23}$$

5.2 Selection of membership functions

The membership of data in the judgment indicator matrix corresponding to different evaluation comments can be calculated using membership functions. This paper adopts the Gauss-type membership function $f(y)$ which is expressed below:

$$f(y) = e^{-\frac{(y-c)^2}{2\sigma^2}} \tag{24}$$

where y is the data of the active distribution network power quality evaluation index, σ and c are 2 parameters of the Gauss membership function. In this paper, σ is taken as 0.3, The parameter c signifies the center location of the membership function, and the paper uses five c values: $c_1 = 1$, $c_2 = 0.75$, $c_3 = 0.5$, $c_4 = 0.25$, $c_5 = 0$, to ensure that each index has five evaluation comment memberships.

Substituting parameters σ and c into Equation 24 yields the membership calculation formulas relevant to the five judgment sets. By substituting index y_{ij} from the evaluation index matrix Y into the membership functions for the five judgment levels, we obtain the judgment matrix F as Equation 25:

$$F_1 = \begin{bmatrix} f_{V_1}(y_{i1}) & \cdots & f_{V_5}(y_{i1}) \\ \vdots & \ddots & \vdots \\ f_{V_1}(y_{in}) & \cdots & f_{V_5}(y_{in}) \end{bmatrix} \tag{25}$$

where $f_{V_k}(y_{ij})(k = 1, 2, \cdots, 5;\ j = 1, 2, \cdots, n)$ represents the membership degree of evaluation index y_{ij} to judgment level V_k.

5.3 Fuzzy comprehensive evaluation of power quality in ADN

The paper employs $M(\cdot, \oplus)$ operator (weighted average fuzzy comprehensive operator) to conduct fuzzy multiplication operations on the weights and the judgment matrix, obtaining *en bloc* power

TABLE 2 Quantitative grading of electrical energy quality evaluation results.

Grade	Power quality	Rating intervals	Quantified scores
V_1	Excellent	(85,100]	95
V_2	Good	(75,85]	80
V_3	Average	(60,75]	70
V_4	Poor	(50,60]	55
V_5	Very poor	(0,50]	40

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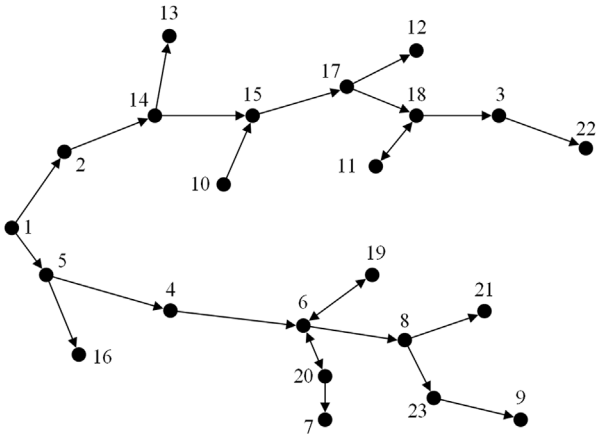

FIGURE 3
Distribution network topology diagram.

quality assessment in advanced distribution networks, as shown in Equation 26 below:

$$B_i = \left[b_i(V_1) \;\; b_i(V_2) \;\; b_i(V_3) \;\; b_i(V_4) \;\; b_i(V_5) \right] \tag{26}$$

where $b_i(V_k) = \sum(\omega_i \cdot f_{V_1}(y_{i1}))$, $b_i(V_k)$ represents the degree of membership of each power quality indicator relative to the evaluation grade V_k.

Finally, the quantified evaluation result is calculated using the method shown in Equation 27:

$$Z_i = \sum_{k=1}^{n} b_i(V_k) \times V_k \tag{27}$$

Based on the computed power quality evaluation results and the corresponding quantified grading intervals for power quality, the evaluation comments for the power quality of the advanced distribution network are obtained.

6 Case study

This paper calculates the distribution network system's topology parameters and its power quality parameters as shown in Figure 3.

6.1 Calculation of comprehensive decision value for complex network node importance

The centrality metrics, including degree centrality, betweenness centrality, and eigenvector centrality, for each node calculated using the method described in Chapter 2 of this paper are presented in Table 3. The comparison of feature indicator values for each node is illustrated in Figure 4.

The node characteristic indicator matrix $\Psi_{m\times n}$ is obtained by collecting the parameters of each node. Through the analysis of $\Psi_{m\times n}$ using the CRITIC method, the weights of each indicator θ^* are obtained:

$$\theta^* = \left[0.2057 \;\; 0.5249 \;\; 0.2694 \right]$$

The calculated comprehensive decision values of each node's importance are shown in Figure 5.

From Figure 5, it can be seen that nodes such as node 6, 8, and 17, which are centrally located in the distribution system, have higher comprehensive decision values for node importance. The electrical quality of these nodes has a significant impact on the electrical quality of nodes directly or indirectly connected to them, hence their higher importance comprehensive decision values.

6.2 Electrical quality data processing and indicators weight calculation

Combining the comprehensive decision values of node importance obtained in Section 5.1 with the measured electrical quality data, Table 4 displays the power quality data matrix for each individual node.

TABLE 3 Indicators of each node.

Node number	Degree	Betweenness	Eigenvector centrality	Node number	Degree	Betweenness	Eigenvector centrality
1	1	0	0.0170	13	0.5	0	0.0331
2	1	0.0195	0.0243	14	1.5	0.0346	0.0377
3	1	0.0173	0.0543	15	1.5	0.0519	0.0475
4	1	0.0346	0.0274	16	0.5	0	0.0274
5	1.5	0.0216	0.0243	17	1.5	0.0541	0.0574
6	3	0.0693	0.0971	18	2	0.0433	0.0876
7	0.5	0	0.0360	19	1	0	0.0445
8	1.5	0.0390	0.0445	20	1.5	0.0108	0.0445
9	0.5	0	0.0476	21	0.5	0	0.0360
10	0.5	0	0.0170	22	0.5	0	0.0632
11	1	0	0.0543	23	1	0.0152	0.0360
12	0.5	0	0.0415				

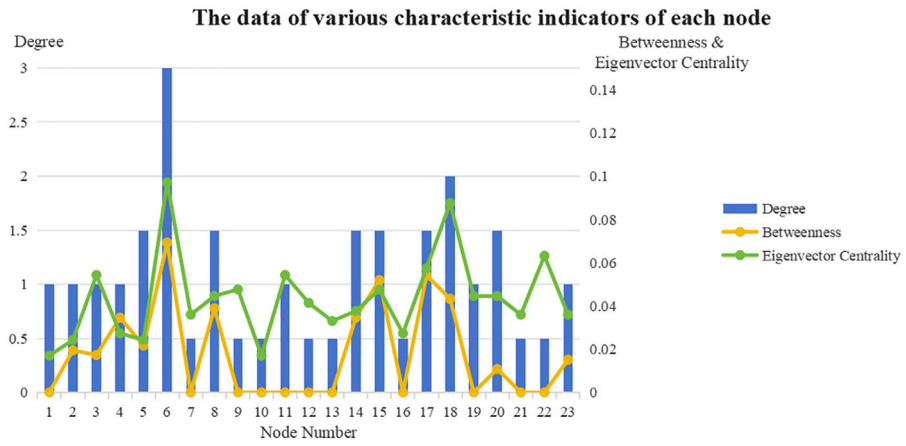

FIGURE 4
The data of various characteristic indicators of each node.

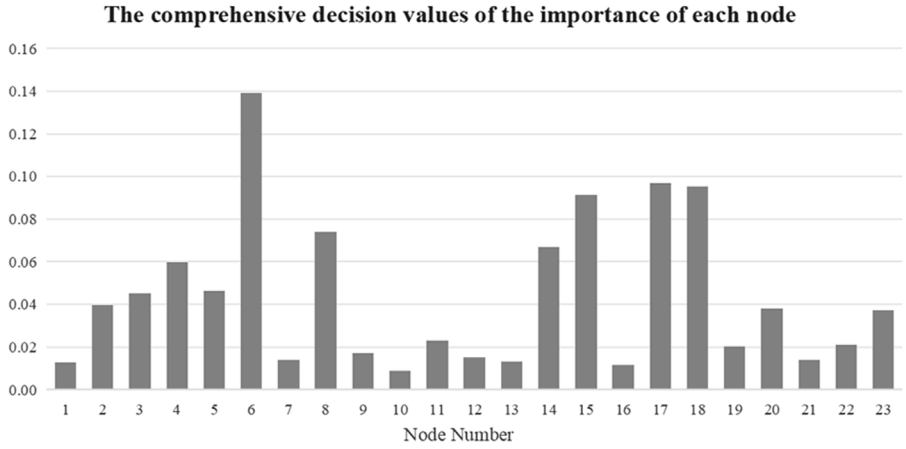

FIGURE 5
The comprehensive decision values of the importance of each node.

According to opinions of experts, the evaluation indicators for the electric power quality of the new distribution network are ranked in descending order of importance as follows:

Voltage deviation > Harmonics > Voltage fluctuation > Three-phase imbalance > Voltage sag > Frequency deviation = Node importance.

The ratio of importance levels is: $r_2 = 1.3$, $r_3 = 1.6$, $r_4 = 1.2$, $r_5 = 1.2$, $r_6 = 1.2$, $r_7 = 1.0$.

The subjective weight, objective weight, and comprehensive weight values obtained using the method described in this paper are as follows:

$$\omega = [\,0.2824 \;\; 0.1358 \;\; 0.0943 \;\; 0.1131 \;\; 0.2172 \;\; 0.0786 \;\; 0.0786\,]$$
$$\theta = [\,0.1386 \;\; 0.1443 \;\; 0.1338 \;\; 0.1197 \;\; 0.1405 \;\; 0.1468 \;\; 0.1603\,]$$
$$\lambda = [\,0.2045 \;\; 0.1447 \;\; 0.1161 \;\; 0.1303 \;\; 0.1774 \;\; 0.1110 \;\; 0.1160\,]$$

The final weight obtained after optimization through the two-stage algorithm starting with the comprehensive weight λ is:

$$W = [\,0.2831 \;\; 0.1003 \;\; 0.1558 \;\; 0.1111 \;\; 0.1378 \;\; 0.1092 \;\; 0.1026\,]$$

The data from various monitoring points in Figure 3 are subjected to fuzzy comprehensive assessment, resulting in judgment matrices for each monitoring point. Using the weighted average operator for overall evaluation, the fuzzy assessment scores for each monitoring point are calculated using Equation 27.

The power quality assessment values considering and not considering the node importance are shown in Figure 6:

6.3 Analysis of results

Based on the comparison of scores shown in Figure 6, for nodes with high importance, such as nodes 6, 8, 15, and 18, the scores after considering node importance are lower than those without considering importance. However, for nodes with lower importance, such as nodes 7, 10, and 13, there is no significant decrease or increase in scores before and after considering importance. The evaluation results obtained using different methods are compared based on the score rating, as shown in Table 5.

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TABLE 4 The matrix of power quality data.

Node number	Voltage deviation/ %	Voltage fluctuation/ %	Voltage sag/%	Three-phase imbalance/%	Harmonics/ %	Frequency deviation/%	Comprehensive decision value of node importance
1	2.5300	0.9600	53.1200	0.8800	1.1200	0.1300	0.0128
2	2.0100	0.8500	23.5400	0.5800	0.8200	0.2500	0.0396
3	1.6600	1.0500	65.2300	1.0700	1.2600	0.1700	0.0449
4	1.9500	0.8000	26.4200	0.4600	0.7700	0.1000	0.0598
5	3.0500	1.0700	68.5100	0.5400	0.9400	0.0700	0.0465
6	1.2200	0.5500	31.0400	0.4600	0.7500	0.0900	0.1392
7	2.5400	1.0100	55.5400	0.7100	0.8200	0.1600	0.0138
8	1.6600	0.8500	57.2300	0.4300	0.8700	0.2200	0.0741
9	2.3400	0.9400	34.8200	0.8000	1.0200	0.3100	0.0169
10	1.5200	0.8700	31.9200	0.7400	0.7500	0.1800	0.0087
11	2.4300	0.9100	50.4200	0.9000	0.9900	0.3000	0.0228
12	2.0900	0.8600	25.7900	0.6100	0.7300	0.1900	0.0153
13	1.5600	1.0300	59.2300	1.0000	1.0700	0.2200	0.0130
14	2.9200	0.9800	61.0700	1.0300	1.0900	0.1800	0.0667
15	1.7600	1.1500	61.0100	1.0200	1.1000	0.2500	0.0915
16	1.7000	1.0200	59.2300	0.9700	1.0600	0.2900	0.0115
17	2.0000	0.8500	26.7800	0.6300	0.8200	0.1400	0.0969
18	1.9100	0.9900	60.5600	0.7700	0.8500	0.0900	0.0953
19	1.6500	0.9100	41.8200	0.9800	1.0700	0.0800	0.0202
20	1.2700	0.7600	59.9800	0.9700	0.9600	0.1900	0.0382
21	1.4800	0.8900	61.8400	0.8300	1.0000	0.0800	0.0138
22	2.0000	0.7200	46.8200	0.9900	0.7900	0.1000	0.0211
23	1.7300	1.0600	61.3900	0.8300	1.0100	0.0900	0.0373

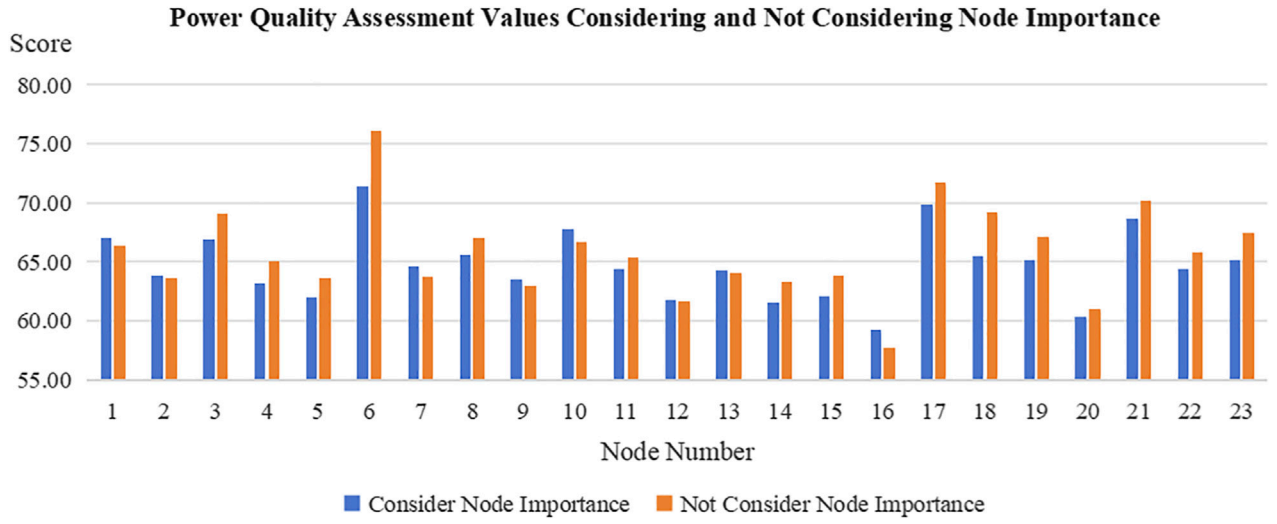

FIGURE 6
Power quality evaluation values considering and not considering the node importance.

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TABLE 5 Comparison of different methods.

Assessment methods	Two-stage weighting (consider node importance)	Two-stage weighting (not consider node importance)	Integrated weighting (consider node importance)	Integrated weighting (not consider node importance)
1	V_3	V_3	V_3	V_3
2	V_3	V_3	V_3	V_3
3	V_3	V_3	V_3	V_3
4	V_3	V_3	V_3	V_3
5	V_3	V_3	V_3	V_3
6	V_3	V_2	V_3	V_2
7	V_3	V_3	V_3	V_3
8	V_3	V_3	V_3	V_3
9	V_3	V_3	V_3	V_3
10	V_3	V_3	V_3	V_3
11	V_3	V_3	V_3	V_3
12	V_3	V_3	V_3	V_3
13	V_3	V_3	V_4	V_3
14	V_3	V_3	V_3	V_3
15	V_3	V_3	V_3	V_3
16	V_4	V_4	V_4	V_4
17	V_3	V_3	V_3	V_3
18	V_3	V_3	V_3	V_3
19	V_3	V_3	V_3	V_3
20	V_3	V_3	V_3	V_3
21	V_3	V_3	V_3	V_3
22	V_3	V_3	V_3	V_3
23	V_3	V_3	V_3	V_3

As evident from Table 5, the results of the two-stage power quality assessment method, which accounts for node importance, align generally with the findings of other evaluation approaches, thereby validating the adaptability of this technique.

In the evaluations using both the two-stage weighting method considering node importance and the subjective-objective comprehensive weighting method, for Node 13, the weighting values for voltage fluctuation by both subjective and objective weights are close, leading to an overflow of the comprehensive weight for voltage fluctuation when only one comprehensive calculation is performed. However, after optimizing the weights in the two-stage method, the weights return to a reasonable range, aligning better with the principle of balancing subjective and objective weights and resulting in a more reasonable score. In the evaluations using both the two-stage weighting method considering node importance and the subjective-objective comprehensive weighting method, the rating for Node 6 is consistent, whereas the ratings for Node 6 in the two methods that do not consider node importance tend to increase due to the lack of constraint from the node importance indicator.

7 Conclusion

This article proposes a two-stage comprehensive evaluation method for power quality considering the ADN network structure. Firstly, based on the theory of complex networks, the degree centrality, betweenness centrality, and eigenvector centrality of each node were comprehensively analyzed to quantify the importance of each node in the network. Subsequently, the decision values of node importance were added to the comprehensive evaluation process of power quality, and a two-stage weighting method was introduced to make the final weight values more reasonable.

The evaluation results of the case study validate the effectiveness of the proposed method. Through complex network theory, the method can distinguish the importance levels of different nodes in complex distribution network, and the final weights are made more reasonable through a two-stage weighting method. It imposes stricter evaluation on important nodes, facilitating effective assessment and targeted optimization of power quality in complex network environments for operators.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

JZ: Writing–original draft, Writing–review and editing. RC: Writing–original draft, Writing–review and editing, Methodology, Validation. ZZ: Writing–original draft, Writing–review and editing, Conceptualization. XW: Writing–original draft. JX: Supervision, Writing–review and editing.

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Conflict of interest

Authors ZJ, CR, ZZ, WX, and XJ were employed by State Grid Fujian Economic Research Institute.

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