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HARMONIC SOURCE ESTIMATION OF DISTRIBUTION NETWORKS USING ICA METHOD

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Abstract- This paper presents a new methodology to estimate harmonic sources in a distribution network, based on measurements of limited number of given buses. The algorithm utilizes independent component analysis (ICA), a method of solving blind source separation theory. In this method, pseudo impedance matrix of distribution network is estimated. The location of harmonic sources will be identified by estimated matrix. The power quality management system presented in this paper has been developed for synchronizing measurement data. The simulations and data of a system has been an industrial zone in Tabriz is presented to show validity of proposed strategy.

Keywords: Independent Component Analysis (ICA), Power System Harmonic, Harmonic Source Identification.

I. INTRODUCTION

The costs of harmonic injections and mitigations are important issues in deregulated networks. Due to this reason, identification and measurement of harmonic sources studies have become an important issue in electric power systems [1]. Harmonic studies are considered as of two types. In the first type known as the forward harmonics analysis, the harmonic sources in a power system are assumed to be known and harmonic load-flow is carried out to determine the propagation of harmonics in the network. The second one, in the reverse harmonic analysis method, the aim is to identify the harmonic sources in a power system from a set of available measurements.

During the last decade, interest has been paid for solving the reverse harmonic problem. The harmonic state estimation (HSE) consists of a process which is the reverse of a simulation process [2-11]. Simulators determine the power system response to harmonic injection in one or more locations. The HSE algorithm is based on the network topology and the corresponding harmonic frequency admittance matrices, passive (linear) loads, PQ meter locations and measurements. One of the earlier methods [2] identifies sources of harmonic signals in electric power systems by using the least square based state-estimation technique to identify the locations of the harmonic sources.

An algorithm to estimate the partial harmonic state of the network is developed using a limited number of measurements [8]. The number and the location of harmonic measurements for HSE are determined from observability analysis [8-10]. All of these methods use traditional techniques that demand a total observability from the measurement system or a mathematical method to find a harmonic response in a wide solution space.

Estimation of the network harmonic distortion states is a complex problem. The main problems for harmonic analyses have the following issues.

Number of measurements: It is not easy and economical to obtain a large number of harmonic measurements due to cost of instrumentation installation, maintenance, and related measurement acquisition issues. Thus, the measurements can't be provided for all buses. Another important aspect is related to the synchronization data from different PQ meters. Thus, many research, focused on solving these problems with high technology, such as GPS clock for measurements, and intelligent computation theory [8, 9].

It is therefore desirable to estimate the harmonic sources with less knowledge of network topology and parameters, using only a small number of harmonic measurements. Intelligent computation can be used as a good hand to evaluate harmonic sources, as it is herein proposed. Blind Source Separation (BSS) techniques have received attention in applications where there is little information available on underlying physical environment and sources [12-15]. The BSS algorithms estimate source signals from observed mixtures data (measurements data). One of the important techniques for solving BSS problem is Independent Component Analysis (ICA), which is based on the statistical independence of source signals [13, 14].

This paper considers a new vision on result of ICA method for estimate nonlinear load location in the electric distribution system. The measuring management system to solve synchronization problem is explained. By using information technology (IT), the power quality monitors are connected to each other and share their data with each other. The data analyzed by several power quality monitors are gathered by main server system through network connection.

The structure of this paper is organized as follows: The next section describes the theory of Independent Component Analysis. Section 3 presents and analyzes the outline of harmonic source estimation and presents of the proposed method. The last section 4 uses the proposed method for a practical case study. That is of an industrial distribution zone.

II. THEORY OF INDEPENDENT COMPONENT ANALYSIS

Blind Source Separation (BSS) techniques have received attention in applications where there is little information available on underlying physical environment and the sources. The only available information is the measurements, which is a mixture of the sources. The BSS techniques are based on certain properties of sources such as statistical independence. Independent component analysis (ICA) is a statistical technique whose main application is solving BSS problem. The ICA transforms the observed signals into mutually statistically independent signals [13]. The linear mixing model of ICA, with assuming no noise, is given as:

$$X\left(t_i\right) = AS\left(t_i\right) \tag{1}$$

Where:

$S(t_i) = [S_1(t_1), \ldots, S_N(t_i)]^T$ is the N-dimensional vector of unknown source signals having independent component, $X(t_i) = [X_1(t_1), \ldots, X_M(t_i)]^T$ is the M-dimensional vector of observed signals, $A = [a_{ij}]_{M*N}$ is an unknown nonsingular mixing matrix, and t_i is the time or sample index.

The basic problem of ICA is to find a separation matrix W_{N*M} without knowing $S(t)$ and A make $Y(t) = W*X(t)$ is the estimation of $S(t)$ the BSS is based on the following assumption:

First, source vector $S(t)$ is mutually statistics independence, and only one of them is subject to Gaussian distribution. Second, the number of sensor is greater than or equal to source signal.

The separation matrix "W" is unknown matrix that must be obtained using an optimal method. To simplify the ICA algorithm, signals are preprocessed by centering and whitening. Centering transforms the observed signals to zero-mean variables and whitening linearly transforms the observed and centered signals, such that transformed signals are uncorrelated, have zero mean, and their variances equal unity. There are different approaches for estimating the ICA model using the statistical properties of signals. One of the most conventional methods is fast ICA algorithm. The procedure of this algorithm for estimating one of the independent sources is as follow [13, 14]:

Step 1- Center the observed signals (centering transforms the observed signals to zero-mean variables). Make expectation of observed signal equal to 0, whitening $X = X - E\{X\}, H = D^{-\frac{1}{2}}F^T X$, where, H is the observed signal. After whitening, D, F, are eigenvalue and eigenvector of covariance matrix ($E\{X.X^T\}$).

Step 2- Choose an initial for vector "w" with norm 1.

Step 3- Update vector "w" as:

$$w \leftarrow E\left\{x_u g\left(w^T x_u\right)\right\} E\left\{g'\left(w^T x_u\right)\right\} w .$$

where, G operator is a differentiable nonlinear function, which measures the nonlinear autocorrelation degree of the estimated source signal; g is the derivative of G. Three choices of G are given in [15].

Step 4- Orthogonalize w via $w \leftarrow w - \sum_{i=1}^{lenght\,(w)} (ww^H)w$

Step 5- Normalize w by w -----$w/||w||$

Step 6- If $\|w_{new}|$-$|w||>\epsilon$, $w = w_{new}$, and go back to step 3; else go to step 7.

Step 7- Obtain optimum solution $W = [W_1^*, W_2^*, \cdots, W_g^*]$

III. OUTLINE OF PROPOSED HARMONIC SOURCES ESTIMATION METHOD

A. Harmonic Source Amplitude Estimation and Identification of Harmonic Bus Location

A general mathematical model relating the measurement vector V to state vector I, to be estimated, can be formulated as follows:

$$V_h\left(t_i\right) = Z_h I_h\left(t_i\right) \tag{2}$$

where, $[I_h]$, $[Z_h]$ and $[V_h]$ are the bus injection current vector, bus impedance matrix, and bus voltage vector at the kth harmonic order, respectively.

Now, at the buses where the nonlinear (harmonic) loads are connected, the value of I_h is non-zero and the other buses where there are no harmonic loads, the value of I_h is zero. If the vector $[I_h]$ can be estimated accurately, harmonic buses would be identified correctly. Comparing the measurement model in Equation (2) with the ICA model in Equation (1), suggest that harmonic current and impedance matrix $I_h(t_i)$, Z_h can be estimated using ICA. In the BSS model, the mixing matrix "A" represents the impedance matrix $[Y_H]^{-1}$ in the harmonic domain.

Estimation with ICA requires statistical independence of sources. Therefore, we investigate the statistical properties of load profiles as reference [12]. The fast varying components of loads in each bus can be modeled as a stochastic process, which represents temporal variation. Generally, electrical loads are not statistically independent because of the slow-varying component. This dependency can be removed by applying a linear filter to observed data [12, 15]. Therefore, in this study we use fast varying components to estimate the independent sources.

The harmonic sources identification problem consists evaluating the system state for each harmonic order. The measurement matrix (bus voltage) for each harmonic order is usually available by PQ measurement system. As PQ meters costs are considerably high, a few measurement points are generally available. Since, harmonic analyze have the following problems:

A- Number of Measurements: For an actual power system, it is easy to obtain fundamental voltages at all substations, but harmonics are not always measured at all substations.

B- Synchronization of Harmonic Data: Synchronization of harmonic voltages between measurements at every substation is necessary. It is difficult to maintain the synchronization solely on the basis of the conventional measurement that is carried out at each substation individually.

In order to overcome these problems, a practical method of harmonic synchronization measurements is proposed. The architecture of power quality management system is shown in Figure 1. Power quality monitoring systems (PQMS) measure and detect power quality events as: voltage at main and other frequencies. The PQ data made by PQMSs saved and transfers to the analyzing main system (server) through the network line. The PQ meters calculate the RMS value of voltages and its harmonic components represented by the magnitude and phase angle of each individual harmonics.

The main analyzer system manages and controls PQMSs that are connected to system. The server sends time signals to PQMSs for synchronizing the time of PQMSs to the time of the server. Therefore, the time of whole system can be synchronized and the time stamp of each data can be meaningful. The main system analyzed individual data received from PQMSs for determine state of the system. The proposed method consists of two parts:

1- Load flow or main frequency state estimation for determine system state in main frequency.

2- Determination phase of harmonic voltage respect to main frequency state of system for network.

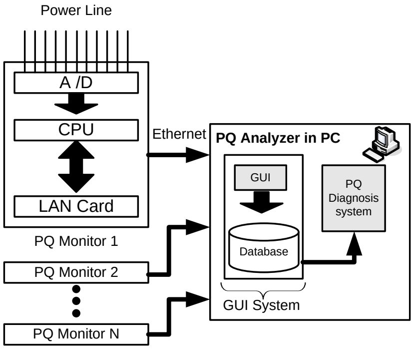

Figure 1. Architecture of proposed power quality management system

The flowchart in Figure 2 illustrates the proposed methodology for harmonic source identification techniques.

B. Fundamental Frequency State Estimation

The system fundamental frequency state, represented by the stage (i) in Figure 2, can be obtained in two ways. Load flow using the active and reactive power load measurements and the generators state, conventional state estimators, where power flow and voltage measurements compose a redundant measurement set. In this work, the fundamental frequency system state is obtained by using a conventional load flow model.

Active and reactive power in load buses and voltage in generation buses (incoming feeder in substation) are assumed to be known. In particular, for this specific application, the network simulated in "DIgSILENT" software for load flow algorithm determines the fundamental frequency system state [16]. From output results of this software, one can derive the voltage vector at load buses as a function of known supply voltages and load injected currents.

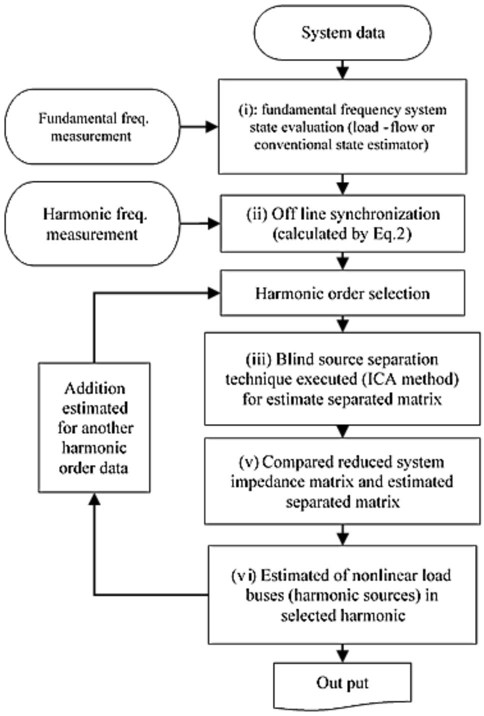

Figure 2. Flowchart of proposed harmonic source identification

C. Offline Synchronization for Each Harmonic Order

Waveforms stored in PQ meters as well as power flow information can be used to synchronize data from the meters. This consideration is a valuable alternative to reduce the costs of PQ monitoring systems. The voltage or current measured values in a network bus, for a harmonic order, are available in magnitude and angle. As the PQ meters also provide the fundamental frequency data, the harmonic angles can be referenced to the fundamental frequency values. By taking as reference the bus angles obtained by the load flow the harmonic angles, for each harmonic order, are able to be synchronized. This step is represented by the stage (ii) of Figure 2. The phasor $\bar{V}_1^i$ regarding the voltage at bus *i*, can be written as:

$$V_1^i = \left|v_1^i\right| \exp_1^{je_i} \tag{3}$$

In PQ monitoring systems where information regarding the Phasor of harmonic voltages are not known. The Phasors in Equation (3) that correspond to the system state at the fundamental frequency, and especially the phase angles $\theta_1^i, i = 1,...,n$, are used by the algorithm to adjust the Phasor angles for the different harmonic frequencies, which are measured by the PQ meter. In this way, a given measured harmonic voltage at bus *i*, which is an output from the meter, is as follows:

$$\bar{V}_{hM}^i = \left|V_{hM}^i\right| \exp^{j\phi_{hM}^i} \tag{4}$$

This can be adjusted to:

$$\bar{V}_{hM}^i = \left|V_{hM}^i\right| \exp^{j(\phi_{hM}^i + h\theta_1^i)} = \left|V_{hM}^i\right| \exp^{j\theta_{hM}^i} \tag{5}$$

This procedure promotes the synchronization of measurement information according to the variations of the harmonic voltage angles with respect to the fundamental frequency voltage, at each system bus.

This method provides a simple technique to compensate a possible unavailability of more sophisticated GPS based PQ meters that would provide synchronized Phasors at different sites.

IV. IDENTIFICATION OF HARMONIC BUS LOCATION

The main goal of ICA technique is the estimation of separation matrix W, corresponding to the (pseudo) inverse of mixing matrix A. This section focuses on the separating matrix W and mixing matrix A for the location estimation of harmonic sources. The main scheme of the approach is to estimate the approximate system measurement matrix with ICA and use this matrix for the location estimation of harmonic sources. The measurement matrix is actually the system impedance matrix. Since, the voltage measurements are considered in limited buses the reduced measurement matrix represents the linear mixing model with limited measurement and source is as follow:

$$[V_h]_{1*M} = [Z_{h\,red}]_{M*N}[I_h]_{1*N} \tag{6}$$

where, $[V_h]_{1*M}$ is a vector of voltage observed in M buses, and $[Z_{h\text{-}red}]_{M*N}$ is a reduced impedance matrix. Those rows correspond to measurement buses and columns corresponding to number of system buses (all possible locations of harmonic sources).

The reduced impedance matrix provides a reference map for location of sources. The main objective of the algorithm is to find the matching columns of the normalized estimated mixing matrix and normalized system impedance matrix, which will correspond to the harmonic source locations. Thus, system impedance matrix, at known harmonic frequencies, is the estimated mixing matrix A through ICA. Since, in the ICA algorithm the inverse of mixing matrix Z_h (e.g. Y_h) is estimated, if the harmonic current estimation error be small, it can be said that the inverse of Y_h ($[Z_{h\text{-}est}]$) is an acceptable estimation of $[Z_h]$. Thus, the procedure of identifying harmonic bus location, represented by the stage (V, VI) in Figure 2 can be obtained as follow:

Step 1- System impedance matrix is created (for each harmonic separated).

Step 2- Bus reduced impedance matrix $[Z_{h\text{-}red}]_{M*N}$ are considered the rows numbered on the represent the location of measurements.

Step 3- Estimated mixing matrix by Fast-ICA method named $Z_{est\text{-}n}$.

Step 4- Normalized reduced impedance matrix and estimated mixing matrix by each column with respect to maximum element in each column and obtain two matrices named $Z_{red\text{-}n}$ and $Z_{est\text{-}n}$.

Step 5- Matching the columns of the normalized measurement matrix and the estimated mixing matrix with each other to create a new matrix which their elements have the following objective function:

$$\mathit{\Delta}(j,i) = \min\left(\sum_{k=0}^{m}\sum_{l=1}^{m} \frac{\left| Z_{red,n}(l+k,i) Z_{est,n}(l,j) \right|}{Z_{red,n}(l+k,i)} \right) \tag{7}$$

$$\langle \text{if} \quad (l+k) \quad m \Rightarrow l+k=k \rangle$$

There is the search space of objective function is $(M*N)*M$, the number of the columns of reduced estimated mixing matrix and reduced measurement matrix). Thus, a column of estimated mixing matrix, which has minimum distance with the kth Column of measurement matrix, represents a harmonic source located at the k_{th} bus of the electric network.

Step 6- The minimum of each row in new established matrix $\Delta_{m,n}$ (combination columns of two matrixes $Z_{red\text{-}n}$ and $Z_{est\text{-}n}$) denoting that there are harmonic sources.

Step 7- All the matrices and vectors can be established for each harmonic order of interest, (Start from step 1).

V. CASE STUDY

The case study single line diagram is shown in Figure 3. The locations of the harmonic measurements are in buses 3, 4, 6, 8 and 13. The network is a part of distribution system in Tabriz Salimi industrial zone. This area is fed from 132/20 kV substation with "YN D11" vector group transformer. The feeder (No. 1) is assumed to be a balanced three-phase system. Total peak load of this area is 25 MW. The historical voltage data of a specified period are collected from low voltage side of distribution consumer's substations. The main functions of the PQ meters are only to collect the data of voltage and its phase angle respect to main frequency voltage in each harmonic order at installed point. Data are transferred through Ethernet (GPRS) communication to an analyzer computer.

Table 1. Errors between estimated and actual smoothed harmonic current profiles at buses 5, 9, 12

		5th harmonic	7th harmonic	11th harmonic
Correlation Coefficient	Bus 5	0.973	0.971	0.979
	Bus 9	0.9541	0.9701	0.9788
	Bus 12	0.9567	0.9669	0.9636
Maximum Percentage Error (%)	Bus 5	8.33	4.48	8.92
	Bus 9	12.51	4.79	14.39
	Bus 12	11.93	8.17	4.86
Mean Absolute Error (%)	Bus 5	0.66	0.78	0.66
	Bus 9	1.15	1.11	1.04
	Bus 12	0.84	1.21	0.58

In this study, the voltage domain in each harmonic order was 1-min. During a 24-h period, 1440 data points for each node. The network simulated in "DIgSILENT" software to compare the results of purposed method and harmonic load flow. Harmonic measurement vectors (the harmonic bus voltage) are simulated by harmonic power flow. The "DIgSILENT" program was modified to carry out fundamental and harmonic power flow calculations. Figure 4 shows profile of 5th voltage harmonic at bus 5 for a weak.

A. Harmonic Current Amplitude Estimation

The harmonic voltage measurement vector applied to ICA algorithm for each harmonic separately. Output and results of algorithm is estimated current vector (sources), and pseudo impedance matrix. Figures 5, 6 and 7 show the actual and estimated harmonic current amplitude for harmonics 5, 7 and 11 at buses 5, 9 and 12.

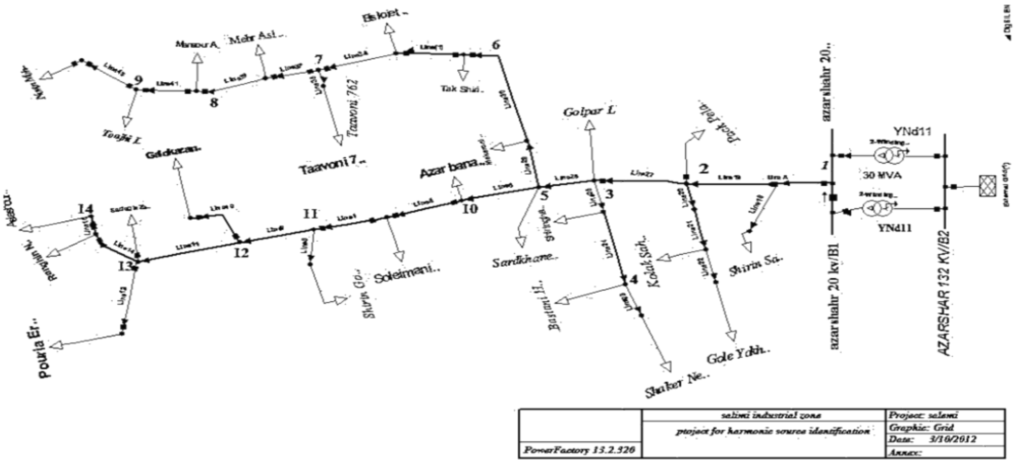

Figure 3. Single line diagram of feeder 1 in Tabriz Salimi Industrial Zone

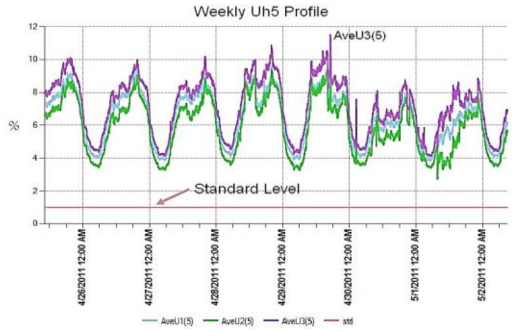

Figure 4. Measured values of 5th harmonic voltage at node 5

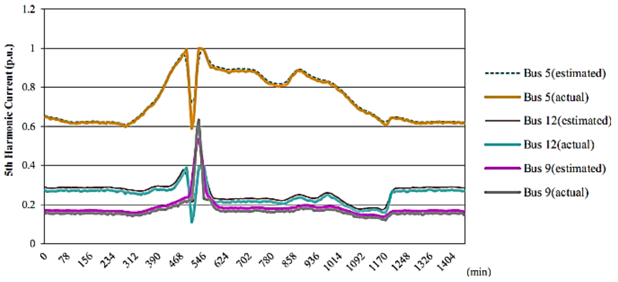

Figure 5. Actual and estimated 5th harmonic current at buses 5, 9 and 12

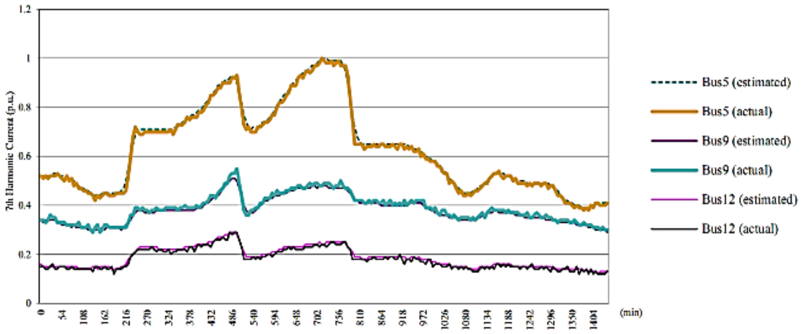

Figure 6. Actual and estimated 7th harmonic current at buses 5, 9 and 12

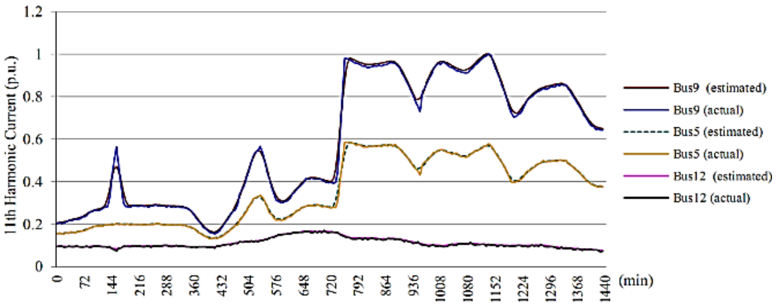

Figure 7. Actual and estimated 11th harmonic current at buses 5, 9 and 12

According to the results, Table 1 shows the error, and the correlation coefficients between estimated and actual source shapes. The results from mentioned Figures and Table 1 show that the proposed algorithm is capable of estimating the sources (harmonic current) within a small error range. Correlation coefficients are close to 1, indicating the matching of high accuracy between estimated and actual harmonic currents.

B. Identification of Harmonic Bus Location

Suppose that the harmonic voltage meters are placed at buses 3, 4, 6, 8 and 13. The network impedance matrix Z at 5th harmonic (absolute value) is:

$$\begin{bmatrix} 4.83 & 4.84 & 4.84 & 485 & 4.85 & 4.85 & 4.85 & 4.85 & 4.85 & 4.85 & 4.85 & 4.85 & 4.85 & 4.85 \\ 4.84 & 5.11 & 4.84 & 4.85 & 4.85 & 4.85 & 4.85 & 4.85 & 4.85 & 4.85 & 4.85 & 4.85 & 4.85 & 4.85 \\ 4.84 & 4.84 & 5.01 & 5.01 & 5.01 & 5.01 & 5.01 & 5.01 & 5.01 & 5.01 & 5.01 & 5.01 & 5.01 & 5.01 \\ 4.85 & 4.85 & 5.02 & 5.33 & 5.02 & 5.02 & 5.02 & 502 & 5.02 & 5.02 & 5.02 & 5.02 & 5.02 & 5.02 \\ 4.84 & 4.84 & 5.01 & 501 & 5.15 & 5.15 & 5.15 & 5.15 & 5.15 & 5.15 & 5.15 & 5.15 & 5.15 & 5.15 \\ 4.84 & 4.84 & 5.01 & 5.01 & 5.15 & 6.04 & 6.04 & 6.04 & 5.15 & 5.15 & 515 & 5.15 & 5.15 & 515 \\ 4.84 & 4.84 & 5.01 & 5.01 & 5.15 & 6.03 & 631 & 6.04 & 5.14 & 5.15 & 5.15 & 5.15 & 5.15 & 5.15 \\ 4.84 & 4.84 & 5.01 & 5.01 & 5.15 & 6.03 & 6.03 & 6.31 & 5.15 & 5.15 & 5.15 & 5.15 & 5.15 & 5.15 \\ 4.84 & 4.84 & 5.01 & 5.01 & 5.15 & 5.15 & 5.15 & 5.15 & 5.92 & 5.92 & 5.93 & 5.93 & 5.93 & 5.93 \\ 4.84 & 4.84 & 5.01 & 5.01 & 5.15 & 5.15 & 5.15 & 5.15 & 5.9 & 6.1 & 5.93 & 5.93 & 5.93 & 5.93 \\ 4.84 & 4.84 & 5.01 & 5.01 & 5.15 & 5.15 & 5.15 & 5.15 & 5.92 & 5.92 & 6.07 & 6.07 & 6.07 & 6.07 \\ 4.84 & 4.84 & 5.01 & 5.01 & 5.15 & 5.15 & 5.15 & 5.15 & 5.92 & 5.92 & 6.07 & 6.22 & 6.07 & 6.07 \\ 4.84 & 4.84 & 5.01 & 5.01 & 5.15 & 5.15 & 5.15 & 5.15 & 5.92 & 5.92 & 6.07 & 6.07 & 6.24 & 6.07 \\ 4.84 & 4.84 & 5.01 & 5.01 & 5.15 & 5.15 & 5.15 & 5.15 & 5.92 & 5.92 & 6.07 & 6.07 & 6.07 & 6.36 \end{bmatrix}$$

The reduced impedance matrix Z_{red} is obtained from 3, 4, 6, 8 and 13 rows. The $Z_{red\text{-}n}$ (normalized by maximum of each column) is as follows:

$$\begin{bmatrix} 0.99 & 0.99 & 0.96 & 0.96 & 0.94 & 0.8 & 0.8 & 0.76 & 0.81 & 0.81 & 0.79 & 0.79 & 0.77 & 0.79 \\ 1 & 1 & 1 & 1 & 1 & 0.85 & 0.85 & 0.82 & 0.87 & 0.87 & 0.85 & 0.85 & 0.82 & 0.85 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0.87 & 0.87 & 0.85 & 0.85 & 0.82 & 0.85 \\ 1 & 1 & 1 & 1 & 1 & 0.85 & 0.85 & 0.82 & 1 & 1 & 1 & 1 & 0.97 & 1 \\ 1 & 1 & 1 & 1 & 1 & 0.85 & 0.85 & 0.82 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}$$

From the ICA method estimated mixing matrix is:

$$Z_{est} = \begin{bmatrix} 0.182 & 0.1578 & 0.1359 \\ 0.265 & 0.2532 & 0.2042 \\ 0.2268 & 0.3565 & 0.7089 \\ 0.2326 & 0.6003 & 0.3171 \\ 0.221 & 0.4023 & 0.895 \end{bmatrix}$$

$$Z_{est,n} = \begin{bmatrix} 0.6867 & 0.2628 & 0.1519 \\ 1 & 0.4218 & 0.2281 \\ 0.8558 & 0.5938 & 0.7920 \\ 0.8777 & 1 & 0.3543 \\ 0.8339 & 0.6701 & 1 \end{bmatrix}$$

The resulting matrix from Equation (5) given as:

$$\text{Compared matrix} = \begin{bmatrix} 0.74 & 0.75 & 0.71 & 0.69 & 0.26 & 0.26 & 0.36 & 0.4 & 0.4 & 0.43 & 0.43 & 0.47 & 0.47 & 0.43 \\ 2 & 2 & 2 & 2 & 2 & 1.6 & 1.6 & 1.5 & 1.7 & 1.8 & 1.7 & 1.7 & 1.6 & 1.7 \\ 2.5 & 2.4 & 2.4 & 2.4 & 2.4 & 2.1 & 2.1 & 2.1 & 2.2 & 2.2 & 2.2 & 2.2 & 2.18 & 2.2 \end{bmatrix}$$

The minimum of each row in the above matrix shows candidate of present harmonic source. Then, they can be obtained as follow:

Row 1: 0.26 in column 6, 7
Row 2: 1.6 in column 7, 8, 13
Row 3: 2.1 in column 6, 7, 8

The minimum of above array that correspond to buses 6, 7, 8 and 13 are to be with huge probability place of harmonic currents injectors.

VI. CONCLUSIONS

The ICA is used to estimate the harmonic currents amplitude without prior knowledge of network topology and parameters and to identify the location of harmonic buses. This method is based on the statistical properties of loads. The proposed algorithm is validated using computer simulation data. The simulation results for an industrial distribution zone show that harmonic currents can be estimated by using only a small number of harmonic voltage measurements. Also, the proposed method for identification of the location of harmonic buses results in accurate location.

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