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Identification of Multiple Harmonic Sources in Electric Power System with Erroneous Measurements Using Several Indices

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ABSTRACT
This Article shows that the current Total Harmonic Distortion (THD) can be used reliably as index to identify the location of multiple harmonic sources in a power network. It isproved that the current THD locate the harmonic sources with a$\pm 1\%$uniformly distributed erroneous measurement. Current THD, Euclidean norm and the magnitude of the nodal harmonic current are compared as indices to identify harmonic sources in Electric Power Systems. It is shown that with an erroneous measurement of $\pm 1\%$, uniformly distributed, it is not possible to locate multipleharmonic sources using the Euclidean norm and the nodal harmonic current.A 30 nodes system with three harmonic sources is tested with de Heydt's method, the Euclidean norm and the current THD.
Keywords: Harmonic, Electric Power System, Current injections method, THD, Euclidean norm, Static Vars Compensator (SVC)**.**

I. INTRODUCTION

Due to the increase of nonlinear loads and power electronic controlled devices, different methods to locate harmonic sources in Power Systems have been developed [1-19].These methods can be used to locate harmonic sources, solve harmonic power flows, and solve problems generated by the harmonic sources.

Utility companies cannot always locate harmonic sourcesthatdoes not meet quality standards.

Heydt G.T. in [1] propose a method to locate harmonic sources in Electric Power System, based on the current injection method, proposed by Mahmoud in [20].This method states that the nodes where there is a harmonic source will have a nodal harmonic current magnitude different to zero. This asumption is used as an index to identify harmonic sources [1-19], i.e., the estimators locate the harmonic sources using the nodal harmonic current magnitude as index.

Harmonic voltage and current measurements are necessaryin these methods to locate harmonic sources. Other articles propose to use other measurements, like line harmonic current and harmonic power flows [10, 12, 16].

Heydt [1] and Nguyen [2] methodologies were not tested with measurement error presence. The proposed methods to locate harmonic sources are susceptible to erroneous measurements, this leads to an unreliable identification of harmonic sources [10-14]. Because of this problem a different solution has been proposed, such as weighting measurements [9-11] or the Euclidean norm [12].

The use of current THD as an index to locate harmonic sources in Electric Power Systems is proposed in this paper [25]. The current THD is compared with the Euclidean norm, as index to identify harmonic sources. Prior to the calculation of this index, the nodal harmonic currents and voltages must be calculated usingHeydt's method.

IEEE 30 nodes system was tested [26], with three Static Vars Compensator (SVC), and with erroneous measurements of $\pm 1\%$ distributed uniformly, like Kanao et. Al. in [10]. The results in this paper show that the current THD can be used as a reliable index to locate harmonic sources in Electric Power Systems, even with erroneous measurements. When the current THD is greater than 2.5% (limit established by IEEE 519-1992 standard [21]), the harmonic sources were identified consistently. When the Euclidean norm and the nodal harmonic current magnitude are used as index for the identification of harmonic sources, it is not possible locate the harmonic sources with erroneous measurements.

II. HEYDT'S PROPOSED METHOD FOR THE IDENTIFICATION OF HARMONIC SOURCES

Heydt's proposed method in [1], is based on the current injection technique [20] to solve the harmonic power flow method, using the Kirchoff's laws, as follows:

$$\boldsymbol{I_h} = \boldsymbol{Y_h V_h} \quad (1)$$

Where:

$\boldsymbol{I_h} \in \mathbb{C}^{\boldsymbol{n}}$, is a vector that contains the nodal harmonic currents injected for the harmonic sources.

$\boldsymbol{Y_h} \in \mathbb{C}^{n\times n}$,is the $\boldsymbol{Y_{bus}}$ matrix affected by the harmonics in the net.

$\boldsymbol{V_h} \in \mathbb{C}^{n}$, is the nodal harmonic voltage vector.

$\boldsymbol{n}$,is the system node number.

$\boldsymbol{h}$,is the harmonic number.

Rearranging eq. (1), grouping the known or measured data, and the unknown data, eq. 2 is obtained.

$$\begin{bmatrix} \boldsymbol{I_{bu_h}} \\ \boldsymbol{V_{bu_h}} \end{bmatrix} = \boldsymbol{Y_h V_h} = \begin{bmatrix} \boldsymbol{G_h} & \boldsymbol{H_h} \\ \boldsymbol{J_h} & \boldsymbol{K_h} \end{bmatrix} \begin{bmatrix} \boldsymbol{V_{bu_h}} \\ \boldsymbol{V_{bk_h}} \end{bmatrix} \quad (2)$$

Where:

$\boldsymbol{I_{bk_h}} \in \mathbb{C}^{m}$, $\boldsymbol{V_{bk_h}} \in \mathbb{C}^{m}$are the nodal harmonic current and voltage measured vectors.

$\boldsymbol{I_{bu_h}} \in \mathbb{C}^{u}$,$\boldsymbol{V_{bu_h}} \in \mathbb{C}^{u}$,are the nodal harmonic current and voltage unknown vectors.

$\boldsymbol{G_h} \in \mathbb{C}^{u\times u}$,$\boldsymbol{H_h} \in \mathbb{C}^{u\times m}$,$\boldsymbol{J_h} \in \mathbb{C}^{m\times u}$,$\boldsymbol{K_h} \in \mathbb{C}^{m\times m}$,are sub-matrices obtained when the $\boldsymbol{Y_h}$ matrix is rearranged.

$\boldsymbol{m}$,is the total nodal measurement.

$\boldsymbol{u}$,is the total unknown data.

Solving with Least Squares sense:

$$\boldsymbol{I_{bu_h}} = \boldsymbol{G_h J_h^{+} I_{bk_h}} + [-\boldsymbol{G_h J_h^{+} K_h} + \boldsymbol{H_h}]\boldsymbol{V_{bk_h}} (3)$$

The pseudoinverse of $\boldsymbol{J}$must be used to solve (3), because $\boldsymbol{J}$ isnot a square matrix [1, 23-24].

Where:

$\boldsymbol{J^{+}}_{\boldsymbol{h}} \in \mathbb{C}^{u\times m}$,is $\boldsymbol{J_h}$ pseudoinverse and is defined as$\boldsymbol{J_h^{+}} = [\boldsymbol{J_h^{T} J_h}]^{-1}\boldsymbol{J_h^{T}}$ [1, 23-24].

The process is not iterative, so the result to each harmonic in the system is obtained directly.

Figure 1, shows the flow chart that resumes the Heydt's method proposed to locate harmonic sources.

Unknown nodal harmonic currents are estimated with this method, so it is necessary to use (1) to calculate the unknown nodal harmonic voltages.

Heydt's method propose the nodal harmonic current magnitude as index to locate harmonic sources in Electric Power Systems, i.e., the node where there isnot a harmonic source connected should have a harmonic nodal current magnitude equal or closer to zero. So the node with a harmonic source will have a harmonic nodal current magnitude different of zero.

Unfortunately, Heydt's method fails when erroneous measurements are present [9-12, 14,25].Then,it is necessary to propose other indexes, such as the Euclidean norm [12] or current THD [25].

Heydt's method not only provides the harmonic source location, it mayidentify the kind of harmonic sources too. Unfortunately, in the presence of erroneous measurementsit isnot possible to locate unknown harmonic sources.

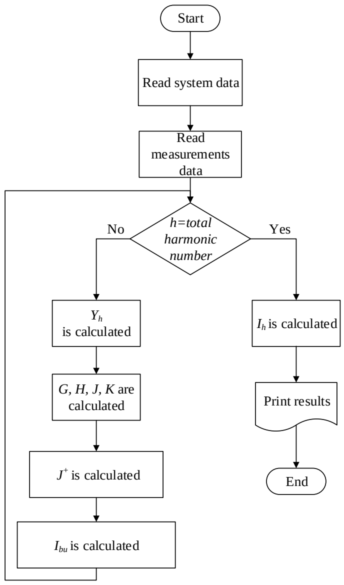

Fig. 1. Heydt's method flow chart [1].

III. HARMONIC SOURCE LOCATION USING THE EUCLIDEAN NORM

The Euclidean norm was proposed in [12] as an index to identify harmonic sources in an Electric Power System. Prior to calculate the Euclidian norm, the nodal harmonic current must be known, so it can be used a harmonic estimation method. In this paper it'll be used the Heydt's method proposed in [1].

Once estimated the nodal harmonic currents, the nodes with a possible harmonic source are discriminated. The index to discriminate suspicious nodes with a harmonic source connected is the harmonic nodal current [12]. A bus with a nonzero nodal harmonic current magnitude is suspicious, where a harmonic source may be connected.

When the suspicious nodes are known, there are c possible combinations of nodes with harmonic sources connected [12]. $c$iscalculated with eq. (4):

$$c = C_1^m + C_2^m + \cdots + C_m^m = \sum_{p=1}^{p=m} C_p^m \quad (4)$$

Where:

p, is one of the c possible combinations of nodes with harmonic sources connected.

m, is the total number of combinations of nodes with harmonic sources connected.

$C_1^m$is the probability of have one node with unidentified harmonic source.

$C_2^m$is the probability of have two node with unidentified harmonic source.

$C_m^m$is the probability of have m node with unidentified harmonic source.

Once obtained the c possible combinations, the harmonic nodal voltage is calculated for each possible combination. Then, the Euclidean norm of the difference between the estimated and measured harmonic nodal voltages is calculated for the c combinations. The harmonic sources are located in the node combination with the least Euclidean norm value.

$$\left\|\hat{V}_h - \bar{V}_h\right\|_p = \sum_{i=1}^{meas} \left(\left|\hat{V}_h^1 - \bar{V}_h^1\right|^2 + \left|\hat{V}_h^2 - \bar{V}_h^2\right|^2 + \cdots + \left|\hat{V}_h^{meas} - \bar{V}_h^{meas}\right|^2 \right)^{1/2} \quad (5)$$

Where:
$\| \ \|$, is the Euclidean norm
$\widehat{\ }$, is anestimated value
$\bar{\ }$, is a measured value
$meas$, is the total of measurements

Figure 2 shows the flow chart of the Euclidean norm method to identify harmonic sources in Electric Power Systems.

The Euclidean norm method uses the nodal harmonic voltage as index to locate harmonic sources, while the method explained before, use the nodal harmonic current.

With this method it is not possible to know the kind of harmonic sources in a node, nevertheless, the nodal harmonic voltage are estimated, so it can be used (1) to know the kind of harmonic sources connected in the system.

IV. HARMONIC SOURCES LOCATION USING CURRENT TOTAL HARMONIC DISTORTION (THD)

THD is defined as the square root of the summation of the RMS value of the harmonics, divided by the RMS value of the fundamental. The THD is a measure that indicates the nodal harmonic pollution with respect to the fundamental, for this reason, THD can be used as index to locate harmonic sources in an Electric Power System.

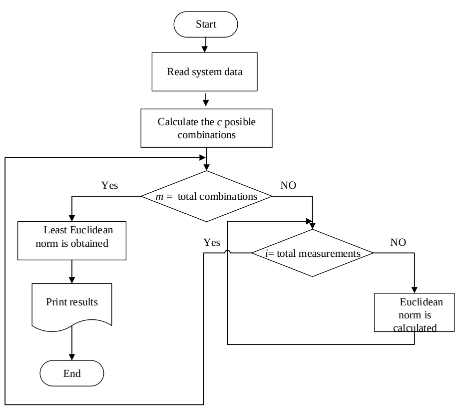

Fig. 2. Flow chart of the Euclidean norm method to identify harmonic sources in Electric Power Systems

In this paper, the current THD is proposed as an index for the identification of harmonic sources [25]. Prior to the current THD calculation, it is necessary use an estimation method to know the nodal harmonic current, hence Heydt'smethod, proposed in [1], was used to estimate the nodal harmonic currents. Once the nodal harmonic currents are determined, the current THD is calculated in each Power System bus. The nodes with a current THD greater than 2.5% (limit allowed by the IEEE 519-1992 [21]) have a harmonic source connected.

The current THD is defined as:

$$THD = \frac{1}{I_1}\sqrt{\sum_{h=2}^{\infty} I_h^2}$$

Where:
I_1, is the fundamental current.

Figure 3 shows the flow chart of the current THD method as index to identify harmonic sources in Electric Power Systems.

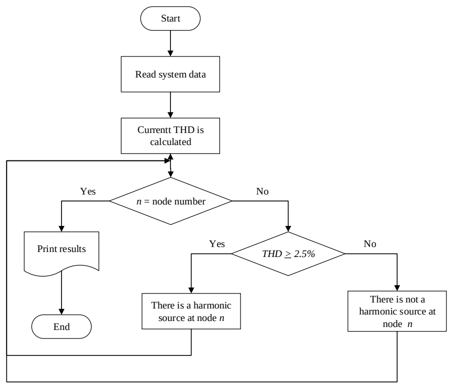

Fig. 3. Flow chart ofthe current THD method as index to identify harmonic sources in Electric Power Systems.

This method is not iterative; just requires the previous knowledge of network nodal harmonic currents. The network nodal harmonic currents can be calculated using a harmonic estimation method, in this case the Heydt´s method.

With this method it is not possible to know the kind of harmonic sources connected in the system, so, the current THD only can be used as an index to locate harmonic sources.

V. TEST SYSTEM

IEEE 30 nodes test system is used in this paper; it is presented in Figure 4. Three harmonic sources are connected: nodes 7, 12 and 21. The three harmonic sources are SVCs.This system isutilized to test the three methods;Heydt´s, current THD and the Euclidean norm.

The test system data were taken from [26], while SVC data are available in [21] and on Table 1 of this paper. The voltage measurements are perturbed with a$\pm$1% uniformily distributed error, like Kanao et. al. in [10].

In Figure 4, the nodes with nodal harmonic voltage and current measurements are marked with a black square.

Table 1. Harmonic current percent of the fundamental injected by the SVC [16]

Harmonic	Harmonic current percent	Lagging
5	7.02	46.92
7	2.5	-29.87
11	1.36	-23.75
13	0.75	71.5
17	0.62	77.12
19	0.32	173.43
23	0.43	178.02
25	0.13	-83.45
29	0.4	-80.45

VI. RESULTS

VI.1. Results Obtained Using The Heydt's Method

Table 2 presents the estimated harmonic nodal currents with Heydt's method.

It is observed on Table 2, that it is not possible to locate the harmonic sources in the test system, because all the nodes have a harmonic current magnitude different to zero. Therefore, according to the obtained results, all the nodes without measurement have a harmonic source connected, which is incorrect, because there are harmonic sources only in nodes 7, 12 and 21.

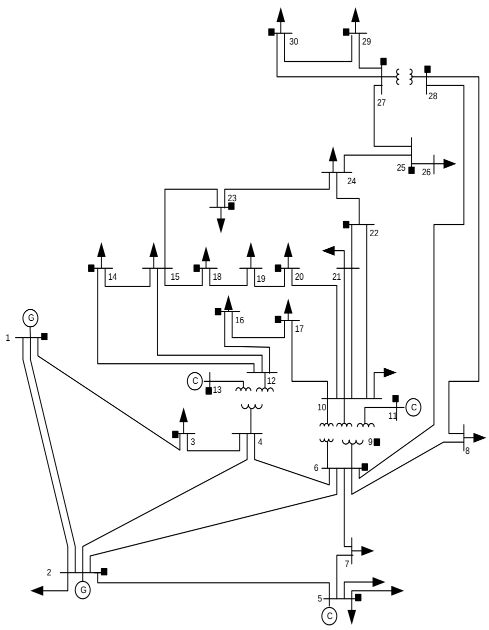

Fig. 4. IEEE 30 nodes system

VI.2. Results Obtained Using The Euclidean Norm.

It is necessary to know the nodal harmonic currents in the system previously for this method. Bus Harmonic information is taken from Table 2. A node is considered suspiciouswhen it has a nonzero harmonic current magnitude. It is important to observe that all the nodes in Table 2 are suspicious, because they have a nonzero nodal harmonic current magnitude.

For this case, the Euclidean norm must be calculated for the 1804 combinations. The unknowns are greater than using the current THD, which represents more complexity and computational time.

Once the $c$possible nodes combination with a harmonic source connected is obtained, nodal harmonic voltages are calculated using equation (1) for all the possible combinations.

After nodal harmonic voltages are calculated, the Euclidean norm of the difference between the estimated and measured nodal harmonic voltages is obtained. The harmonic sources are identified on the node combination with the least Euclidean norm

Table 2. Harmonic currents estimated using Heydt's method.

Harmonic	Node	Current Magnitude	Current Angle
5	4	0.05244	-29.14526
	7	0.51634	37.95395
	8	0.01805	151.2976
	10	0.05737	150.2769
	12	0.47789	42.22538
	15	0.08258	-32.69866
	19	0.02558	146.069
	21	0.5443	25.52365
	24	0.07635	147.7675
	26	0.02145	-30.89148
7	4	0.0042	0.53649
	7	0.18975	-38.10252
	8	0.00302	-165.9232
	10	0.00465	-169.3179
	12	0.18394	-38.87131
	15	0.01551	-174.7489
	19	0.00662	6.24152
	21	0.17658	-43.0926
	24	0.01254	5.84101
	26	0.0054	-174.1768
11	4	0.00273	6.64711
	7	0.0996	-34.00909
	8	0.00392	-167.1774
	10	0.00068	-40.87262
	12	0.0951	-35.24238
	15	0.00054	-38.51659
	19	0.00034	141.4175
	21	0.09759	-35.68853
	24	0.00021	-44.86901
	26	0.00017	141.272
13	4	0.00023	-120.1048
	7	0.05559	61.69102
	8	0.00015	-65.02871
	10	0.00001	76.4007
	12	0.05291	60.06713
	15	0.0002	49.66085
	19	0.00009	-124.4183
	21	0.05408	59.46381

	24	0.00007	-120.6972
	26	0.00002	29.05268
17	4	0.00067	-134.5783
	7	0.04602	66.97454
	8	0.00151	45.22181
	10	0.00005	-87.92987
	12	0.04413	65.62669
	15	0.00001	176.6073
	19	0.00002	31.96162
	21	0.04502	65.02678
	24	0	31.81417
	26	0	-110.9143
Harmonic	Node	Current Magnitude	Current Angle
19	4	0.00027	-165.0147
	7	0.02384	163.7968
	8	0.00032	170.9907
	10	0.00006	1.68469
	12	0.0228	161.8754
	15	0.00025	-25.59733
	19	0.00004	150.676
	21	0.02315	161.42
	24	0.00004	-32.72941
	26	0.00011	-7.59551
23	4	0.0001	55.44044
	7	0.03158	168.1325
	8	0.00043	150.9051
	10	0.00108	19.71677
	12	0.03059	166.4789
	15	0.00018	-43.77839
	19	0.00014	33.10193
	21	0.03059	165.4211
	24	0.00007	-67.372
	26	0.00005	177.391
25	4	0.00002	6.96216
	7	0.0096	-93.30957
	8	0.00006	-160.6385
	10	0.0009	-52.89224
	12	0.00927	-94.73791
	15	0.0002	109.3187
	19	0.00011	-53.20313
	21	0.00951	-94.29516
	24	0.0002	98.29692
	26	0.00006	104.553
29	4	0.00034	-41.29469
	7	0.02975	-90.1825
	8	0.00011	-130.7203
	10	0.01155	-85.70278
	12	0.0443	-91.70417
	15	0.03299	95.28408
	19	0.00589	-83.82865
	21	0.01298	-102.0905
	24	0.05353	92.19901
	26	0.00853	98.69428

Since the number of possible nodes combination is too large, 1804, on Table 3 are listed the least Euclidean norm for up to $m = 5$. In Table 3, the actual node combination of harmonic sources is presented with bold letters.

Table 3. Least Euclidean norm for up to five nodes with unidentified harmonic source

Possible node combination with harmonic sources	*Harmonic*				
	5	*7*	*11*	*13*	*17*
8	0.0219	0.0014	0.0008	0	0.0004
4, 19	0.0296	0.0071	0.0007	0	0.0001
4, 8, 19	0.0345	0.0059	0.0002	0	0.0003
7, 12, 21	**3.12**	**0.3484**	**0.0163**	**0.0032**	**0.01**
8, 15, 24, 26	0.0417	0.0035	0.0008	0	0.0001
4, 15, 19, 24, 26	0.0422	0.0073	0.0007	0	0.0001

Possible node combination with harmonic sources	*Harmonic*			
	19	23	25	29
8	0.0001	0	0	0
4, 19	0	0	0	0.0002
4, 8, 19	0.0001	0	0	0.0002
7, 12, 21	**0.0058**	**0.0048**	**0.0011**	**0.0196**
8, 15, 24, 26	0	0	0	0
4, 15, 19, 24, 26	0	0	0	0.0002

It is noted in Table 3, that it is not possible to locate the harmonic sources in the test system using the smallest Euclidean norm. The Euclidean norm calculated for the node combination where the actual harmonic sources are connected (7, 12 and 21) is greater than the other combinations showed in Table3.

Euclidean norm isnot a reliable index to locate harmonic sources in Electric Power Systems with erroneous measurements of $\pm 1\%$ distributed uniformly.

VI.3. Results Obtained Using the Euclidean Norm.

Prior to the calculation of the current THD, it is necessary to know the nodal harmonic currents in the system. With the Table 2 information, the current THD in each node is calculated. Table 4 presents the current THD in each system node.

As mentioned previously, the nodes with a current THD greater than 2.5% (limit allowed by the IEEE519-1992 standard [21]) have a harmonic source connected. In Table 4, nodes 7, 12 and 21 exceed the limit established of current THD, it means that there are harmonic sources connected in these nodes.

Tabla 4. Current THD

Node	***THD***	***Node***	***THD***
1	0	16	0
2	0	17	0
3	0	18	0
4	0.165967	19	0.267643
5	0	20	0
6	0	**21**	**4.764308**

7	**4.420703**	22	0
8	0.062511	23	0
9	0	24	0.867507
10	0.237188	25	0
11	0	26	0.51029
12	**3.143242**	27	0
13	0	28	0
14	0	29	0
15	1.012626	30	0

Current THD as index to locate harmonic sources in Electric Power Systems identifies correctly the three harmonic sources connected on the test system, even in the presence of $\pm 1\%$erroneous measurements, uniformly distributed.

With the current THD, the kind of harmonic source cannot be identified. This index only can be used to locate harmonic sources in Electric Power Systems.

VII. CONCLUSIONS

It is showed that the current THD locate consistently the harmonic sources in the test system, even with erroneous measurements.

The current THD method to locate harmonic source is simple, it is necessary only to calculate the current THD for each network node, and determine the buses that exceed the limit proposed in the IEEE519-1992 standard.

With $\pm 1\%$ uniformly distributed erroneous measurements,it is not possible to locate the harmonic sources in the test systemusing Heydt'sor the Euclidian norm method. Nevertheless, nodal harmonic currents estimated by Heydt's method can be used for other indexes like current THD or Euclidean norm.

In the Euclidean norm method, when there is a big number of combinations of nodes with unidentified harmonic sources, the method becomes more complex, and may require more computational time.

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