A MULTIPLE HARMONIC SOURCES LOCALIZATION METHOD BASED ON DATA ANALYSIS

Xian ZHENG
Sichuan University – China
scuzxx@163.com

Xianyong XIAO
Sichuan University – China
xiaoxianyong@163.com

Shuangting XU
Sichuan University – China
986257195@qq.com

Ying WANG
Sichuan University – China
769429505@qq.com

Yiran LI
Sichuan University – China
624515756@qq.com

Huaying ZHANG
Shenzhen Power Supply Bureau-China
zhyszpower@163.com

ABSTRACT

In this paper, a multiple harmonic sources localization method based on data analysis has been proposed. Firstly, the relationship between the node harmonic voltage and the branch harmonic current is established according to the circuit theory. Secondly, in power system, there are many power quality monitor data. To reduce the calculation amount, the harmonic active power direction is utilized to the preliminary screening of the harmonic source branches. Then, the mutual information between the suspicious harmonic source branch current and the node harmonic voltage is calculated, if the mutual information exceeds a threshold, the branch is considered to be a main harmonic source branch which results in the harmonic voltage of the concerned point exceed the prescriptive level. The performance and engineering feasibility of the proposed method are verified by the computer simulation and field data.

INTRODUCTION

With the widely growing of the power system and the higher growing permeability of the power electronic equipment, more and more harmonic sources, like photovoltaic, wind power and energy storage devices, are connected to the power system, which make the topology of the power system complex and result in serious harmonic distortion. Therefore, the harmonic analysis has become a complicated task in power quality area. The critical point of the harmonic analysis and mitigation is the localization of the harmonic source.

Many published works focus on the localization of harmonic source, which can be divided into two categories: single-point method and multi-point method. Single-point method, concentrated on the PCC (point of common coupling, PCC), intends to find out the main harmonic source is the supply side or the customer side. Several single-point methods have been published, for instance, the harmonic active power direction method[1], critical impedance method[2] and the method based on the nonactive power comparison[3]. However, single-point method can only find out the main harmonic source is located in supply side or the customer side rather than the specific location, when the harmonic sources are scattered in the power system, these methods are invalid.

The multi-point method, in contrast, intend to obtain the correct and integrated harmonic propagation information based on the synchronous measurement data. Therefore, the accuracy of the harmonic source localization is higher than that of the single-point method.

A lot of multi-point methods have been proposed. For example, in [4], Heydt proposed a multi-point harmonic source localization method based on harmonic state estimation. In this method, the apparent power is regarded as the measurement data, then the harmonic sources are located by utilizing least square method. However, power theory in distortion condition isn't well established, the validity of this method can't be guaranteed. In [5], harmonic voltage is considered as the state variable, and the branch current and node voltage are considered as the measurement data, which is more universal than apparent power. In this paper, the harmonic state estimation problem is regarded as the optimization problem, and the least variance estimation method is used to harmonic state estimation. In [6], when the measurement points aren't sufficient, harmonic sources are located based on sparse maximization theory. In power system, harmonic impedance is unknown in most cases, to solve this problem, in [7], the independent component analysis is used to harmonic state estimation, then the harmonic sources are located by optimal algorithm. In these methods, harmonic state estimation is based on the circuit equations, we need know the topology information of the target grid. However, in practice, the information is complicated to obtain. Benefit from the connection of large amount of power quality monitors, there are a lot of power quality recorded data in these monitors, which provides an opportunity for harmonic source localization. In this paper, a multi-point harmonic source localization method based on measurement data analysis is proposed.

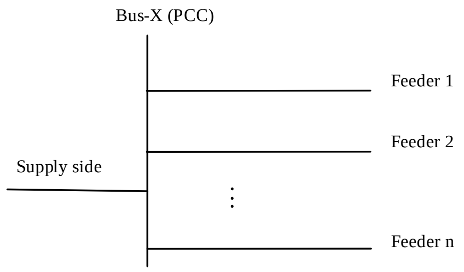
In proposed method, the branches current and the node voltage which come from the power quality monitors are used to harmonic source localization. The mutual information between harmonic voltage level exceeded node and the branch current play an important role for the main harmonic source localization. The rest of this paper can be divided into four part. In the second part, the principle for harmonic source localization is introduced based on circuit theory. The proposed method is then presented in the third part. The computer simulation and field verification are conducted to verify the performance of the proposed method in part four. Finally, a simple conclusion and outlook of the proposed method is drawn.

THE PRINCIPLE OF MULTI-HARMONIC SOURCE LOCALIZATION

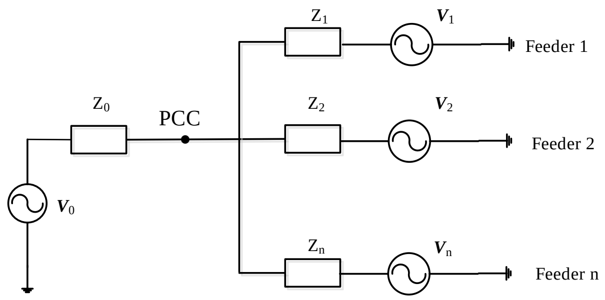
Based on the relationship between the harmonic source and the harmonic voltage exceeded node, multi-harmonic source localization problem can be divided into centralized and distributed multi-harmonic localization.

Centralized Multi-harmonic Source Localization

The centralized multi-harmonic source localization problem, based on the circuit in Fig 1(a), intends to find out the main harmonic source branches connected to PCC which cause the node harmonic voltage exceeded the standard level. The Thevenin equivalate circuit is shown in Fig 1(b).



(a) the principle diagram of centralized multi-harmonic source localization



(b) the Thevenin equivalent circuit of centralized multi-harmonic source localization

Fig. 1 Diagram of centralized multi-harmonic source system

Based on superposition theory, the harmonic voltage at PCC can be expressed as:

$$\boldsymbol{V}_{\text{hpcc}} = \sum_{k=1}^{n} \boldsymbol{V}_{\text{hpcc\_k}} + \boldsymbol{V}_{\text{hpcc\_0}} = \sum_{k=1}^{n} Z_{\text{hk\_shunt}} \boldsymbol{I}_{\text{h,k}} + \boldsymbol{V}_{\text{hpcc\_0}} \quad (1)$$

Where: n represents the amounts of loads; h represents the h$^{\text{th}}$ harmonic; $\boldsymbol{V}_{\text{hpcc\_k}}$ represents the harmonic contribution of load k to the harmonic voltage at PCC; $\boldsymbol{V}_{\text{hpcc\_0}}$ represents the background harmonic voltage; $Z_{\text{hk\_shunt}}$ represents the equivalent harmonic impedance except load k; $\boldsymbol{I}_{\text{hk}}$ represents the harmonic current at PCC when there is only the load k. When the harmonic current at the feeder is large, $\boldsymbol{I}_{\text{hk}}$ and the feeder current are consistent, thus, $\boldsymbol{I}_{\text{hk}}$ can be replaced with the feeder current.

Distributed Multi-harmonic Source Localization

In contrast, for the distributed multi-harmonic source localization problem, the harmonic sources are distributed in the grid, and calculate the harmonic contribution of each harmonic source to the concerned bus X, so that the main harmonic sources are located. The diagram of distributed multi-harmonic source system is shown in Fig 2.

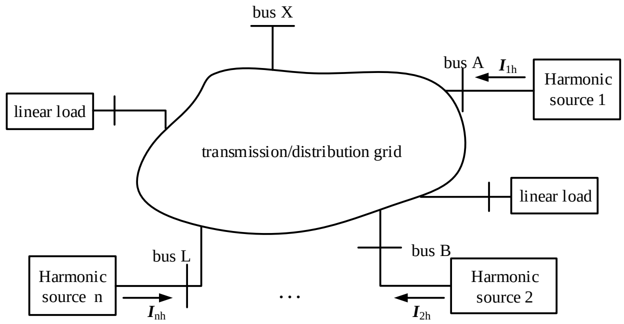


Fig. 2 Diagram of distributed multi-harmonic source system

According to nodal voltage equation, the relationship of the concerned bus harmonic voltage and the branch harmonic current are established as follow:

$$\boldsymbol{V}_{\text{hX}} = Z_{\text{hXA}} \boldsymbol{I}_{\text{hA}} + Z_{\text{hXB}} \boldsymbol{I}_{\text{hB}} + Z_{\text{hXC}} \boldsymbol{I}_{\text{hC}} + \boldsymbol{V}_{\text{hX0}} \quad (2)$$

Where: $\boldsymbol{I}_{\text{h,k}}$ represents the injection h$^{\text{th}}$ harmonic current from the branch where the harmonic source k located; Z_{hXk} represents the self/mutual harmonic impedance between bus X and load k; $\boldsymbol{V}_{\text{hX0}}$ represents the background h$^{\text{th}}$ harmonic voltage. In power system, the impedance of the supply side is smaller than customer side in most cases, therefore, $\boldsymbol{I}_{\text{hk}}$ can be replaced by the branch current.

In conclusion, according to (1) and (2), the harmonic current of the harmonic source branches is correlated with the concerned node harmonic voltage. Thus, the main harmonic source can be located by measurement data analysis.

HARMONIC SOURCE LOCALIZATION BASED ON DATA ANALYSIS

Preliminary Screening of Harmonic Source Branches

The harmonic distribution in the power system can be divided into two categories: one is the nodal harmonic voltage result in the harmonic distortion of the branches current. The other is the branch harmonic current cause the node harmonic voltage distortion. The main harmonic source identification aims to find the second condition. Although the localization method based on mutual information has been proposed, it doesn't distinguish these two conditions. Therefore, before the utilization of mutual information, harmonic active power direction method is used to preliminary screening of the harmonic source branches. In this paper, when the harmonic power flow into the branch, the harmonic active power is considered as with a positive sign or vice versa. If the h$^{\text{th}}$ harmonic active power of branch i is less than zero, there is the h$^{\text{th}}$

harmonic source in branch i. The hth harmonic active power of branch i is calculated by equation (3):

$$P_{hi} = V_{hi} I_{hi} \cos(\alpha_{Vhi} - \beta_{Ihi}) \quad (3)$$

Where: h is the hth harmonic; i is the measurement point i; α_{Vhi} and β_{Ihi} is the phase of hth harmonic current and voltage.

Harmonic Source Localization based on Data Analysis

The suspicious harmonic source branches have been selected out through harmonic active power direction method. In this part, the mutual information between the hth harmonic current of the suspicious branches and the concerned node hth harmonic voltage are calculated. Mutual information can reflect the strength of correlation between two random variables. Therefore, the calculated mutual information can be used to measure the correlation information between the suspicious branches and concerned node. According to the calculated mutual information, when the mutual information exceeds the threshold, we can conclude this branch is one of the main harmonic sources which result in the concerned node harmonic voltage exceeded the limit.

Assuming the magnitude set of the concerned node hth harmonic voltage is: $V=\{V_1,V_2,\dots,V_n\}$; and the magnitude set of the suspicious branch hth harmonic current is: $I=\{I_1,I_2,\dots,I_n\}$. Then, the mutual information between them is calculated by follow steps:

(1) Data segment

Firstly, V and I are divided into n intervals averagely. The length of each interval are as follows:

$$h_V = \frac{V_{max} - V_{min}}{n} \qquad h_I = \frac{I_{max} - I_{min}}{n} \quad (4)$$

Where: V_{max} and V_{min} are the maximum and minimum value of the voltage magnitude set respectively; I_{max} and I_{min} are the maximum and minimum value of the current magnitude set separately.

The ith distinguish interval of current and voltage magnitude set are as follows:

$$a_i = [V_{min} + (i-1) * h_V, \quad V_{min} + i * h_V]$$
$$b_i = [I_{min} + (i-1) * h_I, \quad I_{min} + i * h_I] \quad (5)$$

(2) Calculation of probability density distribution

The probability value of the harmonic voltage magnitude in each distinguish interval are then calculated by frequency distribution histogram method. If there are m voltage magnitude located in interval a_i, the probability value of V in the interval a_i is as follow:

$$p(a_i) = m/n \quad (6)$$

Similarly, we can obtain the probability value of the harmonic voltage magnitude in each distinguish interval $p(b_i)$ and the joint probability density distribution $p(a_i,b_i)$ between V and I.

(3) Calculate joint distributed entropy between V and I by follow equation:

$$H(V) = -\sum p(a_i) \times \log p(a_i)$$
$$H(I) = -\sum p(b_i) \times \log p(b_i) \quad (7)$$
$$H(V,I) = -\sum p(a_i,b_i) \times \log p(a_i,b_i)$$

(4) Calculate Standardized mutual information

$$MI(V,I) = \frac{H(V) + H(I) - H(V,I)}{\sqrt{H(V) \cdot H(I)}} \quad (8)$$

Thus, the mutual information between branch harmonic current and node harmonic voltage have been calculated. When mutual information exceeds the threshold, this branch is considered as one of the main harmonic sources of the concerned node. The flow diagram of proposed method is shown in Fig 3.

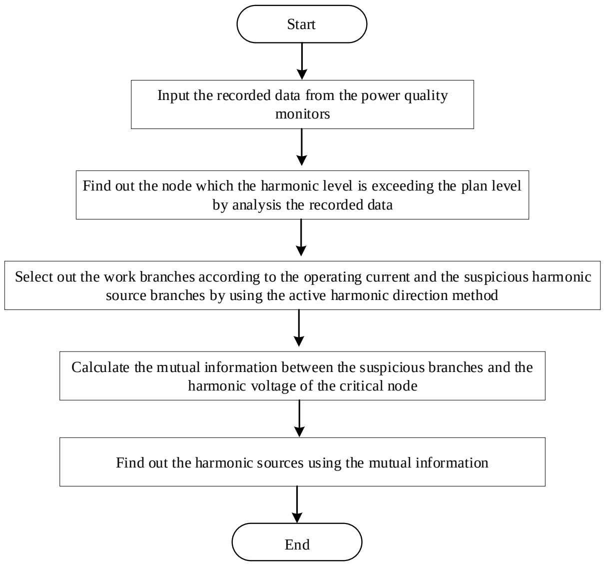


Fig. 3 The flow diagram of the proposed method

SIMULATION AND FIELD TEST

Simulation

The performance of proposed method is verified by the IEEE-13 bus system[8] as shown in Fig 4 where the measurement branches are marked in red.

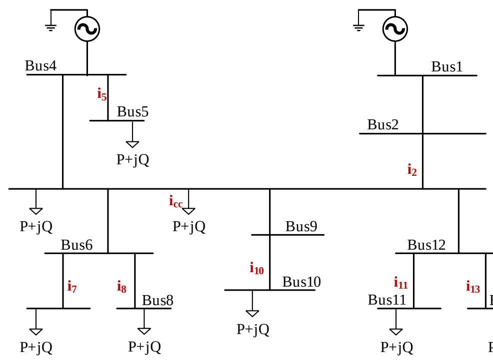


Fig. 4 Diagram of the IEEE 13 bus power system

Firstly, this system is established using PSCAD/EMTDC, and then the sample data are analyzed using MATLAB. The proposed method and correlation analysis method are compared in this paper. The harmonic sources are connected to node 5, 7, 8, 10, 11, 13. The specific parameter are shown in Tab 1, and the reference phase is the fundamental source voltage.

Tab.1 9th harmonic source parameter

node	5	7	8	10	11	13
I_h/kA	0.001972	0.00286	0.0056	0.00197	0.02472	0.0256
phase/°	-70	40	70	100	100	70

Then, the harmonic active power direction method is used to preliminary screening. According to the parameter, the harmonic active power of the monitored branches is shown in Tab 2.

Tab.2 Harmonic active power

branch	i_{33}	i_5	i_7	i_8	i_{10}	i_{11}	i_{13}	i_{cc}
P_h/kW	0.99	0.62	0.38	-0.12	0.65	-0.11	-0.18	0.13

According to the Tab 2, the suspicious 9th harmonic source may locate in branch 8, 11, 13.

Finally, the R (correlation coefficient, R) and MI (mutual information, MI) between suspicious branches and concerned node are calculated using correlation analysis method and proposed method respectively. The results are as shown in Tab 3.

Tab.3 Mutual information and correlation coefficient

node	3		6		10		11		13	
	MI	R	MI	R	MI	R	MI	R	MI	R
i_8	0.43	0.77	0.43	0.79	0.83	0.44	0.83	-0.2	0.83	0.32
i_{11}	0.44	0.07	0.44	0.07	0.85	-0.4	0.86	0.7	0.86	0.09
i_{13}	0.42	0.71	0.42	0.72	0.82	0.32	0.83	-0.1	0.83	0.88

From Tab 3, the main 9th harmonic sources based on proposed method are branches 8, 11, and 13. The correlation analysis method are branches 8 and 13. Based on Tab 1, the main 9th harmonic sources are located in branches 11 and 13. The proposed method is more reliable than that of correlation analysis method.

Field Test

To prove the engineering performance of proposed method, the field measurement data from Henan province, China are used to evaluate the effectiveness. The diagram of the measured power system is as shown in Fig 5. It includes 9 feeders, and the load character for each feeder have shown in the Fig 5. The measurement data for each feeder include: the harmonic active power for each frequency, total harmonic voltage distortion, harmonic current for each frequency, and harmonic voltage for each frequency. The time interval for measurement data is 3min, and there are 480 measurement data for a whole day.

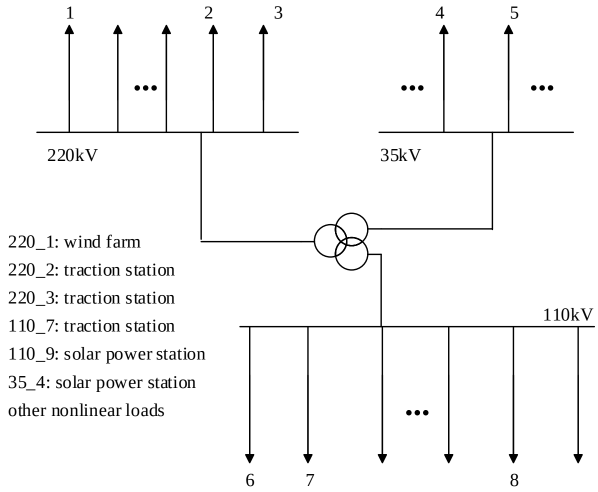


Fig. 5 Diagram of analytical power system

The steps for the field test are as follows:

(1) According to the total harmonic voltage distortion requirements for different voltage level regulated in Chinese harmonic standard GB/T 14549-1993, the node whose total harmonic voltage distortion exceed the standard and the moment when the node harmonic voltage exceed the standard are selected out.

(2) Screen the branches which are at work at the exceeded moment. When the branch current at the moment is less than 5% of the maximum current of the branch, we can conclude the branch is empty at this moment and it is excluded in the later calculation.

(3) Calculate the main harmonic sources of the concerned node harmonic voltage by utilizing the proposed method. The data involved in the calculation is 30 data before and after the exceeded moment.

In this paper, the 17th harmonic voltage from 110kV bus is used to verify the proposed method. According to the measurement data, the harmonic voltage exceeded moment is 03:21-03:24, then, the main harmonic sources which result in the harmonic voltage exceeds the limit are calculated by utilizing proposed method.

Firstly, the work branches at 03:21-03:24 are selected out based on the current data. According to the measurement current data, the branches which are at work at 03:21-03:24 are 220_1, 220_3, 110_6, 110_7. Then, based on the measurement data, the branches 17th harmonic active power at 03:21-03:24 are shown in Tab 4.

Tab.4 Harmonic active power

branch	220_1	220_3	110_6	110_7
P_h/kW	-424.8	-12.79	-70.32	-300.46

Based on Tab 4, the suspicious 17th harmonic source branches screened by harmonic active power method are 220_1, 220_3, 110_6, 110_7. Then calculate the mutual information and the correlation coefficient between the suspicious 17th harmonic source branches and the 17th harmonic voltage of 110kV bus, the calculation results are shown in Tab 5.

Tab.5 Mutual information and correlation coefficient

branch	220_1		220_3		110_6		110_7	
	MI	R	MI	R	MI	R	MI	R
110kV bus	0.85	0.83	0.81	0.89	0.83	0.90	0.91	0.96

Based on the measurement data, at the moment, the wind farm which is connected to the feeder 220_1 is at work peak and the traction station which is connected to the 110_7 feeder is at work. In theory, these two feeders are the main 17th harmonic sources branches which result in the 17th harmonic voltage exceeds the limit. According to the calculation result shown in Tab 5, the main harmonic sources located by proposed method are feeder 220_1 and feeder 110_7, which accord with the theoretical analysis. However, by correlation analysis method, the main harmonic sources are located in feeder 220_3 and feeder 110_7, which don’t conform with the practical condition. From the field test, the proposed method has more reliable results than that of correlation analysis method.

CONCLUSION

The proposed multi-harmonic source localization method realizes the localization by the measurement data analysis, compared with the traditional methods, it doesn’t need the topology of the grid and the harmonic impedance information. To except the condition that node harmonic voltage result in the branch harmonic current, the harmonic active power method is used to preliminary screening, then, calculate the mutual information between suspicious harmonic current branch and the concerned node harmonic voltage. Compared with the traditional methods, the proposed method is more reliable and it is more suitable for the engineering practice. However, there are still some problems have to be solved, for example, the criterion to ensure the threshold of the mutual information isn’t well established. Thus, a specific method should be provided to solve the problem.

REFERENCES

[1] SWART P H, VAN WVK J D, CASE M J, 1996, " On techniques for localization of sources producing distortion in three-phase networks", *European transactions on electrical power*, vol. 6, 391-396.

[2] LI C, LIU X, 2004, "Critical impedance method-a new detecting harmonic sources method in distribution systems", *IEEE Trans. Power Del.*, vol. 19, 288-297.

[3] BARBARO P V, CATALIOTTI A, COSENTINO V, et al, 2007, "A novel approach based on non-active power for the identification of disturbing loads in power systems", *IEEE Trans. Power Del.*, vol. 22, 1782-1789.

[4] HEYDT G, 1989, "Identification of harmonic sources by a state estimation technique", *IEEE Trans. Power Del.*, vol. 4, 569-576.

[5] MELIOPOULOS A P S, ZHANG F, ZELINGHER S, 1994, "Power system harmonic state estimation", *IEEE Trans. Power Del.*, vol. 9, 1701-1709.

[6] LIAO H, 2007, "Power system harmonic state estimation and observability analysis via sparsity maximization", *IEEE Trans. Power Syst.*, vol. 22, 15-23.

[7] GURSOY E, NIEBUR D, 2009, "Harmonic load identification using complex independent component analysis", *IEEE Trans. Power Del.*, vol. 24, 285–292.

[8] BURCH R, CHANG G, GRADY M, 1999, "Test systems for harmonics modeling and simulation", *IEEE Trans. Power Del.*, vol. 14, 579-587.