A Method for Harmonic Sources Detection based on Harmonic Distortion Power Rate

Ruixing Lin [1], Lin Xu[1] and Xian Zheng[2],*

[1]State Grid Sichuan Electrical Power Research Institute, Chengdu, China.
[2]College of Electrical Engineering and Information Technology, Sichuan University, Chengdu, China

*Corresponding author e-mail: scuzxx@163.com

Abstract. Harmonic sources detection at the point of common coupling is an essential step for harmonic contribution determination and harmonic mitigation. The harmonic distortion power rate index is proposed for harmonic source location based on IEEE Std 1459-2010 in the paper.The method only based on harmonic distortion power is not suitable when the background harmonic is large. To solve this problem, a threshold is determined by the prior information, when the harmonic distortion power is larger than the threshold, the customer side is considered as the main harmonic source, otherwise, the utility side is. A simple model of public power system was built in MATLAB/Simulink and field test results of typical harmonic loads verified the effectiveness of proposed method.

1. Introduction

With the proliferation of power electronic equipment in power system, power system harmonic has become the spotlight in power quality area[1]. The harmonic source detection at the point of common coupling(PCC) is the precondition for harmonic contribution evaluation and it is also the basis for harmonic mitigation[2].

Currently, there are a plenty of harmonic source location methods have been investigated, and these methods can be divided into single-point method[1][2]and multi-point method[3]. The multi-point method is based on the distributed measurement and the simultaneous data record at different points in the grid, then the harmonic current and voltage can be calculated by harmonic state estimation to detect where the harmonic source is. The result of these methods usually more accurate than that of the single-point method, but the equipment installation cost is too expensive to implement in practice[4]. On the other hand, in single-point method the harmonic source is located at the downstream (customer) side or upstream (utility) side, although the result of these methods is not as accurate as multi-point method, it is simple and convenient to realize in engineering application. In[1][5], a single-point method to harmonic source detection is proposed by comparing the non-active power. In[6], a method based on Budeanu distortion power is proposed which provides a new direction for methods based on power. The apparent power was decomposed into fundamental component and harmonic, highlighting the effect of the fundamental power In IEEE Std 1459-2010. The harmonic distortion power defined by this standard is obviously different when the load is linear or the harmonic source, so the method based on the harmonic distortion power rate method is generated. In this method, the threshold is set using the prior information of the grid, when the harmonic distortion power is larger than it, customer

side is considered as the main harmonic source, on the contrary, the utility side. the effectiveness of proposed method is verified by simulation and field test.

2. Proposed method

According to the IEEE Std 1459-2010[7], non-sinusoidal periodic voltage or current can be decomposed as (1):

$$v(t) = v_1 + v_H = \sqrt{2}V_1 \sin(\omega t - \alpha_1) + \sqrt{2}\sum_{h=2}^{n} V_h \sin(h\omega t - \alpha_h)$$

$$i(t) = i_1 + i_H = \sqrt{2}I_1 \sin(\omega t - \beta_1) + \sqrt{2}\sum_{h=2}^{n} I_h \sin(h\omega t - \beta_h)$$

(1)

Where, v_1, i_1, v_H, and i_H represent fundamental and harmonic voltage and current components respectively; V_1, I_1, V_h and I_h represent the RMS values of the fundamental and harmonic components. $\alpha_1, \beta_1, \alpha_h$ and β_h are the phase angle of fundamental and harmonic voltage and current, and $h=2,3,\ldots,n$.

The root mean square value of the harmonic current can be decomposed into two orthogonal components as (2):

$$I_h^2 = (I_h \cos\theta_h)^2 + (I_h \sin\theta_h)^2$$

(2)

Where $\theta_h = \beta_h - \alpha_h$ is the phase difference of the harmonic voltage and current. Then the apparent power can be decomposed as (3):

$$S^2 = V^2 I^2 = (V_1 I_1)^2 + (V_1 I_H)^2 + (V_H I_1)^2 + (V_H I_H)^2 = S_1^2 + D_I^2 + D_V^2 + S_H^2$$

(3)

Where, D_I, D_V are current and voltage distortion power; S_H is the harmonic apparent power, and according to (2) and Lagrange's identity, S_H can be further decomposed into harmonic active power and harmonic distortion power (4):

$$P_H = \sum_{h=2}^{n} V_h I_h \cos\theta_h, \quad D_H^2 = \left(\sum_{h=2}^{n} V_h I_h \sin\theta_h\right)^2 + \sum_{i=2}^{n-1}\sum_{j=i+1}^{n}\left[(V_i I_j)^2 + (V_j I_i)^2 - 2V_i V_j I_i I_j \cos(\theta_i - \theta_j)\right]$$

(4)

In (4), D_H is the distortion power defined in IEEE Std 1459-2010, it is only affected by harmonic voltage and current, the harmonic source detection method based on it is more reasonable. From (4), the same harmonic distortion power value can be caused by utility side or customer side, the method only based on harmonic distortion power will not be suitable when the background harmonic is large. And the harmonic distortion power index can only identify the load condition, it is difficult to the location of the main harmonic source when both utility and customer side have harmonic load. To solve this problem, the prior information of the grid is used to determine the threshold, when the harmonic distortion power is larger than the threshold, it can be considered that the customer side has more harmonic contribution to the harmonic pollution at PCC, so the customer side is the main harmonic source; on the contrary, when the distortion power is smaller than the threshold, the customer side has no contribution to the harmonic pollution, and the utility side is the main harmonic source.

From (4), it can be found that the harmonic distortion power is the complicated result of the interaction between harmonic voltage and harmonic current, it increases with the harmonic current and voltage. Accordion to the definition of total harmonic distortion (THD), D_H can be represented as (5):

$$THD = \frac{\sqrt{\sum_{h=2}^{n} V_h^2}}{V_1} = \frac{V_H}{V_1}, \quad D_H = \sqrt{S_H^2 - P_H^2} = \sqrt{V_1^2 I_1^2 \frac{V_H^2}{V_1^2}\frac{I_H^2}{I_1^2} - P_H^2} = \sqrt{S_1^2 (THD_V)^2 (THD_I)^2 - P_H^2}$$

(5)

To quantify the contribution of the harmonic distortion power D_H to the apparent power S, the harmonic distortion power rate (HDPR) is defined as (6):

$$HDPR = \frac{D_H}{S_1} \times 100\%$$

(6)

When the load is linear and is powered by the sinusoidal voltage, harmonic distortion power is zero, except this condition, the harmonic distortion power will change with the variation of the load

components and background harmonic (THD$_{VB}$). To verify the effectiveness of this index, different type of Z_L in **Figure 1** will be discussed as follows.

(1)   Resistance

In **Figure 1**, when the linear load is resistance, it means that $Z_L=R$, the total harmonic current distortion of i_{pcc} at PCC is (7):

$$\left(THD_I^R \right)^2 = \frac{\sum_{h=2}^{n} I_h^2}{I_1^2} = \frac{\sum_{h=2}^{n} V_h^2 \big/ R^2}{V_1^2 \big/ R^2} = THD_{VB}^2 \tag{7}$$

From (7), the total harmonic current distortion is equal to the background voltage THD$_{VB}$, which means the resistance doesn't make sense to the harmonic pollution at PCC. The harmonic distortion power in this condition is equal to zero.
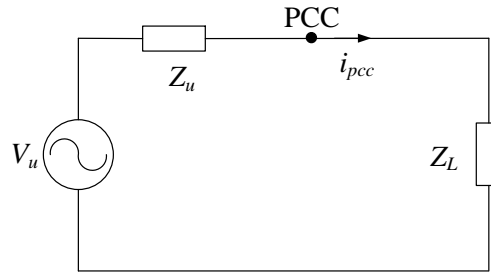
Figure 1. The equivalent circuit for harmonic analysis

(2)   Inductance

When the linear load is inductance, it means that $Z_L=j\omega L$, the total harmonic current distortion of i_{pcc} is (8):

$$\left(THD_I^L \right)^2 = \frac{\sum_{h=2}^{n} I_h^2}{I_1^2} = \frac{\sum_{h=2}^{n} V_h^2 \big/ (j\omega hL)^2}{V_1^2 \big/ (j\omega L)^2} = \frac{\sum_{h=2}^{n} V_h^2 \big/ h^2}{V_1^2} < THD_{VB}^2 \tag{8}$$

According to (8), when the load is inductance, the total harmonic current distortion of i_{pcc} is smaller than the background voltage THD$_{VB}$, which means that the inductance can decrease the harmonic distortion at PCC, but the effectiveness is small when the background harmonic is tiny and there is no harmonic resonance, the THD$_I^L \approx$THD$^2{}_{VB}$, and the harmonic active power is equal to zero, from (5), the harmonic distortion power is (9):

$$D_H^L = S_H < S_1 THD_{VB}^2 \tag{9}$$

(3)   Capacitor

When the linear load is capacitor, it means that $Z_L=1/j\omega C$, the total harmonic current distortion of i_{pcc} is (10):

$$\left(THD_I^C \right)^2 = \frac{\sum_{h=2}^{n} I_h^2}{I_1^2} = \frac{\sum_{h=2}^{n} V_h^2 (j\omega hC)^2}{V_1^2 (j\omega C)^2} = \frac{\sum_{h=2}^{n} V_h^2 h^2}{V_1^2} > THD_{VB}^2 \tag{10}$$

From (10), when the load is capacitor, the total harmonic current distortion of i_{pcc} is larger than the background voltage THD$_{VB}$, which means that the capacitor can increase the harmonic distortion at PCC, if the background harmonic is not large or there is no harmonic resonance, the impact is tiny, and the THD$_I^L \approx$THD$^2{}_{VB}$. What's more, when the background harmonic is large and the impact of capacitor is non-negligible, it is not conflict with the detection of harmonic source because the linear load has responsibility for the harmonic amplification.

(4)   Resistance-Inductance or Resistance-Capacitor

For resistor and inductance load, the harmonic distortion power is between case (1) and (2), so for resistor and inductance load, and the resistance and capacitor load have the same result. The value of the distortion power is as (11):

$$D_H^{RL} \le S_1 THD_{VB}^2, \quad D_H^{RC} \le S_1 THD_{VB}^2 \tag{11}$$

Where D_H^{RL} and D_H^{RC} represent the harmonic distortion power for resistance-inductance and resistance-capacitor loads respectively. From (9) and (11), the HDPR of linear is smaller than THD_{VB}, as (12):

$$HDPR \le THD_{VB}^2 \tag{12}$$

(5)   Linear and nonlinear load

In this condition, the harmonic pollution at PCC is caused by both utility and customer side, according to superposition theory, the harmonic pollution caused by utility side is estimated when the customer harmonic source side doesn't work, so it is same as case (1), (2) and (3) that the customer side is linear load, the total harmonic current distortion THD_I is smaller than THD_{VB}^2. From these discussions, the $HDPR_B$ is small than THD_{VB}^2 when the harmonic pollution is only caused by utility side.

In a word, THD_{VB}^2 can be regarded as the threshold, when equation (12) is satisfied, the utility side is considered as the main harmonic source; otherwise, the customer side is. In practice, the value of the background harmonic voltage THD_{VB} is difficult to obtain because the lack of the utility harmonic impedance information, but the harmonic voltage distortion THD_{Vpcc} is easy to obtain. And when the background harmonic is tiny, the trend of the THD_{VB} is same as the THD_{Vpcc}, to some degree, THD_{Vpcc} can represent the THD_{VB}. Therefore, in this paper, the background harmonic voltage distortion is replaced by the harmonic voltage distortion at PCC, and the threshold is defined as (13):

$$THR = THD_{VPCC}^2 \approx THD_{VB}^2 \tag{13}$$

The procedures of the proposed method are summarized as follows:

1)   Measure the voltage and current sample data at PCC, and then analyze the harmonic component;

2)   Calculate the harmonic distortion power rate HDPR and the threshold THR based on the sample data;

3)   The detection of main harmonic source at PCC: if the HDPR is larger than THR, the main harmonic source is customer side, on the contrary, the main harmonic source is utility side.

3. Simulation and field test

3.1. Simulation

A simple model of the public supply network is established is MATLAB/Simulink to test the proposed method, and in the simulation model, some typical non-linear loads are connected to the public network as **Figure 2**,
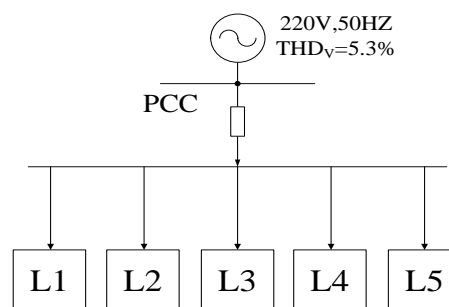
Figure 2. Simulation model for typical non-linear loads

Where L1 is the linear R-L loads; L2 is installed an active power filter on basis of L1; L3 is the thyristor controlled reactor(TCR) circuit; L4 is the bridge controlled rectifier; and L5 is PWM (pulse width modulation) circuit.

The background harmonic voltage THD_V=5.3%, the fundamental voltage is 220V and frequency is 50Hz. The simulation results are shown in **Table 1**. The method based on the active power direction[8](M1), the method based on Budeanu distortion power[6](M2), and the method proposed in this paper are compared in the simulation.

Table 1. Simulation result for typical nonlinear loads

	L1	L2	L3	L4	L5
THD_V	5.31%	5.31%	5.31%	5.31%	5.31%
THD_I	5.31%	0.92%	47.25%	104.84%	13.64%
P_H/W	20.27	0.24	-7.33	-76.22	194.88
D_B/var	0	84.52	2768.07	5749.18	5508.85
THR/‰	2.82	2.82	2.82	2.82	2.82
HDPR/‰	0	0.02	5.23	6.27	5.85
Actual result	utility	utility	customer	customer	customer
M1	utility	utility	customer	customer	utility
M2	utility	customer	customer	customer	customer
M3	utility	utility	customer	customer	customer

From the simulation result, the result of M1 is wrong for the detection of L5; For L2 which installed the active power filter, the harmonic current is small, but the harmonic distortion power is large, M2 has a wrong result. The method proposed in this paper is effective for all branches.

3.2. Field Test

To verify the engineering effectiveness of proposed method, some typical household loads included water kettle, personal computer, air conditioners which worked in cooling mode(CM) and heating mode(HM) which represent different loads are connected to the same PCC to test the effectiveness of proposed method. And the sample data is extracted to calculate the harmonic distortion power in MATLAB, the test result is shown in TABLE 2.

Table 2. The result of field test

	PCC	Water kettle	PC	Air conditioner	
				CM	HM
S/VA	7232.57	1 394.16	98.97	1 711.49	3 525.06
THD_V/%	2.73	2.71	2.72	2.72	2.71
THD_I/%	58.29	2.76	83.67	18.02	9.48
D_H/var	10.27	0.38	1.69	8.17	8.12
THR/%	0.0745	0.0734	0.0740	0.0740	0.0734
HDPR/%	0.1423	0.0276	2.1497	0.4898	0.2538
Result	Customer	Utility	Customer	Customer	Utility

From **Table 2**, when the background harmonic is within the limit (THD_V≈2.7%), and the apparent power of the tested household loads are low, so the distortion of each load is small. The water kettle is composed with resistor, although the apparent power is 1394VA, the harmonic distortion power is smaller than other loads; and there is much electronic equipment in PC, it is the typical harmonic loads, the harmonic distortion power and HDPR of PC is large. For the different two work conditions of the air conditioner, they have contribution for the harmonic pollution at PCC, the harmonic distortion power is relatively large, and the HDPR is bigger than the threshold. The results of the measurement points are consistent with the actual facts.

4. Conclusion

In this paper, a method for harmonic source detection based on harmonic distortion power rate have been proposed. The harmonic source detection only based on harmonic distortion power is not applicable when the background harmonic is large. In this paper, to solve this problem, the prior information for the network is used to determine a threshold, then the main harmonic source is located by comparing the harmonic distortion power with the threshold, if it is larger, the main harmonic source is customer side, on the contrary, the utility side. The simulation and field test results proved that the proposed method is effective for harmonic source detection.

References

[1] Barbaro P V, Cataliotti A, Cosentino V, et al. A Novel Approach Based on Nonactive Power for the Identification of Disturbing Loads in Power Systems[J]. IEEE Transactions on Power Delivery, 2007, 22(3):1782-1789.

[2] Li C S, Bai Z X, Xiao X Y, et al. Research of harmonic distortion power for harmonic source detection[C]// International Conference on Harmonics and Quality of Power. IEEE, 2016.

[3] Muscas C, Peretto L, Sulis S, et al. Implementation of multi-point measurement techniques for PQ monitoring[C]// Instrumentation and Measurement Technology Conference, 2004. Imtc 04. Proceedings of the, IEEE. IEEE, 2004:1626-1631 Vol.3.

[4] Davis E J, Emanuel A E, Pileggi D J. Evaluation of single-point measurements method for harmonic pollution cost allocation[C]// Power Engineering Society Summer Meeting. IEEE, 1999:373-378 vol.1.

[5] Cataliotti A, Cosentino V, Nuccio S. Comparison of Nonactive Powers for the Detection of Dominant Harmonic Sources in Power Systems[J]. IEEE Transactions on Instrumentation & Measurement, 2008, 57(8):1554-1561.

[6] Stevanović D, Petković P. A single-point method for identification sources of harmonic pollution applicable to standard power meters[J]. Electrical Engineering, 2015, 97(2):165-174.

[7] IEEE Standard definitions for the measurement of electric power quantities under sinusoidal，nonsinusoidal，balanced，or unbalanced conditions．IEEE Std 1459-2010,2010

[8] XU W, LIU X. An investigation on the validity of power direction method for harmonic source determination[J]. IEEE Trans on power delivery, 2003,18(1): 214-219.