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POWER QUALITY EVALUATION WITH SET PAIR ANALYSIS MODEL BASED ON ENTROPY WEIGHT

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Abstract. *Considering that the evaluation indexes of power quality of wind farm are uncertain, set pair analysis theory is applied in the comprehensive evaluation on power quality of wind farm. This paper calculates the connection degree between sample and index to primarily classify the sample, and then evaluates the level of sample using set pair analysis with identity, difference and opposition. Entropy theory of information theory is introduced to calculate the information entropy which reflects measured data's utility value to calculate the evaluation index weight and create theoretical reasonable weight distribution. Final example analysis shows that the evaluation result of set pair analysis model based on entropy weight is reasonable and objective.*
Keywords: Power quality, Set pair analysis, Entropy weight

1. **Introduction.** In recent years, the installed capacity of Chinese wind power generation develops rapidly, so does the proportion of wind farm in network capacity. The volatility and intermittence of wind farm and the operation characteristics of wind turbines determine the volatility of output power and the imbalance of power quality. Grid-connected wind turbine operation has significant impact on local power network. Meanwhile, under the power market environment, comprehensive power quality index is the basis of power pricing. On this basis, establishing an effective evaluation method for comprehensive power quality evaluation is beneficial to achieve secure wind power grid-connection, reasonable power pricing and to provide high quality services for consumers.

Current comprehensive evaluation methods on wind power quality of wind farm include Fuzzy Theory, Decision Theory, Intelligent Evaluation [1,2], Combination Evaluation, etc. During the process of comprehensively evaluating the power quality, Fuzzy Theory is affected by subjective factors and the objectivity of the evaluation result is weakened; Decision Theory can significantly reduce the influence of subjective factors on evaluation result; Intelligent Evaluation needs no subjective factors but numerous sample data and has unclear physical meaning; Combination Evaluation makes up for the disadvantages of single evaluation methods and has comparatively strong subjectivity. Jiang et al. [3] evaluated power quality with Normal Distribution, Analytic Hierarchy Process and Cloud Matter-Element Model, and obtained credible evaluation result. Mao et al. [4] combined Language Evaluation with D-S (Dempster-Shafer) Evidential Theory, considered expert knowledge and user requirement for evaluation and got satisfactory result. On the basis of improved radar chart method, Qiao et al. [5] put forward new evaluation method by evaluating with the circumference and the area of radar chart. By using economic equivalent balance theory, Ding et al. [6] reasonably and scientifically evaluated the power quality.

Considering that the evaluation indexes of power quality of wind farm are uncertain, set pair analysis theory is applied in the comprehensive evaluation on power quality of wind farm. This paper calculates the connection degree between sample and index to primarily classify the sample, and then evaluates the degree of sample using set pair analysis with identity, difference and opposition. Entropy theory of information theory is introduced to calculate the information entropy which reflects measured data's utility value to calculate the evaluation index weight and create theoretical reasonable weight distribution. Final example analysis shows that the evaluation result of set pair analysis model based on entropy weight is reasonable and objective. Method in this paper provides new thinking and advisory opinion for further analyzing and evaluating power quality of wind farm.

2. **Problem Statement and Preliminaries.**

2.1. **Set pair analysis introduction.** Set pair analysis theory put forward by Chinese scholar Keqin Zhao in 1989 is a new system theory method dealing with uncertainty problems, and its core thinking is identifying certainty and uncertainty as a determining uncertainty system which divides certainty into "identity" and "opposition", calls uncertainty "difference" and analyzes item and its system from 3 aspects of identity, difference and opposition. Identity, difference and opposition have interrelationship, interaction and mutual restriction and can be mutually transferred under certain conditions. By introducing connection degree and its mathematical expression, different uncertainties can be described to transfer uncertainty into mathematical operation.

Set pair refers to the pair composed of two relative sets. The basic thinking of set pair analysis theory is [7]: under certain specific problem, launch analysis on the set pair characters of sets A and B, and among these N characters, S characters are common in two sets, P characters are opposite and F characters are uncertain about their relationship, so the connection degree of these two sets are:

$$\mu = \frac{S}{N} + \frac{F}{N}i + \frac{P}{N}j = a + bi + cj, \quad a + b + c = 1 \tag{1}$$

among which, μ is the connection degree; S/N is the identity degree of sets A and B, denoted as a; F/N is the difference degree, denoted as b; P/N is the opposition degree, denoted as c; i is the difference label and ranges among $[-1, 1]$, and i can only work as labels; j is the opposition degree, $j = -1$, and j can only work as labels. According to Equation (1), expression equation of connection degree shows the relation, influence and transferring of identity, difference and opposition. The difference degree will transfer into identity degree and opposition degree if $i = 1$, and if i ranges among $(-1, 1)$, difference degree and identity degree have certain proportions. Connection degree μ and uncertainty coefficient i are the basis of the theory which can describe uncertainty phenomenon in random, fuzzy and grey problems.

2.2. **Set pair analysis on power quality of wind farm.** The essence of power quality of wind farm is the analysis process which is composed of certain evaluation index and evaluation standard and uncertain evaluation factor and its changing content. Power quality based on set pair analysis creates a set pair composed of power condition and vested evaluation standard, and comparatively analyzing of power condition and vested evaluation standard can obtain the quantized index of evaluating power quality. Suppose that there are N evaluation indexes during power quality evaluation, among them, S indexes are superior to the standard, P indexes are inferior to the standard and P indexes are not tested or compared. Then using Equation (1) can calculate the connection degree of evaluation sample, and the size relation of a, b and c can primarily analyze the power quality. However, even though power qualities in different measuring points are at the same level, the results will be different because of different index values, so it is necessary to launch identical, different and opposite set pair analysis on classification standard.

The evaluation index characters of power quality can divide it into the smaller the better type and the larger the better type [9]. The connection degree of index of the smaller the better type is:

$$\mu_{sk} = \begin{cases} 1 + 0i + 0j & x \in [0, S_1] \\ \dfrac{S_2 - x}{S_2 - S_1} + \dfrac{x - S_1}{S_2 - S_1} i + 0j & x \in [S_1, S_2] \\ 0 + \dfrac{S_3 - x}{S_3 - S_2} i + \dfrac{x - S_2}{S_3 - S_2} j & x \in [S_2, S_3] \\ 0 + 0i + 1j & x \in [S_3, +\infty] \end{cases} \tag{2}$$

The connection degree of index of the larger the better type is:

$$\mu_{sk} = \begin{cases} 1 + 0i + 0j & x \in [S_1, +\infty] \\ \dfrac{S_2 - x}{S_2 - S_1} + \dfrac{x - S_1}{S_2 - S_1} i + 0j & x \in [S_2, S_1] \\ 0 + \dfrac{S_3 - x}{S_3 - S_2} i + \dfrac{x - S_2}{S_3 - S_2} j & x \in [S_3, S_2] \\ 0 + 0i + 1j & x \in [0, S_3] \end{cases} \tag{3}$$

In Equation (3), S_1, S_2 and S_3 are the threshold values of evaluation indexes; k indicates the k-th evaluation index; s is the s-th measuring point waiting for measuring; x is the measured value of k-th index in s-th measuring point.

2.3. **Weight determination with entropy weight.** All evaluation indexes have equal weights in existing power quality evaluation methods based on set pair analysis, and the comparative importance of different indexes is ignored, which has influence on final evaluation result. As to information theory, the entropy value reflects information's disordering degree to measure the information: if one index carries more information, then this index will play a more important role in decision-making, the entropy value is smaller and its disordering degree is also smaller. Therefore, the disordering degree and utility of obtained information can be measured with information entropy evaluation, namely the evaluation matrix composed of evaluation index values can determine the weight. The main calculation steps are as follows [8].

(1) Suppose there are m evaluation objects, each of them has n evaluation indexes, so the evaluation matrix R is:

$$R = (r_{st})_{m \times n}, \ (s = 1, 2, \ldots, m; \ t = 1, 2, \ldots, n) \tag{4}$$

where r_{st} is the measured value of the t-th index of the s-th measuring object.

(2) Normalizing R can generate the normalized matrix B, and the element of B is:

$$b_{st} = \frac{r_{st} - r_{\min}}{r_{\max} - r_{\min}} \tag{5}$$

where $r_{\max}$ and $r_{\min}$ are respectively the most satisfied value (the larger the better) and the most dissatisfied value (the smaller the better) of the same evaluation index of different objects.

(3) Determine the entropy of index with traditional entropy concept:

$$H_t = -\left(\sum_{s=1}^{m} f_{st} \ln f_{st} \right) \Big/ \ln m, \ (s = 1, 2, \ldots, m; \ t = 1, 2, \ldots, n) \tag{6}$$

where $f_{st} = b_{st} \Big/ \sum\limits_{s=1}^{m} b_{st}$. Obviously, if $f_{st} = 0$, $\ln f_{st}$ is meaningless, so the calculation of f_{st} is modified to be:

$$f_{st} = (1 + b_{st}) \Big/ \sum_{s=1}^{m} (1 + b_{st}) \tag{7}$$

(4) Calculate the entropy weight of index:

$$W = (w_t)_{1\times n},\ w_t = (1 - H_t) \Bigg/ \left(n - \sum_{t=1}^{n} H_t \right),\ \text{and} \sum_{t=1}^{n} w_t = 1 \tag{8}$$

2.4. **Set pair analysis model based on entropy weight.** Suppose the average connection degree of the s-th sample is μ_s, and the calculation of μ_s has 3 steps: using power quality evaluation standard Equation (1) to primarily calculate the average connection degree μ_s of the s-th sample, then calculate the connection degree μ_{sk} of the k-th index using set pair analysis with Equation (2) (or Equation (3)), the weight vector $W = (w_1, w_2, \ldots, w_n)^T$ of each index can be calculated with Equations (4) to (8) and the normalization condition is $\sum\limits_{t=1}^{n} w_t = 1$. So the set pair analysis model based on entropy weight is obtained:

$$\overline{\mu}'_s = \mu_s \times \sum_{t=1}^{n} (w_t \times \mu_{ts}) \tag{9}$$

where there are n evaluation indexes.

At last, normalizing the identity, difference and opposition components of $\overline{\mu}'_s$ can generate the average connection degree $\overline{\mu}_s$. Comparing a, b and c of $\overline{\mu}_s$ can evaluate the level of power quality s with the evaluation criterion [10]: 1) if $\max[a, b, c] = b$, the level is II; 2) if $\max[a, b, c] = a$ and $a + b \geq 0.7$, the level is I, otherwise, the level is II; 3) if $\max[a, b, c] = c$ and $b + c \geq 0.7$, the level is III, otherwise, the level is II.

3. **Example Analysis.** Select 5 main transformer substation bus nodes of certain large wind farm for wind quality measurement and obtain 5 wind quality index data sets [3]. These 5 bus nodes include: 10KV bus nodes of Jinniu transformer substation, denoted by A; 110KV bus nodes of Waipu transformer substation, denoted by B; 10KV bus nodes of NiuTouling transformer substation, denoted by C; 35KV bus nodes of ZuZaiao transformer substation, denoted by D; 10KV bus nodes of Da Lankou transformer substation, denoted by E. And corresponding power quality measurement data is showed in Table 1.

Data in this example are distributed in first three levels and three levels of data is easy for set pair analysis, so only three levels are chose in this example (showed in Table 2).

By calculation, the average connection degrees of measuring points A-E are:

$$\overline{\mu}_1 = i,\ \overline{\mu}_2 = 0.192 + 0.7i + 0.108j,\ \overline{\mu}_3 = 0.811i + 0.189j,$$
$$\overline{\mu}_4 = 0.158 + 0.797i + 0.045j,\ \overline{\mu}_5 = 0.68i + 0.32j.$$

Table 1. Initial data set of wind quality in different measuring points

Measuring point	Frequency offset /Hz	Voltage deviation /%	Voltage fluctuation /%	Voltage flicker /%	Harmonic voltage /%	Three-phase unbalance /%
A	0.09	2.53	0.96	0.22	1.12	0.88
B	0.04	1.66	1.05	0.34	1.26	1.07
C	0.19	3.85	1.41	0.47	1.18	0.83
D	0.11	2.01	0.85	0.38	0.82	0.58
E	0.07	3.18	1.27	0.53	1.35	1.23

Table 2. Level bounds of evaluation indexes of power quality evaluation

Evaluation index		Frequency offset	Voltage deviation	Voltage fluctuation	Voltage flicker	Harmonic voltage	Three-phase unbalance
Level bound	Level 1	$[0.001, 0.05)$	$[0.01, 1.20)$	$[0.01, 0.50)$	$[0.01, 0.20)$	$[0.10, 1.00)$	$[0.01, 0.50)$
	Level 2	$[0.05, 0.10)$	$[1.20, 3.00)$	$[0.50, 1.00)$	$[0.20, 0.50)$	$[1.00, 2.00)$	$[0.50, 1.00)$
	Level 3	$[0.10, 0.15)$	$[3.00, 4.50)$	$[1.00, 1.50)$	$[0.50, 0.80)$	$[2.00, 3.00)$	$[1.00, 1.50)$

Table 3. Evaluation result

Method \ Measuring point	Measuring point A	Measuring point B	Measuring point C	Measuring point D	Measuring point E
Set pair analysis	II	II	II	II	II

According to evaluation standard, $\max[a, b, c] = b$ means the power quality level is level II. And $\max[a, b, c]$ in 5 measuring points are equal to b, so the evaluation level of 5 measuring points is level II (showed in Table 3).

Table 3 shows the evaluation result of power quality evaluation in this example. According to Table 3, the levels of 5 measuring points are level II, therefore, power of this wind farm is acceptable to connect the grid, but the power quality also has certain influence on the grid, so timely measuring is needed to avoid unexpected events and unnecessary loss.

4. **Conclusions.** This paper uses set pair analysis method to analyze the power quality in different points of the wind farm and obtain that whether the power quality is safe for grid-connection or not. Introducing the entropy value theory of information theory can better determine the index weight and provide theoretical foundation for weight distribution. Final example analysis has verified that the model is scientific and efficient.

Due to complex investment and operator characters of wind farm, it needs further research to establish a better real time monitor and control platform for data collection, as well as effective measures and methods for timely result analysis to clearly and directly understand the power supply quality situation, which can provide effective decisions and ensure the power quality in accord with national standards. In addition, better control methods of power quality and suggestions for reference should be concluded in further research.

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