

Application of Modified Close Value Method in Power Quality Evaluation

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Abstract: For enhancing the accuracy and rationality of power quality (PQ) evaluation, close value method (CVM) based on the target optimization principle is introduced to symbolize the performance of PQ samples. To tackle with the defect, in calculating close value of PQ samples, that the calculation formula of close value is divided by zero, a modified CVM is correspondingly developed to adapt to the randomness of PQ samples. Meanwhile, for analyzing the impacts of weighting approaches on the evaluation outcome, different weighting approaches are orderly utilized to improve CVM. Case analysis shows that the new calculating method of close value is proved to be more simplified and applicable; the impacts different weighting approaches have on the evaluation outcome differ to some extent.

1. Introduction

Power quality (PQ) is closely related to power supply companies and their economic benefits, as well as the security and reliability of electric power components such as domestic appliances, generators, transformers, etc, which enables PQ evaluation definitely indispensable to formulate the electricity price in accordance with its authentic performance. Presently, PQ evaluation is commonly regarded as a multi-dimension mathematic or multi-attribute decision-making problem that recently researchers have applied numerous evaluation approaches to handle with, such as fuzzy evaluation method, probability theory, projection pursuit method, matter-element analysis, ideal interval method, etc. Most of these methods are on the basis of reduction dimensions, namely, conversion from a multi-dimension problem to a unidimensional problem to compare different PQ samples [1]. In literature [2-5], fuzzy evaluation methods are discussed from the perspective of weighting but the subjective factor of fuzzy subordinating degree functions remains existence. The literature [6] illustrates the utility of probability theory in PQ evaluation which can effectively quantify and normalize the criterion values of PQ, but without considering the criterion weights. Projection pursuit method in [7,18] whose optimal projection vector is vulnerable to various samples is an effective approach to reduce dimensions. Matter-element analysis in [8] is usefully applied to

the structural establishment and the weighting of criterion, but neglecting the preference information of criterion. Ideal interval method based on the similarity theory is combined with analytic hierarchy method, a subjective weighting approach, which overlooks the significant objective information of PQ samples [19].

Although these approaches above have made extraordinary response to some peculiar problems from diverse perspectives, for mitigating the deficiencies of above methods to some extent, many researchers concentrated on the application of close value method (CVM) in the multi-objective or multi-attribute decision-making of alternatives in the field of aerospace industry, engineering, missile defense system, etc [9-12]. Nevertheless, the situation that the calculating formula of close value of evaluated subject is probably divided by zero with fluctuating samples results in the failure of CVM. Therefore, the modified calculating formula of close value is proposed in this paper and used to conduct PQ evaluation. Additionally, disparate weighting methods are drawn into modifying CVM and comparing their impacts on the evaluation outcome.

2. Principle of Close Value Method

There are several procedures to demonstrate the process of CVM. Firstly, a set of PQ samples is collected in the initial decision matrix which is converted into the normalized matrix. Secondly, the set of optimal or pessimal sample from the normalized matrix is catalogued as a benchmark to compute the set of Euclidean distance between each evaluated sample and the optimal or pessimal sample. Finally, calculating close value of each evaluated sample is obtained respectively which implies the priority of all evaluated samples [9-12]. It is assumed that there is a PQ sample set $S=[s_1, s_2, \dots, s_m]$ ($i=1, 2, \dots, m$), and a criterion set $X=[x_1, x_2, \dots, x_n]$ ($j=1, 2, \dots, n$). Each expression which pertains to CVM can be shown as follows.

2.1. Normalization of initial decision matrix

The normalization of initial decision matrix $C=[c_{ij}]_{m \times n}$ can be represented by $R=[r_{ij}]_{m \times n}$,

$$r_{ij} = \pm c_{ij} / \sqrt{\sum_{i=1}^m c_{ij}^2} \quad (1)$$

where c_{ij}, r_{ij} ($i=1, 2, \dots, m; j=1, 2, \dots, n$) denote the initial value and the normalized value of the criterion x_j of PQ sample s_i . If the criterion x_j is a positive one whose value gets larger, the performance of criterion x_j will be better, then $r_{ij} \geq 0$; or the criterion x_j is a negative one whose value gets smaller, the performance of criterion x_j will be better, then $r_{ij} < 0$.

2.2. Definition of the Euclidean distance

The optimal or pessimal sample can be searched from R and presented as

$$A^+ = \{r_j^+\} = \{\max_{1 \leq i \leq m} \{r_{ij}\}\} \quad (2)$$

$$A^- = \{r_j^-\} = \{\min_{1 \leq i \leq m} \{r_{ij}\}\} \quad (3)$$

Where r_j^+ ($j=1, 2, \dots, n$) is the optimal value of criterion x_j within all samples while r_j^- ($j=1, 2, \dots, n$) is the pessimal value of criterion x_j within all samples. Then the set of Euclidean distance between each evaluated sample and the optimal or pessimal sample can be expressed separately as

$$D_i^+ = [\sum_{j=1}^n (w_j r_{ij} - w_j r_j^+)^2]^{1/2} \tag{4}$$

$$D_i^- = [\sum_{j=1}^n (w_j r_{ij} - w_j r_j^-)^2]^{1/2} \tag{5}$$

$$\sum_{j=1}^n w_j = 1 \tag{6}$$

where D_i^+ , D_i^- successively denote the Euclidean distance between the sample s_i and the optimal or pessimal sample. And w_j signifies the weight of criterion x_j .

2.3. Calculating formula of close value

The calculating formula of close value is deduced as

$$E_i = \frac{D_i^+}{\min\{D_i^+\}} - \frac{D_i^-}{\max\{D_i^-\}} \tag{7}$$

Where E_i named the close value of sample s_i indicates the extent of closeness to the optimal sample and estrangement to the pessimal sample. And the smaller E_i gets, the closer to the optimal the sample will be.

3. Demonstration of Modified Close Value Method

3.1. Modified formula of close value

Considering the fluctuation of PQ samples which prompts the possibility that $\min\{D_i^+\}=0$ or $\max\{D_i^-\}=0$ exists may encounter with the failure of performing CVM [9-12], a modified formula of close value is correspondingly developed as

$$E_i = \frac{D_i^+}{D_i^-} \tag{8}$$

Note that $E_i=0$ means the sample s_i is closest to the optimal, otherwise, $E_i=\infty$ suggests the sample s_i is equivalent to the pessimal.

3.2. Discussion of different empowerment methods

For this reason that some literatures applies the CVM provided that all the criteria are empowered with the equal weight [11,12], in this study different weighting approaches such as Analytic hierarchy method (AHP), Variation coefficient method (VCM) and synthetical empowerment (SE), are separately introduced in CVM to discuss the influences on the assessment result.

AHP is a subjective empowerment method based on the structural framework of PQ evaluation [13]. Firstly, the hierarchical structure constituted by target layer, criterion layer and index layer is established. Then, forming pair comparison matrices is followed by the ranking of each layer and the consistency verification. Finally, the overall ranking of index layer is performed to determine the index weight vector $U=[u_1, u_2, \dots, u_n]$.

Reversely, VCM is an objective empowerment method which traces the fluctuation of differentiation information of sample to compute the variable coefficient of index that hints the

importance or weight of index represented as $V=[v_1, v_2, \dots, v_n]$,

$$v_i(r) = |\delta_i / R_i| / (\sum_{i=1}^n |\delta_i / R_i|) \tag{9}$$

Where δ_i , R_i , δ_i / R_i ordinally denote the standard deviation, the average value, and the variable coefficient of index [14].

Then the combination of AHP and VCM formulates SE which can be expressed as $W=[w_1, w_2, \dots, w_n]$, indicating the index weight vector [4],

$$w_i = u_i v_i / \sum_{j=1}^n u_j v_j \tag{10}$$

4. Index Framework of Power Quality Evaluation

The indices of PQ Evaluation can be mainly catalogued into the technical index set which consists of voltage quality indices (such as voltage deviation (VD), voltage sags (VS), voltage flicker (VF1), three-phase unbalance (TPU), voltage fluctuation (VF2), Harmonic distortion (HD)), frequency deviation (FD), power supply reliability (PSR) and the non-technical index like service satisfactory (SS). The index framework of PQ evaluation can be deployed in Figure 1.

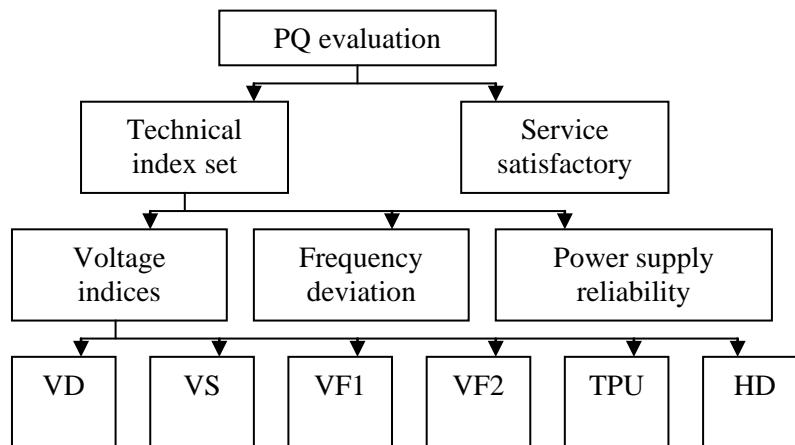


Figure 1 The index framework of PQ evaluation

Recent years have also seen the gradually accumulating achievements relevant to PQ standards of China which define the general PQ index set and can be excerpted as a cardinal limit criterion of PQ. The index grade boundaries of PQ evaluation can be showed in Table 1.

Table 1 Index grade boundaries of PQ evaluation

index/grade NO.	1	2	3	4	5
VD (%)	≤1.20	≤3.00	≤4.50	≤7.00	>7.00
VS	≥0.90	≥0.80	≥0.50	≥0.10	<0.10
TPU (%)	≤0.50	≤1.00	≤1.50	≤2.00	>2.00
VF2 (%)	≤0.50	≤1.00	≤1.50	≤2.00	>2.00
VF1	≤0.20	≤0.50	≤0.80	≤1.00	>1.00
HD (%)	≤1.00	≤2.00	≤3.00	≤5.00	>5.00
FD	≤0.05	≤0.10	≤0.15	≤0.20	>0.20
PSR	≥0.95	≥0.85	≥0.80	≥0.70	<0.70
SS	≥0.90	≥0.80	≥0.70	≥0.60	<0.60

In accordance with current national standards, in Table 1 PQ are generally divided into five grades where voltage sags (VS), power supply reliability (PSR), service satisfactory (SS) are compiled as negative index characterising that its smaller value favors the evaluation result. Reversely, except above negative index set, other indices in Table 1 are expressed as positive index which gets larger, the evaluation result may be better.

5. Numerical Case analysis

Analyzing the failure of CVM associated with its incomplete formula of close value is firstly discussed in this study by five random samples of PQ as well as coupled with a substantiation of new formula. Then another case of eight random samples of PQ is demonstrated under the modified CVM to compare the complicated influences from diverse empowerment approaches on the case result.

5.1. Assessment of five random samples of PQ

According to [7], five random samples of PQ collected from Shapinba district of Chongqin in China can be cited to assess their performances and obtaining D^+ , D^- are respectively depicted by equation (1) to (6) as below.

$$D^+=[0.3135 \ 0.8281 \ 0.5821 \ 0.6949 \ 0.7606 \ 0 \ 0.3031 \ 0.6257 \ 1.0245]$$

$$D^-=[0.7502 \ 0.2422 \ 0.4957 \ 0.3855 \ 0.3338 \ 1.0245 \ 0.7391 \ 0.4159 \ 0]$$

Apparently, $\min\{D^+\}=0$ contributes to the invalidity of CVM and the disruption of evaluation and ranking which manifests the vulnerability of CVM to random samples. Hence, the new formula of close value, equation (8), is applied to compute the case result listed in the Table 2.

Table 2 evaluation result of 5 samples

Sample	s_1	s_2	s_3	s_4	s_5
Ranking	3	4	3	4	4

The final ranking from Table 2 shows the modified CVM can tackle with the situation of unsuccessfully calculating close value and make clear.

5.2. Assessment of eight random samples of PQ

For the further demonstration of the validity of modified CVM and the impacts of different empowerment approaches on the evaluation, another eight random samples of PQ from [3] are similarly gathered and shown in the initial decision-making matrix C

$$C = \begin{bmatrix} 52.44 & 4.80 & 0.122 & 0.83 & 1.33 & 2.72 & 0.54 & 0.54 & 0.832 \\ 75.89 & 1.68 & 0.062 & 0.36 & 0.53 & 1.28 & 0.33 & 0.83 & 0.713 \\ 3.56 & 4.35 & 0.180 & 1.35 & 1.95 & 4.67 & 0.93 & 0.32 & 0.864 \\ 17.30 & 6.38 & 0.177 & 1.74 & 1.37 & 3.36 & 0.84 & 0.54 & 0.684 \\ 62.30 & 3.22 & 0.102 & 0.83 & 0.88 & 2.57 & 0.32 & 0.76 & 0.783 \\ 31.30 & 4.69 & 0.138 & 1.14 & 1.67 & 3.31 & 0.66 & 0.67 & 0.765 \\ 17.60 & 4.74 & 0.144 & 1.09 & 1.46 & 2.79 & 0.57 & 0.75 & 0.841 \\ 19.20 & 6.20 & 0.186 & 1.34 & 1.57 & 4.06 & 0.76 & 0.31 & 0.697 \\ 90 & 1.20 & 0.05 & 0.50 & 0.50 & 1.00 & 0.20 & 0.95 & 0.90 \\ 80 & 3.00 & 0.10 & 1.00 & 1.00 & 2.00 & 0.50 & 0.85 & 0.80 \\ 50 & 4.50 & 0.15 & 1.50 & 1.50 & 3.00 & 0.80 & 0.80 & 0.70 \\ 10 & 7.00 & 0.20 & 2.00 & 2.00 & 5.00 & 1.00 & 0.70 & 0.60 \end{bmatrix}$$

Then, A^+ and A^- ensue the normalized matrix C , which are deduced as

$$A^+=[0.5074 \quad -0.0746 \quad -0.1016 \quad -0.0845 \quad -0.1034 \quad -0.0902 \quad -0.0865 \quad 0.3940 \quad 0.3376 \quad]$$

$$A^-=[0.0201 \quad -0.4354 \quad -0.4064 \quad -0.4696 \quad -0.4135 \quad -0.4509 \quad -0.4327 \quad 0.1286 \quad 0.2251 \quad]$$

Through AHP, VCM, and SE, Calculated index weight vectors U , V , W , can also be listed orderly as below.

$$U=[0.0154 \quad 0.0302 \quad 0.0104 \quad 0.0194 \quad 0.0666 \quad 0.0328 \quad 0.4583 \quad 0.2002 \quad 0.1667 \quad]$$

$$V=[0.2000 \quad 0.1179 \quad 0.1028 \quad 0.1199 \quad 0.1070 \quad 0.1164 \quad 0.1168 \quad 0.0864 \quad 0.0327 \quad]$$

$$W=[0.0317 \quad 0.0366 \quad 0.0110 \quad 0.0240 \quad 0.0732 \quad 0.0393 \quad 0.5503 \quad 0.1779 \quad 0.0560 \quad]$$

With the application of CVM with equitable weight (CVM1), CVM with AHP (CVM2), CVM with VCM (CVM3), and CVM with SE (CVM4), the corresponding close value set can be separately represented as E, E_1, E_2, E_3

$$E=[14.1358 \quad 3.2890 \quad 26.3986 \quad 23.9514 \quad 8.9401 \quad 18.3294 \quad 18.2813 \quad 24.1933 \quad 0 \quad 8.2498 \quad 17.7501 \quad 29.3988]$$

$$E_1=[0.8807 \quad 0.2079 \quad 4.7254 \quad 2.9398 \quad 0.2962 \quad 1.3041 \quad 0.8838 \quad 2.8863 \quad 0.0150 \quad 0.4832 \quad 1.5952 \quad 3.9197]$$

$$E_2=[0.8192 \quad 0.1512 \quad 4.5598 \quad 3.6218 \quad 0.4521 \quad 1.6489 \quad 1.8507 \quad 3.4335 \quad 0.0285 \quad 0.3176 \quad 1.1703 \quad 8.4337]$$

$$E_3=[0.7854 \quad 0.1946 \quad 9.6119 \quad 3.6328 \quad 0.2018 \quad 1.3250 \quad 0.8498 \quad 2.4886 \quad 0.0040 \quad 0.5662 \quad 2.3509 \quad 6.7578]$$

Therefore, the final assessment results derive from CVM1 to CVM4 and [3, 5, 8, 17] can be compared in the Table 3.

Table 3 ranking results of PQ by various methods

Sample	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8
CVM1	3	2	4	4	3	4	4	4
CVM2	3	2	4	4	2	3	3	4
CVM3	3	2	4	4	3	4	4	4
CVM4	3	2	5	4	2	3	3	4
[3]	1	3	5	4	2	3	3	4
[17]	2	4	5	4	2	3	2	4
[5]	3	2	4	4	2	3	3	4
[8]	2	4	5	4	2	3	3	4

Through Table 3 there are some findings as follow:

(1) As for CVM1~CVM4, the result of each method is basically similar. Meanwhile, the ranking of CVM1 is totally the same with CM3's, while the ranking of CVM2 is almost the same with CVM4's. Whereas, the key nuance between CVM with objective empowerments-CVM1, CVM3, and CVM with subjective empowerments-CVM2, CVM4, is attributed to the judgment of $s_5 \sim s_7$ which manifests CVM containing subjective information such as expertise prefers much more optimistic ranking.

(2)The results from CVM1~CVM4 and [5] are almost consistent while those of [3], [8] and [17] are basically similar. Actually, the key discrepancy concentrates on the priority of s_1 and s_2 . Through the original data of each index from the initial matrix C , the positive index group of s_2 except for SS are virtually superior to those of s_1 . Similarly, the negative index group of s_1 are seen

to be inferior to those of s_2 , though s_1 holds a higher PSR. Therefore, s_2 is more likely to be preferential than s_1 provided each index is configured with apt weight; that's to say, CVM1~CVM4 and [5] may get a more rational assessment in this circumstance.

6. Conclusion

The developed new formula of CVM is valid and simplified to answer its invalidity of CVM when random samples evaluated lead to the formula of close value divided by zero. And diverse empowerment approaches introduced in CVM are discussed to demonstrate special influences on the final judgment of samples and conclude that subjective empowerment approaches are more likely to be optimistic about the assessment. Additionally, compared to other evaluating methods, the analytic outcome turns out the modified CVM set (CVM1~CVM4) is more preferable.

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