A Method for Judging the Accuracy of Harmonic Impedance Calculation Results

Ping Li[1], Xuke Cheng[1], Guanfeng Zhang[1], Jiayu Li[1], Shenghui Li[1], Xue Bai[1], Cijian Xie[1] and Jinshuai Zhao[2,*]

[1]*State Grid Liaoning Electric Power Research Institute, Shengyang, China*

[2]*Sichuan University, Chengdu, China*

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Abstract: The issue of harmonic pollution in the power grid has received widespread attention. The harm of harmonics includes causing equipment overheating, shortening equipment life, increasing additional line losses, and reducing operational efficiency. Accurately calculating harmonic impedance is one of the keys to studying harmonic problems. Based on harmonic measurement data at common connection points, existing scholars have proposed several non-invasive harmonic impedance estimation methods. After calculating the harmonic impedance, it is necessary to verify the correctness of the calculation results. Accurately solving the harmonic impedance of the system and user sides is of great significance for accurately quantifying harmonic responsibility, guiding the development of filter design related work, guiding harmonic suppression and resonance mitigation, and other aspects. However, there is currently no unified method to verify the correctness of obtaining harmonic impedance. Therefore, this article proposes a method for determining the accuracy of harmonic impedance calculation results.

1 INTRODUCTION

Electric energy, as a clean and convenient secondary energy source, permeates every aspect of people's daily life and industrial and agricultural production, and is the main foundation for the development and progress of modern society. Among the loads connected to the distribution network, in addition to those with good conventional symmetry and no harmonic pollution to the power grid, there are also impulsive, large capacity, and nonlinear load equipment, such as electric arc furnaces, electric locomotives, etc. At the same time, in the context of the construction of smart distribution networks, new elements such as source load network storage and charging are developing on a large scale in 10kV distribution networks and 400V low-voltage distribution stations, and the "power electronics" characteristics of distribution networks are becoming increasingly evident. A large number of power electronic devices are distributed or centrally connected in the distribution network, resulting in disorderly transmission and superposition of broadband harmonic disturbances in the distribution network. This exacerbates harmonic pollution in the distribution network, deteriorates the power quality environment of the distribution network, and affects the reliable and economic operation of power equipment on both sides of the power supply and consumption. It has become an important challenge for power quality management.

In summary, in order to ensure the safe and economical operation of the power grid, the normal use of conventional electrical equipment, and the provision of continuous and reliable electricity to users, it is necessary to control the harmonic content of the distribution network within the allowable limit range. Many countries and relevant authoritative institutions have formulated, promulgated, and implemented relevant standards and regulations to limit the harmonic distortion value of the distribution network. Power engineers from various countries have also proposed various methods for harmonic analysis based on corresponding standards and regulations, including frequency domain analysis, time domain analysis, Fourier transform analysis, etc.

This article proposes a method for determining the correctness of harmonic impedance calculation (Yao Xiao, Jin Hui). The main idea of existing methods is to compare the calculated harmonic voltage of the utility side with the harmonic voltage

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measured at the PCC point after the user exits the operation (Jin Hui - Xi Zhao). If the difference between the calculated harmonic voltages of the utility side and the measured voltage at the point of common coupling is not significant, it indicates that the harmonic impedance has been calculated accurately(Farzad Karimzadeh - V.G. Reju); On the contrary, it indicates that there is a significant error in obtaining the harmonic impedance. The harmonic voltages of the utility side can be calculated according to IEC61000-3-6 or the superposition principle method (Bofill Pau, Zhang Jie). However, when verifying the accuracy of the harmonic impedance obtained, the existing research has neglected one point, that is, because the basic principles of IEC method and Superposition principle method are different, they need to be selected according to the actual working conditions, and cannot be selected arbitrarily, otherwise there may be a risk of miscalculation of the accuracy of harmonic impedance (Yuanqing Li, Fasong Wang). This article divides nonlinear users into two categories based on their cessation of operation: 1) only cutting off the harmonic source while retaining their user side impedance to connect to the power grid (such as photovoltaic stations), and 2) cutting off the harmonic source and user side impedance (such as electric arc furnaces) . Then, this paper studies the difference between IEC method and Superposition principle method and their respective application scope in the process of verifying the accuracy of harmonic impedance. Finally, according to the characteristics of these 2 methods and the category of nonlinear users, a method that can accurately verify the correctness of obtaining harmonic impedance is proposed.

2 CALCULATE HARMONIC VOLTAGE PRODUCED BY THE UTILITY SIDE BASED ON THE IEC METHOD

The corresponding modal is shown in Figure 1, Zu, Zc, $\dot{I}_u$ 、 $\dot{I}_c$, are the harmonic impedances and harmonic current sources on the system side and user side, respectively. The harmonic voltage measured at the PCC point and the harmonic current measured on the public line, respectively.

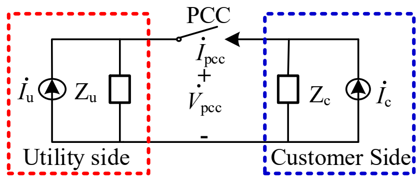

Figure 1: Circuit for analyzing the utility and customer sides.

When the switch is closed, we have

$$\dot{V}_{pcc\text{-}post} = \dot{I}_u Z_u + \dot{I}_{pcc} Z_u \quad (1)$$

When the switch is disconnected, the user side stops running, we have

$$\dot{V}_{pcc\text{-}pre} = \dot{I}_u Z_u \quad (2)$$

Based on the definition of harmonic emission level in IEC61000-3-6 standard, we have

$$\dot{V}^{IEC}_{c\text{-}pcc} = \dot{I}_{pcc} Z_u \quad (3)$$

$$\dot{V}^{IEC}_{u\text{-}pcc} = \dot{I}_u Z_u \quad (4)$$

3 CALCULATE THE HARMONIC VOLTAGE OF UTILITY SIDE ACCORDING TO THE SUPERPOSITION PRINCIPLE

Figure 2 shows the corresponding modal of the Superposition principle method. When the system side harmonic source and the user side harmonic source operate separately, and when the nonlinear user side harmonic source operates separately, the harmonic voltages generated by them at the common connection point, that is, the emission levels of the system side and user side harmonic voltages, can be expressed as

$$\dot{V}^{sup}_{u\text{-}pcc} = \frac{Z_c Z_u}{Z_c + Z_u} \dot{I}_u \quad (5)$$

$$\dot{V}^{sup}_{c\text{-}pcc} = \frac{Z_c Z_u}{Z_c + Z_u} \dot{I}_c \quad (6)$$

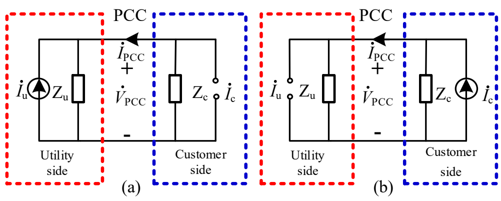

Figure 2: Equivalent circuit corresponding to Superposition principle method

4 METHOD FOR VERIFYING THE ACCURACY OF OBTAINING HARMONIC IMPEDANCE

When nonlinear users are connected in, if the harmonic impedance of the system and user sides can be accurately calculated, then the obtained harmonic voltage of the utility side is also accurate. By comparing the calculated harmonic voltage of the utility side with the reference voltage, the correctness of the obtaining harmonic impedances on the system side and the user side can be verified.

The present invention divides nonlinear users into the following two categories based on their way of exiting operation.

4.1 Model A

For non-linear users such as electric arc furnaces, when the user is not working, after accurately obtaining Zu, $\dot{V}_{\text{u-pcc}}^{\text{IEC}}$ will be equal to $\dot{V}_{\text{u-pcc}}^{\text{A}}$. It is worth noting that since equation (4) does not contain Zc, this modal cannot verify the correctness of obtaining harmonic impedance of customer side.

4.2 Model B

When Zc and Zu are accurately determined, $\dot{V}_{\text{u-pcc}}^{\text{B}}$ and $\dot{V}_{\text{u-pcc}}^{\text{B}}$ are equal. It is worth noting that since equation (5) contains both Zc and Zu, this method can simultaneously verify the correctness of obtaining Zc and Zu.

After determining the user class, the accuracy of harmonic impedance can be verified according to the magnitude relationship between the system side and the user side harmonic impedance. The specific process is as follows.

(1) The amplitude of Zc is not much greater than that of Zu

When | Zc | is not much greater than | Zu |, according to equations (4) and (5), the background harmonic voltages $\dot{V}_{\text{u-pcc}}^{\text{IEC}}$ and $\dot{V}_{\text{u-pcc}}^{\text{sup}}$ obtained are not equal to each other. Therefore, $\dot{V}_{\text{u-pcc}}^{\text{IEC}}$ will not be equal to $\dot{V}_{\text{u-pcc}}^{\text{B}}$, and $\dot{V}_{\text{u-pcc}}^{\text{sup}}$ will not be equal to $\dot{V}_{\text{u-pcc}}^{\text{A}}$.

In order to avoid the above misjudgment, it is necessary to use the correct method (IEC method or Superposition principle method) to match the user model.

(2) The amplitude of Zc is far greater than that of Zu

Under this situation, the error in obtaining Zc is usually large, so only the accuracy of obtaining Zu needs to be verified. Due to | Zc |>>| Zu |, $Z_{\text{u}}/Z_{\text{c}} \approx 0$ holds, and equation (5) can be changed into equation (7). Therefore, when the harmonic impedance of the user side is unknown, the superposition principle can be used.

$$\dot{V}_{\text{u-pcc}}^{\text{sup}} = \frac{Z_{\text{u}}}{1 + Z_{\text{u}} / Z_{\text{c}}} \dot{I}_{\text{u}} \approx Z_{\text{u}} \dot{I}_{\text{u}}. \quad (7)$$

It is worth noting that equation (7) is equivalent to equation (5), and the obtained $\dot{V}_{\text{u-pcc}}^{\text{IEC}}$ and $\dot{V}_{\text{u-pcc}}^{\text{sup}}$ are approximately equal to each other. Therefore, both Class A and Class B nonlinear users can verify the accuracy of Zu based on IEC method or Superposition principle.

(3) Method for determining the size relationship between Zc and Zu

When | Zc |>>| Zu |, $Z_{\text{u}}/Z_{\text{c}} \approx 0$ is established, resulting in

$$\dot{I}_{\text{pcc}} = \frac{Z_{\text{c}}}{Z_{\text{c}} + Z_{\text{u}}} \dot{I}_{\text{c}} - \frac{Z_{\text{u}}}{Z_{\text{c}} + Z_{\text{u}}} \dot{I}_{\text{u}} \approx \dot{I}_{\text{c}}. \quad (8)$$

Thus, by quantifying the similarity between $\dot{I}_{\text{pcc}}$ and $\dot{I}_{\text{c}}$, we can indirectly evaluate whether | Zc |>>| Zu | is valid. In this evaluation process, the independent component analysis (ICA) can be used to reconstruct the source signal $\dot{I}_{\text{c}}$.

Based on the Norton modal shonw in Figure 1 or Figure 2, when a nonlinear user is connected to the system, there is

$$\underbrace{\begin{bmatrix} \dot{V}_{\text{pcc}} \\ \dot{I}_{\text{pcc}} \end{bmatrix}}_{X} = \underbrace{\begin{bmatrix} \frac{Z_{\text{c}}Z_{\text{u}}}{Z_{\text{c}} + Z_{\text{u}}} & \frac{Z_{\text{c}}Z_{\text{u}}}{Z_{\text{c}} + Z_{\text{u}}} \\ \frac{Z_{\text{c}}}{Z_{\text{c}} + Z_{\text{u}}} & -\frac{Z_{\text{u}}}{Z_{\text{c}} + Z_{\text{u}}} \end{bmatrix}}_{Z} \cdot \underbrace{\begin{bmatrix} \dot{I}_{\text{c}} \\ \dot{I}_{\text{u}} \end{bmatrix}}_{I} \quad (9)$$

In the formula, matrix X is composed of observation signals $\dot{V}_{\text{pcc}}$ and $\dot{I}_{\text{pcc}}$, matrix I is composed of harmonic current sources $\dot{I}_{\text{u}}$ and $\dot{I}_{\text{c}}$, and the impedance matrix ***Z*** is composed of harmonic impedances on both sides of PCC points. Before using the ICA algorithm, it is necessary to extract the rapidly changing components of the signal through median filtering technology to ensure the independence between the source signals. The harmonic source signal $\hat{I} = \left[\dot{I}_c^{fast}\dot{I}_u^{fast}\right]^T$ can be reconstructed using the ICA algorithm. The similarity between signal $\dot{I}^{fast}{}_{\mathrm{pcc}}$ and $\dot{I}^{\mathrm{fast}}_{\mathrm{c}}$ is quantified through correlation coefficients. The greater the correlation coefficient, the more similar the two signals are.

5 CONCLUSION

Harmonic pollution has a significant impact on the safe, stable, and economic operation of the power grid. In order to accurately carry out harmonic control work, this article conducts research on solving harmonic impedance and evaluating harmonic emission levels. In practical engineering applications, by comparing the background harmonic voltage obtained with the voltage measured at the common connection point when the user is not working, the accuracy of the harmonic impedance obtained on the system side and the user side can be indirectly verified. Generally speaking, there are 2 ways for calculating harmonics produced by the utility sides harmonic sources. This paper discusses the applicability of these two methods. Based on the research results of this article, the correctness of the results of quantifiable harmonic impedance calculation, harmonic responsibility quantification, and harmonic emission level evaluation has guiding significance for precise harmonic control.

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