MATEC Web of Conferences **100**, 01014 (2017) DOI: 10.1051/matecconf/201710001014
GCMM 2016

An Identification Method of Main Harmonic Current Indicator Based On Active Power Direction Method

Junyi Zhao [1], Chaoying Yang [1], Zhiwei Xue[1] and Lin Yuan [2,*]

[1] State Grid Shanxi Electric Power Company, Taiyuan, Shanxi province, China
[2] School of Electrical Engineering and Information, Sichuan University, Chengdu, Sichuan province, China
Corresponding Email: 583599338@qq.com

Abstract. It is difficult to determine the harmonic current which flows through the line element in power grid, the paper proposed a new method for identifying the main harmonic current indicator at the Point of Common Coupling (PCC) based on the strict mathematic constraints. At the fundamental of the harmonic Norton equivalent circuit, the paper analysed that the harmonic active power direction method can be completely correct and valid in a certain interval. Combined the basic principles of the circuit and the strict inequality constraints, the paper discussed various fundamental characteristic of the harmonic impedance on both the system side and the user side, with the harmonic voltage and current measured amplitude and phase angle at the PCC. When the indicator of main harmonic current is the user side, the method can directly get the conclusion with the phase angle difference between harmonic voltage and current. When the indicator of main harmonic current is the system side, the method can get the conclusion combined the phase angle difference between harmonic voltage and current and harmonic impedance. Finally, the paper used the measured data of a variety of practical engineering scenarios to verify the correctness and effectiveness of the method.

1 Introduction

Harmonic current flowing through line components (such as transformers) is one of the main factors that cause adverse effects, such as increased losses and reduced operating efficiency. It is not conducive to the operation efficiency of the power grid, and makes the power supply sector bear huge economic losses [1-6]. At present, there are few literatures to study the mechanism of identifying the main harmonic current source from the system or the user side, but the engineering is always concerned [4, 5, 7]. Based on this, the paper deduced from the basic circuit law that can directly identify the main harmonic current source through the simple condition, but also provides the theoretical basis for further quantifying the harmonic current contributions from both sides. It’s very important to theoretical and practical significance.

The core of the main harmonic current source identification is to compare the launch harmonic current contribution at PCC of the system side or the user side, that is, use the harmonic current indicator as the basic criteria [2, 8, 9]. Most of the relevant methods to estimate harmonic impedance of the system side or the user side firstly [10-15], and determine secondly. The main methods are fluctuation method [10-12], threshold voltage method [13], independent random vector covariance method [14] and fast independent component analysis method [15] and so on. The fluctuation method is used to estimate the harmonic impedance based on the measured harmonic voltage and current information at the PCC. According to the basic properties of the grid impedance, it can distinguish the estimation result is system-side or user-side. Independent random vector covariance method is used to estimate the harmonic impedance by using the basic properties that harmonic voltage and current are independent approximation in the power grid and the covariance equals zero. It weakens the effect of background harmonics to a certain extent. The threshold voltage method uses the estimated harmonic impedance value to identify. Fast independent component analysis is one of blind source separation methods. This method is applied to the estimation of harmonic impedance, which has a better effect than the previous. The main harmonic current source identification is the qualitative conclusion, but the above method to determine whether the system side or the user side are required to estimate harmonic impendent form the historical data, and cannot draw the conclusion directly only through the measured harmonic voltage and current information.

Harmonic active power direction method was proposed on the base of harmonic state estimation. It was widely used in the actual power grid because of simple and easy to use [2, 8, 16]. But the relevant literature reported that the method result was seriously affected by the harmonic source phase angle difference value between the system side and the user side. And the difference phase angle of the both harmonic source sides can vary arbitrarily in the whole circumference and cannot be measured directly, so the use of this method is limited [16]. However, there is no literature to study the wide range of the method which can be applied correctly.

On the basis of harmonic active power direction method, the paper deduced to the corresponding interval constraint identification method with various situations of harmonic impedance on the system side and the user side under the physical conditions of actual power grid. For the situation that the main harmonic current source is the user side, it can get identification result only depending on the harmonic voltage and current phase angle difference; and for the situation that the main harmonic current source is the system side, it can get result by using the harmonic voltage and current phase angle and the user-side impedance range which is estimated by relevant literature. Finally, the paper method is validated by using the measured data of several engineering scenarios. And the results show that the proposed method is effective and accurate.

2 Harmonic active power direc-tion method

Figure 1 is the Norton equivalent circuit model and it's the basis of active power direction method. In the figure, $\dot{I}_s$ and $\dot{I}_c$ respectively denote system-side and user-side harmonic source current; I_s and I_c respectively denote their own modulus value; Z_s and Z_c respectively denote system-side and user-side harmonic impedances; $\dot{U}_{pcc}$ and $\dot{I}_{pcc}$ respectively denote harmonic voltage and current value which measured at the PCC; U_{pcc} and I_{pcc} respectively denote the modulus value of the two.

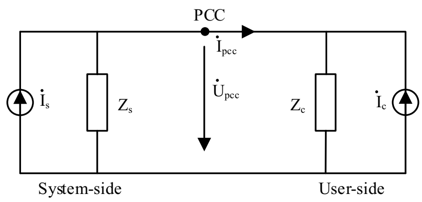


Fig. 1. The model of Norton equivalent circuit.

$$P = U_{pcc} I_{pcc} \cos\varphi \tag{1}$$

Harmonic active power direction method considered that when the harmonic active power flows from the system side to the user side, that is, P > 0, the system side's harmonic current contribution is bigger; when the harmonic active power flows from the user side to the system side, that is P < 0, the user side's harmonic current contribution is bigger [2, 16].

Equation (1) is the harmonic active power calculation formula and we can see the essence of this method. It though the positive or negative cosine value of the harmonic voltage and current phase angle difference φ to determine which side is the main harmonic current contribution.

2.1 Harmonic Current Indicators

According to the superposition theorem of the circuit, the PCC harmonic current $\dot{I}_{pcc}$ is the superposition of the harmonic current which contributed by the system side and the user side, as shown in formula (2).

$$\dot{I}_{pcc} = \dot{I}_{spcc} - \dot{I}_{cpcc} = \frac{Z_s \dot{I}_s - Z_c \dot{I}_c}{Z_s + Z_c} \tag{2}$$

Harmonic current phasor decomposition is shown in Figure 2, Isf and Icf respectively denote the projection value of $\dot{I}_{spcc}$ and $\dot{I}_{cpcc}$ in the $\dot{I}_{pcc}$ direction, they each ratio of I_{pcc} are the harmonic current indicator.

$$I_{sf} - I_{cf} = \frac{I_{spcc}^2 - I_{cpcc}^2}{I_{pcc}} = \frac{(|Z_s| I_s)^2 - (|Z_c| I_c)^2}{|Z_s + Z_c|^2 I_{pcc}} \tag{3}$$

With the help of the cosine theorem and formula(3), it can see the essence of harmonic current indicator is to compare the size of $|Z_s| I_s$ and $|Z_c| I_c$.

DOI: 10.1051/matecconf/201710001014

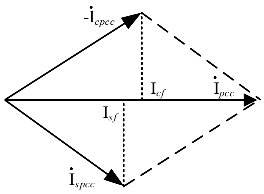


Fig. 2. Decomposition of current phasor.

2.2 Applicable Analysis of the Method

Literature [16] pointed out that the harmonic active power direction method is not entirely valid, there is a misjudgment. The harmonic voltage and current size and phase angle difference of actual power grid can be measured only at the PCC, and the phase angle difference can range from 0 ° to 360 °. The paper take the PCC harmonic voltage and current phase angle difference φ as the change amount, and the step length takes 1 °. The other parameters are shown in Tab1 and the experimental result is shown in Figure 3.

Table 1. The parameters of experiment.

Impedance characteristic	$\lvert U_{\mathrm{pcc}}\rvert$/V	$\lvert I_{\mathrm{pcc}}\rvert$/A	Z_s/Ω	Z_c/Ω
Both sides are inductive	15	1	1+*j*8	5+*j*25

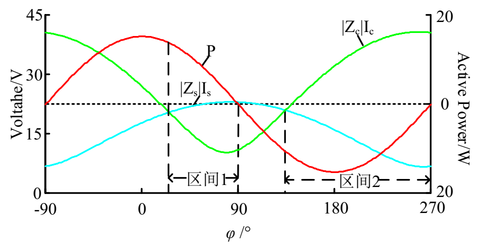


Fig. 3. The judgment conditions of active harmonic power direction method.

According to Figure 3, we can see that in the interval 1, $|Z_c|I_c < |Z_s|I_s$ and $P > 0$, in the interval 2, $|Z_c|I_c > |Z_s|I_s$ and $P < 0$, they are all in line with harmonic active power direction method. In other words, harmonic active power direction method is able to correctly identify which the harmonic current index side is greater in a certain interval. There is a certain range of application for it.

3 The identification method of main harmonic current indica-tor

3.1. Fundamental Theory

The purpose of the main harmonic current indicator identification is to compare the size of the two sides' harmonic current indicator. That is, to compare the size between $|Z_s|I_s$ and $|Z_c|I_c$. According to the basic circuit theory, it can be drawn from Figure 1:

$$\begin{cases} \dot{I}_s Z_s = \dot{U}_{\mathrm{pcc}} + \dot{I}_{\mathrm{pcc}} Z_s \\ \dot{I}_c Z_c = \dot{U}_{\mathrm{pcc}} - \dot{I}_{\mathrm{pcc}} Z_c \end{cases} \tag{4}$$

Both sides calculate the modulus values and the formula can be:

$$E_s^2 = U_{\mathrm{pcc}}^2 + 2U_{\mathrm{pcc}} I_{\mathrm{pcc}} |Z_c| \frac{\cos(\varphi - \theta_s)}{k} + I_{\mathrm{pcc}}^2 \frac{|Z_c|^2}{k^2} \tag{5}$$

$$E_c^2 = U_{\mathrm{pcc}}^2 - 2U_{\mathrm{pcc}} I_{\mathrm{pcc}} |Z_c| \cos(\varphi - \theta_c) + I_{\mathrm{pcc}}^2 |Z_c|^2 \tag{6}$$

Where,

$$E_s = |\dot{I}_s Z_s|, E_c = |\dot{I}_c Z_c|, k = |Z_c| / |Z_s| \tag{7}$$

θ_s is the system-side's harmonic impedance angle; θ_c is the user-side's harmonic impedance angle; k is the harmonic impedance modulus ratio between the user-side and the system-side, generally $k > 1$.

Because of the actual grid physical limit, the real part of the harmonic impedance must be positive, that is, harmonic impedance angle θ_s and θ_c range [-90 °, 90 °]. For theory, the impedance angle ranges from 0° to 90° is inductive, and it ranges from -90° to 0° is capacitive [10]. The components and loads in the power grid are mostly inductive. For the system side impedance, its characteristic is usually inductive and its ratio of the inductive part is greater than the resistive part, and the higher the voltage level is, the higher the ratio [17]. It's easy to know the impedance angle is in [45°, 90°] interval. For the user-side impedance, the relevant literature [18, 19] study gives out the load harmonic impedance model and its calculation method. Without considering the reactive power compensation devices or a large number of urban distribution network cable case, power factor of the distribution network load is less than or equal to 0.85 mostly[20]. For example this takes the load power factor as 0.85, the harmonic impedance angle is shown in Fig 4. It can be seen that the impedance angles of the harmonics are in the range of [45 °, 90 °] and the impedance is inductive, so the same conclusion can be obtained in the other cases where the power factor is less than 0.85. According to the relevant literature [21, 22], the resonance point of the city distribution network which uses cable, low-voltage capacitors and other reactive power compensation device in the large-scale must be appeared in the higher harmonics. That led to the character of the low-order harmonic impedance is capacitive, but in this case the capacitive reactance part is less than the resistive part, so the harmonic impedance angle is range in [-45 °, 0 °].

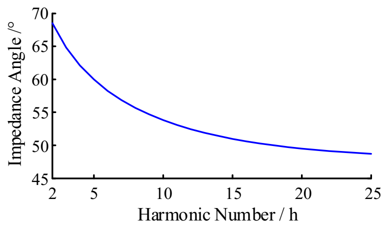


Fig. 4. Each harmonic impedance phase angle.

In summary, this paper considers the both sides' characteristics of harmonic impedance to meet the common engineering scene in the grid, but also makes the method in the course of simple. Therefore, in this paper, when the harmonic impedance is inductive, it is regarded as the impedance angle range in [45 °, 90 °]. When the harmonic impedance is capacitive, it is regarded as the impedance angle range in [45 °, 0 °].

3.2 The Identification Method: User-Side

Place the figure as close as possible after the point where it is first referenced in the text. If there is a large number of figures and tables it might be necessary to place some before their text citation. If a figure or table is too large to fit into one column, it can be centred across both columns at the top or the bottom of the page.

$$E_c^2 - E_s^2 = I_{\text{pcc}}^2 |Z_c|^2 (1 - \frac{1}{k^2}) - 2I_{\text{pcc}} U_{\text{pcc}} |Z_c| [\frac{1}{k}\cos(\varphi - \theta_s) + \cos(\varphi - \theta_c)] \tag{8}$$

In order to get the user side identification method of main harmonic current indicators, the paper uses the formula (6) minus (5) and the result is formula(8). When the right part of the formula is greater than 0, then $E_c^2 > E_s^2$, that is, harmonic current indicator identification result is the user side. With the same and different characteristic of the harmonic impedance, we discuss the following four cases:

Both sides' characteristic are the same

The harmonic impedance characteristic of the system-side and the user-side are inductive, that is, θ_s and θ_c range in [45 °, 90 °], and the phase angle difference φ is between [180 °, 270 °]. We can easily get $cos(\varphi-\theta_s) < 0$, $cos(\varphi-\theta_c) < 0$, what's more $k > 1$ and $1-1/k^2 > 0$. So the right part of equation (8) is greater than 0, it meets the conclusion.

Similarly, both the system side and the user side of the harmonic impedance properties are capacitive, that is, θ_s and θ_c are between [-45 °, 0 °], the user side identification method of main harmonic current indicators is the phase angle φ ranging in the (90 °, 225 °] interval.

Both sides' characteristic are the different

The harmonic impedance characteristic of the system-side is inductive and the user-side's is capacitive, that is, θ_s ranges in [45 °, 90 °] and θ_c ranges in [-45 °, 0 °], and the phase angle difference φ is between [180 °, 225 °]. We can easily get $cos(\varphi-\theta_s) < 0$, $cos(\varphi-\theta_c) < 0$, what's more $k > 1$ and $1-1/k^2 > 0$. So the right part of equation (8) is greater than 0. So it's the identification method.

Similarly, the harmonic impedance characteristic of the system-side is capacitive and the user-side's is inductive, that is, θ_s ranges in [-45 °, 0 °] and θ_c ranges in [45 °, 90 °], the identification method is that the phase angle difference φ is between [180 °, 225 °].

In summary, based on the reference direction shown in Fig1 and the both sides' various cases of impedance characteristic, the identification method of the main harmonic current indicator for the user side is as shown in Table 2.

Table 2. The identification method of main harmonic current indicator for the user side.

impedance characteristic		the phase angle difference φ
Z_s	Z_c	
inductive	inductive	[180°，270°)
inductive	capacitive	[180°，225°]
capacitive	capacitive	(90°，225°]
capacitive	inductive	[180°，225°]

3.3 The Identification Method: System-Side

In order to get the system side identification method of main harmonic current indicators, the paper uses the formula (6) minus (5) and the result is formula(9).

$$\begin{aligned} E_s^2 - E_c^2 &= I_{\mathrm{pcc}}^2 \left|Z_c\right|^2 \left(\frac{1}{k^2} - 1\right) + \\ &2 I_{\mathrm{pcc}} U_{\mathrm{pcc}} \left|Z_c\right| \left[\frac{1}{k}\cos(\varphi - \theta_s) + \cos(\varphi - \theta_c)\right] \end{aligned} \tag{9}$$

When the right part of the formula is greater than 0, then $E_s^2 > E_c^2$, that is, harmonic current indicator identification result is the system side. With the same and different characteristic of the harmonic impedance, the paper discussed the following four cases:

Both sides' characteristic are the same

The harmonic impedance characteristic of the system-side and the user-side are inductive, that is, θ_s and θ_c range in [45 °, 90 °], and the phase angle difference φ is between [0 °, 90 °]. We can easily get $cos(\varphi-\theta_s) > 0$, $cos(\varphi-\theta_c) > 0$, what's more $k > 1$ and $1-1/k^2 < 0$. So it cannot draw the conclusion directly.

According to the cosine correlation knowledge, E_s^2 equals $E_{s\,\min}^2$ when θ_s is under the condition of formula (10). Similarly, when θ_c is in the formula (11) conditions, E_c^2 equals $E_{c\,\max}^2$. So we can get the conclusion.

$$\begin{cases} \theta_s = 90^\circ, \varphi \in [0^\circ, 67.5^\circ) \\ \theta_s = 45^\circ, \varphi \in [67.5^\circ, 90^\circ) \end{cases} \tag{10}$$

$$\begin{cases} \theta_c = 90^\circ, \varphi \in [0^\circ, 67.5^\circ) \\ \theta_c = 45^\circ, \varphi \in [67.5^\circ, 90^\circ) \end{cases} \tag{11}$$

This makes the equation(9) > 0 and combine with the formula (10) and (11), it's easy to get the flowing identification method addition condition.

$$\begin{cases} \cos(\varphi - 90^\circ) > \dfrac{I_{\mathrm{pcc}}\left|Z_c\right|}{2U_{\mathrm{pcc}}}, \varphi \in [0^\circ, 67.5^\circ) \\ \cos(\varphi - 45^\circ) > \dfrac{I_{\mathrm{pcc}}\left|Z_c\right|}{2U_{\mathrm{pcc}}}, \varphi \in [67.5^\circ, 90^\circ) \end{cases} \tag{12}$$

Similarly, both the system side and the user side of the harmonic impedance is all capacitive, that is, θ_s and θ_c are in the [-45 °, 0 °], the identification method of main harmonic current indicator is the phase angle difference φ range in (-90 °, -22.5 °] and satisfies the addition condition (13).

$$\cos\varphi > \frac{I_{\mathrm{pcc}}\left|Z_c\right|}{2U_{\mathrm{pcc}}} \tag{13}$$

Both sides' characteristic are the different

The harmonic impedance characteristic of the system-side is inductive and the user-side's is capacitive, that is, θ_s ranges in [45 °, 90 °] and θ_c ranges in [-45 °, 0 °], and the phase angle difference φ is between [0 °, 45 °]. We can easily know when, θ_s is 90°, E_s^2 equals $E_{s\,\min}^2$ and when θ_c is -45°, E_c^2 equals $E_{c\,\max}^2$. Make equation (9) greater than 0, we can get the additional constraint condition as follows.

$$\cos(\varphi + 45^\circ) > \frac{I_{\mathrm{pcc}}\left|Z_c\right|}{2U_{\mathrm{pcc}}} \tag{14}$$

Similarly, the harmonic impedance characteristic of the system-side is capacitive and the user-side's is inductive, that is, θ_s ranges in [-45 °, 0 °] and θ_c ranges in [45 °, 90 °], the identification method is that the phase angle difference φ is between [0 °, 45 °] and the addition condition is formula(15).

$$\cos(\varphi - 90^{\circ}) > \frac{I_{\mathrm{pcc}}|Z_c|}{2U_{\mathrm{pcc}}} \tag{15}$$

From the above analysis, the user-side harmonic impedance modulo is included in the additional condition that the identification method of main harmonic current indicator. And only when the fluctuation of the harmonic source on the user side is small, a better impedance estimation result can be obtained [10, 11, 13]. Therefore, this paper only uses the correlation method to estimate the range of the harmonic impedance of the user side for auxiliary judgment.

The voltage waveform of the medium-low voltage distribution network is usually a flat-top wave, so it can be equivalent to the user-side model by the harmonic Norton circuit. Related literature [14, 15, 23] is a new harmonic impedance calculation method proposed in recent years, first measured harmonic voltage and current phase angle difference φ meet the interval constraints, and the user side of the small harmonic fluctuations situation, can be more accurate calculation of the user side harmonic impedance mode value. At the same time, in order to make this method as simple as possible in the application, the method of literature [15] is used to calculate the harmonic impedance of the user side.

To sum up, according to the reference direction shown in Figure 1 and the both sides of the impedance properties of classification, the identification method of main harmonic current indicator for the system side of the interval constraints. It is summarized in Table 3 below.

Table 3. The identification method of main harmonic current indicator for the system side.

Impedance Characteristic		the phase angle difference φ	Addition Conditions
Zs	Zc		
inductive	inductive	[0°，90°)	formula(12)
inductive	capacitive	[0°，45°]	formula(14)
capacitive	capacitive	(-90°，-22.5°]	formula(13)
capacitive	inductive	[0°，45°]	formula(15)

4 Case studies

4.1 Electric Arc Furnace Load Calculation

Figure 5 shows the measured data of the 3rd harmonic voltage and current of a 150kV bus (PCC) from an industrial electric arc furnace plant. There is about 1h downtime in this period, and the PCC point on both sides of this harmonic impedance Were inductive.

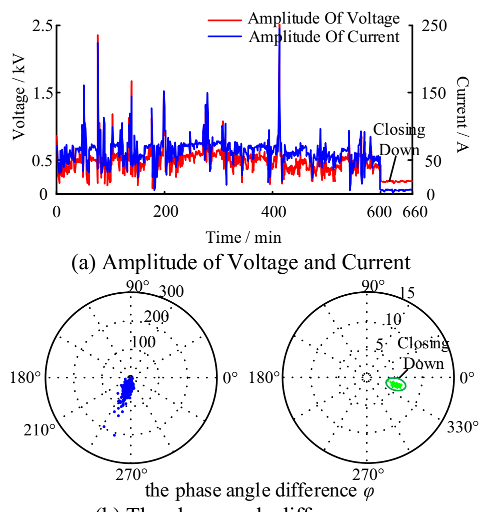
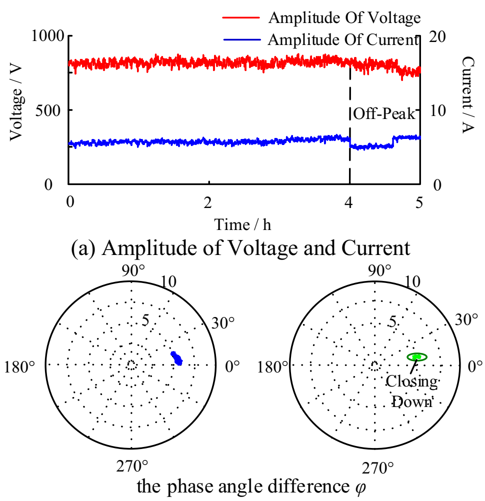


Fig. 5. The measured data of the 3rd harmonic voltage and current.

In the figure, the harmonic voltage and current amplitude fluctuate very much in 0 to 600 minutes, but the phase angle difference of harmonic voltage and current is almost entirely concentrated in the range of [210 °, 270 °]. According to the constraint in Table 2, the harmonic current contributed by PCC at the user side is larger and the main harmonic current source is the user side. As we all know, the use of thermistor rectifier load in the work of the arc furnace will launch a large number of harmonic current, especially in the low harmonic [6]. At the same time, the harmonic voltage and current amplitude of PCC point decrease sharply during the 600 to 660min downtime period, and the phase angle difference between PCC point and PCC point is in the range of [330 °, 0 °], not within the constraint condition of Table 2. And the contribution from the user side to the harmonic current index of the PCC point is greater; and the evaluation results in [11] show that the harmonic level emitted by the user side is greater. Therefore, the above analysis and results verify the correctness and effectiveness of this method.

4.2 Example Calculation of Urban Distribution Network



(a) Amplitude of Voltage and Current

(b) The phase angle difference φ

Fig. 6. The measured data of the 11th harmonic voltage and current.

Table 4. The parameters of PCC.

$\lvert Z_c\rvert/\Omega$	$\lvert U_{pcc}\rvert$/V	$\lvert I_{pcc}\rvert$/A	$\varphi/(°)$
103.7	781	5.3	15.2

Figure 6 shows the measured data of the 11th harmonic voltage and current of the 66kV bus (PCC) of a city power grid near the DC drop point. The whole data interval is about 1h. PCC point known as the equivalent system-side harmonic impedance inductive nature of the city because of the large-scale use of underground power cables, and to ensure that the user power quality with a large number of capacitors and other devices, resulting in the user side of the sub-harmonic impedance nature of Capacitive [17].

It can be seen from the figure, 0 to 4h time period of the normal power consumption period, the harmonic voltage and current amplitude changes are small, which is the user side of the basic conditions of harmonic impedance estimation, while the figure shows the harmonic voltage and current The phase angle difference is concentrated in the [0 °, 30 °] interval. Using the constraints in Table 3, it can be seen that the current condition satisfies the range of the phase angle difference φ of the main harmonic current source as the system side, and the additional condition of Equation (14) is satisfied. Using the method of literature [15] to calculate the harmonic impedance of the user side, we can get PCC related parameters of 95% probability maximum value in this time period, as shown in Table 4. With the formula (14) Constraint, so you can determine the current situation, the main harmonic current source for the system side.

From 4h to 5h trough time can be seen, compared to the PCC normal point of time the second harmonic voltage and current amplitude are not significantly reduced, the harmonic voltage and current phase angle difference is still concentrated 0 ° to 30 ° interval. In [17], using Dig-silent to simulate the urban power network, about 70% of the 11th harmonic current measured by each branch bus near the DC drop point is contributed by the 500kV DC drop point, so it can be determined that the system side pair PCC's 11th harmonic current contribution is greater, the main harmonic current source for the system side. Therefore, the correctness and validity of the method are verified.

5 Conclusions

Based on the analysis of harmonics active power direction method the paper deduced the identification method of the main harmonic current indicator, and the following conclusions are drawn:

1) Analyzing and drawing the harmonic active power direction method can be completely accurate conclusions in a certain region. Combined with the basic principle of the circuit and the constraint condition of the strict inequality constraints, it can effectively solve the problem that the main source of the harmonic current flowing through the line components in practical engineering.

2) In the basic properties of the power grid, the paper considered the various cases of the two sides' harmonic characteristics to meet the most project usage scene. Finally, the correctness and effectiveness of the method are verified by using the measured data from several engineering scenarios.

The identification method of main harmonic current indicator is deduced from the mechanism, and it provides a theoretical basis for the use of harmonic current active power direction method and the quantitative division of power equipment caused by the loss of harmonic current. There is a great theoretical significance and engineering practical value.

References

1. Wilsun X, Yilu L. A method for determining customer and utility harmonic contributions at the point of common coupling. IEEE Transactions on Power Delivery, 2000, 15(2)：804-811.
2. Wilsun X, Xian L, Yilu L. An investigation on the validity of power-direction method for harmonic source determination. IEEE Transactions on Power Delivery, 2003, 18(1)：214-219.
3. Li C, Xu W, Tayjasanant T. A critical impedance based method for identifying harmonic sources. IEEE Transactions on Power Delivery, 2004, 19(2)：671-678.
4. LIU Hua, LIU Rui, FU Yangyang, et al. Calculation of Harmonic Loss in Converter Transformer Tank Shells Based on the Impedance Boundary Condition. High Voltage Engineering, 2015, 41(9)：3171-3176.
5. YE Jianxin, HUANG Jiaohao, ZHANG Luliang, et al. Analysis of harmonic harm to distribution transformers. Electric Power Automation Equipment, 2011, 31(7)：146-149.
6. YE Jianxin, HUANG Jiaohao, ZHANG Luliang, et al. Analysis of harmonic harm to distribution transformers. Electric Power Automation Equipment, 2011, 31(7)：146-149.
7. ZHANG Liangxian, CHEN Mosheng, PENG Zongren, et al. Study on the Harmonic Losses of UHV Converter Transformer Windings Subject to Non-sinusoidal Load Current. Proceedings of the CSEE, 2014, 34(15)：2452-2459.
8. ZHOU Lin, ZHANG Feng, LI Qiuhua, et al. Methods for Localizing the Harmonic Source in Power Distribution Network. High Voltage Engineering, 2007, 33(5)：103-108.
9. Hua Huichun, JIA Xiufang, CAO Dongsheng, et al. Harmonic Contribution Estimation Under Power Quality Data Interchange Format. Power System Technology, 2013, 37(11)：3110-3117.
10. Yang H, Pirotte P, Robert A. Harmonic emission levels of industrial loads statistical assessment. CIGRE, 1996, 96：1936-1996.
11. HUI Jin, YANG Honggeng, YE Maoqing. Assessing Harmonic Emission Level Based on the Impedance Gathering Trend Discrimination, Proceedings of the CSEE, 2011, 31(10)：73-80.
12. CHE Quan, YANG Honggeng. ASSESSING THE HARMONIC EMISSION LEVEL BASED ON ROBUST REGRESSION METHOD, Proceedings of the CSEE, 2004, 24(4)：39-42.
13. SUN Yuanyuan, LI Peixin, YIN Zhiming. Harmonic Source Identification Based on Threshold Voltage Method . Automation of Electric Power Systems, 2015(23)：145-151.
14. HUI Jin, YANG Honggeng, LIN Shunfu, et al. Assessment Method of Harmonic Emission Level Based on Covariance Characteristic of Random Vectors. Automation of Electric Power Systems, 2009, 33(7)：27-31.
15. ZHAO Xi, YANG Honggeng. Method of Calculating System-side Harmonic Impedance Based on FastICA . Automation of Electric Power Systems, 2015, 39(23):139-144.
16. Xu W. Power direction method cannot be used for harmonic source detection// Power Engineering Society Summer Meeting. IEEE, 2000：873-876 vol. 2.
17. LI Yong, XU Youping, XIAO Hua, et al. Simulation Study on Load Model Parameters for Stability Analysis of Central China Power Grid. Power System Technology, 2007, 31(5)：17-20.
18. Robert A, Deflandre T. Guide for assessing the network harmonic impedance. Electra, 1996 (167): 96-131.
19. Wu X, Sadullah S, Matthews B, et al. Nodal harmonic impedance derivation of AC network in PSS/E// 9th IET International Conference on Ac and Dc Power Transmission. IET, 2010：02-02.
20. Zhao X, Yang H. A New Method to Calculate the Utility Harmonic Impedance Based on FastICA. IEEE Transactions on Power Delivery, 2016, 31(1):381-388.

21. CHEN Tiantian, HU Rong, Jin Zuyang, et al . Analysis Research on Harmonic Transmission Characteristics of Urban Power Network Adjacent to UHVDC Terminal Location. Power System Technology, 2015, 39(10)：3000-3004.
22. WANG Jianxun, LIU Huijin, LIU Chunyang. Identification of harmonic and interharmonic sources based on composite criterion . Electric Power Automation Equipment, 2013, 33(7)：63-69.
23. QiuSiyu, YANG Honggeng. Assessment Method of Harmonic Emission Level Based on the Improved Weighted Support Vector Machine Regression. Transactions of China Electrotechnical Society, 2016, 31(5)：85-90.