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Study of the Power Quality Comprehensive Evaluation Method

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Abstract. The scientific evaluation of power quality is the basic condition for the treatment of electric energy pollution. In this paper, the relevant concepts and various indexes of power quality are analyzed based on the internal and external power quality standards. The evaluation method of power quality is divided into the specific analysis of single index evaluation and comprehensive evaluation. This paper proposes four evaluation methods of single index, including based on fuzzy mathematical single index evaluation method, based on fuzzy mathematics in various energy index commonly used membership function method, based on probability and statistics of the single index evaluation method and based on the main use of power grid planning, power grid construction and interference load before access to the simulation of the individual indicators to predict the assessment method. The weight selection method used in the comprehensive evaluation of power quality is analyzed from the subjective weight to the objective weight.

Introduction

In recent years, more and more attention has been paid to power quality of power grid, and many methods have been used in power quality assessment at home and abroad. According to the basic requirements of power quality assessment, it can be divided into single index evaluation and comprehensive evaluation. According to the different evaluation objects, it also can be divided into test point evaluation and power system comprehensive evaluation. The evaluation of power quality involves many factors and different standards. Thus there is no accepted definition of an authoritative assessment, at present, the main basis for the evaluation of power quality is whether or not the power grid or the user's harmonic is over standard[1].

The main evaluation methods of power quality include the evaluation method based on fuzzy mathematics, the evaluation method based on probability statistics, the evaluation method based on intelligent algorithm, and the method of determining the subjective weight, the method of determining the objective weight, and the method of weighted combination selection method. These methods have their own advantages, disadvantages and the scope of use[2].

Overview of Power Quality Assessment Methods

Power quality assessment is a multi-index comprehensive evaluation problem, which has been studied at home and abroad. According to the different indexes of power quality assessment, it can be divided into single index evaluation and comprehensive evaluation. According to the different forms of the results, it can be divided into quantitative evaluation and index grade evaluation. According to the evaluation object, it can be divided into test point evaluation and power system comprehensive evaluation. According to the purpose of evaluation, it can be divided into custom assessment and public assessment. The evaluation of power quality is so complex that there is no universally accepted definition of complete evaluation[3,4].

Single Evaluation of Power Quality

The single evaluation of power quality refers to the evaluation of a certain index of power quality, or a certain characteristic parameter. For example, in order to evaluate the detection point of harmonic condition or voltage sag condition, the harmonic and voltage sag of power quality are evaluated separately. The evaluation results can be the numerical indicators quantized or the power quality grade. Single index evaluation is the basis of comprehensive evaluation of power quality, and many comprehensive evaluation methods are based on the evaluation of power quality indexes.

Single Index Evaluation Method Based on Fuzzy Mathematics

The index of power quality is often fuzzy when describing the power quality and fuzzy mathematics theory can deal with this kind of fuzzy problem effectively. Firstly, the fuzzy mathematics evaluation of power quality should be established membership function power quality indexes. Secondly, the measured data of each index are obtained the membership of each index. Lastly, the classification of membership grades for different index levels.

It is necessary to select proper membership function for fuzzy mathematics evaluation, and the membership function can be divided into two categories: continuous membership function and discrete membership function. In order to ensure the accuracy of the fuzzy model, we must choose a reasonable membership function. It can be seen from the method of determining membership degree that the choice of membership is subjective. But as long as the modeling object can be described accurately, the membership function is reasonable. The membership function used in power quality evaluation is introduced as follows:

(1) The membership function of voltage deviation is shown in equation (1) and (2)

$$\mu(\Delta U)=\begin{cases} 0 & \Delta U \le -U_2 \\ 0.5+0.5\sin\left[\dfrac{\pi}{U_2-U_1}(\Delta U-\dfrac{U_2+U_1}{2})\right] & -U_2<\Delta U<-U_1 \\ 0.5-0.5\sin\left[\dfrac{\pi}{U_2-U_1}(\Delta U-\dfrac{U_2+U_1}{2})\right] & U_1<\Delta U<U_2 \\ 0 & U_2 \le \Delta U \end{cases}. \tag{1}$$

$$\mu(\Delta U)=\begin{cases} 0 & |\Delta U| \ge U_2 \\ \dfrac{1}{\sqrt{2\delta}}e^{-\Delta U^2/2\sigma^2} & else \\ 1 & |\Delta U| \le U_1 \end{cases}. \tag{2}$$

Formula: ΔU is the voltage deviation, the other is based on the actual situation of constant determination.

(2) Membership function of duration of voltage deviation

$$\mu(T_{\Delta U})=\begin{cases} 1 & T_{\Delta U} \le T_{\Delta U_0} \\ e^{-k(T_{\Delta U}-T_{\Delta U_0})} & T_{\Delta U} > T_{\Delta U_0} \end{cases}. \tag{3}$$

Formula: $T_{\Delta U}$ represents the duration of the voltage deviation, k and $T_{\Delta U_0}$ are constants.

(3) The voltage fluctuation and flicker, harmonic distortion, three-phase unbalance, etc.

$$\mu(äU)=\begin{cases}1 & äU<U_3\\ \frac{1}{2}-\frac{1}{2}\sin\left[\frac{\delta}{U4-U3}äU-\frac{U_3+U_4}{2}\right] & U_3<äU<U_4\\ 0 & äU_1>U_4\end{cases}. \quad (4)$$

(4) Count index

The reliability of power supply, voltage sag, short-time interruption is usually used as the membership function of type $\mu(x)=1-x$. For the reliability index $x=t_r/t_T$, t_r is used to evaluate the time of interruption of power supply in the period of time, t_T is the total time. The voltage swell or voltage sag, $x=\sum N_i/N_T$, N_i is the number of users in the evaluation region of the voltage sag or swell, N_T to assess the total number of users in the region.

Single Index Evaluation Method Based on Probability and Statistics

For the deviation of voltage and frequency deviation, we should pay attention to the magnitude and duration of the deviation. Scientists commonly used methods of mathematical statistics to do continuous monitoring on voltage and frequency in the assessment period, record numerical and time of the variable voltage and frequency, and make analysis of the monitoring data. So the corresponding index can be calculated.

Averaging the national standard limit according to the national standards and the actual situation and establishing evaluation level. Then, measuring the power quality index which belongs to the time of each grade and obtaining the variance and standard deviation. Then analysing the expected value and standard deviation which accord to the given expected value and standard deviation[5].

Single Index Evaluation Method Based on Prediction

This evaluation method is used to evaluate the potential quality problems by using the method of simulation calculation before the power grid planning, power grid construction or interference load access. First of all, the power supply department should be familiar with the special load data and then can evaluate by the prediction method. Details of the load include: power supply capacity, load working mode, load working time, grid location and so on. The grid parameters and the above details are analyzed and simulated. Then the power quality problems are analyzed.

The steps of predictive analysis are: the equivalent circuit diagram is determined and the simulation calculation is carried out by the characteristics of power grid and load. If calculating harmonic or three-phase sequence. The network parameters are the corresponding harmonic parameters and three phase sequence parameters. Pouring into harmonic current by calculating the harmonic current and the voltage fluctuation of the connection point is calculated according to the load current, then getting the various indicators by simulation calculation[6].

Comprehensive Evaluation of Power Quality

Single Power Quality Comprehensive Evaluation

Evaluation of harmonic quality belongs to the evaluation of single power quality and it is not comprehensive evaluation when the total harmonic distortion rate or the harmonic frequency (as 3 times) and characteristic harmonics are separate evaluated. However, because of many characteristics of harmonic measurement parameters, for example, China's national standard GB/T14549-1993 fixes the total harmonic distortion rate and the harmonic contains rate from 2 to 19 and European EN50160 standard also fixes harmonic rate from 2 to 40. A large number of characteristic indexes and their limits determine that the complete evaluation of harmonics should be a single index.

There are two methods of fuzzy comprehensive evaluation, such as fuzzy clustering[7] and genetic projection pursuit[8]. Fuzzy clustering method is a kind of multivariate analysis method that assorts samples with fuzzy boundaries by mathematical methods. Determining quantified the similarity and difference in samples.

Genetic projection method is a kind of objective data analysis method, which is used to transform

the high dimensional data through the projection function, convert the high dimensional data to the low dimension, and analyze the structural characteristics of the high dimensional data according to the projection value. The method uses the projection function to describe the similarity and the difference of the analysis data, and uses the genetic algorithm to calculate the projection value of the optimal projection function to analyze the structural characteristics of the high dimensional data[7].

The harmonic evaluation index generally contains the harmonic and the harmonic current. According to our country's harmonic limit standard, the harmonic index such as the oil content of each harmonic voltage, the harmonic current value and the total distortion rate of harmonic voltage are classified and subject projection index. The projection function is the mathematical relationship between the M data and the N evaluation level （i=1,2...n; j=1,2...m)x(i,j). The projection pursuit method integrates the n-dimensional data into a one-dimensional projection value Z (I) in the direction of a=2:

$$z(i)=\sum_{j=1}^{m}a(j)x(i,j),\quad i=1,2\cdots n;\ j=1,2\cdots m. \tag{6}$$

The projection index function is

$$f(a)=\mathrm{S}_{\mathrm{Z}}\left|Rzy\right|. \tag{7}$$

Projection value Z(i) should be as large as possible to extract x (i,j) in the variation of information. Z (i)'s standard deviation S_{Z} should be as large as possible and requiring Z (i) and Y (i) correlation coefficient R_{ZY} absolute value of $\left|Rzy\right|$ as much as possible.

The best projection direction is:

$$\max\ f(a)=S_z\left|R_{zy}\right|. \tag{8}$$

$$a(j)>0,\ \sum_{j=1}^{p}a(j)=1. \tag{9}$$

By solving the equation (8) and (9), the best projection direction can be obtained.

A Comprehensive Evaluation Method of Correlation Probability Theory

Because of the power quality index, the probability statistics method can be used to grasp the main characteristics of the power quality indexes and to evaluate the power quality. The application of probability theory to power quality assessment, first of all, it is necessary to combine the national limit standards to divide power quality indicators into several levels. and then according to the probability theory to calculate probability distribution function $f(x)$ of the assessment period of the power index for each grade, and use expectations and contrast of the distribution function to reflect the data characteristics of index in the assessment period. That is to get the standard deviation $R(x)$ and expected value $E(x)$ of the probability function $f(x)$, and use given the standard value of $R(x)$ and $E(x)$ to normalize the results of the indicators, which is convenient for the subsequent comprehensive analysis.

Comprehensive Evaluation Method Based on Intelligent Algorithm

In addition to the application of single index evaluation of genetic algorithms, as well as neural network methods. Neural network method is a kind of artificial intelligence method through

simulating the working principle of biological neural system. It has good self-organization and fault tolerance. A typical BP neural network contains input layer, hidden layer and output layer. Through inputting the training samples, each node of each layer is trained, when the training error accuracy meets the requirements, it can be used to analyze the test data[7].

Comprehensive Evaluation Method Based on Fuzzy Mathematics

Some indexes of power quality are fuzzy, They can be evaluated by fuzzy mathematics and can be classified into fuzzy pattern recognition method and fuzzy comprehensive evaluation method.

The evaluation procedure of fuzzy pattern recognition method:

(1) According to the national standard, the power quality is divided into several grades; Finally, the sample set of index membership degree is formed; (2) Establish the fuzzy model of power quality indexes; (3) the measured data are substituted into the fuzzy model to get the fuzzy sets of each index; (4) take the arithmetic mean of fuzzy set to get the membership degree of each index, and use the membership set to express it; (5) use the mathematical method to calculate the degree of closeness of the membership degree to the each grade of power quality index; (6) determine the grade of power quality.

Fuzzy comprehensive evaluation method:

(1) Establish the membership function of each index of power quality; (2) the measured data of each index are brought to obtain the membership of each index; (3) grading of each index; (4) find out the percentage of each index data in each grade; (5) use the fuzzy comprehensive method to judge the grade of the two grade judgment matrix.

Power Quality Comprehensive Evaluation Weight Selection Method

Subjective Weighting Method

Subjective weighting method is a qualitative analysis method, the core of which is based on the knowledge and experience of experts, the subjective judgment of the important degree between the indexes through the comprehensive index weight.

AHP (Analytic hierarchy process) is the most widely used, which makes the complex evaluation problem hierarchical, and compares the qualitative comparison of the indexes with the scale quantization, it's suitable for multi objective decision making problem with multi hierarchy. Firstly, the hierarchy of the index system should be determined, and the hierarchy of the index system can be divided into the target layer, the criterion layer and the solution layer. The judgment matrix is obtained according to the 5 scale or the 9 scale method's mutual comparison for index, then we can get index weight by calculating the eigenvector of the maximum eigenvalue of the judgement matrix and normalized processing. The consistency test is needed to solve the feature vector, and the judgment matrix is not adjusted by the consistency test until satisfying consistency check[8].

Superiority chart compares indexes in pairs and establishes $(n\times n)$ icon matrix for n evaluation index. If the index i is more important than the index j, then the index is 1, equal to the importance of 0.5, otherwise for the 0, score as x_{ij} and form matrix $x_{ij}(n\times n)$. Finally, λ_i is calculated by the formula (10) as the weight of the index i.

$$\lambda_i = \sum_{j=1}^{n} X_{ij} \Big/ \left[0.5n(n-1)+0.5n\right]. \tag{10}$$

For example, as shown in table 1. According to the formula (10), the weight of the index a to g can be obtained as（0.14,0.14,0.1,0.14,0.14,0.18,0.14）.

The advantage of subjective weighting method is that it can give full play to the role of expert knowledge, and can determine the weight of each index according to different practical problems. The weight of each index can not be accurate by the subjective weighting method, but in normal circumstances, the order of weight given by the subjective weighting method should be accurate. And through the subjective weight can be defined to limit the weight of the index, to avoid the objective weight method in the index weight divorce from the actual.

Table 1. Instance of superiority chart.

Indexes	a	b	c	d	e	f	g
A	0.5	0	0	1	0	1	1
B	1	0.5	1	0	1	0	0
C	1	0	0.5	0	0	0	1
D	0	1	1	0.5	0	1	0
E	1	0	1	1	0.5	0	0
F	0	1	1	0	1	0.5	1
G	0	1	0	1	1	0	0.5

Subjective advantage is also the disadvantage. Expert opinion has a decisive effect on the results, different experts' opinions will get different weights. By increasing the number of experts, the use of a more comprehensive method of expert opinion to improve the accuracy of subjective weight. Different methods of improvement can weaken its disadvantages but not eliminate it.

Objective Weighting Method

The core idea of objective weighting method is to determine the index weight by excavating dates based on the structural characteristics of the data. There are mainly weighted entropy endow entropy model, principal component analysis weighting method, variation coefficient weighting method, open grade weighting method, multi-objective programming weighting method, Correlation function weighting method, standard variance weighting method, etc. The entropy weight method and the principal component analysis method are applied more[7].

Entropy weighting method derived from information theory, in information theory, entropy is used to measure the degree of disorder of the system. For the multi index evaluation, the weight of the n indexes depends on the information provided by each index, the greater the impact of indicators on the evaluation, the greater the value of the index weight. Firstly, the original data matrix is Y.

The matrix is normalized, the ratio of the column vectors of the matrix and the sum of all the elements in the matrix is taken as the normalization result, the formula is as follows (11):

$$z_{ij} = \frac{y_{ij}}{\sum_{i=1}^{n} Y_{ij}} \quad (j = 1,2,\cdots,m) . \tag{11}$$

$$E_j = -(\ln n)^{-1} \sum_{i=1}^{n} z_{ij} \ln z_{ij} \qquad j = 1,2,\cdots,m . \tag{12}$$

Where: when $z_{ij} = 0$, regulating $z_{ij} \ln z_{ij} = 0$. Then:.

$$\mu_j = \left(1 - E_j\right) \Big/ \sum_{k=1}^{m} 1 - E_k \qquad j = 1,2,\cdots,m . \tag{13}$$

Objective weight vector:

$$\mu = (\mu_1, \mu_2, \cdots, \mu_m)^T$$

Principal component analysis weighting method is a kind of objective weighting method. Assume that there are n indicators: F1,F2,…,Fn, Data collected for each indicator: X1,X2,…Xn.

We first compute the covariance matrix, then the eigen values $\lambda_1, \lambda_2, \cdots, \lambda_n$ of the covariance

matrix and the variance contribution rate are calculated and the weight is determined.

$$a_k = \lambda_k \Big/ \sum_{i=1}^{n} \lambda_i \tag{14}$$

Objective weighting method is based on the information contained in the data to determine the weight, do not have subjective arbitrariness, the structure of a good enough mathematical theory. It is the advantage of the objective weighting method, but the data processing method depends on the actual problem, it may be because the data is too large to make the calculation lock.

Comprehensive Weight Calculation

While determining the weight of the evaluation index, the subjective weighting method and the objective weighting method have their own advantages and disadvantages. It is difficult for a single weighting method to achieve satisfactory weighting effect, and therefore many papers use two or more methods to determine the final weight. The following two algorithms are commonly used to synthesize various weighting methods to obtain comprehensive weights.

(1) Multiplication

$$\omega_j = \prod_{k=1}^{m} \omega_j^k \Big/ \sum_{j=1}^{n} \prod_{k=1}^{m} \omega_j^k \qquad (j = 1,2,\cdots,n) \tag{15}$$

Where m is the number of methods which is used to weight, ω_j is the weight of item J of the first k weighting method.

This comprehensive approach considers that there is no difference among the various weighting methods, and weights obtained by various methods are equally important. While synthesizing various weighting methods, this approach virtually is a tacit admission that various weighting methods are equally important.

(2) Addition

$$\omega_j = \sum_{k=1}^{m} \lambda_k \omega_j^k \Big/ \sum_{j=1}^{n} \sum_{k=1}^{m} \lambda_k \omega_j^k \qquad (j = 1,2,\cdots,n) \tag{16}$$

Where m is the number of methods which is used to weight, ω_j is the weight of item J of the first k weighting method and λ_k is the "importance" coefficient for the weights which is obtained by various weighting methods.

This comprehensive approach considers that there are advantages and disadvantages among the various weighting methods, and weights obtained by various weighting methods have different importance. By calculating the weights of different methods, important weighting methods make a greater impact on the final weight.

Conclusion

In this paper, the existing evaluation methods of power quality are analyzed and compared. The evaluation method of power quality can be divided into the scientific analysis of single index evaluation and comprehensive evaluation, and the comprehensive evaluation can be divided into single index comprehensive evaluation and multi index comprehensive evaluation.

Single index evaluation mainly analyzes four evaluation methods, including based on fuzzy mathematical single index evaluation method, based on fuzzy mathematics in various energy index commonly used membership function method, based on probability and statistics of the single index evaluation method and based on the main use of power grid planning, power grid construction and interference load before access to the simulation of the individual indicators to predict the assessment method, and proposes other indicators such as evaluation method of service index. The weight selection method used in the comprehensive evaluation of power quality is analyzed from the subjective weight to the objective weight.

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