REVIEW ON HARMONIC IMPACTS ASSESSMENT INDICES AND METHODS OF MULTIPLE HARMONIC SOURCES

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ABSTRACT

Estimating the harmonic contribution of various loads is the key prerequisites for the harmonic control scheme, is an urge concern in the field of harmonic research. This paper reviews the basic principle, advantages and disadvantages of the existing quantitative indicators and method of multi-harmonic source responsibilities, the mathematical models and algorithms of typical methods are analysed in depth, and the accuracy of various methods are compared and analysed combined with the simulation example. Finally, the existing problems and further research directions of the study are prospected.

INTRODUCTION

With the development of industrialization and the acceleration of power electronicization, a large number of nonlinear time-varying loads, power electronic devices and switching power supplies are connected to the power grid , which makes the system harmonic pollution problem more prominent. Quantifying the harmonic responsibility of various loads, and to formulate a reasonable reward and punishment scheme, which is the key to solving the harmonic pollution problem.

In recently, a lot of researches have been done on the harmonic impacts determination, and it can be divided into two categories: single-point methods and multi-point methods. The single-point methods can quantifies the responsibility of the customer and the utility at the customer-utility interface point. However, the harmonic distortion at the concerned bus is commonly caused by several harmonic sources in the system. The multi-point methods aim to quantify the respective responsibilities of multiple harmonic sources that cause harmonic pollution of a certain bus, it contain two major parts of quantitative indicators and algorithms. The quantitative indicators mainly includes the harmonic voltage index based on the superposition projection [1-9], the nonactive power-based index [10-12] and the total harmonic distortion contribution index [13]. The quantitative methods includes the binary regression [1-5], multiple regression [6-8] and the method based on the covariance characteristic [9]. Due to the difference in system structure and characteristics of harmonic sources, there are no recognized quantitative index and algorithm for estimating harmonic impacts. It is urgent to find more reasonable quantitative indicators and methods for different scenarios through comparative research.

The paper reviews the existing multi-harmonic source responsibility quantitative indices and algorithms, and simulation tests are carried out to compares the accuracy and rationality of different methods in different scenarios. It is further pointed out the problems that is worth of further study for determining the multiple harmonic loads impacts. Hoping this paper can make contribution to reasonable solution of the problem of determining the harmonic responsibility.

HARMONIC IMPACTS ASSESSMENT INDICES

Problem Description

Based on the relationship between harmonic source and concerned bus, harmonic responsibility quantification problem can be divided into distributed and centralized. Distributed multi-harmonic source responsibility quantification means that determine the harmonic contribution of each harmonic source to the concerned bus X when several harmonic sources are randomly connected from different buses, as shown in Fig 1. The h-th harmonic voltage at the bus X is related to harmonic current I_{hk} which injected by harmonic source k

$$\boldsymbol{V}_{hX} = Z_{hXk}\boldsymbol{I}_{hk} + \sum_{i=1,i\neq k}^{n} Z_{hXi}\boldsymbol{I}_{hi} = \boldsymbol{V}_{hXk} + \boldsymbol{E}_{hXk} \qquad (1)$$

Where Z_{hXk} is the h-th harmonic self/mutual impedance between bus X and harmonic source k, $\boldsymbol{V}_{hXk}$ is the harmonic voltage caused by harmonic source k on bus X, $\boldsymbol{I}_{hk}$ is the current generated by the harmonic load k, $\boldsymbol{E}_{hXk}$ is the harmonic voltage producing by the harmonic loads except for the harmonic load k.

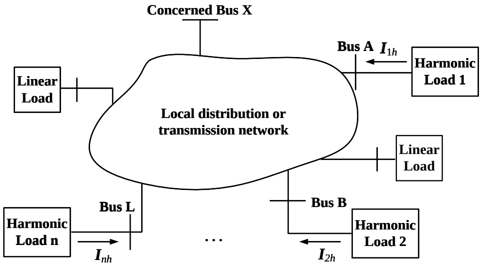

Fig 1. Distributed multi-harmonic source system

Centralized multi-harmonic source responsibility quantification problem is determining the impact of each feeder on the harmonic distortions at the concerned bus X, as shown in Fig 2. In accordance with the principle of superposition, the harmonic voltage at the bus X can be presented as,

$$\boldsymbol{V}_{hX} = \sum_{k=1}^{n}\boldsymbol{V}_{hXk} + \boldsymbol{V}_{hX0} = \sum_{k=1}^{n} Z_{hk\_shunt}\boldsymbol{I}_{hk} + \boldsymbol{V}_{hX0} \qquad (2)$$

Where Z_{hk_shunt} is the parallel harmonic impedance at the bus X except for the harmonic load k, $\boldsymbol{V}_{hX0}$ is the harmonic voltage generated by other unknown harmonic sources

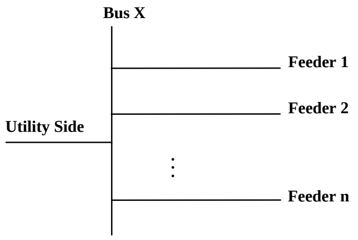

Fig 2. Centralized multi-harmonic source system

Superimposed projection-based index

The harmonic voltage index based on the superimposed projection is defined as the ratio of the projection of $\boldsymbol{V}_{hXk}$ at the $\boldsymbol{V}_{hX}$ to the $\boldsymbol{V}_{hX}$. For the case of the number that harmonic sources m is 3, the phasor of harmonic voltage on the bus X can be shown in Fig 3. For the distributed and concentrated multi-harmonic sources, it can be presented as,

$$HR_{hXk} = \frac{|Z_{hXk}||\boldsymbol{I}_{hk}|}{|\boldsymbol{V}_{hX}|}\cos\theta_k$$
$$HR_{hXk} = \frac{|Z_{hk\_shunt}||\boldsymbol{I}_{hXk}|}{|\boldsymbol{V}_{hX}|}\cos\theta_k \quad (3)$$

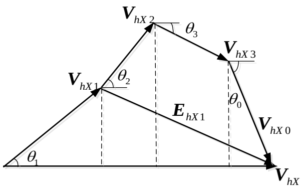

Fig.3 Phasor diagram for the harmonic voltages on bus X

The index will be unreasonable in 2 cases: (1) if $V_{pcc\_}$ is vertical to V_{pcc_k}, the harmonic load k also causes a change on harmonic voltage at the PCC, but the harmonic impact computed by the (3) is zero. (2) In some cases, the impact of harmonic load k is positive according to the projection index, but the harmonic voltage of the PCC would be reduced after removing harmonic load k.

Nonactive power-based index

For the case where the harmonic voltage and harmonic current indices have inconsistent conclusions, the harmonic apparent power is proposed as the harmonic contribution index in [10],

$$S_{hXk} = \boldsymbol{V}_{hXk}\boldsymbol{I}_{hXk} \quad (4)$$

However, the index is simply a simple multiplication of the harmonic voltage and current indices. The specific physical meaning is not clear. In [11,12] the authors presented a quantitative index of multi-harmonic source contribution based on nonactive power,

$$S_k = \sqrt{D_{Ik}^2 + D_{Vk}^2 + S_{Hk}^2} = \sqrt{V_1^2 I_{kH}^2 + I_1^2 V_{kH}^2 + I_{kH}^2 V_{kH}^2} \quad (5)$$

The index which bases on the fact that the essence of power system is electric energy conversion and transmission, and according with the physical mechanism of power flow when voltage and current are distorted. However, it is only applicable to centralized multi-harmonic source calculation. The calculation requires the reference impedance of each feeder and system, and is only the contribution index.

Total harmonic distortion contribution index

The total harmonic distortion contribution index is presented in [13], it can be defined as follows,

$$HII_k^{sign} = \frac{\sqrt{\sum_{h=2}^{h_{\max}} (RI_{hk}^{sign})^2}}{|\boldsymbol{I}_{1,pcc}|} \times 100\%$$
$$HIV_k^{sign} = \frac{\sqrt{\sum_{h=2}^{h_{\max}} (RV_{hk}^{sign})^2}}{|\boldsymbol{V}_{1,pcc}|} \times 100\% \quad (6)$$

Where RI_{hk} and RV_{hk} are the scalar indices of harmonic voltage and current contribution of each harmonic source calculated based on the superposition projection principle. The total harmonic distortion index comprehensively considers the harmonic source contribution to the concerned bus at different frequencies, which is beneficial to the harmonic comprehensive management. However, when the harmonic voltage or current of the bus is too high at a certain frequency, the index cannot provide evidence for managing harmonics at the frequency. There are also inconsistencies in voltage and current indices.

HARMONIC IMPACTS ASSESSMENT METHOD

The binary regression method

In [1], the author first proposed the multi-harmonic source contribution quantification problem, and proposed an solved method which is extend the basic correlation idea. The correlation between the harmonic source and the harmonic voltage and current at the bus is proved by the measured data. Then the harmonic self/mutual impedance and the amplitude of the background harmonic voltage are estimated. The mathematical model is further proposed and solved by the least square method to quantify the responsibility of the multi-harmonic source in [2].

In accordance with cosine theorem and Fig 3, the harmonic voltage at the bus X can be presented as,

$$|\boldsymbol{V}_{hX}|^2 = |\boldsymbol{Z}_{hXk}|^2|\boldsymbol{I}_{hk}|^2 + |\boldsymbol{E}_{hXk}|^2 - 2|\boldsymbol{E}_{hXk}||\boldsymbol{Z}_{hXk}||\boldsymbol{I}_{hk}|\cos\theta_k \quad (7)$$

Assuming that θ_k and $\boldsymbol{E}_{hXk}$ is a constant, the least squares estimation is performed on the equation (7), and the value of $\boldsymbol{I}_{hk} \cdot cos\theta_k$ is obtained [2]. Further, the harmonic responsibility of the harmonic source k can be obtained according to the equation (3).

Since the objective function of the least squares estimation is to minimize the sum of the squares of the residuals, some abnormal raw data have a great impact on the sum of squared residuals, which will make the calculation error larger. Therefore, [3] proposed robust regression method, adding iterative weights, determining the weight of each point according to the residual value, the weight value is inversely proportional to the residual, and iteratively iteratively improves the weight coefficient to make the regression robust.

One of the preconditions of the binary regression method is that $\boldsymbol{E}_{hXk}$ is treated as a constant, so some data selecting methods have been proposed. In [2], it is proposed to set the current threshold and directly extract the data segment whose all-harmonic source injection current fluctuation value is lower than the threshold value except the harmonic source k. [4] proposed a stepwise clustering of harmonic currents based on the improved k-means method. In [5], proposed to use the dominant volatility to solve the background harmonic voltage and then cluster it. However, when the number of harmonic sources increases, the data segment that satisfies the premise assumption may be insufficient or even missing which may affect the further resolution of harmonic contribution.

The multiple regression method

In order to solve the defect that binary regression needs data screening, which may make the valid data segment insufficient, a multiple linear regression method is proposed in [6]. According to equation (1) and the phasor diagram shown in Fig 3,

$$\begin{aligned}|\boldsymbol{V}_{hX}| = |Z_{hX1}||\boldsymbol{I}_{h1}|\cos\theta_1 + |Z_{hX2}||\boldsymbol{I}_{h2}|\cos\theta_2 + \\ |Z_{hX3}||\boldsymbol{I}_{h3}|\cos\theta_3 + |\boldsymbol{V}_{hX0}|\cos\theta_0\end{aligned} \tag{8}$$

The above equation is solved by least square method [6], and further combined with equation (3), the harmonic liability of harmonic source k can be calculated.

The premise of solving multiple linear regression is that the harmonic voltage $\boldsymbol{V}_{hk0}$ generated by other unknown harmonic sources does not change in the test data section, from only one harmonic source to the background harmonic, and the effective data section is enlarged, so that the observed data can be used more effectively.

In [4,7], a complex form of multiple regression is proposed, the real part is taken as an example, that is,

$$V_{hX,ch} = \sum_{i=1}^{n} (Z_{hXi,ch} I_{i,ch} - Z_{hXi,sh} I_{i,sh}) + V_{hX0,ch} \tag{9}$$

Where ch and sh represent real and imaginary parts respectively. The harmonic impedance Z_{hxi} can be obtained by regression solution of equation (11) and the harmonic responsibility of each harmonic source can be obtained by substitution of equation (3). This method still needs to satisfy the background harmonic $V_{hX0,ch}$ unchanged, and needs the phasor value of bus voltage and injected harmonic current.

For multiple regression, when there is multiple collinearity between the column vectors of the independent variable matrix X, solving with the least squares method will produce large errors. Therefore, the ridge estimation method is proposed in [7] to increase the ridge parameter matrix in the process of least squares inversion, so that the regression is less affected by the anomalous data, and there is no normality requirement for the error term distribution, which can make the estimation more stable. The difficulty of the generalized ridge estimation lies in the calculation of the inverse matrix and the determination of the ridge parameter.

The key difficulty of solving centralized multi-harmonic source responsibility quantification problem based on multiple regression is that I_{hXk} is difficult to obtain, and is replaced by the measured current of each feeder in [8]. The equation (2) is solved by multiple regression method, and further combined with equation (3), the harmonic contribution of harmonic source k can be calculated. The method uses the feeder branch current to replace the actual harmonic source injection current. When the harmonic current is small, there is no consistency between the two trends, and the calculation error is large.

The method based on the covariance characteristic

A method based on the covariance characteristic of the random vector is proposed in [9]. The harmonic current injected by load can be divided into two parts by linear filtering: slow varying component and fast varying component. The fast-changing component of each load is independent, so its covariance is 0,

$$\boldsymbol{E}\left\{\left[\boldsymbol{I}_{hkF} - E(\boldsymbol{I}_{hkF})\right] - \left[\boldsymbol{I}_{hiF} - E(\boldsymbol{I}_{hiF})\right]\right\} = 0 \tag{10}$$

Where the subscript F represents the fast varying component. Combines with the mathematical expectation of (1), the harmonic mutual impedance can be represented as,

$$Z_{hXk} = \frac{E\left\{[\boldsymbol{V}_{hXF} - E(\boldsymbol{V}_{hXF})]\left[\boldsymbol{I}_{hkF} - E(\boldsymbol{I}_{hkF})\right]\right\}}{E\left\{\left[(\boldsymbol{I}_{hkF} - E(\boldsymbol{I}_{hkF})\right]^2\right\}} \tag{11}$$

The method is simple in principle and convenient in calculation, but when the harmonic variation is large, the premise that the fast varying component between the loads are independent of each other is may not satisfied, resulting in a large calculation error.

SIMULATION RESULTS

For centralized multi-harmonic source contribution quantification problem, the existing studies are few, and the influence of different impedance ratio, feeder current and actual current trend consistency on the accuracy of the proposed method are be simulation verified in [8]. Therefore, this paper only simulates and compares various methods under the distributed multi-harmonic source responsibility quantization scenario.

In order to compare various method, simulation tests are carried on the 14-bus IEEE test system (see Fig.4). The load A, B connected to bus 5,6 are considered as major harmonic source, 5-th typical harmonic source current [14] are considered as the slow varying components of harmonic current sources, there are 1440 samples for entire day, that is, one sample per minute. The fast varying components of harmonic current sources are produced by adding the zero-mean Laplace distributed random variables with variance of 0.002. Set the harmonic source on buses 4 and 10 to the background harmonic and their slow varying component of harmonic current is a constant value.

Six methods (the least squares and robust methods based on the binary regression model, the least squares based on real-domain multiple regression model, the least squares and ridge estimation based on complex-domain multiple regression model, the method based on the covariance characteristic) are used to quantify the responsibility of different harmonic sources for harmonic voltage on concerned bus 6. The harmonic contribution quantification index based on superimposed projection is adopted. The total sample data is divided into 36 groups and the average value is taken as the quantification result. The average value of relative error calculated by each group of data is taken as the method error,

$$e_i = \frac{1}{n}\sum_{i=1}^{n}\left|HI_{ki} - HI_{0i}\right| \times 100\%, \quad n = 36 \qquad (12)$$

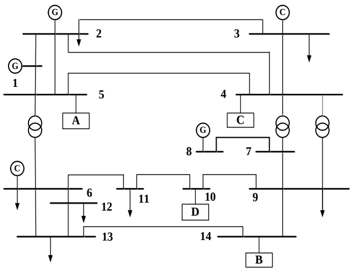

Fig. 4 IEEE 14-bus system

(1) There is only one harmonic source fluctuation

Only harmonic source A is set as the major harmonic source, and the fast varying component of background harmonic voltage is zero. The harmonic responsibility of harmonic source A to harmonic voltage on bus 6 is calculated, and the error is evaluated by equation (12). The results are as shown in Tab 1.

Tab 1. Result in only one harmonic source fluctuating

Method	Harmonic Source A /%	
	Estimated	Error
Method 1	79.80	1.99
Method 2	79.93	2.04
Method 3	79.97	2.08
Method 4	78.50	0
Method 5	78.50	0
Method 6	78.50	0

Methods 1, 2 and 3 (the least squares and robust methods based on the binary regression model, the least squares based on real-domain multiple regression model) are all real domain methods. Under these conditions, the error originates from the fluctuation of phase angle of harmonic source A, which makes the angle between the voltage generated on the concerned bus $\boldsymbol{V}_{hXA}$ and the voltage of the concerned bus not constant. However, as can be seen from Tab 1, in the case of only one harmonic source fluctuation, the calculation errors of all methods are small.

(2) Background harmonic fluctuation.

Random fluctuations of ±20% are added to the amplitudes and phases of harmonic currents of harmonic sources at buses 4 and 10, and calculate the quantification results and errors as shown in Tab 2.

Tab 2. Result in background harmonic fluctuating

Method	Harmonic Source A /%		Harmonic Source B /%	
	Estimated	Error	Estimated	Error
Method 1	54.89	20.22	47.70	13.65
Method 2	55.24	22.06	48.28	15.32
Method 3	51.91	13.45	46.53	11.18
Method 4	51.14	13.53	45.74	10.06
Method 5	51.70	13.23	45.34	10.05
Method 6	47.29	6.58	43.11	1.26

The regression method assumes that the background harmonic voltage is constant, and thus a large error occurs based on regression in this scenario. For binary regression, the current fluctuation threshold is set to 3% for data screening, and the effective data segments of harmonic source A and B are 33 and 9, respectively. The calculation data are reduced, and the $\mathbf{E}_{\mathrm{hX}k}$ and θ_k are not constant in the calculation data segment, so there will still be large errors. The independent random vector statistics method is based on the premise that the fast varying components of each harmonic source are independent. It is less affected by the background harmonic fluctuation, so the calculation accuracy is still high.

(3) Harmonic current of various harmonic sources is highly correlated

Setting the amplitude of the injected harmonic currents of harmonic sources A and B to be the same, and the correlation coefficient between the real and imaginary parts of the fast varying component is greater than 0.95. Random fluctuations of ±5% are added to the amplitudes and phases of harmonic currents of harmonic sources at buses 4 and 10, then the quantified results and method errors of each method are shown in Tab 3.

Tab 3. Result in harmonic currents with highly correlated

Method	Harmonic Source A /%		Harmonic Source B /%	
	Estimated	Error	Estimated	Error
Method 1	85.47	26.91	85.47	62.87
Method 2	85.65	27.09	85.65	63.05
Method 3	76.17	30.73	9.62	27.12
Method 4	49.54	87.09	32.27	87.59
Method 5	53.19	5.91	28.49	8.89
Method 6	75.19	16.63	58.43	35.83

It can be seen from Tab 3 that except for the method 5, the calculation errors of other methods are large. The fast component correlation of harmonic current does not satisfy the application premise of method 6 (the method based on the covariance characteristic), and the least squares regression is used to make the X^TX inversion process unstable when the harmonic source is highly correlated with the harmonic current. Therefore, the calculation error is large. The use of ridge regression to join the ridge parameter matrix can make the estimation more stable and the error is relatively small.

From the simulation results, the main conclusions are summarized as follows.

1) The binary linear regression is applicable to the case

where there is only the concerned harmonic load fluctuation. In other case, the data selecting is required, the valid data for analysis will reduce and the error is still large.
2) The method based on the covariance characteristic is robust to the background harmonic fluctuation.
3) When there is a high correlation between the harmonic currents of each harmonic source, only ridge estimation method based on complex-domain multiple regression model has a small quantization error.

CONCLUSION

Multi-harmonic source contribution assessment is one of the important propositions in the field of harmonic research, and it is the premise and basis for formulating harmonic control schemes and harmonic control strategies. Through a review of the current research on this proposition, it is found that there are still some problems worthy of further study:
1) Based on the superimposed projection index, the quantized value does not conform to the harmonic control direction under certain conditions, and the voltage or current index may be inconsistent separately. The nonactive power-based and the total harmonic distortion contribution indeies are only quantified for centralized multi-harmonic source responsibility and cannot be applied to crossover control. Therefore, it is meaningful to propose a more reasonable index to estimating the harmonic contribution in multi-harmonic source systems.
2) In the distribution system, it is very common to have several harmonic load feeders on the bus, it is necessary to propose a more reasonable centralized multi-harmonic source responsibility quantification method.
3) The existing multi-harmonic source responsibility quantization methods are mostly based on the premise that the harmonic impedance is approximately constant during the evaluation period, but in reality, the harmonic impedance will change, how to achieve the harmonic responsibility in this situation The effective division is also worthy of in-depth study.

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