Research on power quality assessment based on ubiquitous power IoT

Min Zhang¹, Huiqiang Zhi†, Jun Zhao¹, Rui Li¹, Xiao Chang¹, Rui Fan¹, Kai Xu²

2. Shenzhen Zhongdian Power Technology Co., Ltd., Shenzhen, Guangdong, 518040, China.

Abstract

With the rapid development of the Internet in this era, the traditional power grid is no longer able to meet the growing demand of the people for electricity. In order to realize a new generation of power system with comprehensive sensing, reliable transmission, intelligent processing and interconnection, the State Grid proposes the strategic goal of developing ubiquitous power IoT. Firstly, the concept and basic architecture of ubiquitous power IoT are elaborated, and then the main key technologies of the architecture of power energy consumption monitoring and management system are explained. The power quality parameters are measured and calculated, and the G1 method, which is computationally small and does not require consistency testing, is used to determine the subjective weights in the power quality evaluation process, which can truly reflect the power quality level of power grids in different regions. The information entropy method is used to determine the objective weights in the process of power quality evaluation to solve the error of artificially determined weights, and the combination of subjective weights and objective weights can more truly reflect the influence of each index on the comprehensive level of power quality. The results of the study show that PV is rated between 2 and 3 good when grid-connected and off-grid, and wind turbines are rated between 3 and 4 medium when grid-connected and off-grid. The results of the integrated assessment levels are in line with the actual situation and can meet the growing demand for electricity.

Keywords: Ubiquitous power IoT; Power quality; G1 method; Information entropy; of objective weights

AMS 2020 codes: 91B74
1 Introduction

In recent years, the problem of power quality has attracted increasing attention [1]. With the expansion of industrial scale and the development of science and technology, electrification is getting higher and higher, and new technologies and techniques are widely used in all aspects of industrial production and people's life [2-4]. A variety of complex, precise and sensitive high-tech power equipment has been popularized, and the requirements of power users for power quality are increasing [5-7]. At the same time, the number of rectifier-type, impact, and other nonlinear loads in the power system is increasing [8]. These nonlinear loads often lead to distortion of the grid waveform, voltage fluctuation, voltage flicker and three-phase unbalance, which cause increasing hazards and impacts on the safe operation of the power system and the normal work of power-using equipment, and have attracted the general attention of the power supply department and the majority of power users [9-11].

The assessment of power quality is to use the collected operating parameters of the power system to check whether the relevant indicators meet the specified standards [12-15]. A single evaluation index has a single connotation and does not reflect the operation of the whole system; therefore, a comprehensive assessment needs to be carried out [16-18]. The comprehensive assessment of power quality reflects the overall level of quality of electrical energy provided by the grid and essentially represents the level of operation of the entire grid structure as well as the power supply capacity of the power system [19-21]. Determining the market price of electric energy according to the quality of electric energy is an important trend in the current power supply market, so the quality of electric energy will be an important factor affecting the feed-in tariff [22-23]. In addition, the comprehensive quantitative results obtained after the assessment are an important reference for power companies to maintain and improve the quality of electric energy. Therefore, it is significant to carry out an accurate and effective comprehensive assessment of electric energy [24-26].

Preliminary studies have been conducted to address this issue, such as the literature [27], which argues that smart grids (SGs) face several challenges to efficiently transmit the generated electricity to electricity consumers. Therefore, a robust monitoring tool is needed to monitor the transmission lines to ensure the safety of the resources. This power transmission monitoring is a good example of ultra-reliable and low-latency application of 5G with the aim of providing quality of service and quality of experience. The main objective of this study is to design a wireless network for real-time monitoring of transmission lines to take preventive measures. An IoT real-time transmission line monitoring system consisting of wireless, wired and cellular technologies is proposed. The aim is to reduce the time delay with minimum network installation cost. In our proposed model, all sensors are powered by renewable energy sources (RES), such as wind and solar. The placement problem is formulated to determine the location of the transmission towers that support the cellular network. In addition, feasible areas are calculated to show the relationship between time delay and energy consumption. The results show that the proposed model provides an efficient solution with shorter time required for data transmission and is more energy efficient. The literature [28] proposes the QuAM (Quality Assessment Model), a model to assess the overall quality and value of the services provided by a company by analyzing consumer satisfaction. In fact, quality is measured by defining some subjective criteria, which are collected through questionnaires filled by consumers. The consumer's judgment of the goods/services provided can evaluate the reputation and success of a company. In this work, QuAM has been applied in the field of electric networks to evaluate an electric company. In this area, the overall evaluation of the organization is based on the measurement of service quality in terms of response time and cost. Service quality often comes at a cost, and there is concern that an electric utility's pursuit of profit incentives may have a negative impact on service quality. The role of the customer is crucial to estimate the market demand curve for service quality, and maximizing customer satisfaction means increasing profitability, productivity, and corporate image. QuAM was designed
by utilizing a fuzzy linguistic approach and the computational language (CWW) paradigm: customer feedback is modeled by linguistic labels that are naturally suited to describe human judgment; then, the linguistic operator LOWA (Linguistic Ordered Weighted Average) allows aggregating all collected judgments into a synthetic linguistic representation. Finally, heuristic measures allow for a comprehensive assessment of the company. The literature [29] investigated a single line diagram of a 0.4 kV network, whose initial parameters were refined in a network survey, and investigated the current load on the outgoing lines. An experimental study of the power quality was carried out using the complex measuring device EnergotesterPKE-A-C4 and the level of losses in the low-voltage network was evaluated. Results. As a result of the study, data on daily power consumption of individual outgoing lines, information on consumer characteristics, numerical information on power quality indicators in the low-voltage network (database) were obtained. It has been determined that the main factors affecting the power losses in the low-voltage network are: disproportionate transformer power of transformers and consumers, uneven loading of individual phases, significant influence of individual converters on energy quality. Measures to reduce losses and improve power quality in the low-voltage rural network at 0.4 kV are predicted. The literature [30] study aimed at examining the key drivers for achieving efficient electricity management (EEM) practices in public universities. Design/methodology/approach To achieve this objective, 23 drivers of EEM practices were identified through a comprehensive literature review and an empirical questionnaire survey was administered to 1386 electricity end-users in three public universities with staff and student hostels in Nigeria. The data collected were analyzed using the Statistical Package for Social Sciences (SPSS version 21) to determine the number of components that could represent the 23 identified drivers. The results of the relative importance index ranking of the study findings indicated that 18 drivers were critical. The top five most critical drivers were understanding of the problem, understanding of the vision and goals of the energy management program, knowledge and skills, risk identification, and good and effective communication among relevant stakeholders. Exploratory factor analysis revealed that the basic subgroup drivers were awareness raising, top management support and a strong energy management team, risk management, and stakeholder engagement. However, in the current power quality monitoring technology, there are still few monitors that can measure a variety of power quality indicators in an integrated manner. Most of the power quality testing equipment in some power supply companies is relatively old and still at a level that requires testers to go to the site to monitor the power quality condition, measuring a single indicator with poor real-time performance.

In view of the above problems, China, which is at a critical point of grid transformation, needs to carry out the deep integration of IoT technology and smart grid. In this paper, we propose research on power quality assessment based on ubiquitous power IoT. First, four basic frameworks of ubiquitous power IoT are constructed, which can finally realize the interactive coupling of energy flow, information flow and business flow. The weights are the key step to rank the importance order of each index in the comprehensive power quality assessment. Hierarchical analysis method is used to determine the weights, but the traditional hierarchical analysis method has problems such as inaccurate consistency verification and judgment accuracy and insufficiently obvious variability when determining the weights. Accordingly, the G1 method is introduced to improve the shortcomings of the traditional hierarchical analysis method, mainly using the three-scale method to determine the judgment matrix and transforming into the consistency matrix by the optimal matrix, which avoids the problems of consistency verification, inaccurate judgment accuracy and inconspicuous difference of the traditional hierarchical analysis method.

2 The concept of ubiquitous power IoT

In 1999, Xerox Corporation, California, USA and Massachusetts institute of technology, USA proposed the concept of ubiquitous network and internet of things, respectively [31]. Ubiquitous IoT
means that information can be connected and interacted without restricting the four elements of time, place, people and things [32]. The essence of ubiquitous power IoT lies in the collection, exchange, fusion and efficient expansion of "energy data" in the power industry, with the basic features of holographic perception, ubiquitous connection, open sharing and business innovation.

In order to realize the power ubiquitous IOT, it is necessary to further build an open, layered and calculable network architecture. Therefore, on the basis of the sense extension layer, network transmission layer and platform application layer of IOT, an edge computing layer is added to finally realize the interactive coupling of energy flow, information flow and business flow. Its basic architecture is shown in Figure 1.

![Figure 1 The 4 basic architectures of ubiquitous power IoT](image-url)

In Figure 1, the sensing extension layer is the foundation of ubiquitous power IoT, which is equivalent to the "nerve endings" of human body and consists of state sensing and execution control main terminals. The network transmission layer is the data transmission channel between the sensing extension layer and the platform application layer, providing efficient and safe, reliable and comprehensive communication information services for all types of services in the ubiquitous power IoT. The communication methods of electric power IOT include close wired/wireless transmission, traditional Internet, mobile air network, etc., of which each classification communication technology is shown in Figure 2.
Compared with traditional IoT, ubiquitous power IoT adds an edge computing layer, which is a
distributed intelligent agent near the end sensing nodes at the edge of the network, as can be seen
from Figure 2. It connects some devices in the sensing layer to the edge computing layer through bus,
wireless self-organized sensor network and other communication methods, and then transmits them
to the cloud platform for centralized processing after processing and analyzing the massive data in
the sensing layer. Based on the grid operation data, the platform application layer combines modern
advanced technology means to fuse and analyze the data, solving the storage problem under the
traditional energy production and operation mode, thus realizing information interconnection and
sharing.

Taking the energy consumption management system in this paper as an example, the four basic
structures of ubiquitous power IoT are represented in the whole system as follows: on the sensing
extension layer, the end sensing nodes of the system can collect all the total data of power energy
consumption in the park in real time on site, and apply them to the platform application layer with
network communication technologies of GPRS, 3G, 4G and Ethernet, and finally present the system's
3 Evaluation strategy of power quality

Under the power market, electric energy is traded in the market as a special commodity, and the principle of "pricing according to quality, quality and price" must be reflected [33]. The scientific and objective monitoring and evaluation of the power quality of the power grid is conducive to coordinating the interests of all parties in the power market and clarifying the responsibility of power quality management.

3.1 Measurement and calculation of power quality parameters

3.1.1 Calculation of AC voltage, current, power and power factor

In the case of sine wave, the active power is \( P = UV \cos \phi \). In the case of non-sine wave, the application of power electronics, impact loads and other non-linear components make the current and voltage contain various harmonics, which distort the waveform, and the waveform is non-sinusoidal. At this point, the active power is defined as:

\[
\begin{align*}
P &= \frac{1}{T} \int_{0}^{T} U idt \\
&= \int_{0}^{1/T} U u d t \\
&= \int_{0}^{1/T} I i d t
\end{align*}
\]

(1)

RMS value of phase voltage:

\[
U = \sqrt{\frac{1}{T} \int_{0}^{T} u^2 dt}
\]

(2)

RMS values of phase currents:

\[
I = \sqrt{\frac{1}{T} \int_{0}^{T} i^2 dt}
\]

(3)

Discrete sampling of the signals \( u(t) \), \( i(t) \) yields the discrete sequence \( \{u_k\}, \{i_k\} \), then:

\[
U \approx \sqrt{\frac{1}{T} \sum_{k=0}^{N-1} u_k^2 \Delta T_k}
\]

(4)

\( N \) describes the number of sampling points in a cycle, \( u_k \) describes the \( m \) time interval sampling instantaneous value, and \( \Delta T_k \) describes the two adjacent sampling intervals.

If the time intervals of two adjacent samples are equal and \( \Delta T_k \) is the time constant \( \Delta T \), we have:
Similarly, the current RMS equation can be obtained as:

$$I = \sqrt{\frac{1}{N} \sum_{k=0}^{N-1} i_k^2}$$ \hspace{1cm} (6)

When $N$ is large enough, the power can be expressed as:

$$P = \frac{1}{N} \sum_{k=0}^{N-1} (u_k i_k \Delta t) = \frac{1}{N} \sum_{k=0}^{N-1} (u_k i_k)$$ \hspace{1cm} (7)

$$T = \sum_{k=0}^{N-1} (\Delta t)$$ \hspace{1cm} (8)

Three-phase active power:

$$P = \frac{1}{N} \sum_{k=0}^{N-1} (u_k i_A + u_k i_B + u_k i_C)$$ \hspace{1cm} (9)

Apparent power:

$$S = U_A I_A + U_B I_B + U_C I_C$$ \hspace{1cm} (10)

Power Factor:

$$\cos \varphi = \frac{P}{S}$$ \hspace{1cm} (11)

### 3.1.2 Measurement of frequency

Frequency measurement is one of the most basic measurements in the field of electronic measurement, there are usually two methods of frequency measurement.

1. Counting method. This refers to a certain time interval $T$, the input periodic signal pulse counted as $N$, the frequency of the signal is $F = N / T$. The relative error of the measurement is $1 / N \times 100\%$. Obviously this method is suitable for high frequency measurement, the higher the frequency of the signal, the smaller the relative error.

2. Circumferential measurement method. This method is to measure the number of pulses $N$ of the standard signal with frequency $F_0$ in one cycle of the measured signal to indirectly measure the frequency, $F = F_0 / N$. Obviously, the longer the period of the measured signal (the lower the frequency), the greater the number of pulses $N$ of the measured standard signal, the smaller the relative error.
The period method based on the simple signal observation model is used to measure the frequency signal. The physical concept of the periodic method is clear and easy to implement. A single-phase voltage or phase current \( x(t) = A \sin(2\pi ft + \theta) \) is universally taken and filtered out by a low-pass filter to remove the higher interference components, and then fed to a compartmentalize to obtain a square wave signal output with the same frequency as the voltage signal, and the counting is done automatically by a programmable logic device to calculate the frequency of.

\[
f = 2.5\text{MHz} / \text{Frequency measurement} \quad (12)
\]

The signal period \( T = \frac{1}{f} \), and the signal period \( N \) is divided equally, the sampling interval of the signal can be obtained, so that the sampling frequency can be tracked to the system frequency.

### 3.1.3 Measurement of three-phase unbalance degree

The value of \( \varepsilon \) (three-phase unbalance) in the national standard refers to the measured value in the production (operation) cycle where the voltage unbalance caused by the load in the minimum way of normal operation of the power system is the largest. For example, steelmaking electric arc furnace should be measured in the melting period; for daily fluctuating load, can be measured on a typical day 24h. For less volatile occasions, should be compared with the arithmetic mean of the five close values measured; for more volatile occasions, should be compared with the 95% probability value of the measured value to determine whether it is qualified. Its short time allowable value is the limit value that cannot be exceeded at any moment.

This measurement is to use the power quality monitoring device to measure the three-phase unbalance degree, generally according to the 3s square root mean value, according to the following formula calculation.

\[
\varepsilon = \sqrt{\frac{1}{m} \sum_{k=1}^{m} \varepsilon_k^2} \quad (13)
\]

Where: \( \varepsilon_k \) represents the unbalance degree measured for the \( k \) time in 3s, \( m \) represents the number of uniform intervals taken in 3s \( (m \geq 6) \).

### 3.2 Evaluation system of power quality

At present, in the field of power quality research, the definition of power quality and the focus of research control are different. Generally speaking, voltage, frequency and power supply reliability are the three main categories of indicators to measure the good or bad power quality. Voltage indicators are divided into voltage deviation, voltage fluctuation and flicker, voltage harmonics and three-phase voltage unbalance. In the comprehensive evaluation system of power quality, all indicators are interrelated, and the change of each parameter will affect the authenticity and accuracy of the whole power quality evaluation. The evaluation system indicators are as follows.

1. Frequency deviation: defines the degree of deviation of the fundamental wave frequency from the rated frequency in the power system.
(2) Voltage deviation: It can be divided into two categories: long-time voltage deviation and short-time voltage deviation. Long-time voltage deviation: Defined as all voltage deviations with a duration of more than one minute and the steady-state frequency voltage RMS value exceeding the specified limit. Short-time voltage deviation: including three categories of voltage dips, voltage rises and voltage losses. Defined as all voltage deviations with a duration of 0.5 cycles ~ within 1 minute where the effective value of the I.F. voltage exceeds the specified limit.

(3) Three-phase unbalance: Defined as the maximum value of phase voltage or phase current for the average value of three-phase voltage or current deviation.

(4) Waveform distortion: defined as the steady-state offset of an ideal frequency sine wave, often described by its spectral content, waveform distortion mainly includes harmonics, DC offset, interharmonics, trapped waves and noise and other five aspects of the content.

(5) Electromagnetic transient: refers to the transition from a stable state to another stable state of the power system, the voltage or current value of temporary changes. The main reasons for electromagnetic transients are power system faults and lightning shocks. Electromagnetic transients can generally be divided into two kinds of shock transients and oscillatory transients.

(6) Voltage fluctuations and flicker: voltage fluctuations refers to a series of relatively rapid changes in the root mean square value of the voltage or continuous change in the phenomenon, but the range of change in the rated value of ± 10% or less. Flicker refers to the impact of voltage fluctuations on the lighting equipment, and this impact is subjectively felt by people.

(7) Harmonics (Harmonics) indicators: containing an integer multiple of the frequency of the fundamental sine wave voltage or current is called harmonics, the waveform can be decomposed into the fundamental and the sum of the harmonics after the generation of distortion.

(8) Power supply reliability index: The reliability of power supply refers to the ability of the power supply system to supply power continuously, which reflects the degree to which the power industry can meet the demand for electric energy of the national economy. It can be measured by power supply reliability rate, average power outage time of users, average number of power outages and average number of fault outages of users.

According to the above analysis of the indicators of power quality evaluation system, combined with the six national standards of power quality, a comprehensive evaluation system of power quality is proposed, as shown in Fig. 3 below. The evaluation indicators can be divided into primary and secondary indicators, among which voltage indicators have six secondary indicators, frequency indicators consist of a secondary indicator, and the reliability of power supply indicators can be determined separately. The secondary indicators \( I_m, m = 1 \sim 8 \), are voltage deviation (%), voltage fluctuation (%), voltage flicker, voltage waveform distortion (%), three-phase unbalance (%), voltage drop, frequency deviation (Hz), and power supply reliability (%). Among them, voltage flicker is the short time flicker value \( P_m \), voltage drop is defined as the ratio of the root mean square reduction of voltage to the rated value, and frequency deviation is taken as the absolute value.
3.3 **G1 method to determine the subjective weight of each index**

G1 method is a method without consistency test which is an improvement of AHP method, and the method has the following characteristics compared with AHP.

(1) The computational volume is greatly reduced compared with AHP, and the computational speed is improved.

(2) There is no need to construct a judgment matrix and no consistency test.

(3) The stretching of the number of elements in the same level is stronger.

(4) Order-preserving, simple, intuitive and easy to use.

To determine the sequential relationship for the set of evaluation indicators \( \{I_1, I_2, \ldots, I_m\} \) using the G1 method, \( I_i \)

(1) Select the most or least important indicator from the set of indicators.

(2) Select the most important or least important indicator \( I_j \) from the remaining indicators.

(3) By analogy, we can obtain a unique sequential relationship \( I_i \succ I_j \succ \ldots \succ I_k \). After that, the relative importance of adjacent indicators in the sequential relationship is determined.

The ratio of the importance of the experts (decision makers) between the adjacent indicators \( I_{k-1} \) and \( I_k \) can be expressed by \( r_k = \frac{W_{k-1}}{W_k} \), where \( W_k \) is the \( k \) indicator weight, \( k = 2,3,\ldots, m \). In this way, the relative importance of each indicator can be calculated according to the sequential relationship.
determined by the previous indicators. \( r_k \) is first determined by each expert alone. The \( r_k \) is determined by each expert and then averaged. For a large number of indicators, the least important indicator \( r_m = 1 \). The value of \( r_k \) can be found in Table 1.

**Table 1. Criteria for forming the ratio of indicators**

<table>
<thead>
<tr>
<th>Level of importance ( r_k )</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>Indicators ( I_{k-1} ) and Metrics ( I_k ) equally important</td>
</tr>
<tr>
<td>1.2</td>
<td>Indicators ( I_{k-1} ) and Metrics ( I_k ) slightly more important</td>
</tr>
<tr>
<td>1.4</td>
<td>Indicators ( I_{k-1} ) and Metrics ( I_k ) obviously important</td>
</tr>
<tr>
<td>1.6</td>
<td>Indicators ( I_{k-1} ) and Metrics ( I_k ) strongly important</td>
</tr>
<tr>
<td>1.8</td>
<td>Indicators ( I_{k-1} ) and Metrics ( I_k ) extremely important</td>
</tr>
<tr>
<td>1.1 1.3 1.5 1.7</td>
<td>Between two indicators</td>
</tr>
</tbody>
</table>

The weight value of the \( m \) indicator in the sequential relationship is found, and then the weight value of each indicator is calculated in turn according to equation (16).

\[
\begin{align*}
  r_{k-1} & \geq r_k \\
  w_m & = \left[ 1 + \sum_{k=2}^{m} \prod_{i=k}^{m} r_i \right]^{-1} \\
  w_{k-1} & = r_k w_k
\end{align*}
\]  

(14) \hspace{1cm} (15) \hspace{1cm} (16)

In the above formula \( k = m, m-1, \ldots, 3, 2 \). Then \( W = (w_1, w_2, \ldots, w_m) \) is the weight vector corresponding to each indicator.

### 3.4 Information entropy to determine the objective weight of each index

The objective weights depend on the measured values of the samples to be evaluated and the standard values of the evaluation factors. Since the measurement evaluation matrix of each sample to be evaluated is derived from the measured values and the standard values, the measurement evaluation matrix contains the weights of each indicator of the sample to be evaluated. The objective weights of the samples to be evaluated can be obtained from the measurement evaluation matrix of the samples to be evaluated.

The maximum value of indicator \( I_j \) in the \( i \) sample is defined as \( Y_{ij} \):

\[
Y_{ij} = 1 + \frac{1}{\log_2} \sum_{k=1}^{k} \mu_{ijk} \log_2 \mu_{ij}
\]  

(17)
In formula (17), $K$ is the number of levels to be evaluated, and let the value of the $j$ indicator of the $i$ sample $x_{ij}$ belong to the attribute measure of attribute $C_k$ as $\mu_{ijk}$ $(1 \leq k \leq K)$, and the size of $Y_{ij}$ reflects the importance of $I_j$. The objective weight $b_{ij}$ of $I_j$ indicator of sample $i$ to be evaluated is obtained after normalizing $Y_{ij}$ of each indicator:

$$b_{ij} = \frac{Y_{ij}}{\sum_{j=1}^{m} Y_{ij}} \quad i = 1, 2, \ldots, n \quad j = 1, 2, \ldots, m \quad (18)$$

Equation (18), $m$ is the number of evaluation indicators, $Y_{ij}$ is the maximum value of the $l$ indicator, $1 \leq l \leq m$. Then $B_i = (b_{i1}, b_{i2}, \ldots, b_{im})$ is the weight vector of each indicator of sample $X_i$, then the $m$ evaluation indicator weight vector of $n$ samples to be evaluated is:

$$B = \begin{bmatrix}
B_1 \\
B_2 \\
\vdots \\
B_n
\end{bmatrix} \quad (19)$$

### 3.5 Determination of comprehensive weights

After determining the subjective weights $W$ and objective weights $B$ using the G1 method and the entropy weight method, the comprehensive weight value of the $j$ index of sample $i$ can be obtained according to equation (20) as follows.

$$\omega_{ij} = \frac{w_i b_{ij}}{\sum_{j=1}^{m} w_j b_{ij}} \quad i = 1, 2, 3 \ldots m \quad (20)$$

Then the comprehensive weight vector $W_i$ of sample $i$ to be evaluated is: $W_i = (\omega_{i1}, \omega_{i2}, \ldots, \omega_{im})$.

### 3.6 Comprehensive evaluation

Identification and comparative analysis are performed according to the confidence criterion. For the confidence level $\lambda$ (generally taken $0.6 \leq \lambda \leq 0.7$) calculation.

$$k_i = \min \left\{ k : \sum_{l=1}^{k} \mu_{il} \geq \lambda, 1 \leq k \leq K \right\} (1 \leq i \leq n) \quad (21)$$

Then the $i$ sample $X_i$ to be evaluated is considered to belong to level $C_k$. The composite score of the $i$ sample $X_i$ to be evaluated is $R_i$: 

Implementation of comprehensive assessment

In the electricity market environment, electric energy has been transformed into a special commodity of electricity supply and auxiliary services provided by the power sector to the electricity users. How to monitor and evaluate the power quality has become a prerequisite for power quality management. The power quality monitoring and evaluation system is an important tool for power quality monitoring and management in modern power system.

The specific implementation steps of this paper have been described above. The selection of the data for the comprehensive power quality assessment is based on the assessment of the power quality of a random power source as a single assessment of the power quality as the data for the comprehensive power quality assessment.

According to the statistical results of each index level of the single assessment of each power index at the time of grid-connected photovoltaic, and according to the ranking of the comprehensive assessment weight statistics to generate the probability distribution matrix of the comprehensive assessment of power quality, the specific comprehensive assessment probability distribution matrix is shown in the following expression.

\[ R_i = \sum_{k=1}^{K} (K + 1 - k) \mu_{ik} \]  

(22)

4 Implementation of comprehensive assessment

Using the comprehensive assessment weights derived from the above G1 method and AHP method respectively multiplied by the probability distribution matrix generated for each individual index when the PV is connected to the grid, the comprehensive power quality assessment matrix is obtained with.

\[ S_i = \begin{bmatrix}
0 & 0.165 & 0.541 & 0.248 & 0.029 & 0.0166 & 0 & 0 & 0 & 0 \\
0.373 & 0.456 & 0.155 & 0.014 & 0.0014 & 0 & 0 & 0 & 0 & 0 \\
0.254 & 0.745 & 0.0014 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.76 & 0.24 & 0 & 0 & 0 & 0 & 0 \\
0.994 & 0.0042 & 0.0014 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix} \]  

(23)

Using the comprehensive assessment weights derived from the above G1 method and AHP method respectively multiplied by the probability distribution matrix generated for each individual index when the PV is connected to the grid, the comprehensive power quality assessment matrix is obtained with.

\[ V = (0.4335, 0.2847, 0.1240, 0.1234, 0.0320, 0.0019, 0, 0, 0, 0) \]  

(24)

\[ V_1 = (0.4115, 0.2934, 0.1286, 0.1302, 0.0338, 0.0021, 0, 0, 0, 0) \]  

(25)

Then the comprehensive assessment matrix is weighted to obtain the PV grid-connected comprehensive assessment unique values \( R \) and \( R_i \). This is PV grid-connected G1 method comprehensive assessment value \( R = 2.0409 \) and PV grid-connected AHP method comprehensive assessment \( R1 = 2.0473 \). The assessment results of each individual index of power quality when PV is connected to the grid are shown in Figure 4(a).

According to the comprehensive assessment results of PV grid-connected, the comprehensive assessment of power quality grade determined by AHP method and G1 method are between 2~3, and their performance form is good. By looking at the assessment results of each single item of power
quality when PV is grid-connected, most of the PV indicators are mainly concentrated between 2~3. Therefore, AHP method and G1 method to determine the weight of comprehensive assessment of power quality level is more reasonable.

Similarly, the comprehensive assessment matrix for off-grid PV is generated $S_2$.

$$
S_2 = \begin{pmatrix}
0 & 0 & 0 & 0.0444 & 0.6990 & 0.2540 & 0.0030 & 0 & 0 & 0 \\
0.1054 & 0.2700 & 0.4700 & 0.1370 & 0.0166 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.7130 & 0.2870 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.7160 & 0.2840 & 0 & 0 & 0 & 0 & 0 & 0 \\
0.9972 & 0 & 0.0028 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{pmatrix}
$$

In the same way, we get the unique values $R_2$ and $R_3$ for the comprehensive assessment of power quality when PV is off-grid. i.e. $R_2 = 2.5690$, $R_3 = 2.6312$ for the comprehensive assessment of off-grid. The evaluation results of each individual index of power quality when PV is off-grid are shown in Figure 4(b).
According to the PV off-grid comprehensive assessment results, it can be seen that the comprehensive assessment power quality grade determined by the AHP method and G1 method is between 2 and 3, and the performance form is good, and through the PV off-grid power quality individual assessment results, most of the indicators are mainly concentrated between 2 and 3. Therefore, this paper's method to determine the weight of the comprehensive assessment of power quality level is more reasonable.

According to the statistical results of each index level of the single assessment of each electrical energy index when the wind turbine is connected to the grid, and according to the ranking statistics of the comprehensive assessment weight to generate the probability distribution matrix \( S_3 \) of the comprehensive assessment of power quality, the specific comprehensive assessment probability distribution matrix is shown in the following expression.

\[
S_3 = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0.0984 & 0.9016 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.3156 & 0.6844 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.1434 & 0.8115 & 0.0451 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\] (27)

The comprehensive assessment matrix was weighted to obtain the unique values of \( R4 \) and \( R5 \) for the comprehensive assessment of wind turbines on grid connection, i.e. \( R4 = 3.4832 \) for the G1 method and \( R5 = 3.5783 \) for the AHP method when the wind turbines are off-grid. The results of the single indicators of power quality when the wind turbines are on grid connection are shown in Figure 5(a).

According to the comprehensive assessment results when the wind turbine is connected to the grid, it can be seen that the comprehensive assessment power quality assessment results grade by AHP method and G1 method to determine the weights are between 3 and 4, and its comprehensive performance form is medium. Looking at the results of each single assessment of the power quality of wind turbines connected to the grid when they are connected to the grid, most of the indicators are mainly concentrated between grades 3 and 4. Therefore, from the results of each single assessment, it is clear that the AHP method and G1 method to determine the weight of the comprehensive assessment of power quality level is more reasonable.

According to the statistical results of each index level of each single assessment of each electrical energy index when the wind turbine is off-grid, and according to the ranking statistics of comprehensive assessment weights, the probability distribution matrix of comprehensive assessment of electrical energy quality is generated.

\[
S_4 = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0.2049 & 0.5246 & 0.2705 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.4467 & 0.5533 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.8402 & 0.1598 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\] (28)

Similarly, the only values of \( R6 \) and \( R7 \) were obtained for the comprehensive assessment of the wind turbine off-grid, i.e., the value of \( R6 = 3.0561 \) for the G1 method and \( R7 = 3.1403 \) for the
hierarchical analysis method. The evaluation results of each individual index of power quality when the wind turbine is off-grid are shown in Figure 5(b).

According to the comprehensive assessment results of the wind turbine off-grid, it can be seen that the comprehensive assessment of the power quality level through the AHP method and G1 method to determine the weights are between 3 and 4, and the performance form is medium. Looking at the results of each individual assessment of power quality when the wind turbine is off-grid, most of the indicators are mainly concentrated between grades 3 and 4. Therefore AHP method and G1 method to determine the weight of the comprehensive assessment of power quality level is more reasonable. In summary, the unique values of the final comprehensive assessment results of random power supply are listed in Table 2 below.
Table 2. Final assessment results of random power supply

<table>
<thead>
<tr>
<th>Stochastic power supply</th>
<th>Status</th>
<th>AHP method</th>
<th>G1 method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photo voltaic</td>
<td>Grid connection</td>
<td>2.0473</td>
<td>2.0409</td>
</tr>
<tr>
<td></td>
<td>Off-grid</td>
<td>2.6312</td>
<td>2.5690</td>
</tr>
<tr>
<td>Fans</td>
<td>Grid connection</td>
<td>3.5783</td>
<td>3.4832</td>
</tr>
<tr>
<td></td>
<td>Off-grid</td>
<td>3.1403</td>
<td>3.0561</td>
</tr>
</tbody>
</table>

The traditional and improved integrated assessment results of stochastic power supply PV in grid-connected and off-grid remain almost consistent, with good grades between 2 and 3. The traditional and improved integrated assessment results of wind turbine in grid-connected and off-grid also remain almost consistent, with moderate grades between 3 and 4. Looking at the individual assessment results of PV and wind turbine, we can see that their respective integrated assessment results are reasonable. In the process of comprehensive assessment of power quality weight is a very important factor, the accuracy of the weight is directly related to the accuracy of the assessment results, based on the weight determination method of the AHP method to determine the weight has the disadvantages of the scale value is not precise enough and the difference is not obvious enough. Accordingly, the G1 method is proposed to use three scales and introduce the optimal matrix to generate the consistency matrix to improve the shortcomings of the AHP method. Finally, the comprehensive evaluation results of the five electric energy indicators were assessed to be in line with the actual situation.

5 Conclusion

With the large-scale use of sensitive loads, the traditional power quality assessment can hardly reflect the impact of power quality on equipment objectively, and some transient power quality problems are increasingly highlighted. For this reason, a research on power quality assessment based on ubiquitous power IoT is proposed. Firstly, we start from the definition and basic framework of ubiquitous power IOT, and introduce the main key technologies of power energy consumption monitoring and management. Then the measurement and calculation methods of power quality parameters are analyzed in detail, and how to measure and calculate each parameter of power quality in practical engineering is introduced to provide an important theoretical basis for the data processing algorithm of the power quality monitor. The G1-method is used to determine the comprehensive weight coefficients of each power quality indicator by using the properties of objective weights related to the indicator measurement matrix, which overcomes the one-sidedness of the single assignment method, reduces the calculation volume and makes the comprehensive assessment results more scientific and accurate. The results of the study show that: assessing the five electric energy indicators, most of each indicator is mainly concentrated between 3 and 4 levels. Voltage deviation is a common problem for both power sources, and frequency deviation is also an indicator that dominates the influence of both power sources when they are off-grid, while other indicators perform well in the evaluation. Networked power quality monitoring and evaluation is the inevitable development trend in the future. The future power quality monitoring should realize the power quality monitoring in different locations within the same power supply system or in several different power supply systems. In terms of function, in addition to the functions of query, calculation and display, it should also have certain advanced functions such as control, judgment, analysis and decision making.
References


**Funding**

Intelligent Internet of Things Oriented Power Quality Fusion Perception and Data Mining Technology and Application in Distribution Network (5205302000X).