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Study on Harmonic Impedance Estimation and Harmonic Contribution Evaluation Index

ZITENG LIU, YONGHAI XU, (Member, IEEE), HAIWEI JIANG, AND SHUN TAO, (Member, IEEE)

State Key Laboratory of Alternate Electrical Power System with Renewable Energy Source, North China Electric Power University, Beijing 102206, China

Corresponding author: Shun Tao (tao_shun@sina.com)

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ABSTRACT Harmonic impedance estimation and suitable evaluation index selection are the key steps of harmonic contribution evaluation. Most of the traditional harmonic impedance estimation methods are only applicable to the scenario, where the background harmonic is stable and the utility impedance is constant. However, this scenario will change in many cases due to the fluctuation of harmonic, the change of system operation mode and so on. In order to improve the estimation accuracy for harmonic impedance, a harmonic impedance estimation method is proposed in this paper based on similarity measure and ordering points to identify the clustering structure (OPTICS). The total harmonic contribution index and harmonic comprehensive contribution index are proposed based on subjective analytic hierarchy process to simplify the evaluation results. Simulation analysis and their comparison with the traditional methods reveal that the proposed harmonic impedance estimation method can reduce the influence of background harmonic voltage fluctuation and utility impedance change, making the harmonic impedance estimation result more accurate. Besides, the proposed total harmonic contribution index and harmonic comprehensive contribution index can effectively simplify contribution evaluation results, which provide a new methodology for the evaluation of harmonic contribution.

INDEX TERMS Harmonic impedance, harmonic contribution evaluation, evaluation index, similarity measure, OPTICS, subjective analytic hierarchy process.

I. INTRODUCTION

With the access of high permeability distributed generation to power grid and the popularization of the electric vehicles, the harmonic pollution caused by a large number of power electronic devices such as rectifiers and inverters in power systems has become an increasingly serious problem [1]–[3]. Accurate assessment of harmonics contribution on utility side and customer side is conducive to the implementation of rewards and punishments, which can achieve the purpose of suppressing harmonic emissions and controlling harmonics [4].

Accurate estimation of harmonic impedance is the key to the evaluation of harmonic contribution [5]–[7]. Traditional harmonic parameter estimation methods are generally used when the background harmonic voltage fluctuation is small and the utility impedance is constant. However, the background harmonic voltage usually fluctuates in the actual operating system [8]. For example, the photovoltaic power source is easily affected by the light intensity, whose harmonic emission level and fluctuation degree are in a state of change throughout the day. Meanwhile, changes in power system operation mode, switching capacitor bank or reactive power compensation mode may lead to changes of utility impedance.

There are many studies about harmonic parameter estimation at present, mainly including fluctuation method [9], linear regression method [10]–[12], covariance method [13], blind source separation method [14], [15], and other estimation methods.

In the fluctuation method, harmonic impedance is formulated as the ratio of the harmonic voltage fluctuation and the harmonic current fluctuation. But the method is difficult to obtain accurate results, when utility harmonic voltage fluctuating. In [13], the background harmonic voltage fluctuation is eliminated by covariance method. In [14] and [15], the blind source separation method solves the utility impedance value by unmixing the values of equivalent

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harmonic current sources on the utility side and the customer side, but only for the case where the source signals are strongly independent.

The linear regression method estimates the harmonic impedance by using the relation between harmonic voltage and harmonic current at the point of common coupling (PCC), but data filtering needs to be performed when the background voltage fluctuates [16], [17]. In [16], the utility impedance is calculated by dominant fluctuation filtering at first, and then the different background harmonic voltages are segmented by hierarchical K-means clustering to make the background harmonic voltage fluctuation of each segment smaller. However, the small number of segments could result in the low calculation accuracy, whereas, if the number of segments is large, the data classification process will be cumbersome and difficult to be implemented in project. In [17], the kurtosis detection principle is proposed to screen valid data segments, but this method is mainly applicable to the case where the mean values of the harmonic voltage and harmonic current at the PCC have frequent and large-scale mutations.

There are already some researches on harmonic contribution estimation with impedance change considered. In [18], the wavelet transform modulus maximum method is used to detect the time point of the utility harmonic impedance change. However, the detection of abrupt change points may be interfered by large background harmonic voltage fluctuations. In [19], the DBSCAN method is used to distinguish the data segments corresponding to the different utility impedance values, but DBSCAN is too sensitive to the initial parameters, which is not conducive to obtaining correct results.

Obtaining reasonable evaluation indices is another significant process for harmonic contribution evaluation. Reference [20] points out that harmonic voltage and harmonic current indices are not equivalent. Reference [21] attempts to give different index schemes from the perspective of the voltages and currents, non-fundamental apparent power and distortion rate, but the evaluation results are very cumbersome, which is not conducive to the specific implementation of reward and punishment schemes.

Harmonic voltage contribution index and harmonic current contribution index are the most commonly used contribution evaluation indices at present, but these two indices are responsible for estimating of a certain harmonic order and the evaluation results are not equivalent. Otherwise, harmonics of different orders often exist at the same time, which makes the evaluation results very cumbersome.

In this paper, considering the background harmonic voltage fluctuation and utility impedance change, a harmonic impedance estimation method is proposed, based on similarity measure algorithm and ordering points to identify the clustering structure (OPTICS). In addition, the total harmonic contribution index and harmonic comprehensive contribution index are proposed to simplify the evaluation results.

Firstly, the similarity of harmonic voltage and harmonic current is measured at the PCC, and the data segment with stable background harmonic voltage is screened out. Secondly, OPTICS algorithm is used to obtain the cluster-ordering diagram, which is helpful for selecting input parameters, so that the sampled data can be divided into different clusters according to the utility impedance value. Thirdly, the complex domain robust regression method is used to calculate the harmonic parameters for the data of different clusters. Then, the harmonic voltage and current contribution of each harmonic is calculated, and the total harmonic contribution is obtained according to the harmonic ratio and the subjective analytic hierarchy process. Furtherly, the harmonic comprehensive contribution can be obtained. Finally, the simulation results show that the proposed method has higher estimation accuracy than the traditional method, and the evaluation results are more concise. It should be noted that many existing methods for estimating utility harmonic impedance require that the impedance of customer side is much higher than that of utility side [22]. There is no such special requirement in this proposed method, which means the proposed method is more suitable for the scenario where the impedance values of both utility and customer side are the similar due to filter and reactive power compensation or other reasons. The assumption of impedance at utility side and customer side is the same as [22], which is based on similarity analysis of harmonic impedance estimation method.

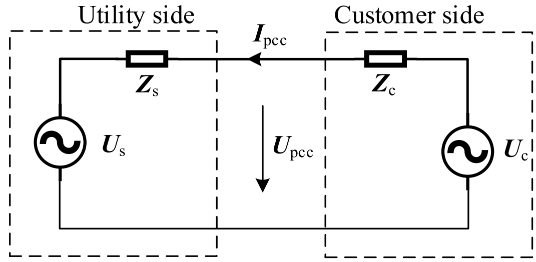

FIGURE 1. Thevenin equivalent circuit diagram.

In general, the contributions of this paper can be summarized as follows:

1) The data segment of stable background harmonic voltage can be screened by similarity measurement, and the data of constant utility impedance can be clustered together by OPTICS, which improves estimation accuracy of the harmonic impedance.
2) By using the subjective analytic hierarchy process, the evaluation indices of total harmonic contribution and harmonic comprehensive contribution are obtained, which can effectively simplify the evaluation results when multiple harmonic orders existing in the power grid.

II. HARMONIC PARAMETER ESTIMATION

The harmonics at the PCC are usually generated by harmonic sources of the utility side and the customer side. Considering the concerned customer as the customer side and the other parts as the utility side, the Thevenin equivalent circuit diagram shown in Fig.1 can be obtained.

$\boldsymbol{U}_{\mathrm{s}}$ and $\boldsymbol{U}_{\mathrm{c}}$ represent the equivalent harmonic voltage sources on the utility side and the customer side, respectively. $\boldsymbol{Z}_{\mathrm{s}}$ and $\boldsymbol{Z}_{\mathrm{c}}$ represent the equivalent harmonic impedance of the utility side and the customer side, respectively. And $\boldsymbol{U}_{\mathrm{pcc}}$ and $\boldsymbol{I}_{\mathrm{pcc}}$ represent the harmonic voltage and harmonic current at the PCC, respectively.

Harmonic parameter estimation includes the estimation of harmonic impedance and voltage of harmonic source. The following relationship can be obtained from Fig.1:

$$\boldsymbol{U}_{\mathrm{pcc}} = \boldsymbol{Z}_{\mathrm{s}}\boldsymbol{I}_{\mathrm{pcc}} + \boldsymbol{U}_{\mathrm{s}} \tag{1}$$

$$\boldsymbol{U}_{\mathrm{pcc}} = -\boldsymbol{Z}_{\mathrm{c}}\boldsymbol{I}_{\mathrm{pcc}} + \boldsymbol{U}_{\mathrm{c}} \tag{2}$$

A. FILTER DATA SEGMENTS BY SIMILARITY MEASURE

There are four voltage fluctuation cases for utility side and customer side equivalent harmonic sources shown in Fig.1:

1) No fluctuation: since the harmonic sources on both sides do not fluctuate, $\boldsymbol{U}_{\mathrm{pcc}}$ and $\boldsymbol{I}_{\mathrm{pcc}}$ are constant values, and it is impossible to calculate the equivalent impedance value with linear regression or other methods;
2) Only customer side fluctuation: as shown by (1), $\boldsymbol{U}_{\mathrm{s}}$ and $\boldsymbol{Z}_{\mathrm{s}}$ can be calculated because of the positively correlation of $\boldsymbol{U}_{\mathrm{pcc}}$ and $\boldsymbol{I}_{\mathrm{pcc}}$;
3) Only utility side fluctuation: as shown by (2), $\boldsymbol{U}_{\mathrm{c}}$ and $\boldsymbol{Z}_{\mathrm{c}}$ can be calculated because of the negatively correlation of $\boldsymbol{U}_{\mathrm{pcc}}$ and $\boldsymbol{I}_{\mathrm{pcc}}$;
4) Both fluctuations: the harmonic impedance and the harmonic voltage cannot be accurately calculated when the correlation between $\boldsymbol{U}_{\mathrm{pcc}}$ and $\boldsymbol{I}_{\mathrm{pcc}}$ is low.

Therefore, the accuracy of harmonic parameter estimation can be improved by measuring the similarity between $\boldsymbol{U}_{\mathrm{pcc}}$ and $\boldsymbol{I}_{\mathrm{pcc}}$, and screening out data segments with high correlation.

The similarity measure methods of time series mainly include distance similarity measure (Euclidean distance, Mahalanobis distance and Minghan distance), angle similarity function and Pearson correlation coefficient, in which Pearson correlation coefficient is more suitable because $\boldsymbol{U}_{\mathrm{pcc}}$ and $\boldsymbol{I}_{\mathrm{pcc}}$ are linear in the ideal state, and it can distinguish between positive correlation (case 2 and case 4) and negative correlation (case 3 and case 4).

The amplitude of $\boldsymbol{U}_{\mathrm{pcc}}$ and $\boldsymbol{I}_{\mathrm{pcc}}$ are detected by a sliding window. According to (1), when the $\boldsymbol{U}_{\mathrm{c}}$ dominates the fluctuation, that is, when the $\boldsymbol{U}_{\mathrm{s}}$ fluctuation is small, there is a good and positive linear correlation between $\boldsymbol{U}_{\mathrm{pcc}}$ and $\boldsymbol{I}_{\mathrm{pcc}}$. In the same way, according to (2), when the $\boldsymbol{U}_{\mathrm{s}}$ dominates the fluctuation, that is, when $\boldsymbol{U}_{\mathrm{c}}$ fluctuation is small, there is a good and negative linear correlation between $\boldsymbol{U}_{\mathrm{pcc}}$ and $\boldsymbol{I}_{\mathrm{pcc}}$. Therefore, the time series of $\boldsymbol{U}_{\mathrm{pcc}}$ and $\boldsymbol{I}_{\mathrm{pcc}}$ amplitude can be detected by sliding window to screen the dominant fluctuation and calculate the utility impedance. Pearson correlation coefficient between the time series X ($\boldsymbol{U}_{\mathrm{pcc}}$) and Y ($\boldsymbol{I}_{\mathrm{pcc}}$) is:

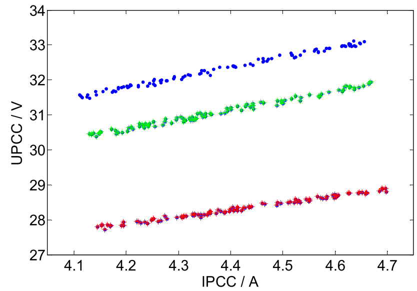

FIGURE 2. Spot diagram of harmonic voltage and current.

$$r = \frac{\sum_{i=1}^{n}(X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \overline{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \overline{Y})^2}} \tag{3}$$

where r is a value between -1 and 1, n is the number of samples. If the customer side fluctuation is dominant, r tends to be 1; if the utility side dominates the fluctuation, r tends to be -1. Therefore, the data segments of $r > r_1$ and $r < r_2$ are screened out, and the harmonic impedance values of the utility and customer are estimated respectively. A large number of simulations in this paper concluded that when the value of r_1 is 0.85~0.95, and the value of r_2 is -0.95~-0.85, utility and customer impedance values can be estimated more accurately, respectively.

B. CLUSTER DATA SEGMENTS BY OPTICS

The utility impedance may change due to changes of system operation mode, reactive power compensation or new device input. Therefore, whether the impedance value changes should be determined firstly when calculating harmonic contribution. If it changes, data should be processed in segments.

For the estimation of the utility impedance, after the Pearson correlation coefficient is used to screen out dominant fluctuation caused by customer side, the scatter plot of $\boldsymbol{I}_{\mathrm{pcc}}$ and $\boldsymbol{U}_{\mathrm{pcc}}$ as shown in Fig.2. It can be seen from (1) that the slope values of the three strips (represented by different colors in Fig.2) in the figure are related to the utility impedance, which correspond to three impedance values. So, it is necessary to use the clustering algorithm to make these three strips separated before the harmonic parameters are calculated.

Most of the common clustering methods divide different clusters according to the distance between the points, which may be not correct for this kind of long strip scatter plot.

Different from ordinary clustering methods, density clustering defines a cluster as the maximum set of connected points of density, which can divide regions with sufficient high density into clusters and find clusters of arbitrary shape in the spatial database of noise [23]. The idea of density clustering, which can solve the clustering in special data distribution (such as non-convex, mutual enveloping and of strip),

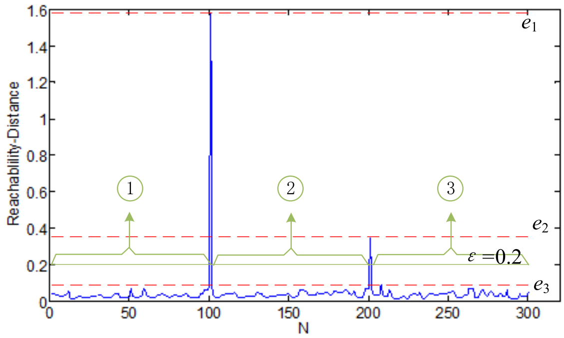

FIGURE 3. Cluster-ordering of OPTICS.

is more in line with human thinking. For density-based clustering algorithms, DBSCAN and OPTICS are better choices. However, DBSCAN is very sensitive to the value of the input parameter, and it will be difficult to get the appropriate clustering result if the parameter selection is inappropriate.

OPTICS algorithm is an improved method for DBSCAN algorithm [24], in which the core-distance and reachability-distance are defined as follows: For $p \in$ D (D is the set of all data), the core-distance of p is the minimum neighborhood radius that makes p a core point. For p, $q \in$ D, the reachable distance of q with respect to p is defined as the maximum distance between the core-distance of p and the Euclidean distance between p and q.

A cluster-ordering used to represent the density-based clustering structure of sample points is generated before the clustering result is obtained in OPTICS algorithm. The closer the cluster-ordering data is, the more likely it is that the samples will be grouped in the same cluster, and the closer the positions in the cluster-ordering will be. Taking the result queue of the sample points as the horizontal axis and the reachable-distance as the vertical axis, the cluster-ordering diagram of OPTICS is shown in Fig.3.

In Fig.3, the clustering results of the samples are shown as the valley region in the figure (shown in green). e_i ($i = 1, 2, 3 \ldots$) represent the peak values from high to low, in which 2 peaks are more obvious. These 2 peaks divide the data into three clusters, which correspond to the three long bars in Fig.2. When $e_3 < \varepsilon < e_2$, such as $\varepsilon = 0.2$ (indicated by the green line in fig. 3), 3 clusters can be obtained through the extraction of the valley data. When larger parameters are used as the threshold, such as $e_2 < \varepsilon < e_1$ and $\varepsilon > e_1$, the data is clustered into 2 clusters and 1 cluster respectively, while when smaller parameters are chosen, the data is divided into more clusters. The range of parameters ε can be obtained according to the number of strips in Fig.2 and cluster-ordering graph. So, the correct clustering results can be obtained, and the shortcoming of DBSCAN clustering algorithm sensitive to parameters is improved.

The harmonic impedance clustering steps of OPTICS algorithm are shown as follows:

1) Obtain the scatter diagram of harmonic voltage $|\boldsymbol{U}_{\text{pcc}}|$ and harmonic current $|\boldsymbol{I}_{\text{pcc}}|$, establish the ordered queue O and the result queue R, and mark all data in D as unprocessed.
2) If all the data in D has been processed, jump to step 7; otherwise, select an unprocessed core sample point p ($p \in$ D and $p \notin$ R) and find all its direct density accessible sample points, then put it into O and sort it according to the reachability-distance.
3) If O is empty, go back to step 2; otherwise, take the first sample point (the sample point with the smallest distance) from O to expand. Save the taken sample point into R to determine whether the expansion point m is the core points. If so, enter step 4; otherwise, go back to step 3.
4) Find all direct density reachable point $c_m(j)$ of m and judge whether $c_m(j)$ has existed in R; otherwise, judge whether $c_m(j)$ has existed in O. If so, enter step 5; otherwise, skip to step 6.
5) If the new reachability-distance $rd^{n+1}(i)$ is less than the old reachability-distance $rd^{n}(i)$, then the $rd^{n+1}(i)$ is used to replace the $rd^{n}(i)$, reorder O and go back to step 3;
6) Reorder O and go back to step 3;
7) Take the output order of R as the abscissa and the reachable-distance as the ordinate, generate the cluster-ordering graph. Determine the value of the parameter ε according to the cluster-ordering graph, then output the valley data, and form the final clustering result.

C. HARMONIC PARAMETER ESTIMATION

The complex domain robust regression method is used to estimate the harmonic impedance of the filtered and clustered data in order to reduce the effect of outliers.

Different weights can be applied to different points in the robust regression method, i.e., a larger weight can be given to the points with small residuals, while a smaller weight can be given to the points with large residuals, establishing a weighted least-squares estimation accordingly. The weight coefficient is improved by repeated iteration until the change of the weight coefficient is less than a certain allowable error, achieving the purpose of robustness. When there are anomalous values in the data, robust regression has obvious advantages. The optimized objective function is:

$$\sum_{i=1}^{n} w_i (y_i - \sum_{j=1}^{p} x_{ij}\beta_j)^2 = \min \tag{4}$$

where β_{j} is the regression coefficient; x and y represent the independent and dependent variables of the regression equation, respectively. The weight w_i is defined as (5):

$$w_i = \begin{cases} 0 & |u_i/\mathrm{c}| > 1 \\ (1 - |u_i/\mathrm{c}|^2) & |u_i/\mathrm{c}| \leq 1 \end{cases} \tag{5}$$

where c is a constant, generally 4.685; $\boldsymbol{U}_i$ is the standardized residual index.

$$\mathrm{mid}(e_1, \cdots, e_{\mathrm{n}}) = \mathrm{Med}\,|e_1 - \mathrm{Med}(e_1, \cdots, e_{\mathrm{n}})| \tag{6}$$

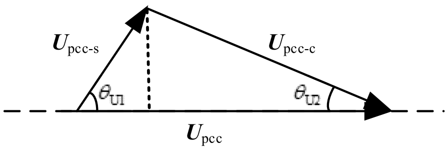

FIGURE 4. Harmonic voltage contribution evaluation diagram.

$$s = \mathrm{mid}(e_1, \cdots, e_n)/0.6745 \tag{7}$$

$$u_i = e_i/s \tag{8}$$

where Med is the Median of the variable, e_i is the residual vector.

The steps of robust regression are shown as follows:

1) select the $\hat{\boldsymbol{\beta}}^{(0)} = (\boldsymbol{X}^{\mathrm{T}}\boldsymbol{X})^{-1}\boldsymbol{X}^{\mathrm{T}}\boldsymbol{Y}$ obtained by the least square estimation as the initial iteration value, and calculate the initial residual vector $\boldsymbol{e}^{(0)}$;
2) use (6)-(8) to calculate normalized residual $\boldsymbol{u}$, substitute it into (5), and convert it into diagonal weight vector $\boldsymbol{W}$;
3) use $\hat{\boldsymbol{\beta}} = (\boldsymbol{X}^{\mathrm{T}}\boldsymbol{W}\boldsymbol{X})^{-1}\boldsymbol{X}^{\mathrm{T}}\boldsymbol{W}\boldsymbol{Y}$ to obtain $\hat{\boldsymbol{\beta}}^{(j+1)}$ instead of $\hat{\boldsymbol{\beta}}^{(j)}$ to calculate new residuals;
4) return to step 2) and calculate $\hat{\boldsymbol{\beta}}^{(j)}$ iteratively. When $\max\left|\hat{\boldsymbol{\beta}}^{(j)} - \hat{\boldsymbol{\beta}}^{(j-1)}\right| < \varepsilon$, that is, the iteration will end when the maximum value of the absolute value of the difference between adjacent two-step regression coefficients is less than the preset standard error.

The voltage value of harmonic source can be obtained according to (1) and (2) after completing harmonic impedance estimation

III. HARMONIC CONTRIBUTION EVALUATION INDEX

A. EVALUATION INDEX OF HARMONIC VOLTAGE (CURRENT)

Harmonic voltage evaluation index and harmonic current evaluation index are the most commonly used evaluation indices. According to Fig.1, when $\boldsymbol{U}_{\mathrm{s}}$ or $\boldsymbol{U}_{\mathrm{c}}$ acts alone, based on the superposition theorem, the voltage at the PCC can be obtained as follows:

$$\begin{cases} \boldsymbol{U}_{\mathrm{pcc-s}} = \dfrac{\boldsymbol{Z}_c}{\boldsymbol{Z}_s + \boldsymbol{Z}_c}\boldsymbol{U}_{\mathrm{s}} \\ \boldsymbol{U}_{\mathrm{pcc}-c} = \dfrac{\boldsymbol{Z}_s}{\boldsymbol{Z}_s + \boldsymbol{Z}_c}\boldsymbol{U}_c \\ \boldsymbol{U}_{\mathrm{pcc}} = \boldsymbol{U}_{\mathrm{pcc-s}} + \boldsymbol{U}_{\mathrm{pcc-c}} \end{cases} \tag{9}$$

The relationship between $\boldsymbol{U}_{\mathrm{pcc-s}}$, $\boldsymbol{U}_{\mathrm{pcc-c}}$ and $\boldsymbol{U}_{\mathrm{pcc}}$ is shown in Fig.4.

Then the harmonic voltage contribution of the utility side and the customer side can be calculated respectively:

$$\begin{cases} D_{\mathrm{Us-h}} = \dfrac{\left|\boldsymbol{U}_{\mathrm{pcc-s}}\right|\cos\theta_{\mathrm{U1}}}{\left|\boldsymbol{U}_{\mathrm{pcc}}\right|} \times 100\% \\ D_{\mathrm{Uc-h}} = \dfrac{\left|\boldsymbol{U}_{\mathrm{pcc-c}}\right|\cos\theta_{\mathrm{U2}}}{\left|\boldsymbol{U}_{\mathrm{pcc}}\right|} \times 100\% \end{cases} \tag{10}$$

Similarly, when $\boldsymbol{U}_{\mathrm{s}}$ or $\boldsymbol{U}_{\mathrm{c}}$ acts individually, the current at the PCC can be obtained as follows:

$$\begin{cases} \boldsymbol{I}_{\mathrm{pcc-s}} = -\dfrac{1}{\boldsymbol{Z}_{\mathrm{s}} + \boldsymbol{Z}_{\mathrm{c}}}\boldsymbol{U}_{\mathrm{s}} \\ \boldsymbol{I}_{\mathrm{pcc-c}} = \dfrac{1}{\boldsymbol{Z}_{\mathrm{s}} + \boldsymbol{Z}_{\mathrm{c}}}\boldsymbol{U}_{\mathrm{c}} \\ \boldsymbol{I}_{\mathrm{pcc}} = \boldsymbol{I}_{\mathrm{pcc-s}} + \boldsymbol{I}_{\mathrm{pcc-c}} \end{cases} \tag{11}$$

The corresponding harmonic current contribution is:

$$\begin{cases} D_{\mathrm{Is}-h} = \dfrac{\left|\boldsymbol{I}_{\mathrm{pcc-s}}\right|\cos\theta_{\mathrm{I1}}}{\left|\boldsymbol{I}_{\mathrm{pcc}}\right|} \times 100\% \\ D_{\mathrm{Ic}-h} = \dfrac{\left|\boldsymbol{I}_{\mathrm{pcc-c}}\right|\cos\theta_{\mathrm{I2}}}{\left|\boldsymbol{I}_{\mathrm{pcc}}\right|} \times 100\% \end{cases} \tag{12}$$

B. TOTAL CONTRIBUTION INDEX OF HARMONIC VOLTAGE (CURRENT)

1) DETERMINE THE WEIGHTS ACCORDING TO THE HARMONIC CONTENT RATIO

Harmonic voltage evaluation index and harmonic current evaluation index are all evaluated for a specific harmonic order. However, there are many harmonics of different order in the actual power grid. If there are n harmonics of different order, there will be $2n$ evaluation results, which makes the evaluation results very complicated. In this paper, by weighting each order harmonic contribution with harmonic ratio and subjective analytic hierarchy process, total contribution of harmonic voltage and harmonic current are obtained, which effectively simplify the complex estimation results, and is more conducive to the implementation of reward and punishment programs.

Harmonic ratio is an important parameter to measure harmonic pollution. For the utility side or the customer side, there is likely to be large contribution of a certain harmonic order, but the harmonic ratio is low, which causes no great harm to the power grid. Therefore, the total contribution cannot be calculated by simply calculating the average value. In this paper, the total harmonic contribution index is proposed, based on the subjective analytic hierarchy process. The subjective analytic hierarchy process can formalize the expression and processing of people's subjective judgment, and gradually eliminate subjectivity so as to transform it into objective facts as much as possible. In this paper, the harmonic ratio is used to improve the scale value of the subjective analytic hierarchy process, so as to make the weighted results more objective.

If there are harmonic of k orders in total (may contain 3rd, 5th, ..., h-th harmonic) that need to be evaluated, and their harmonic voltage indices (or harmonic current indices) are denoted by index 1, 2, ..., k, then the scale values are formulated as the ratio of the harmonic content for two indices:

$$t_{i(i+1)} = \frac{HRX_i}{HRX_{i+1}} \quad i = 1, 2, \cdots, (k-1) \tag{13}$$

where the parameter HRX_i is the harmonic ratio of voltage (current) of index i. Then, the judgment matrix is

TABLE 1. Subjective analytic hierarchy process scale.

Scale	Meaning
1	Both indices are equally important
3	One index is slightly more important than the other
5	One index is more important than the other
7	One index is significantly more important than the other
9	One index is absolutely more important than the other

shown as:

$$\boldsymbol{W}_t = \begin{bmatrix} 1 & t_{12} & \cdots & t_{12}t_{23}\cdots t_{(k-1)k} \\ 1/t_{12} & 1 & \cdots & t_{23}\cdots t_{(k-1)k} \\ \vdots & \vdots & \ddots & \vdots \\ 1/t_{12}t_{23}\cdots t_{(k-1)k} & 1/t_{23}\cdots t_{(k-1)k} & \cdots & 1 \end{bmatrix} \tag{14}$$

On the basis of the judgment matrix, the weight of index i is calculated as:

$$A_i = \frac{1}{\sum_{j=1}^{n} \frac{1}{w_{t-ij}}} \tag{15}$$

where w_{t-ij} is in row i, column j of the matrix W_t, and then the weight matrix $A = [A_1, A_2, \cdots A_k]^{\mathrm{T}}$ is obtained.

The total contribution of harmonic voltage (current) can be expressed as:

$$C_{\mathrm{U}}(C_{\mathrm{I}}) = A \cdot D_{\mathrm{U}}(D_{\mathrm{I}}) \tag{16}$$

where $D_{\mathrm{U}} = [D_{\mathrm{U}1}, D_{\mathrm{U}2}, \cdots D_{\mathrm{U}k}]^{\mathrm{T}}$, and $D_{\mathrm{U}i}$ $(i = 1, 2, \ldots, k)$ is the weight of the utility side or customer side harmonic voltage (current) corresponding to index $1, 2, \ldots, k$.

2) THE WEIGHTS DETERMINED ACCORDING TO THE HARMONIC INFLUENCE

In some special cases, the system may be sensitive to the harmonics of some orders, and the weights can't be simply determined by harmonic ratio. Therefore, a method is proposed to weight different harmonic orders by 1-9 scale among the subjective hierarchy analysis (as shown in Table 1). The scale values are selected according to the influence caused by harmonics, and the weight values are calculated according to (15).

C. HARMONIC COMPREHENSIVE EVALUATION INDEX

Harmonic voltage evaluation index and harmonic current evaluation index evaluate harmonic contribution from two different perspectives, so the contribution evaluation results are not equivalent. The harmonic comprehensive contribution index is put forward in this paper, which can determine the contribution for each harmonic voltage and current comprehensively and simplify the tedious evaluation results furtherly.

When obtaining a comprehensive evaluation result, a method is proposed to comprehensively weight the two indices of harmonic voltage and harmonic current total contribution by 1-9 scale value (as shown in Table 1) among the subjective hierarchy analysis. When the harmonic voltage index and harmonic current index are respectively recorded as index 1 and index 2, the judgment matrix can be expressed:

$$\boldsymbol{W}_t = \begin{bmatrix} 1 & t_{12} \\ 1/t_{12} & 1 \end{bmatrix} \tag{17}$$

The weight value is calculated according to (15). Two ways to determine the scale value are provided in this paper:

One is to determine the scale by the exceeding standard of harmonic voltage and harmonic current, which is suitable for the systems that is sensitive to the exceeding standard of harmonic. t_{12} represents the scale value corresponding to the importance of the harmonic voltage index compared with the harmonic current index. If the exceeding standard degree of harmonic voltage is stronger than that of harmonic current, then t_{12} take the corresponding values from Table 1. Instead, t_{12} can take the reciprocal of the values in Table 1. For example, when compared with the harmonic current, the exceeding standard of the harmonic voltage is slightly higher, so that $t_{12} = 3$ can be obtained.

The other is to determine the scale value according to the impact of voltage and current on the grid, which is suitable for systems with different requirements on voltage and current. For example, it is generally believed that the responsibility of the power grid is to provide qualified voltage, and the harmonic voltage index is used more widely. When considering that voltage is slightly more important than current, $t_{12} = 3$ can be obtained according to Table 1. Thus, the weight value can be shown as

$$A_{\mathrm{UI}} = \begin{bmatrix} \frac{3}{4} & \frac{1}{4} \end{bmatrix} \tag{18}$$

The scale value about the comprehensive evaluation index can be changed according to different applicable situations, which is subjective but more flexible to some extent. It requires to decide according to the actual situation to get more reasonable evaluation results.

D. EVALUATION PROCESS

The proposed method works as follows: firstly, Pearson correlation coefficient is used to screen out the customer-side dominant fluctuation segment and utility-side dominant fluctuation segment. For the former, OPTICS algorithm is used to divide the data segments into different clusters according to the utility impedance value, and the complex domain robust regression method is used to calculate the utility impedance value and harmonic voltage value for each cluster data, respectively. For the latter, the complex domain robust regression method is also used to calculate the impedance and harmonic voltage.

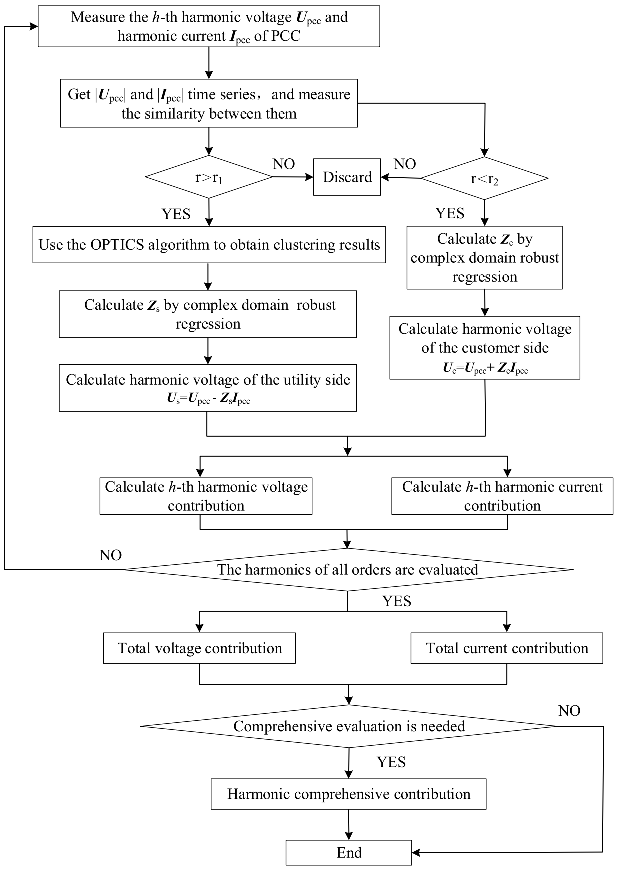

FIGURE 5. The process of harmonic contribution evaluation.

Then, the harmonic voltage and harmonic current contribution are solved according to (9)-(12). The total contribution of harmonic voltage and harmonic current is obtained according to (13)-(16), simplifying the cumbersome evaluation results. If the evaluation results need to be further simplified, the comprehensive evaluation results can be obtained according to Table 1, (15) and (17). The evaluation process is shown in Fig.5.

IV. SIMULATION ANALYSIS

The simulation consists of two parts. Only the background harmonic voltage fluctuation is considered in the first simulation, which verifies the effectiveness of similarity measurement proposed in this paper. Both the background harmonic voltage fluctuation and impedance variation are considered in the second simulation, which verifies the feasibility of the utility impedance calculation method based on similarity measurement and OPTICS proposed in this paper, as well as the evaluation of harmonic contribution using (voltage/current) total index and comprehensive index.

A. ONLY BACKGROUND HARMONIC VOLTAGE FLUCTUATION

The equivalent circuit model is built as shown in Fig.1. Taking the 3rd harmonic as an example, the simulation parameters

TABLE 2. Simulation parameters.

	R/Ω	L/mH	amplitude/V	phase/°
Utility side	2.5	3	15	10
Customer side	30	60	300	50

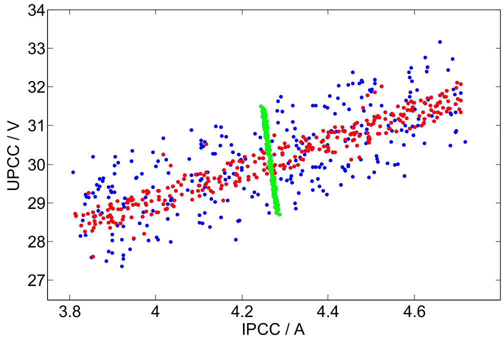

FIGURE 6. Scatter plot.

are shown in Table 2. The fluctuation of different sizes within 20% is added to the harmonic voltage sources of the utility side and customer side, with the simulation time for 16s and a sample every 0.02 seconds, obtaining a total of 800 data points.

The 3rd harmonic voltage and current at the PCC are measured, obtaining the scatter plot corresponds to $|\boldsymbol{I}_{\mathrm{pcc}}|$ and $|\boldsymbol{U}_{\mathrm{pcc}}|$ (as shown in Fig.6). Two data segments are selected, one with a Pearson correlation coefficient greater than 0.9 (customer-side dominant fluctuation segment) and the other with the Pearson correlation coefficient less than −0.9 (utility-side dominant fluctuation segment), which correspond to the red and green parts of the scatter plot in Fig.6, after using sliding windows to detect the similarity of $|\boldsymbol{I}_{\mathrm{pcc}}|$ and $|\boldsymbol{U}_{\mathrm{pcc}}|$ time series.

For the estimation of utility impedance, a higher estimation accuracy can be obtained with the complex domain partial least square method, complex domain robust regression method and dominant fluctuation filtering method, which are the improved algorithms of the classical partial least square method, robust regression method and fluctuation filtering method respectively [8], [12], [25]. For this reason, the proposed method is compared with the methods mentioned above for analysis. Methods 1 to 5 represent complex domain partial least square method, complex domain robust regression method, dominant fluctuation filtering method, correlation coefficient filtering (proposed in this paper) combined with complex domain partial least square method, the proposed method in this paper (correlation coefficient filtering combined with complex field robust regression), respectively. The results of the utility impedance estimation are shown in Table 3.

In Table3, Z_{s-x} and Z_{s-y} are the real part and imaginary part of the utility impedance, respectively. Simulation repeats 50 times, and the calculation results of each method are shown in Fig.7.

TABLE 3. Calculation results of harmonic impedance.

	Z_{s-x}		Z_{s-y}	
	E/Ω	Error/%	E/Ω	Error /%
Method 1	2.439	-2.43%	2.753	-2.62%
Method 2	2.446	-2.18%	2.768	-2.10%
Method 3	2.676	7.04%	2.949	4.30%
Method 4	2.538	1.52%	2.806	-0.75%
Method 5	2.491	-0.36%	2.821	-0.22%
T	2.500	—	2.827	—

T represents the theoretical calculation result, E represents the estimation calculation result, which is also suitable for the following table.

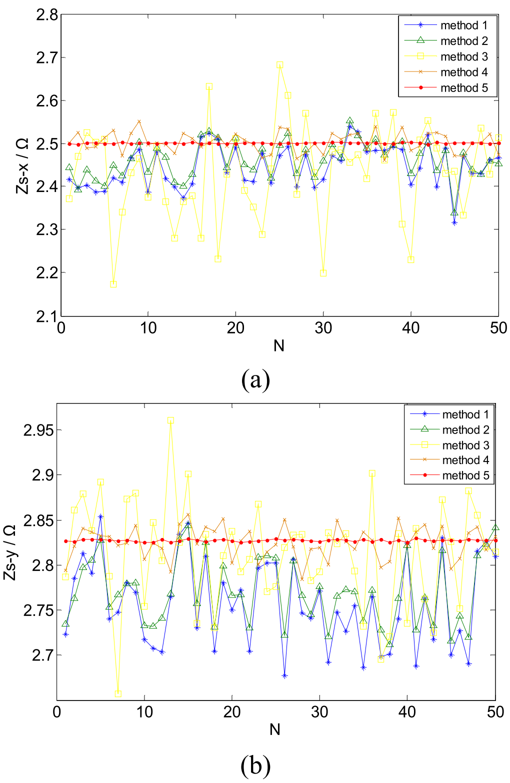

FIGURE 7. (a) Evaluation result of the utility impedance real part and (b) evaluation result of the utility impedance imaginary part.

TABLE 4. Customer side impedance estimation.

	Z_{s-x}	Z_{s-y}
T/Ω	29.714	54.921
E/Ω	30.000	56.549
Error /%	-0.95%	-2.88%

For the estimation of customer impedance, the data segment with Pearson correlation coefficient less than −0.9 for calculation is selected (methods 1-3 cannot obtain the customer side impedance value). The calculation results are shown in Table 4.

Then the utility harmonic voltage and customer harmonic voltage values can be obtained according to (1) (2), and the average value of harmonic contribution calculated according to (9)-(12) is shown in Table 5.

TABLE 5. Harmonic contribution estimation.

		Harmonic voltage contribution	Harmonic current contribution
Utility side	T/%	45.73	-3.88
	E/%	45.70	-3.96
	Error/%	-0.07	2.06
Customer side	T/%	54.27	103.88
	E/%	54.30	103.96
	Error/%	0.06	0.08

TABLE 6. Calculation results of harmonic impedance.

	Z_{s-x}		Z_{s-y}	
	E/Ω	Error/%	E/Ω	Error /%
Method 1	2.318	-7.28%	2.568	-9.16%
Method 2	2.355	-5.80%	2.626	-7.11%
Method 3	2.389	-4.44%	2.709	-4.17%
Method 4	2.477	-0.92%	2.748	-2.79%
Method 5	2.511	0.44%	2.822	-0.18%
T	2.500	—	2.827	—

According to the utility impedance estimation results in Table 3 and Fig.7, the method in this paper is superior to the other four methods, which proves the validity of Pearson correlation coefficient filtering data segment and the accuracy of complex domain robust regression method to estimate parameters. By comparing Table 3 with Table 4 and Table 5, the method in this paper can estimate the harmonic contribution value more accurately.

In addition, there are many existing methods for estimating utility harmonic impedance requiring that the impedance of customer side is much higher than that of utility side [22]. There is no such special requirement in this proposed method. For example, when the customer side impedance in Table 2 is $3 + j4\ \Omega$, the results of the utility impedance estimation are shown in Table 6.

According to Table 6, when the impedance values of utility side is similar to the customer side, the proposed method can also accurately estimate the utility impedance.

B. BACKGROUND HARMONIC VOLTAGE FLUCTUATION AND UTILITY IMPEDANCE CHANGE

When the impedance of the utility side changes due to the switching of large impedance or reactive compensation and the change of operation mode, it is necessary to separate the data segments corresponding to different impedances before estimating the contribution.

The built circuit model is shown in Fig.1, where the utility side and customer side contain 3rd, 5th and 7th harmonics. The fundamental voltage is 10.5 kV and other simulation parameters are shown in Table 7. Fluctuation of different

TABLE 7. Simulation parameters.

		R/Ω	L/mH	amplitude/V	phase/°
Utility side	0~16s	1.5	1	15 (3rd)	10 (3rd)
	16~24s	2	2	10 (5th)	60 (5th)
	24~32s	2.5	3	20 (7th)	30 (7th)
Customer side		50	60	300 (3rd)	50 (3rd)
				200 (5th)	20 (5th)
				100 (7th)	40 (7th)

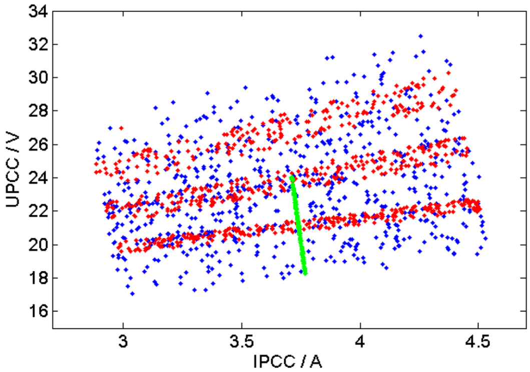

FIGURE 8. Scatter plot.

sizes within 20% is added to the amplitude and phase of the harmonic voltage source, with the simulation time for 32s and a sample every 0.02 seconds, obtaining a total of 1600 data points.

The harmonic voltage and harmonic current of each harmonic at PCC are measured. With the results of 3rd harmonic taken for example, the scatterplot diagram about $|\boldsymbol{U}_{\text{pcc}}|$ and $|\boldsymbol{I}_{\text{pcc}}|$ is gained. The data segment with the Pearson correlation coefficient greater than 0.9 (customer dominant wave data section) being marked in red, and the data segment with Pearson correlation coefficient less than 0.9 (utility dominant wave data section) being marked in green, the scatterplot diagram is shown in Fig.8.

It can be seen from Fig.8 that the red part of the scatter diagram is distributed in the shape of three long strips corresponding to three possible utility impedance values. Firstly, K-means, spectrum clustering and DBSCAN (proposed in [19]) are used to cluster the scatter diagram, and the clustering results are shown in Fig.9.

It can be seen from Fig.9 that K-means and spectral clustering are difficult to cluster accurately when impedance changes little, and DBSCAN is too sensitive to initial parameters to get ideal results. Then, cluster analysis is carried out by using OPTICS algorithm to obtain cluster-ordering graph shown in Fig.10 (a). Selecting the parameter $\varepsilon = 0.35$, the data can be clustered into three clusters, which is shown in Fig.10 (b).

It can be seen from the figure that the method in this paper can accurately separate the data clusters corresponding to

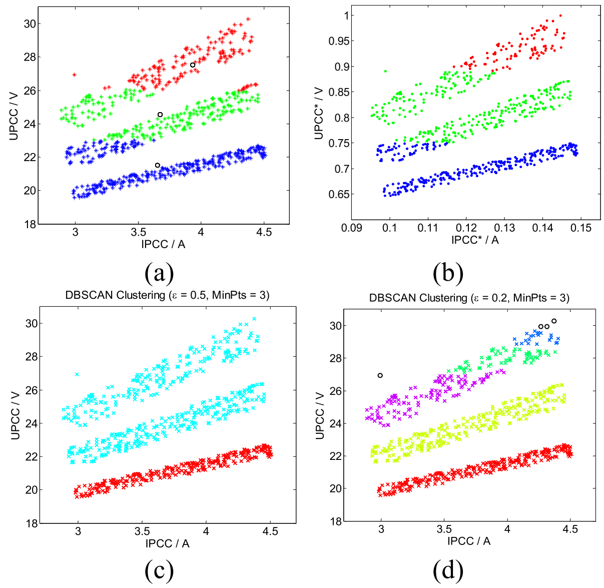

FIGURE 9. (a) The clustering result of K-means, (b) the clustering result of spectrum clustering, (c) the clustering result of DBSCAN ($\varepsilon = 0.5$) and (d) the clustering result of DBSCAN ($\varepsilon = 0.2$).

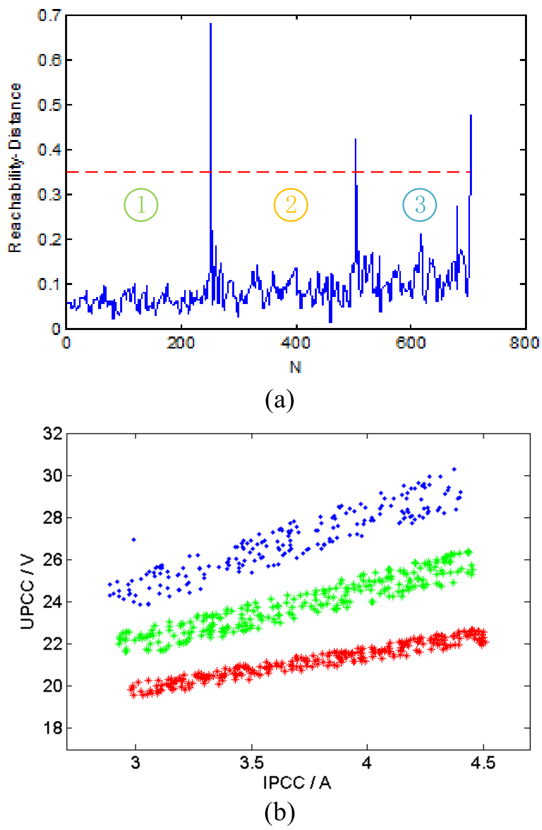

FIGURE 10. (a) cluster-ordering graph and (b) the clustering result of OPTICS.

different utility impedances. After obtaining three clusters of data from the OPTICS, the mean value of harmonic contribution of utility side and customer side in each period is calculated.

TABLE 8. Results of harmonic voltage contribution estimation.

		0~2s	2~4s	4~8s
Utility side (3rd)	T/%	68.77	58.60	50.02
	E/%	68.50	58.95	52.28
	Error/%	-0.39	0.60	4.52
Customer side (3rd)	T/%	31.23	41.40	49.98
	E/%	31.50	41.05	47.72
	Error/%	0.86	-0.85	-4.52
Utility side (5th)	T/%	75.68	60.64	50.14
	E/%	75.20	61.65	50.39
	Error/%	-0.63	1.67	0.50
Customer side (5th)	T/%	24.32	39.36	49.86
	E/%	23.80	38.85	49.61
	Error/%	1.97	-2.57	-0.50
Utility side (7th)	T/%	91.41	85.84	80.25
	E/%	90.82	86.80	80.33
	Error/%	0.65	1.12	0.10
Customer side (7th)	T/%	8.59	14.16	19.75
	E/%	9.18	13.20	19.67
	Error/%	6.87	6.78	0.41

TABLE 9. Results of harmonic current contribution estimation.

		0~2s	2~4s	4~8s
Utility side (3rd)	T/%	-3.89	-3.89	-3.89
	E/%	-3.87	-3.88	-4.11
	Error/%	-0.51	-0.26	5.66
Customer side (3rd)	T/%	103.89	103.89	103.89
	E/%	103.87	103.88	104.11
	Error/%	-0.02	-0.01	0.21
Utility side (5th)	T/%	-3.89	-3.96	-3.92
	E/%	-4.04	-4.08	-3.94
	Error/%	3.86	3.03	0.51
Customer side (5th)	T/%	103.89	103.96	103.92
	E/%	104.04	104.08	103.94
	Error/%	0.14	0.12	0.02
Utility side (7th)	T/%	-24.77	-24.20	-24.88
	E/%	-24.46	-24.54	-24.80
	Error/%	-1.25	-1.40	-0.32
Customer side (7th)	T/%	124.77	124.20	124.88
	E/%	124.46	124.54	124.80
	Error/%	0.25	0.27	0.06

Similarly, the 5th and 7th harmonic contribution are calculated. The results of harmonic voltage contribution estimation are shown in Table 8, and the results of harmonic current contribution estimation are shown in Table 9.

The weight of each harmonic contribution index is determined according to Section IV Part B. Method of determining the weight based on harmonic ratio is taken for an example, then the harmonic ratio of each harmonic is calculated as shown in Table 10, and the weight values of each harmonic index is determined according to (13)-(15), as shown in Table 11.

TABLE 10. Harmonic ratio of each harmonic.

		0~2s	2~4s	4~8s
Voltage	3rd	0.207	0.209	0.212
	5th	0.122	0.123	0.125
	7th	0.211	0.213	0.215
Current	3rd	1.939	1.986	1.996
	5th	0.918	0.944	0.950
	7th	0.291	0.293	0.298

TABLE 11. Weight values.

		Time 1	Time 2	Time 3
Voltage	3rd	0.383	0.383	0.384
	5th	0.226	0.226	0.226
	7th	0.391	0.391	0.390
Current	3rd	0.617	0.616	0.615
	5th	0.293	0.293	0.293
	7th	0.090	0.091	0.092

TABLE 12. Total harmonic contribution.

	0~2s	2~4s	4~8s
Voltage (utility side)	78.73	70.41	62.78
Voltage (customer side)	21.27	29.59	37.22
Current (utility side)	-5.77	-5.82	-5.96
Current (customer side)	105.77	105.82	105.96

TABLE 13. Harmonic comprehensive contribution.

	0~2s	2~4s	4~8s
Utility side	57.605	51.3525	45.595
Customer side	42.395	48.6475	54.405

According to Table 11 and (16), the total harmonic contribution results are shown in Table 12.

If there is no need to calculate the comprehensive contribution, the evaluation is completed. When it is necessary to obtain the comprehensive contribution, the weights of contribution indices of harmonic voltage and harmonic current are determined according to Section IV Part C. By using the weight value in (18) as an example, the comprehensive contribution is obtained, and the results are shown in Table 13.

The simulation results show that when the utility impedance changes, OPTICS algorithm is better than other clustering algorithms for the clustering of data segment. In addition, the total harmonic contribution index and comprehensive harmonic contribution index effectively simplify the evaluation results.

V. CONCLUSION

1) In this paper, a utility impedance calculation method and two harmonic evaluation indices (total harmonic contribution index and harmonic comprehensive contribution index) are proposed. The simulation results

demonstrated that the proposed method can effectively deal with the complex situation where the background harmonic voltage fluctuates, utility impedance changes and multiple frequency harmonics coexist.

2) The proposed evaluation method of harmonic contribution is not aimed at a certain harmonic, but at comprehensive contribution ratio of the utility and the customer. By using the proposed harmonic contribution indices, the reward and punishment scheme can be directly implemented on the utility side and the customer side, which is conducive to the suppression of harmonic emission and the management of harmonic in the power grid.

3) A method for determining the weight of each harmonic and the contribution of harmonic voltage and current is proposed in this paper. In this method, the weighted result is directly affected by the selection of scale value. Due to the complexity of actual power grid operation, the selection of scale value is relatively subjective. It should be further studied how to determine relatively objective scale value for different forms of power grid in the future.

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ZITENG LIU was born in Bozhou, Anhui, China, in 1996. She received the B.S. degree from China Agricultural University. She is currently pursuing the M.S. degree with North China Electric Power University. Her research interests include power quality and its control, and harmonic contribution assessment.

YONGHAI XU (Member, IEEE) was born in Henan, China, in 1966. He received the B.S. degree from Tsinghua University, Beijing, China, in 1989, the M.S. degree from North China Electric Power University, Beijing, in 1992, and the Ph.D. degree from the Harbin Institute of Technology, Harbin, China, in 2002, all in electrical engineering.

He is currently a Professor with the School of Electrical and Electronic Engineering, North China Electric Power University. His research interests include power quality analysis and control, power electronic transformer, and new energy power systems.

HAIWEI JIANG was born in Jinzhou, Liaoning, China, in 1996. He received the B.S. degree in electrical engineering and automation from Dalian Jiaotong University. He is currently pursuing the M.S. degree from North China Electric Power University. His research interests include power quality and its control.

SHUN TAO (Member, IEEE) was born in China, in November 1972. She received the M.S. and Ph.D. degrees from North China Electric Power University (NCEPU), in 2005 and 2008, respectively. She had a Postdoctoral procedure at the Electrical Engineering Laboratory de Grenoble (G2Elab), Institute National Polytechnique de Grenoble (INPG), Grenoble, France, in 2010. She has been with the NCEPU, since 2008. Her research interests include active distribution networks and its power-quality.