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Fuzzy Comprehensive Evaluation Method of Power Quality Based on Modified Entropy Weights

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Abstract

To improve the limitations of information entropy in the power quality evaluation process, a fuzzy comprehensive evaluation method was proposed on Modified Entropy Weights and Catastrophe Verification. Through summing up the six indexes of power quality, and establishing the evaluation level boundary, the positive and negative entropy weights were reckoned for the power quality monitoring units; The fuzzy features and evaluation was improved to be depicted for power quality with Exponent method, and the five level membership function was set for the power quality evaluation; Then, the mechanism was set up for the fuzzy comprehensive evaluation operation. Finally, with the modified entropy information combination mode and the fuzzy catastrophe mode, the fuzzy comprehensive evaluation and comparative analysis was carried on for such power quality. Case showed, the power quality evaluation conclusion of Information catastrophe mode has the good consistency with the weight combination mode of the positive and negative entropy, which could realize the distinction and system evaluation to the different monitoring units.

Keywords*: power quality; fuzzy comprehensive evaluation; positive entropy; negative entropy; catastrophe theory*

1 Introduction

Power quality is one multi-index set, whose comprehensive evaluation is in fact to scientifically and objectively set the weight to each index [1], to design the corresponding mathematical model and evaluation system, and to carry on the integrated measurement for the power quality, with Fuzzy Mathematics [2] and Artificial Neural Network [3], Extension Cloud Theory [4], Catastrophe Theory [5] and other methods. Therefore, the index weight is the key link in the power quality evaluation, which directly affects the scientific rationality of the evaluation result for power quality [6].

Rooted in the thermodynamic, Entropy method determines the index weight through measuring the variation of all the evaluation objects to each index, which is a kind of widely used objective weighting method [7]; At the same time, Entropy method embodied the strong coupling feature, which is easily combined with other subjective or objective weighting methods, to overcome the sample defect influence and the local differences in entropy weighting method. Reference [8] applied the integrated method with Analytic Hierarchy Process (AHP), Entropy Weighting Method and Average Square Error Method; Reference [9] synthesized AHP and Entropy Weighting Method with the multiplicative synthesis mode; Reference [10] put forward the entropy weighting method and the weighting adjustment strategy with Shapely to determine the comprehensive weighting value about the evaluation indexes for power quality.

The above method played a good role in promoting the development of power quality evaluation, and the combinated weights effectively reduces the random error and system windage; In essence, entropy reflects the information form the objective state to another

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state, showing the objective catastrophe phenomenon of power quality, with the poor explanatory and objective catastrophe difficulty. Therefore, to adapt to the dynamic and different characteristics in power quality monitoring samples, and to explain the different characteristics between the entropy and anti-entropy weights, the research with Modified Entropy Weights and Catastrophe Analysis, tried to explore the new models, methods and ways about the power quality evaluation, in order to overcome the defect about "Partial Replace Overall" in the power quality monitoring samples, which showed the active study value and practical significance, so as to provide the reference for the power quality evaluation and prediction work.

2. Power Quality Indexes and Evaluation Level Boundary

There were many factors about the power quality, and the strong coupling character among these factors, so the characteristic parameters or index system has the different emphasis for the difference in the evaluation objects, environment and others. Reference [3] designed the power quality evaluation system with Voltage Flicker, Voltage Fluctuation, Voltage Imbalance, Harmonic Voltage Containing Rate, Harmonic Current Containing Rate; Reference [4] designed the 9 index system from the technical and service angle; Reference [9] put forward the 6 primacy indexes and the secondary 13 indexes.

Synthetically consider the involved factors for the power quality evaluation, mainly includes Frequency Deviation, Voltage Deviation, Voltage Fluctuation, Voltage Flicker, Harmonic Voltage, Three-phase Imbalance, as shown in Table 1.

Table1. Index and Symbol of Power Quality

ID	Index Name	Ab. Name	Unit	Symbol
D_1	Frequency Deviation	ED	hertz	Hz
D_2	Voltage Deviation	VD	percentage	%
D_3	Voltage Fluctuation	VF	percentage	%
D_4	Voltage Flicker	VL	percentage	%
D_5	Harmonic Voltage	HV	percentage	%
D_6	Three-phase Imbalance	TI	percentage	%

Where, Ab. Name shows the abbreviated index name, and D_j denotes the general mathematical notation of the power quality index, meeting $1 \le j \le n$; and n denotes the element number about the index set D of the power quality, $D_j \in D$; In practice, $n = 6$.

There is much level compartmentalization mode on Power Quality. Reference [11] carries on the quality level with "Low", "Medium", "High" and "Optimal" fuzzy language variables; According to the international and national standards system of power quality, with the order from excellent to low power quality [12], the level is designed as "Optimal", "Good", "Medium", "Qualified" and "Unqualified" [2], which is separately denoted as S_1, S_2, S_3, S_4 and S_5, and the corresponding level boundary is shown in Table 2, whose essence is the standard power quality sample.

Where in Table 2, the level and evaluation boundary root in the level boundary of Reference [2], and the classification boundary of Reference [12] to 110 KV power distribution network. The given boundary value was adjusted to adapt to the actual evaluation need, and to realize the better comprehensive evaluation. According to Table 2,

X_j^k denotes the constraint boundary of index D_j to the evaluation level S_k, satisfied $X_j^1 \leq X_j^2 \leq X_j^3 \leq X_j^4 \leq X_j^5$.

Table 2. Level and Evaluation Boundary on Power Quality

	S_1	S_2	S_3	S_4	S_5
ED	0.05	0.10	0.15	0.20	0.40
VD	1.20	2.80	3.50	5.00	10.0
VF	0.50	1.00	1.50	2.00	4.00
VL	0.15	0.30	0.45	0.60	0.80
HV	0.50	1.00	1.50	2.00	4.00
TI	0.50	1.00	1.50	2.00	4.00

3 Modified Entropy Weights on Power Quality Index

3.1. Standardization and Calculation on Power Quality Index

Power quality sample, presents a data matrix with n indexes and m monitoring units, and $B = \{B_i\}$ denotes the set of Monitoring Units ($1 \leq i \leq m$), B_i denotes the general symbolic expression about the power quality monitoring unit. To simply the word spelling of Monitoring Unit, MU denotes the abbreviated meaning of Monitoring Unit.

To eliminate the comparing difficulty from the different dimension among the indexes, the first work is to standardize the power quality sample. The evaluation level boundary of the power quality shows that, as the index with the positive change characteristic, the power quality takes the higher level. Therefore, the range transformation operator is applied with the positive standardized calculation rule, as the following Formula (1).

$$r_{ij} = \frac{\max\limits_{1\leq i\leq m}(x_{ij}) - x_{ij}}{\max\limits_{1\leq i\leq m}(x_{ij}) - \min\limits_{1\leq i\leq m}(x_{ij})} \tag{1}$$

Where, $\{x_{ij}\}_{1\leq j\leq n}$ denotes the index parameters about the power quality monitoring unit of B_i, and r_{ij} denotes the element of the standardization matrix about such evaluation sample for power quality.

According to the entropy calculation method of Information Entropy Theory [12], the *Shannon* entropy obtained for the power quality index of D_j, as the following Formula (2).

$$e_j = H(D_j) = -\frac{1}{ln(m)}\sum_{i=1}^{m} r_{ij} ln(r_{ij}) \tag{2}$$

Where, e_j denotes the information entropy of the power quality evaluation index of e_j, as the greater value, which reflects the greater internal disorder in such index characteristics; As $r_{ij} = 0$ exists, $r_{ij} = 0.00001$ replaces the above $r_{ij} = 0$.

Thus, $\tilde{\theta}$ denotes the weight set about the power quality evaluation indexes, $\tilde{\theta} = \{\theta_j \mid j = 1,2,...,n\}$. Here, θ_j is set as the weight of the power quality evaluation index D_j, namely:

$$\theta_j = (1-e_j)/(n-\sum_{j=1}^{n} e_j) \quad , \quad \sum_{j=1}^{n} \theta_j = 1 \tag{3}$$

3.2. Anti-entropy Calculation on Power Quality Index

To highlight the conflict characteristics among the power quality indexes, Reference [13] put forward the Anti-entropy weight method, which analyzed the relationship between the index difference and the Anti-entropy with the first Anti-entropy and second Anti-entropy application.

α_j is set as the negative entropy of index D_j for power quality, and β_j denotes the negative entropy weight, $\tilde{\beta}$ denotes the set of β_j, namely:

$$\begin{cases} \alpha_j = N(D_j) = -\dfrac{1}{ln(m)}\sum_{i=1}^{m} r_{ij} ln(1-r_{ij}) \\ \beta_j = (1-\alpha_j)/(n-\sum_{j=1}^{n}\alpha_j), \ \sum_{j=1}^{n}\beta_j = 1 \end{cases} \tag{4}$$

3.3. Modified Weights on Entropy and Anti-entropy of Power Quality Index

Information combination with the positive entropy and negative entropy weights for the power quality indexes, could realize and achieve the optimal weighting operations with Maximizing Deviation Model [1], Multiplication Synthesis [9] and other methods, namely $\varpi_j = Opt(\theta_j, \beta_j)$. And, ϖ_j reflects the weight information allocation between the positive and negative entropy weights with regard to the power quality monitoring units, as shown in Formula (5).

$$\varpi_j = \frac{\theta_j \cdot \beta_j}{\sum_{j=1}^{n} \theta_j \cdot \beta_j} \tag{5}$$

Where, ϖ_j expresses the compromise and negotiation meaning between the positive entropy information support and the anti-entropy information catastrophe, and reflects the maximum entropy, incentive, punishment and other scientific meaning; And, $\tilde{\varpi}$ is denoted as the set of the modified weights $\{\varpi_j\}$.

4. Fuzzy Membership Function Design on Power Quality

$f_k(x_{ij})$ denotes the subjected degree to the level S_k under the index D_j for such monitoring unit B_i. And, the fuzzy membership function is designed for the power quality index, as the following Formula (6), (7), (8), (9) and (10), respectively denoting the fuzzy subjected degree to the level S_1, S_2, S_3, S_4 and S_5.

The index fuzzy membership function to "Optimal" level, is shown in the following expression in Formula (6).

$$f_1(x_{ij}) = \begin{cases} 1.0 & x_{ij} \in [0, X_j^1] \\ e^{(X_j^1 - x_{ij})/(X_j^2 - X_j^1)} & x_{ij} \in [X_j^1, X_j^2] \\ 0 & x_{ij} \in [X_j^2, X_j^5] \end{cases} \tag{6}$$

The index fuzzy membership function to “Good” level, is shown in the following expression in Formula (7).

$$f_2(x_{ij})=\begin{cases} e^{-(x_{ij})/(X_j^1)} & x_{ij}\in[0,X_j^1] \\ 1 & x_{ij}\in[X_j^1,X_j^2] \\ e^{(X_j^2-x_{ij})/(X_j^3-X_j^2)} & x_{ij}\in[X_j^2,X_j^3] \\ 0 & x_{ij}\in[X_j^3,X_j^5] \end{cases} \tag{7}$$

The index fuzzy membership function to “Medium” level, is shown in the following expression in Formula (8).

$$f_3(x_{ij})=\begin{cases} 0 & x_{ij}\in[0,X_j^1] \\ e^{(X_j^1-x_{ij})/(X_j^2-X_j^1)} & x_{ij}\in[X_j^1,X_j^2] \\ 1 & x_{ij}\in[X_j^2,X_j^3] \\ e^{(X_j^3-x_{ij})/(X_j^4-X_j^3)} & x_{ij}\in[X_j^3,X_j^4] \\ 0 & x_{ij}\in[X_j^4,X_j^5] \end{cases} \tag{8}$$

The index fuzzy membership function to “Qualified” level, is shown in the following expression in Formula (8).

$$f_4(x_{ij})=\begin{cases} 0 & x_{ij}\in[0,X_j^2] \\ e^{(X_j^2-x_{ij})/(X_j^3-X_j^2)} & x_{ij}\in[X_j^2,X_j^3] \\ 1 & x_{ij}\in[X_j^3,X_j^4] \\ e^{(X_j^4-x_{ij})/(X_j^5-X_j^4)} & x_{ij}\in[X_j^4,X_j^5] \end{cases} \tag{9}$$

The index fuzzy membership function to “Unqualified” level, is shown in the following expression in Formula (8).

$$f_5(x_{ij})=\begin{cases} 0 & x_{ij}\in[0,X_j^3] \\ e^{(X_j^3-x_{ij})/(X_j^4-X_j^3)} & x_{ij}\in[X_j^3,X_j^4] \\ 1 & x_{ij}\in[X_j^4,X_j^5] \end{cases} \tag{10}$$

5. Fuzzy Comprehensive Evaluation on Power Quality

Applied with Fuzzy Comprehensive Evaluation Theory [14], $\sum \varpi_j f_k(x_{ij})$ denotes the fuzzy summation operator, namely Arithmetic Weighted Average Model. Z_i^k denotes the fuzzy evaluation conclusion to Monitoring Unit of B_i, as the following Formula (11).

$$\begin{bmatrix} Z_1^k \\ Z_2^k \\ \\ Z_m^k \end{bmatrix}=\begin{bmatrix} f_k(x_{11}) & f_k(x_{12}) & \cdots & f_k(x_{1n}) \\ f_k(x_{21}) & f_k(x_{22}) & \cdots & f_k(x_{2n}) \\ \vdots & \vdots & \ddots & \vdots \\ f_k(x_{m1}) & f_k(x_{m2}) & \cdots & f_k(x_{mn}) \end{bmatrix}\begin{bmatrix} \varpi_1 \\ \varpi_2 \\ \\ \varpi_n \end{bmatrix} \tag{11}$$

Where, Z_i^k expresses the probability distribution for Monitoring Unit of B_i to Evaluation Level of S_k.

According to the maximum membership degree principle of Fuzzy Comprehensive Evaluation, the probability is compared and analyzed under all the evaluation level for Monitoring Unit of B_i, as the following Formula (12).

$$Z_i^l = \max_k \{Z_i^1, Z_i^2, Z_i^3, Z_i^4, Z_i^5\} \tag{12}$$

Where, Z_i^l denotes the maximum value in the above comparison, and l denotes the decision-making level about Monitoring Unit of B_i.

6. Case Study and Model Analysis

6.1. Case Sample and Index Weight Calculation

In order to verify the effectiveness and feasibility of the proposed method, some wind Farm in China is selected to test and analyze, as shown in Table 3, whose data is from Reference [5].

Table 3. Monitoring Sample for Power Quality

MU	ED	VD	VF	VL	HV	TI
B_1	0.09	2.53	0.96	0.22	1.12	0.88
B_2	0.04	1.66	1.05	0.34	1.26	1.07
B_3	0.19	3.85	1.41	0.47	1.18	0.83
B_4	0.11	2.01	0.85	0.38	0.82	0.58
B_5	0.07	3.18	1.27	0.53	1.35	1.23

With Formula (1) to Formula (4), the positive entropy, negative entropy and modified weights is reckoned for the power quality indexes, as shown in Table 4.

Table 4. Index Weights for Power Quality

MU	ED	VD	VF	VL	HV	TI
e_j	0.4872	0.5056	0.5010	0.6022	0.6388	0.6071
θ_j	0.1458	0.1513	0.1499	0.1802	0.1911	0.1817
α_j	1.5076	1.3724	1.2685	0.5861	0.2502	0.6672
β_j	0.2667	0.2428	0.2244	0.1037	0.0443	0.1181
ϖ_j	0.2463	0.2327	0.2131	0.1184	0.0536	0.1359

6.2. Fuzzy Comprehensive Evaluation and Calculation for Power Quality

According to Formula (11) and (12), the fuzzy comprehensive evaluation is carried on the monitoring units of power quality case respectively under the condition of the entropy weight $\tilde{\theta}$, the anti-entropy weight $\tilde{\beta}$ and the modified weight $\tilde{\varpi}$, as shown in Table 5, Table 6 and Table 7.

Table 5. Fuzzy Comprehensive Evaluation Under Entropy Weights

MU	S_1	S_2	S_3	S_4	S_5	max	Level
B_1	0.3891	0.9592	0.5802	0.1503	0	0.9592	S_2
B_2	0.2593	0.7620	0.8164	0.5452	0	0.8164	S_3
B_3	0.0939	0.3810	0.7779	0.6766	0.3430	0.7779	S_3
B_4	0.4212	0.8991	0.7472	0.2251	0	0.8991	S_2
B_5	0.0977	0.5307	0.8774	0.5651	0.1057	0.8774	S_3

Table 6. Fuzzy Comprehensive Evaluation Under Anti-entropy Weights

MU	S_1	S_2	S_3	S_4	S_5	max	Level
B_1	0.4353	0.9905	0.4796	0.0348	0	0.9905	S_2
B_2	0.4488	0.7741	0.6726	0.4115	0	0.7741	S_2
B_3	0.0610	0.2478	0.7326	0.7429	0.4029	0.7429	S_4
B_4	0.3818	0.9088	0.7522	0.2792	0	0.9088	S_2
B_5	0.1788	0.6351	0.8692	0.4721	0.0608	0.8692	S_3

Table 7. Fuzzy Comprehensive Evaluation Under Modified Entropy Weights

MU	S_1	S_2	S_3	S_4	S_5	max	Level
B_1	0.4347	0.9886	0.4883	0.0422	0	0.9886	S_2
B_2	0.4209	0.7769	0.6956	0.4335	0	0.7769	S_2
B_3	0.0702	0.2672	0.7355	0.7287	0.3986	0.7355	S_3
B_4	0.3902	0.9064	0.7549	0.2711	0	0.9064	S_2
B_5	0.1651	0.6181	0.8699	0.4902	0.0695	0.8699	S_3

Obviously, the entropy and anti-entropy weight based fuzzy comprehensive evaluation on power quality showed the relative consistent and conflict conclusion: B_1 and B_4 belong to "Good" level, B_5 belongs to "Medium" level, but B_2 and B_3 views the conflict and inconsistent phenomenon. Modified entropy weight based fuzzy comprehensive evaluation shows the close decision-making level with the anti-entropy based fuzzy comprehensive evaluation; And, there is only the quantitative numerical difference to solve the validation problem.

6.3. Catastrophe Calculation and Comprehensive Validation for Power Quality

Around $f_k(x_{ij})$ as the subjected degree of Monitoring Unit B_i to Index D_j under Level S_k, with such Related Complementary Principle of Catastrophe Theory [15], the catastrophe progression could be obtained form the following Formula (13), and the data is shown in Table 8.

$$P_k(B_i) = \frac{1}{n}\sum_{j=1}^{n}[f_k(x_{ij})]^{1/j} \tag{13}$$

Where, $P_k(B_i)$ is set as the catastrophe parameter of Monitoring Unit B_i under Level S_k.

Table 8. Fuzzy Comprehensive Evaluation on Catastrophe Progression

MU	S_1	S_2	S_3	S_4	S_5	max	Level
B_1	0.6908	0.9881	0.7722	0.3571	0	0.9881	S_2
B_2	0.6374	0.8956	0.8899	0.7411	0	0.8956	S_2
B_3	0.3500	0.6227	0.8917	0.8641	0.6621	0.8917	S_3
B_4	0.6872	0.9584	0.8869	0.5640	0	0.9584	S_2
B_5	0.4380	0.7940	0.9455	0.7652	0.3592	0.9455	S_3

Comparative analysis in Table 7 and Table 8, shows that the fuzzy catastrophe comprehensive evaluation and the modified entropy weight has the consistency.

7. Conclusion

A fuzzy comprehensive evaluation model is established on the power quality based on the positive and negative entropy combined weights. The creative work about the entropy and anti-entropy combination, shows the more clear physical meaning, which solves the non-enough information and less sample problems in the power quality evaluation, and improves the scientific objectivity of the evaluation result.

Improved power quality level criterion, the five level fuzzy membership function and fuzzy comprehensive evaluation mechanism, has the good adaptability and operability, which provides a new method for power quality evaluation, and benefits the level separation and quantitative evaluation.

Case analyzes the evaluation difference under the entropy and anti-entropy weighting condition, and validates the modified entropy based evaluation through the fuzzy catastrophe evaluation, which proved rationality and scientific nature of the established evaluation algorithm and model. At the same time, the power quality evaluation is a complicated system engineering, the index synthesis and performance should be combined with the specific issues, continue to supply, improve and rich, to adapt to the complexity of the internal power quality evaluation system structure.

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