Steady-State Power Quality Synthetic Evaluation Based on the Triangular Fuzzy BW Method and Interval VIKOR Method

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Abstract: With the increasing consumption of fossil fuels, renewable sources power generation has attracted more and more attention. However, with the integration of renewable energy and a large number of non-linear loads in power systems, several power quality problems are attracting the attention of researchers. At present, only national standards for an individual power quality index have been set in China. When evaluating power quality in practice, the individual standard cannot reflect a comprehensive level of power quality. In this paper, a synthetic evaluation method for steady-state power quality is proposed. Firstly, the traditional BW (best-worst) method is improved based on the triangular fuzzy number, to obtain the interval weight of each evaluation index. Then, the interval VIKOR method is used to evaluate the steady-state power quality monitoring data, and the final evaluation results are obtained. The validity of the proposed method is verified by the experimental data from the dynamic simulation laboratory of Tianjin University.

Keywords: power quality; synthetic evaluation; triangular fuzzy number; interval weight; interval VIKOR

1. Introduction

In the current world, with the development of various undertakings, the demand for electric power is growing. Renewable energy will become the main energy source in the future due to the depleting nature of fossil fuels, cost, and environmental issues. Massive application of renewable distributed generation is an effective way to solve global energy and environmental problems [1,2]. China has achieved fruitful results in photovoltaic power generation and other renewable energy fields [3]. However, these renewable sources power generation systems may cause power quality problems such as frequency deviation, voltage fluctuation, voltage flicker, and harmonic distortion when they are integrated into a power system. At present, China has established national standards and specific requirements for an individual index of power quality, but they cannot reflect the comprehensive level. Therefore, it is imperative to establish a comprehensive assessment method of power quality in order to ensure the reliability and safety of the power system. At the same time, it also has great significance for the reasonable formulation of electricity price in the power market.

To date, some methods have been proposed for comprehensively evaluating the power quality of systems, including distributed power generation such as photovoltaic. However, existing methods have some shortcomings when applied.

In [4–6], the probabilistic evaluation model is established to evaluate the power quality. However, in [4], computing probabilistic power flows requires very complicated programming. When the methods in [5,6] use the fuzzy evaluation method to determine the membership function, the results are greatly affected by human factors. The evaluation results will vary with the change of membership
functions. In [7], the combination of improved analytic hierarchy process (IAHP) and entropy method is proposed to obtain the weights of the indices, adopting the gray correlation analysis method to evaluate the photovoltaic grid-connected power station, but different people’s process of parameters such as resolution coefficients in the gray correlation method may be inconsistent. Catastrophe decision theory is applied in [8] to evaluate the power quality; the method does not need to determine the weight of indices, but it relies too much on the establishment of the index system. The artificial neural network method needs to collect many samples to train the network. If the sample size is not large enough, it will reduce the accuracy of the evaluation results [9]. In [10–12], the authors used accelerated genetic algorithms to improve the Shepard interpolation theory and projection pursuit method, obtaining reasonable evaluation results. However, these methods are complex and unsuitable for unified evaluation of many evaluation objects [13]. In addition, in [14], the classified evaluation method is applied, adopting the least squares support vector machine (LSSVM) theory to evaluate power quality. An improved principal component analysis method combined with the combination weight is proposed in [15] to evaluate power quality of the steady-state photovoltaic grid connection and to draw conclusions. There are also some publications using fuzzy theory to assess the steady-state power quality [16–18], and an adaptive fuzzy neural theory is proposed in [19] to evaluate the power quality. However, there is still no universally recognized and authoritative comprehensive assessment method of power quality in the world.

To achieve a reasonable approach for setting comprehensive assessment of steady-state power quality, two problems need to be solved. One is to determine the weight of each index, and the other is to process the power quality indicator data. Most existing studies have used crisp numbers to determine the weights of various indicators. This may have produced different results due to the different experience and preferences of decision-makers. This situation also occurs in the use of membership functions. Based on this question, this paper proposes a novel method to improve the comprehensive assessment of steady-state power quality. In this paper, a comprehensive steady-state power quality assessment system is established based on China’s national standards. Then, the traditional best-worst (BW) method is improved by using triangular fuzzy numbers, and a triangular fuzzy BW method is obtained to determine the interval weight of each steady-state power quality index. Next, the value of priority performance index (PPI) of the daily power quality monitoring value is calculated by the interval VIKOR method with the obtained interval weight. Finally, comparing them with the boundary value of each power quality level, the power quality level of the monitoring points is obtained to evaluate the steady-state power quality.

The main contributions of this paper are summarized as follows:

1. Based on the triangular fuzzy theory, we apply triangular fuzzy number theory to the BW method and propose a triangular fuzzy BW method. Then, we use the optimization method to obtain the interval weight of each indicator. The interval weights can reflect the opinions and preferences of decision-makers more accurately than crisp numbers.

2. We combine the triangular fuzzy BW method and the interval VIKOR method to process the experimental monitoring values of power quality indicators. The interval VIKOR method provides an effective approach for handling the data uncertainty present in the interval weights. As the comprehensive evaluation values of power quality are interval numbers, we rank them by a simple yet practical ranking method.

3. By calculating the power quality level boundary value, together with the daily power quality monitoring value, the level of power quality of the monitoring point can be intuitively obtained.

The remainder of this paper is organized as follows. Section 2 introduces the steady-state power quality comprehensive assessment system and presents grade classifications. Section 3 introduces the construction of a triangular fuzzy BW method with triangular fuzzy number, and then determines the interval weight of each power quality index. Section 4 illustrates the interval VIKOR method to achieve a comprehensive evaluation of steady-state power quality based on the obtained interval
weights. Next, Section 5 provides an example to verify the proposed method. Conclusions are drawn in Section 6.

2. Establishment of the Steady-State Power Quality Comprehensive Evaluation System

2.1. Introduction to Power Quality Indicators

The integration of a photovoltaic power generation system will affect the power quality in frequency, voltage fluctuation, flicker, voltage total harmonic distortion, and so on. Based on the content of China’s national standard for power quality [20–24], we choose six indicators as the steady-state power quality indicators: frequency deviation, voltage deviation, three-phase voltage unbalance, voltage fluctuation, voltage total harmonic distortion, and voltage flicker. The allowable limits of these indicators in China’s national standards are shown in Table 1 [25].

Table 1. The allowable limits of steady-state power quality indicators in China’s national standards.

| Standard Number | Standard Name                                      | Allowed Limit Values                                                                 |
|-----------------|---------------------------------------------------|---------------------------------------------------------------------------------------|
| GB/T 15945-2008 | Power quality—Frequency deviation for power system | The allowable deviation under normal conditions is ±0.2 Hz; it can also be changed to ±0.5 Hz according to the system capacity. |
| GB/T 14549-1993 | Quality of electric energy supply                 | Harmonics in public supply network                                                    |
| GB/T 15543-2008 | Power quality—Three-phase voltage unbalance       | The allowable upper distortion rate is 4% for the rated voltage of 6–10 kV, and 5% for 380 V. For the point of common coupling, normal allowable unbalance is 2%; short time allowable unbalance is 4%. For each user, normal allowable unbalance is 1.3%; short time allowable unbalance is 2.6%. |
| GB/T 12325-2008 | Power quality—Deviation of supply voltage         | The allowable deviation is ±5% for the rated voltage of ≥35 kV, and ±7% for ≤10 kV. The allowable voltage variation varies with its frequency, and, if the variation is random and irregular, the allowed allowable voltage variation is 2.5% for high voltage and 3% for others. |
| GB/T 12326-2008 | Power quality—Voltage fluctuation and flicker     |                                                                                        |

The power quality indicators are introduced below [26]. In power systems, the frequency deviation can be determined using Equation (1),

$$\Delta f = f_s - f_N$$

(1)

where $f_s$ is the real-time frequency monitored and $f_N$ is the standard frequency value.

Voltage total harmonic distortion is a commonly used parameter to measure the level of harmonics, and its calculation is shown in Equation (2).

$$THD_u = \sqrt{\frac{\sum_{h=1}^{\infty} U_{h}^2}{U_1}}$$

(2)

where $THD_u$ represents the voltage total harmonic distortion, $U_1$ represents the fundamental voltage root mean square (RMS) value and $U_h$ represents each harmonic voltage RMS value.

The voltage fluctuation value can be determined using Equation (3).

$$d = \frac{U_{\text{max}} - U_{\text{min}}}{U_N} \times 100\%$$

(3)

where $U_{\text{max}}$ and $U_{\text{min}}$ represent two adjacent extreme values of the voltage RMS value, respectively, and $U_N$ represents the rated voltage value.
The short-term and long-term flicker values are two quantitative parameters used to quantify voltage flicker. The measurement period of the short-term flicker value is 10 min, and it can be determined from Equation (4). The measurement period of the long-term flicker value is 2 h, and the value is calculated from the short-term flicker value within 2 h, as shown in Equation (5).

\[
P_{st} = \sqrt{0.0314P_{0.1} + 0.525P_1 + 0.0657P_3 + 0.28P_{10} + 0.08P_{50}}
\]  

(4)

\[
P_{lt} = 3 \sqrt[3]{\frac{1}{12} \sum_{j=2}^{n} (P_{stj})^3}
\]  

(5)

where \(P_{st}\) represents the short-term flicker value; \(P_{0.1}, P_1, P_3, P_{10}, \) and \(P_{50}\) represent instantaneous visual sensitivity exceeding 0.1%, 1%, 3%, 10%, and 50% of the sensing units within 10 min, respectively; \(P_{lt}\) represents the long-term flicker value; and \(P_{stj}\) represents the short-term flicker value in the \(j\)th 10-min interval.

The voltage deviation can be determined using Equation (6).

\[
\Delta U = \frac{U_s - U_N}{U_N}
\]  

(6)

where \(U_s\) represents the measured voltage value and \(U_N\) represents the rated voltage value.

The three-phase imbalance can be determined using Equation (7).

\[
\varepsilon = \frac{U_2}{U_1} \times 100\%
\]  

(7)

where \(\varepsilon\) is the three-phase imbalance, \(U_1\) is the RMS value of the positive sequence voltage component, and \(U_2\) is the RMS value of negative sequence voltage component.

2.2. Steady-State Power Quality Index System

However, the qualification of individual indicators cannot truly reflect the power quality problem. Therefore, we comprehensively consider the above six indicators to evaluate the power quality. The Steady-state power quality comprehensive evaluation system is depicted in Figure 1.

![Figure 1. Steady-state power quality index system.](image-url)
2.3. The Level of Power Quality

Before the assessment, we divide the indices into several levels according to China’s national standard, as shown in Table 2 [20–24]. In this paper, the limits of some indicators, such as voltage deviation, are chosen as the standard of low voltage. If the actual voltage is medium voltage or high voltage, the boundary values of each level can be changed according to Table 1.

| Table 2. Levels of power quality. |
|-------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Indices | \( x_1/\text{Hz} \) | \( x_2/(\%) \) | \( x_3/(\%) \) | \( x_4/(\%) \) | \( x_5/(\%) \) |
| Level 1 | \([0, 0.04]\) | \([0, 1.0]\) | \([0, 0.6]\) | \([0, 0.2]\) | \([0, 1.4]\) |
| Level 2 | \((0.04, 0.08]\) | \((1.0, 2.0]\) | \((0.6, 1.2]\) | \((0.2, 0.4]\) | \((1.4, 2.8]\) |
| Level 3 | \((0.08, 0.12]\) | \((2.0, 3.0]\) | \((1.2, 1.8]\) | \((0.4, 0.6]\) | \((2.8, 4.2]\) |
| Level 4 | \((0.12, 0.16]\) | \((3.0, 4.0]\) | \((1.8, 2.4]\) | \((0.6, 0.8]\) | \((4.2, 5.6]\) |
| Level 5 | \((0.16, 0.20]\) | \((4.0, 5.0]\) | \((2.4, 3.0]\) | \((0.8, 1.0]\) | \((5.6, 7.0]\) |
| Level 6 | \((0.2, +\infty]\) | \((5.0, +\infty]\) | \((3.0, +\infty]\) | \((1.0, +\infty]\) | \((7.0, +\infty]\) |

\( x_1 \) represents the frequency deviation, \( x_2 \) represents the voltage total harmonic distortion, \( x_3 \) represents the voltage fluctuate, \( x_4 \) represents the voltage flicker, \( x_5 \) represents the voltage deviation, and \( x_6 \) represents the three-phase voltage unbalance. Level 6 is an unqualified level and others are qualified levels. In this paper, we only discuss qualified levels.

3. Triangular Fuzzy BW Method to Determine the Interval Weight of Steady State Power Quality Index

3.1. Triangular Fuzzy Number

A fuzzy number in the real number field \( R \) refers to a fuzzy set. If \( A \in F(R) \) and its membership function is shown as Equation (8) [27,28],

\[
A(x) = \begin{cases} 
\frac{1}{m-l} x - \frac{1}{m-l} & x \in [l, m] \\
\frac{1}{m-u} x - \frac{1}{m-u} & x \in [m, u] \\
0 & \text{otherwise}
\end{cases}
\]

then \( A \) is called a triangle fuzzy number and it can be represented by \([l \quad m \quad u]\), where \( l \) and \( u \) represent the lower and upper bounds of \( \tilde{A} \). If \( m - l = u - m \), then \( A \) is called a symmetric triangular fuzzy number. All triangular fuzzy numbers in this paper are symmetric triangular fuzzy numbers.

Triangular fuzzy numbers have been considered an effective tool for presenting many inaccurate data in real life for the past several decades [29].

3.2. Triangular Fuzzy BW Method

The BW method is a multi-indicator decision-making method [30,31]. Compared with the traditional Analytic Hierarchy Process (AHP) method, it determines weights based on the comparison of the best and the worst standard/alternative with other standards/alternatives, as shown in Figures 2 and 3.

Figures 2 and 3 show that, as the number of indices increases, fewer comparisons are made in each index when we apply the BW method. With the increase of the number of indicators, the comparison matrix obtained by the AHP method will be very large and it will be difficult to calculate. Besides, fewer comparisons make it easier to achieve consistency [30].

However, when making decisions using the BW method, the crisp numbers may not reflect the true opinions and preferences of decision-makers. A point in case is that, when a decision-maker thinks that the importance of one indicator relative to another is between 3 and 5, then he will choose 4 when he applies the BW method. However, in comparison, \([3 \quad 5]\) is more able to reflect the actual situation. Therefore, we apply the triangular fuzzy number \([3 \quad 4 \quad 5]\) to describe the importance of
the comparison between these two indices. Thus, the triangular fuzzy best-worst (TFBW) method is produced.

![Image](https://via.placeholder.com/150)

**Figure 2.** Comparison of importance of index by analytic hierarchy process (AHP) method.

![Image](https://via.placeholder.com/150)

**Figure 3.** Comparison importance of index by best–worst (BW) method.

3.3. **Determine the Weight of Steady State Power Quality Index by TFBW Method**

The comprehensive evaluation of power quality first requires determining the weight of each index. According to the TFBW method proposed in this paper, an interval weight of each indicator can be obtained, and the specific steps are as follows:

Step 1. Identify the most important index and the least important index.

These two indices are used as reference indices. After they are determined, they can be compared with the remaining indices. The most important index of the six power quality indices in this paper, according to the consulted experts, is the frequency deviation, which is represented by $I_B$; the least important one is the three-phase voltage imbalance, which is represented by $I_W$ [32].

Step 2. Determine the best-to-others (BO) vector and the others-to-worst (OW) vector.

Suppose there are $n$ indices to be evaluated. Then, we compare $I_B$ with all indices and compare all indices with $I_W$ to determine the BO vector and OW vector via Equations (9) and (10):

$$BO = \left[ \begin{array}{l} l_{B1} & m_{B1} & u_{B1} \\ l_{B2} & m_{B2} & u_{B2} \\ \vdots \\ l_{Bn} & m_{Bn} & u_{Bn} \end{array} \right]$$

$$OW = \left[ \begin{array}{l} l_{W1} & m_{W1} & u_{W1} \\ l_{W2} & m_{W2} & u_{W2} \\ \vdots \\ l_{Wn} & m_{Wn} & u_{Wn} \end{array} \right]$$

where $\left[ l_{Bi} \ m_{Bi} \ u_{Bi} \right]$ and $\left[ l_{Wi} \ m_{Wi} \ u_{Wi} \right]$ are triangular fuzzy numbers. $m_{Bi}$ is the midpoint of $l_{Bi}$ and $u_{Bi}$, and it is also the most likely value in $\left[ l_{Bi} \ m_{Bi} \ u_{Bi} \right]$; $m_{Wi}$ is the midpoint of $l_{Wi}$ and $u_{Wi}$, and it is also the most likely value in $\left[ l_{Wi} \ m_{Wi} \ u_{Wi} \right]$ [33].

The acquisition of the BO and OW vectors requires consultation with experts to judge the importance of each index. Experts can make a judgment on the importance between the $i$th and $j$th indices by a triangular fuzzy number with the membership function shown in Figure 4 [28].
The boundary value of the triangular fuzzy number could be a non-integer, which can reflect the experts’ understanding of the importance of each index more accurately.

As shown in Figure 4, \( [I_{Bn} \ m_{Bn} \ u_{Bn}] = [1 \ 1 \ 1] \) when \( n = B \) and \( [I_{Wn} \ m_{Wn} \ u_{Wn}] = [1 \ 1 \ 1] \) when \( n = W \). If there are a total of \( k \) opinions by \( k \) experts, we can take their average using Equations (11) and (12) [33]:

\[
[I_{Bn} \ m_{Bn} \ u_{Bn}] = \left[ \frac{l_{B1} + l_{B2} + \cdots + l_{Bk}}{k} \ m_{B1} + m_{B2} + \cdots + m_{Bk} \ u_{B1} + u_{B2} + \cdots + u_{Bk} \right]
\]

(11)

\[
[I_{Wn} \ m_{Wn} \ u_{Wn}] = \left[ \frac{l_{W1} + l_{W2} + \cdots + l_{Wk}}{k} \ m_{W1} + m_{W2} + \cdots + m_{Wk} \ u_{W1} + u_{W2} + \cdots + u_{Wk} \right]
\]

(12)

where \( [I_{Bnk} \ m_{Bnk} \ u_{Bnk}] \) and \( [I_{Wnk} \ m_{Wnk} \ u_{Wnk}] \) represent the opinion of the \( k \)th expert.

Step 3. Determine the BO\(_{M}\) and OW\(_{M}\) vectors.

The BO\(_{M}\) and OW\(_{M}\) vectors represent the central BO and OW vectors, respectively, and they can be determined using Equations (13) and (14):

\[
\text{BO}_{M} = \left[ m_{B1} \ m_{B2} \ \cdots \ m_{Bn} \right]
\]

(13)

\[
\text{OW}_{M} = \left[ m_{W1} \ m_{W2} \ \cdots \ m_{Wn} \right]
\]

(14)

where \( m_{Bn} \) represents the most likely value in \( [I_{Bn} \ m_{Bn} \ u_{Bn}] \) and \( m_{Wn} \) represents the most likely value in \( [I_{Wn} \ m_{Wn} \ u_{Wn}] \).

Step 4. Determine the central weight of each index.

Based on the BO\(_{M}\) and OW\(_{M}\) vectors, the central weight of each index can be determined using Equations (15) and (16):

\[
\frac{\omega_{Bn}^{M}}{\omega_{Wn}^{M}} = m_{Bn} (n = 1, 2, \cdots, 6) \tag{15}
\]

\[
\frac{\omega_{Wn}^{M}}{\omega_{Wn}^{M}} = m_{Wn} (n = 1, 2, \cdots, 6) \tag{16}
\]

where \( \omega_{Bn}^{M} \) represents the central weight of the \( n \)th index and \( \omega_{Bn}^{M} \) and \( \omega_{Wn}^{M} \) represent the central weights of \( I_{B} \) and \( I_{W} \), respectively.

However, in general, the central weights of the six indices determined from the BO and OW vectors cannot fully satisfy Equations (15) and (16) simultaneously. Therefore, the optimization problem in
Equation (17) can be adopted to minimize the maximum absolute difference \[\left| \frac{\omega^M_M}{\omega^M_n} - m_{Bn} \right| \] and \[\left| \frac{\omega^M_M}{\omega^M_W} - m_{nW} \right|\] and the central weight of every index can be determined [30,34].

\[
\begin{align*}
\min_{\omega^M_M} & \left\{ \left| \frac{\omega^M_M}{\omega^M_n} - m_{Bn} \right|, \left| \frac{\omega^M_M}{\omega^M_W} - m_{nW} \right| \right\} \\
s.t. & \\
& \sum_{n=1}^{6} \omega^M_n = 1 \\
& \omega^M_n \geq 0, n = 1, 2, \ldots, 6 \\
\end{align*}
\] (17)

The optimization problem in Equation (17) is equivalent to the optimization problem in Equation (18):

\[
\begin{align*}
\min & \xi \\
s.t. & \\
& \left| \frac{\omega^M_M}{\omega^M_n} - m_{Bn} \right| \leq \xi, \left| \frac{\omega^M_M}{\omega^M_W} - m_{nW} \right| \leq \xi \\
& \sum_{n=1}^{6} \omega^M_n = 1 \\
& \omega^M_n \geq 0 \\
\end{align*}
\] (18)

Step 5. Check the consistency.

When \(m_{Bn}\) and \(m_{nW}\) satisfy Equation (19), the comparison is fully consistent. However, it is usually impossible to satisfy due to the subjectivity and ambiguity of the experts in their judgment.

\[m_{Bn}m_{nW} = m_{BW}\] (19)

Therefore, we need to calculate the consistency ratio by Equation (20) to check the consistency.

\[CR = \frac{\xi}{CI}\] (20)

where CI represents the consistency index, \(\xi\) is the value determined by programming Equation (18) and CR is the consistency ratio. The value of CI can be determined using Equation (21). It can also be obtained by Table 3 directly if \(m_{BW}\) is an integer.

\[CI = \frac{2m_{BW} + 1 - \sqrt{8m_{BW} + 1}}{2}\] (21)

\begin{table}[h]
\centering
\begin{tabular}{cccccccc}
\hline
\(m_{BW}\) & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\
\hline
CI & 0.00 & 0.44 & 1.00 & 1.63 & 2.30 & 3.00 & 3.73 & 4.47 & 5.23 \\
\hline
\end{tabular}
\caption{The value of the consistency index (CI).}
\end{table}

The value of CR is distributed in the interval \([0, 1]\). The closer the value of CR is to 0, the better the consistency is; on the contrary, the closer the value of CR is to 1, the worse the consistency is.

In fact, we can take the consistency relation shown in Equation (19) to check the consistency intuitively, as presented in Table 4.
where \( \omega \) represents the interval weight. Thus, the interval weight can also be described by the middle point and radius using

\[
\omega = [\omega_n^M - d_n, \omega_n^M + d_n]
\]

(22)

where \( \omega_n \) represents the interval weight of \( n \)th index and \( d_n \) represents the radius of \( \omega_n \).

The radius is obtained based on interval regression analysis, which is to find the estimated intervals to include the original data. In this problem, \( m_{Br} \) and \( m_{nW} \) are approximated as \([l_{Br}, u_{Br}]\) and \([l_{nW}, u_{nW}]\). Thus, the interval weights of the indices should satisfy the constraints of Equations (23) and (24) [34,35]:

\[
\begin{align*}
[l_{Br}, u_{Br}] &\subseteq [\omega_n^M - d_n, \omega_n^M + d_n] \\
[l_{nW}, u_{nW}] &\subseteq [\omega_n^M - d_n, \omega_n^M + d_n] \\
\end{align*}
\]

(23)

(24)

where \( d_B \) represents the radius of \( IB \)'s interval weight and \( d_W \) represents the radius of \( IW \)'s interval weight. Thus, the interval weight can also be described by the middle point and radius using Equation (25) [36]:

\[
\omega_n = [\omega_c, \omega_r]
\]

(25)

where \( \omega_c \) represents the middle point of interval weight and \( \omega_r \) represents the radius of interval weight.

Under the constraints of Equations (23) and (24), the radius of each index’s interval weight should be minimized. To find the minimum value, we can use the optimization constraint to solve the problem, as shown in optimization problem in Equation (26) [34,35].

\[
\begin{align*}
\text{min} &\lambda \\
\text{s.t.} &\begin{cases}
\frac{\omega_n^M - d_n}{\omega_n^M + d_n} \leq l_{Br}, & \frac{\omega_n^M + d_n}{\omega_n^M - d_n} \geq u_{Br} \\
\frac{\omega_n^M - d_n}{\omega_n^M + d_n} \leq l_{nW}, & \frac{\omega_n^M + d_n}{\omega_n^M - d_n} \geq u_{nW} \\
d_n \leq \lambda \\
\omega_n^M - d_n \geq 0
\end{cases}
\end{align*}
\]

(26)
The interval weight of each power quality index shows the acceptable range for experts.

4. Interval VIKOR Method for Estimating Steady-State Power Quality

Since the weight obtained by the method in Section 3 is an interval number, we use interval VIKOR method for comprehensive power quality assessment. The interval VIKOR method not only has the advantages of the traditional VIKOR method in dealing with multi-objective decision-making problems, but it can also take into account the ambiguity and uncertainty of people in making decisions about certain issues [37].

To comprehensively evaluate steady-state power quality with the interval VIKOR method, it is mainly divided into the following six steps [37–39]:

Step 1. Establish the original matrix.

The original data matrix is the monitored value (the deviation from standard value) of each power quality index. Suppose there are a total of \( m \) datasets, each set containing \( n \) indices. The original matrix can be obtained according to Equation (27):

\[
X = \begin{bmatrix}
    x_{11} & x_{12} & \cdots & x_{1n} \\
    x_{21} & x_{22} & \cdots & x_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    x_{m1} & x_{m2} & \cdots & x_{mn}
\end{bmatrix}
\]  

(27)

where \( x_{ij} \) represents the monitoring value of the \( j \)th index on the \( i \)th set. In this paper, we evaluate the power quality of different dates of the same monitoring point. For comparison, we take the level upper boundary values given in Table 2 as raw data to constitute the original matrix.

Step 2. Standardize the original matrix.

Due to the different dimensions of different indices, the data should be standardized before the evaluation in order to eliminate the impact between different indices. The power quality index is a reverse index: the smaller is the value, the better is the power quality. Thus, we choose the extreme value method to standardize the original matrix by Equation (28) [40]:

\[
y_{ij} = \frac{x_{ij}}{x_{j\text{max}}}
\]  

(28)

where \( x_{j\text{max}} \) represents the maximum value in the \( j \)th index.

Then, the standardized matrix can be presented by Equation (29).

\[
Y = \begin{bmatrix}
    y_{11} & y_{12} & \cdots & y_{1n} \\
    y_{21} & y_{22} & \cdots & y_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    y_{m1} & y_{m2} & \cdots & y_{mn}
\end{bmatrix}
\]  

(29)

Step 3. Determine the positive ideal solutions (PIS) and the negative ideal solutions (NIS).

The PIS and the NIS can be determined using Equations (30) and (31):

\[
P^+ = \left\{ p_1^+, p_2^+, \cdots, p_n^+ \right\} = \left\{ \max_{i} y_{ij} \mid j = 1, 2, \cdots, n \right\}
\]  

(30)

\[
P^- = \left\{ p_1^-, p_2^-, \cdots, p_n^- \right\} = \left\{ \min_{i} y_{ij} \mid j = 1, 2, \cdots, n \right\}
\]  

(31)

where \( P^+ \) and \( P^- \) represent PIS and NIS, respectively.

It should be pointed out that, since the power quality index is a reverse index, PIS and NIS obtained here are opposite to the actual expressions.
Step 4. Determine the value of \( S_i^\pm \) and the value of \( R_i^\pm \).

The interval values of \( [S_i^-, S_i^+] \) and \( [R_i^-, R_i^+] \) can be determined using Equations (32)-(35):

\[
S_i^- = \sum_{j=1}^{n} \frac{\alpha_j}{p_j^- - p_j^+} (p_j^- - y_{ij}) \quad i = 1, 2, \cdots, m
\]

(32)

\[
S_i^+ = \sum_{j=1}^{n} \frac{\alpha_j}{p_j^- - p_j^+} (p_j^+ - y_{ij}) \quad i = 1, 2, \cdots, m
\]

(33)

\[
R_i^- = \max_j \frac{\alpha_j}{p_j^- - p_j^+} (p_j^- - y_{ij}) \quad i = 1, 2, \cdots, m \quad j = 1, 2, \cdots, n
\]

(34)

\[
R_i^+ = \max_j \frac{\alpha_j}{p_j^- - p_j^+} (p_j^+ - y_{ij}) \quad i = 1, 2, \cdots, m \quad j = 1, 2, \cdots, n
\]

(35)

where \( S_i^\pm \) represents the value of group utility of \( i \)th power quality and \( R_i^\pm \) represents the value of individual regret of \( i \)th power quality. The value of group utility and the value of individual regret are both decision values in a multi-index decision problem [41].

It is worth pointing out that the weight of \( j \)th index is determined by the triangular fuzzy BW method in this paper.

Step 5. Determine the comprehensive evaluation value of the data to be evaluated for every day.

Based on the value of \( S_i^\pm \) and the value of \( R_i^\pm \), the comprehensive evaluation value \( [Q_i^-, Q_i^+] \) can be determined using Equations (36) and (37):

\[
Q_i^- = v \frac{S_i^- - \min_{i=1,2,\cdots,m} [S_i^-]}{\max_{i=1,2,\cdots,m} [S_i^+] - \min_{i=1,2,\cdots,m} [S_i^-]} + (1 - v) \frac{R_i^- - \min_{i=1,2,\cdots,m} [R_i^-]}{\max_{i=1,2,\cdots,m} [R_i^+] - \min_{i=1,2,\cdots,m} [R_i^-]}
\]

(36)

\[
Q_i^+ = v \frac{S_i^+ - \min_{i=1,2,\cdots,m} [S_i^-]}{\max_{i=1,2,\cdots,m} [S_i^+] - \min_{i=1,2,\cdots,m} [S_i^-]} + (1 - v) \frac{R_i^+ - \min_{i=1,2,\cdots,m} [R_i^-]}{\max_{i=1,2,\cdots,m} [R_i^+] - \min_{i=1,2,\cdots,m} [R_i^-]}
\]

(37)

where \( Q_i^\pm \) represents the comprehensive evaluation value of power quality on the \( i \)th day. The factor \( v \) could take a value from \([0 \ 1]\) and it is assumed \( v = 0.5 \) in this study.

Step 6. Calculate and rank the PPIs of power quality [31,42].

Calculate the probability that the power quality of the \( i \)th day is better than the power quality of the \( j \)th day, according to Equation (38):

\[
p_{ij} = P(Q_i^+ \geq Q_j^+) = \frac{1}{2} \left( \frac{\max \left\{ 0, Q_i^+ - Q_j^+ \right\} - \max \left\{ 0, Q_i^- - Q_j^- \right\}}{Q_i^+ - Q_j^- + Q_i^- - Q_j^+} \right)
\]

(38)
It is worth pointing out that $P\{Q_i^+ \geq Q_j^+\} = 0.5$ represents $[Q_i^- \ Q_i^+] = [Q_j^- \ Q_j^+]$. We compare the $Q_i^+$ of the power quality of each day to each other to obtain the probability value matrix, as shown in Equation (39). Obviously, $p_{11} = p_{22} = \cdots = p_{mm} = 0.5$.

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1m} \\ p_{21} & p_{22} & \cdots & p_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ p_{m1} & p_{m2} & \cdots & p_{mm} \end{bmatrix}$$

Then, we calculate the PPIs of power quality by Equation (40) [42].

$$\text{PPI} = \frac{1}{m} \sum_{j=1}^{m} p_{ij} + 1 - \frac{m}{2} \quad i = 1, 2, \cdots, m$$

Finally, we can obtain the daily power quality ranking by ranking their value of PPI. Since the power quality index is a reverse index, the smaller is the PPI value, the better is the power quality. When conducting a comprehensive assessment of power quality, by comparing the upper boundary values of each level given in Table 2 with the daily monitoring values, we can get the power quality level for each day.

5. Case Study

A flow chart representing the steady-state power quality evaluation method presented in this paper is shown in Figure 5.

![Flow chart](Figure 5. The flow chart of the steady-state power quality evaluation.)

Step 1. Establish the original matrix.
In this study, we measured the data of the photovoltaic grid-connected point in the Dynamic Simulation Laboratory of Tianjin University for two weeks by using the Fluke 435 II power quality analyzer. The measurement was set with 3 s as a recording point, and the data were used as a group every 24 h. For the measured data, we took 10 min as a time unit, and chose the maximum probability of 95% in each dataset as the final data typical value \[40,43\]. Then, the measured data are shown in Table 5.

### Table 5. Deviation values of measured data.

| Time | \(x_1/Hz\) | \(x_2/(\%)\) | \(x_3/(\%)\) | \(x_4\) | \(x_5/(\%)\) | \(x_6/(\%)\) |
|------|-------------|---------------|---------------|--------|---------------|---------------|
| Day 1 | 0.021       | 1.640         | 0.207         | 0.498  | 9.600         | 0.406         |
| Day 2 | 0.013       | 1.580         | 0.183         | 0.741  | 9.800         | 0.297         |
| Day 3 | 0.017       | 1.640         | 0.196         | 0.512  | 9.600         | 0.302         |
| Day 4 | 0.015       | 1.610         | 0.199         | 0.525  | 10.600        | 0.377         |
| Day 5 | 0.011       | 1.330         | 0.193         | 0.523  | 10.800        | 0.313         |
| Day 6 | 0.014       | 1.650         | 0.192         | 0.293  | 8.300         | 0.364         |
| Day 7 | 0.014       | 1.773         | 0.132         | 0.204  | 8.100         | 0.403         |
| Day 8 | 0.035       | 1.824         | 0.195         | 0.398  | 9.888         | 0.298         |
| Day 9 | 0.036       | 2.011         | 0.191         | 0.495  | 8.294         | 0.295         |
| Day 10| 0.035       | 2.041         | 0.186         | 0.400  | 8.091         | 0.438         |
| Day 11| 0.035       | 1.863         | 0.195         | 0.520  | 8.010         | 0.478         |
| Day 12| 0.035       | 1.863         | 0.214         | 0.402  | 8.169         | 0.412         |
| Day 13| 0.035       | 1.401         | 0.200         | 0.518  | 8.319         | 0.357         |
| Day 14| 0.035       | 1.842         | 0.200         | 0.507  | 8.281         | 0.503         |

Step 2. Determine the BO vector, the OW vector, the \(\text{BO}_M\) vector and the \(\text{OW}_M\) vector.

According to the authors of \[32,44,45\], we could obtain the triangular fuzzy matrix by combining Equations (9)–(12), as shown in Table 6.

### Table 6. The triangular fuzzy matrix of power quality index.

| Power Quality Indices | BO          | OW          |
|-----------------------|-------------|-------------|
| \(x_1\)               | (1 \(1\) \(1\)) | (4 \(4.5\) \(5\)) |
| \(x_2\)               | (2 \(2.5\) \(3\)) | (1 \(1.5\) \(2.1\)) |
| \(x_3\)               | (3 \(1.3\) \(4\) \(3\) \(7\)) | (1 \(4.1\) \(7\) \(2\) \(0\)) |
| \(x_4\)               | (3 \(1.3\) \(4\) \(3\) \(7\)) | (1 \(4.1\) \(7\) \(2\) \(0\)) |
| \(x_5\)               | (1 \(1.5\) \(2\)) | (3 \(3\) \(3\) \(3.6\)) |
| \(x_6\)               | (4 \(4.5\) \(5\)) | (1 \(1\) \(1\)) |

The elements of the \(\text{BO}_M\) vector and the \(\text{OW}_M\) vector could be obtained by Equations (13) and (14), as shown in Table 7.

### Table 7. The \(\text{BO}_M\) vector and the \(\text{OW}_M\) vector.

| Indices | \(x_1\) | \(x_2\) | \(x_3\) | \(x_4\) | \(x_5\) | \(x_6\) |
|---------|--------|--------|--------|--------|--------|--------|
| \(\text{BO}_M\) | 1      | 2.5    | 3.4    | 3.4    | 1.5    | 4.5    |
| \(\text{OW}_M\) | 4.5    | 1.8    | 1.7    | 1.7    | 3.3    | 1      |

Step 3. Calculate the central weight of each index and conduct consistency check.

The central weight of each index and the value of \(\xi\) could be determined by substituting the data in Table 7 into the optimization problem in Equation (18), as presented in Table 8.

### Table 8. The results of the optimization problem in Equation (18).

| \(\xi\) | \(x_1\) | \(x_2\) | \(x_3\) | \(x_4\) | \(x_5\) | \(x_6\) |
|--------|--------|--------|--------|--------|--------|--------|
| 0.2184 | 0.3338 | 0.1399 | 0.1049 | 0.1049 | 0.2457 | 0.0708 |
Since $m_{BW} = m_{16} = 4.5$, the CI could be determined by Equation (21) and $CI = 1.9586$. Then, the CR could be determined by Equation (20), and $CR = 0.1115$. The CR is near to zero and far from one, thus the consistency of the overall comparisons is acceptable.

Step 4. Calculate the interval weight of each index.

The radius in interval weight of each index could be determined by the optimization problem in Equation (26) based on the central weight of each index and the BO and OW vectors. The radius in interval weight of each index is presented in Table 9.

Table 9. The results of the optimization problem in Equation (26).

| Indices | Interval Weight |
|---------|-----------------|
| $x_1$   | (0.2951, 0.3725) |
| $x_2$   | (0.1242, 0.1556) |
| $x_3$   | (0.1007, 0.1091) |
| $x_4$   | (0.1007, 0.1091) |
| $x_5$   | (0.2069, 0.2845) |
| $x_6$   | (0.0321, 0.1095) |

Then, the interval weight of each index could be obtained, as presented in Table 10.

Table 10. The interval weight of the index.

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| $x_4$   | (0.1007, 0.1091) |
| $x_5$   | (0.2069, 0.2845) |
| $x_6$   | (0.0321, 0.1095) |

Step 5. Calculate the value of $S_i^\pm$, $R_i^\pm$, and $Q_i^\pm$ of each day’s power quality data.

Based on the interval VIKOR method introduced in this paper, the $S_i^\pm$, $R_i^\pm$, and $Q_i^\pm$ of each day’s power quality data could be determined by Equations (32)–(37), as shown in Table 11.

Table 11. The values of the $S_i^\pm$, $R_i^\pm$, and $Q_i^\pm$.

| Time- | $S_i^\pm$                | $R_i^\pm$                | $Q_i^\pm$                |
|-------|---------------------------|---------------------------|---------------------------|
| Day 1 | (0.6015, 0.7969)          | (0.2795, 0.3528)          | (0.6046, 0.8317)          |
| Day 2 | (0.5838, 0.7837)          | (0.2920, 0.3686)          | (0.6171, 0.8522)          |
| Day 3 | (0.6083, 0.8100)          | (0.2857, 0.3607)          | (0.6189, 0.8520)          |
| Day 4 | (0.5872, 0.7781)          | (0.2889, 0.3646)          | (0.6135, 0.8425)          |
| Day 5 | (0.5994, 0.7954)          | (0.2951, 0.3725)          | (0.6305, 0.8650)          |
| Day 6 | (0.6678, 0.8809)          | (0.2904, 0.3666)          | (0.6575, 0.8986)          |
| Day 7 | (0.6810, 0.8941)          | (0.2904, 0.3666)          | (0.6643, 0.9054)          |
| Day 8 | (0.5817, 0.7733)          | (0.2576, 0.3252)          | (0.5566, 0.7718)          |
| Day 9 | (0.5983, 0.8006)          | (0.2561, 0.3232)          | (0.5624, 0.7824)          |
| Day 10| (0.6129, 0.8115)          | (0.2576, 0.3252)          | (0.5726, 0.7914)          |
| Day 11| (0.6040, 0.8016)          | (0.2576, 0.3252)          | (0.5680, 0.7863)          |
| Day 12| (0.6159, 0.8164)          | (0.2576, 0.3252)          | (0.5741, 0.7939)          |
| Day 13| (0.6139, 0.8181)          | (0.2576, 0.3252)          | (0.5731, 0.7948)          |
| Day 14| (0.5997, 0.7942)          | (0.2576, 0.3252)          | (0.5658, 0.7825)          |
| Level 1| (0.7960, 1.0586)          | (0.2498, 0.3153)          | (0.6530, 0.9011)          |
| Level 2| (0.6179, 0.8227)          | (0.1874, 0.2421)          | (0.4535, 0.6534)          |
| Level 3| (0.4398, 0.5868)          | (0.1453, 0.1998)          | (0.2893, 0.4590)          |
| Level 4| (0.2617, 0.3509)          | (0.1145, 0.1574)          | (0.1447, 0.2647)          |
| Level 5| (0.0836, 0.1150)          | (0.0836, 0.1150)          | (0.0, 0.0704)             |

According to Equations (38)–(40), the values of PPI of each dataset (including the upper boundary values of each level) could be determined, and the results are presented in Table 12.
Table 12. The calculation results of the priority performance indices (PPIs).

| Monitoring Value | PPI  | Monitoring Value | PPI  | Boundary Value | PPI  |
|------------------|------|------------------|------|---------------|------|
| Day 1            | 0.1452 | Day 8           | 0.1963 | Level 1      | 0.0935 |
| Day 2            | 0.1304 | Day 9           | 0.1882 | Level 2      | 0.3067 |
| Day 3            | 0.1295 | Day 10          | 0.1792 | Level 3      | 0.3812 |
| Day 4            | 0.1362 | Day 11          | 0.1838 | Level 4      | 0.4079 |
| Day 5            | 0.1183 | Day 12          | 0.1772 | Level 5      | 0.4342 |
| Day 6            | 0.0919 | Day 13          | 0.1772 |              |      |
| Day 7            | 0.0862 | Day 14          | 0.1867 |              |      |

The PPI value of the daily power quality with the PPI value of the level upper boundary is compared in Figure 6.

![Graph showing PPI values](https://via.placeholder.com/150)

**Figure 6.** The results of synthetic evaluation of steady-state power quality.

We intuitively can see that the power quality belongs to Level 2 almost every day in Figure 6. Only the PPI value of the power quality on Days 6 and 7 is slightly lower than the upper boundary of Level 1. Therefore, we can conclude that the power quality level of the monitoring point belongs to Level 2. The power quality of the monitoring point is good, which meets the requirements of Chinese national photovoltaic grid connection, and has little effect on the power quality of the local grid.

To verify the feasibility of the method proposed in this paper, we selected several comprehensive power quality evaluation methods introduced in other publications to evaluate the data in this paper and the results are shown in Table 13.

Table 13. The comprehensive power quality evaluation results with different methods.

| Monitoring Value | Evaluation Result Obtained in [32] | Evaluation Result Obtained in [40] | Evaluation Result Obtained in [43] | Evaluation Result Obtained in This Paper |
|------------------|------------------------------------|------------------------------------|------------------------------------|----------------------------------------|
| Day 1            | Level 2                            | Level 2                            | Level 2                            | Level 2                                |
| Day 2            | Level 1                            | Level 2                            | Level 2                            | Level 2                                |
| Day 3            | Level 2                            | Level 2                            | Level 2                            | Level 2                                |
| Day 4            | Level 2                            | Level 2                            | Level 2                            | Level 2                                |
| Day 5            | Level 1                            | Level 2                            | Level 2                            | Level 2                                |
| Day 6            | Level 1                            | Level 2                            | Level 2                            | Level 1                                |
| Day 7            | Level 1                            | Level 2                            | Level 2                            | Level 1                                |
| Day 8            | Level 2                            | Level 2                            | Level 2                            | Level 2                                |
| Day 9            | Level 2                            | Level 2                            | Level 2                            | Level 2                                |
| Day 10           | Level 2                            | Level 2                            | Level 2                            | Level 2                                |
| Day 11           | Level 2                            | Level 2                            | Level 2                            | Level 2                                |
| Day 12           | Level 2                            | Level 2                            | Level 2                            | Level 2                                |
| Day 13           | Level 2                            | Level 2                            | Level 2                            | Level 2                                |
| Day 14           | Level 2                            | Level 2                            | Level 2                            | Level 2                                |
As shown in Table 13, the comprehensive evaluation results of power quality obtained by the method proposed in this paper are basically consistent with those obtained by several other methods, which proves the feasibility of the method proposed in this paper.

When conducting comprehensive power quality assessments for different monitoring points, the PPIs of the level upper boundary value also changed. This is because we calculated the PPIs by calculating the level upper boundary value and monitoring value together.

It is apparent that altering the weights of indices will change the PPIs, and the results of evaluation may also change. To illustrate, we conducted a comprehensive sensitivity analysis by studying the following six cases.

Case 1–6: A dominant interval weight \((0.4 \quad 0.5)\) is assigned to an index, and an equal interval \((0.1 \quad 0.2)\) is assigned to the other five indices (Case 1 means the dominant interval weight is assigned to \(x_1\)).

Here, we take a new style to describe the level of power quality by Equation (41).

\[
\text{Level} = m + \frac{PPI_{\text{day}} - PPI_{l_0,m}}{PPI_{l_0,m+1} - PPI_{l_0,m}}, m = 1, 2, 3, 4
\]  

(41)

where \(PPI_{\text{day}}\) is the PPI value of a certain day, \(PPI_{l_0,m}\) is the PPI value of the \(m\)th level upper boundary in Table 2, and \(PPI_{l_0,m}\) is determined based on the constraints of Equation (42).

\[
\min|PPI_{\text{day}} - PPI_{l_0,m}|
\]

\(s.t.\ PPI_{\text{day}} > PPI_{l_0,m}\)

(42)

If \(PPI_{\text{day}} < PPI_{l_0,1}\), the level of power quality can be by determined by Equation (43). If \(PPI_{\text{day}} > PPI_{l_0,5}\), we directly identified it as unqualified.

\[
\text{Level} = \frac{PPI_{\text{day}}}{PPI_{l_0,1}}
\]  

(43)

The level here may not be an integer, and the results of sensitivity analysis are presented in Figure 7. We can see that the evaluation results vary with the change of the weights of the six indicators. Therefore, the accurate determination of the weights of the indicators is critical for determining the synthetic evaluation result accurately.

6. Conclusions

To ensure the safety and reliability of the power grid, it is necessary to evaluate power quality before the distributed generation is connected to the grid. If it does not meet the standards, it needs
to be equipped with corresponding measures. Accurate and comprehensive evaluation of power quality is of great significance for the realization of distributed power grid connection. Thus, we apply a triangular fuzzy BW method calculated from triangular fuzzy numbers to determine the interval weight of each power quality index, and then adopt an interval VIKOR method to determine the power quality level to which it belongs. The comprehensive assessment of steady state power quality is completed.

Compared with the existing comprehensive evaluation method of power quality, the method applied in this paper has the following advantages. The triangular fuzzy BW method can require fewer comparisons when the evaluation index increases, and it is easy to achieve good consistency across all comparisons. In addition, the triangular fuzzy BW method allows decision-makers to use triangular fuzzy numbers to assess the relative importance of the different indices, which can effectively avoid deviation due to the subjectivity, ambiguity, and vagueness of decision-makers. The interval weight of each power quality index value not only takes into account the ambiguity of the person’s judgment, but also reflects the different importance of each evaluation index.

For the interval weights, the interval VIKOR method can solve the problem of data uncertainty effectively. The power quality level of the monitoring point can be obtained intuitively according to comparison of the daily PPI value with the power quality level upper boundary value directly. Moreover, in this study, the data measured during the day were processed scientifically, and they could also compare the quality of the daily power roughly.

The result of sensitivity analysis by studying six cases shows that the weights of the indices have significant influence on the power quality synthetic evaluation.

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