PERFORMANCE EVALUATION OF HARMONIC CURRENT ESTIMATION USING INDEPENDENT COMPONENT ANALYSIS

Supriya.P, T.N.Padmanabhan Nambiar
Department of Electrical and Electronics Engineering,
Amrita Vishwa Vidyapeetham, Coimbatore, India
910422 2656422, p_supriya@cb.amrita.edu,tnp_nambiar@cb.amrita.edu

Abstract: *An augmented use of non-linear loads results in generation of harmonics, which is difficult to estimate in electric power systems. Using, Independent Component Analysis (ICA) methods like fastICA (FICA)the harmonic currents can be estimated without the knowledge of the topology of the system, particularly when the probability distribution of majority of the harmonic sources is non-gaussian. A typical scenario with all the harmonic sources close to Gaussian is considered and hence efficient variant fastICA (EFICA) algorithm is attempted in the paper. A harmonic state estimation using ICA is implemented on an IEEE 14 bus system and on a laboratory three bus model. A performance evaluation between the two methods of ICA for harmonic current estimation is done in the form of recording and evaluating the infinitesimal error that exists between the actual and estimated harmonic currents for the two interconnected bus systems. The graphical results of both the systems for the two methods also point to the superior performance of EFICA algorithm.*

***Key words**- Harmonic State estimation;Mixing/Demixing matrix; FastICA;Efficient variant fastICA*

1.Introduction:

With the advent of power electronics, non linear loads are inherently present in power systems. The non linear loads inject harmonics into power system networks which propagate into the system. The methods available in literature for estimating the level of harmonics at different frequencies employ information on the topology of the interconnected network. However, using time structured Independent Component Analysis (ICA) the harmonic estimation can be carried out independent of the topology of the system [1-2]. One of the main assumptions for ICA is that only the probability density function of the source is known.

Ekrem Gursoy et al suggested the use of ICA for estimating the harmonics in power system and did a theoretical simulation using FastICA algorithm [1].The FastICA algorithm is based on maximization of non-gaussianity. It is known to converge faster and is simpler to design owing to the absence of a learning parameter. In the presence of finite data samples, FICA's validity is lost. The difference arises due to the variance of the samples which is well compensated in EFICA [3-4]. However, most of the non linear loads possess a near normal or gaussian probability distribution. An accurate harmonic estimation under such a scenario becomes significant. Hence, the EFICA algorithm which is suited for generalized gaussian distribution is attempted in this work. A simulation study is carried out on an IEEE 14 bus along with an experimental verification of the performance edge of EFICA on a three bus laboratory model.

Section two discusses the problem formulation and its relation to harmonic state estimation along with the algorithms of FICA and EFICA. The technique for the generation of data and the brief mention of the sources of the IEEE 14 bus along with the method for implementing the algorithm is given in Section three. Section four gives the results of the current profiles obtained for an IEEE 14 bus system for both the algorithms along with analysis of the error. The descriptions of the three bus laboratory model along with the results of implementation of the two algorithms are presented in Section five. Section six lists the conclusions of the work and directions for future work.

2. Problem Formulation:

2.1 Basics of ICA

Generally, the noiseless linear model of ICA problem is assumed as

$$\boldsymbol{x = As} \qquad (1)$$

where **A** is an R × R mixing matrix, **s** is an original source vector which has P independent components and **x** is an R ×1 observation vector. The output vector is represented as Y. The ICA algorithm aims at determining a matrix W to undo the mixing effect. That is, the output will be given by

$$\boldsymbol{Y = Wx} \qquad (2)$$

where **Y** is an estimate of the sources

The harmonic state estimation problem is:

$$\boldsymbol{I_h = Y_h V_h} \qquad (3)$$

where $\boldsymbol{V_h}$ is the harmonic voltage vector, $\boldsymbol{I_h}$ is the harmonic current vector and $\boldsymbol{Y_h}$ is the harmonic admittance. The harmonic state estimation problem is considered without a noise parameter and is formulated as a BSS problem. The two ICA algorithms are briefly given for the sake of clarity.

2.2 Fast ICA Algorithm

Fast ICA is based on a form of non-gaussianity called as negentropy which is similar to entropy in information theoretic models of ICA. Since evaluation of negentropy is cumbersome, an equivalent activation function weight updating rule is used [6].To prevent various units from converging to the same maxima, the outputs are decorrelated after each iteration using Gram-Schmidt like decorrelation. After estimating $w_1 \ldots w_p$, one unit fixed point algorithm for w_{p+1} is run and after every iteration the projections of previously estimated p vectors are subtracted from w_{p+1} which is normalized as in steps five and six below. The various steps of the algorithm are as follows:

1. Prewhiten and decorrelate the observed vector **X**.
2. Choose N, the number of independent components and set p=1.
3. Select a random vector w_p.
4. Set

$$\begin{aligned} &\mathrm{w}_{pa} = E\{x(w^H x) * g(w^H x^2)\} \\ &\mathrm{w}_{pb} = E\{g\left|w^H x^2\right| + w^H x^2 g'(w^H x^2)\} w \\ &\mathrm{w}_p = \mathrm{w}_{pa} - \mathrm{w}_{pb} \end{aligned} \qquad (4)$$

5. Orthogonalize w_p via

$$\boldsymbol{w_p = w_p - \sum_{j=1}^{p} (w_j w_j^{\,H}) w_p} \qquad (5)$$

6. Normalize w_p by:

$$\boldsymbol{w_p^{\,new} = w_p \big/ \left\| w_p \right\|} \qquad (6)$$

7. If $\boldsymbol{\sum \left| w_p^{\,new} \right| - \left| w_p \right| > \varepsilon}$, $\mathrm{w}_p = \mathrm{w}_p^{\,new}$ repeat from step2
8. Let p = p+1, if p ≤ N, iterate from step 2.
9. Undo the prewhitening and decorrelation, to obtain original values instead of scaled values.
10. Compute the output as given in (2).

2.3 Efficient Variant Fast ICA Algorithm(EFICA):

The variance error in fast ICA is compensated in EFICA by resorting to three simple steps. The weight **W** from FICA is taken as the preliminary estimate. Next, based on the numerical value of fourth order moment, an adaptive choice of non- linearity function is made. Finally, a final tuning is carried out using the non- linearity and the parameters c_p.

The various steps of the EFICA algorithm are listed below:

1. Prewhiten and decorrelate the observed vector X.
2. For the observed data X, this yields

$$\boldsymbol{Z = C^{-1/2}\left(X - \overline{X}\right)} \qquad (7)$$

   where C is the covariance matrix of the sample and $\overline{\mathrm{X}}$ is the sample mean.
3. The fast ICA is applied using the non linear function tanh and w_p estimates are got.
4. Reliable estimates are got using saddle points.

5. Define $\overline{v_p} = \left(\overline{w_p^{sym}}\right)^T Z$ (8)

6. The fourth moment of pth source signal is computed as:

$$\overline{m_{4p}} = {1_N \overline{v_p}^4}/{N} \tag{9}$$

To eliminate the residual error of the algorithm, non linear functions are assigned according to the range of

$$g_p(x) = \begin{pmatrix} x\exp\left(-\eta_1 |x|\right) & \text{for } \overline{m_{4p}} > 3 \\ \text{sign}(x).|x| \min^{\alpha_p - 1} & \text{for } 1.8 < \overline{m_{4p}} \le 3 \\ \text{sign}(x).|x|^{14} & \text{for } m_{4p} \le 1.8 \end{pmatrix}$$

7. The weights $\overline{w_p^{sym}}$ are got from step 3 and a constant k is calculated:

$$k = \left|\overline{w_p^T}\,\overline{w_p^{sym}}\right| \tag{10}$$

If k> 0.95, the one unit fast ICA is iterated. Otherwise $\overline{w_p^{sym}}$ is retained with non-linear function value chosen as tanh.

8. If $\overline{W^+} = [w_1^+, \ldots\ldots w_d^+]^T$ is the result after the convergence of the one unit algorithm, a tuning step is necessary as given in steps 10 and 11.

9. For tuning, five specific parameters based on non linear function and its derivatives are formulated:

$$\overline{\mu_p} = \overline{v_p}^T g_p\left(\overline{v_p}\right)/N \qquad \bar{\tau}_p = \left|\overline{\mu_p} - \overline{\rho_p}\right|$$
$$\overline{\rho_p} = \bar{1}_N^T g'_p\left(\overline{v_p}\right)/N \qquad \bar{\gamma}_p = \overline{\beta_p} - \overline{\mu_p}^2$$
$$\overline{\beta_p} = \bar{1}_N^T g^2_p\left(\overline{v_p}\right)/N$$

Based on these parameters, calculate

$$c_{pl} = \begin{cases} \dfrac{\bar{\tau}_l \bar{\gamma}_p}{\bar{\tau}_p\left(\bar{\gamma}_l + \bar{\tau}_l^{\,2}\right)} & \text{for } l \neq p \\ 1 & \text{for } l = p \end{cases}$$

10. The new weights are obtained from c_{pl} as :

$$\overline{W}^+_p = \text{diag}\left[c_{p1}, \ldots\ldots c_{pd}\right]\overline{W}^+$$
$$\overline{W_p}^{old} = \left(\overline{W}^+_p \overline{W}^{+\,T}_p\right)^{-1/2}\overline{W}^+_p$$
$$\overline{w_p}^{new} = \left(\overline{W_p}^{old}\right)_k^T$$

11. The value of v_p^{new} is redefined as:

$$v_p^{new} = Z^T w_p^{new} \tag{11}$$

12. Thus, the demixing matrix $\overline{W}^{new}$ is:

$$\overline{W}^{new} = \left[w_1^{new}, \ldots\ldots\ldots w_d^{new}\right] \tag{12}$$

13. Undo the prewhitening and decorrelation to get original magnitude instead of reduced values.

14. The output **I_h** is calculated as given in (2)

3. Methodology:

3.1. System Details

The IEEE 14 bus system [11] with three current sources is chosen as the test sample for the work is as shown in fig.1. Three current sources (ASD,SVC and HVDC) are assumed at buses three, six and eight respectively. The profiles of these sources are given in [2] and in [10]. The modeling of the linear loads, along with the methodology is also elaborated in [2].The harmonic analysis is implemented using the relation given in (3).

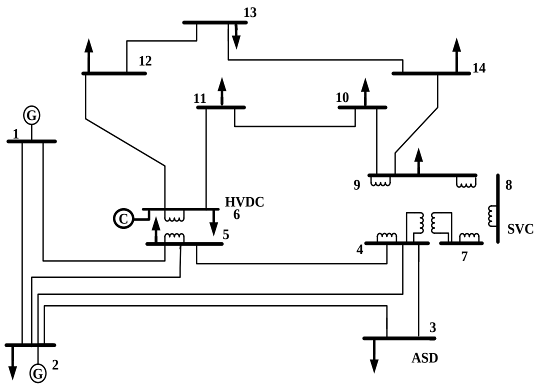


Fig.1 IEEE 14 bus System with harmonic Current Sources at Bus 3, 6 and 8

The equation (3) bears closeness to equation (1) which is the basic ICA model expression. In a deregulated power environment, the admittance details of the transmission lines may not be easily available. However, with the ICA model, the value of $\mathbf{I_h}$ can be evaluated from the available sensor readings ($\mathbf{V_h}$).

3.2. Generation of simulated data

The IEEE 14 bus test system is to be modeled with the power system components like transmission lines, linear loads [12] and the three current sources for the generation of observation data which forms the key component in order to apply the ICA analysis. The methodology employed for the generation of observation data (harmonic voltage) for ICA is as follows:

(1)The linear loads and the other power system components of the IEEE 14 bus system are modeled as in [12]. The harmonic sources are modeled as current sources ASD, SVC and HVDC [7-9]. Thus the admittance of the test system is formulated for a specific harmonic frequency (h = 5).

(2) The harmonic currents of ASD, SVC and HVDC at buses 3,6 and 8 are computed at this frequency while the harmonic current values at the remaining buses are taken as zero and a single harmonic voltage data is generated for the system at h = 5.

(3)Once the modeling of the power system components and the profiles of the loads at different frequencies ‘h’ is fixed, the random profile for the source is modeled as generalised Gaussian distribution to obtain 1440 samples(i.e. 1 sample per minute) on a specific day and the two ICA algorithms are applied.

(4)Using this profile, the harmonic current data is generated at buses 3, 6 and 8 for 1440 readings. Substituting these readings for $\mathbf{I_{bh}}$ and $\mathbf{Z_h}$ **(**inverse of admittance of the test system**)** in the inverse equation (3) defined as: $\mathbf{V_{bh}}$=$\mathbf{Z_h I_{bh}}$, 1440 values for $\mathbf{V_{bh}}$ are obtained at h = 5.

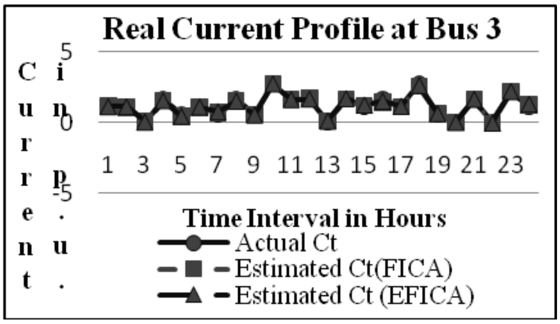
(5)Steps (1) to (4) are repeated for h = 7, 11, 13 and 17 .The corresponding $\mathbf{V_{bh}}$ data generated are defined as the (harmonic voltage) sensor readings.

3.3.Algorithm Implementation

Once the voltage sensor readings for the IEEE 14 bus test system are generated the various ICA algorithms are applied in the following manner:
Step 1: Determine the Harmonic Injection Buses (HIB) using total voltage harmonic distortion.
Step 2: Obtain the sensor readings at buses three, six and eight respectively.
Step 3: Apply FICA algorithm for the sensor readings (h = 5).
Step 4: Compute the error coefficients MAE, AME and MSE as defined in equations (13) to (15) for FICA algorithm.
Step 5: Repeat step (3) and step (4) for EFICA algorithm.
Step 6: Repeat for all harmonics.

4. Simulation Results:

The sensor readings are recorded throughout the entire day and the two blind signal processing algorithms (EFICA and FICA) are applied to the recorded readings. The current profiles obtained using the two algorithms are plotted for h = 5 along with the actual values and are depicted for bus 3, bus 6 and bus 8 in Fig.2, Fig.3 and Fig.4 respectively.



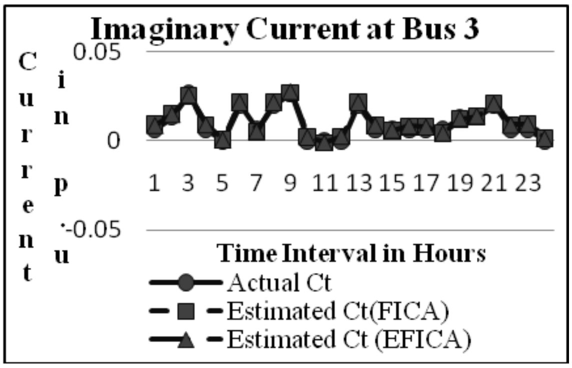


Fig. 2 Real and Imaginary Currents at Bus 3 for h = 5

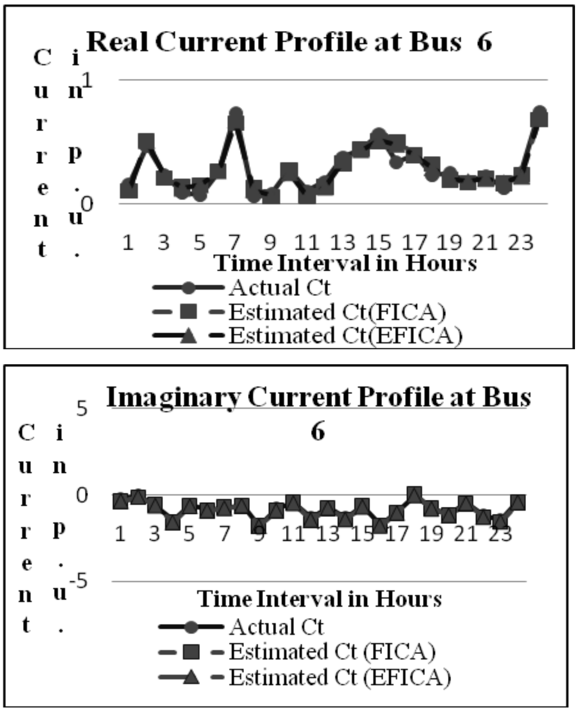
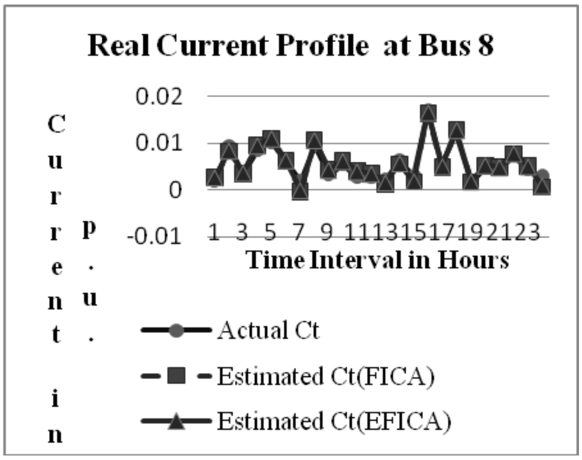


Fig. 3 Real and Imaginary Currents at Bus 6 for h = 5



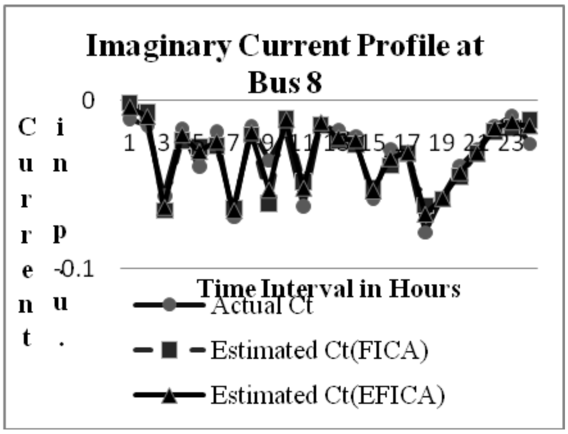


Fig. 4 Real and Imaginary Currents at Bus 8 for h=5

The harmonic analyses are done at harmonic frequencies h = 5, 7, 11, 13 and 17 as these are the dominant harmonic frequencies for the non linear loads considered and the graphs for the three non linear loads at h = 5 is only included in the work. The estimated currents using EFICA and FICA appear to completely agree with the actual value as is evident from figures two, three and four respectively. However a miniscule error e_s (t) occurs

$e_s(t) = I_a(t) - I_e(t)$ where (I_e and I_a) are the estimated and actual current (I_e and I_a) values of current. The error is expressed in terms of three quantities namely maximum absolute error (MAE), mean absolute error (AME) and mean square error (MSE) and is defined as:

$$\mathrm{MAE}=\max(\mathbf{e_s(t)})_{t=1,2,\ldots..T} \tag{13}$$

$$\mathrm{AME}=\frac{1}{T}\sum_{t=1}^{T}\left|e_s(t)\right| \tag{14}$$

$$\mathrm{MSE}=\frac{1}{T}\sum_{t=1}^{T}\left|e_s(t)\right|^2 \tag{15}$$

The values of MAE, AME and MSE are evaluated for both real and imaginary part of the currents at buses three, six and eight for h = 5, h = 7 and h = 11.The computed values are tabularized in Table 1, Table 2 and Table 3.

Table 1 Error Analysis at Bus 3

Real Part of Bus 3						
	h = 5		h = 7		h = 11	
Error	EFICA	FICA	EFICA	FICA	EFICA	FICA
MAE	**0.4057**	0.441	**0.0027**	0.0386	**0.0383**	0.0565
AME	**0.0678**	0.0682	**0.0004**	0.0041	**0.0044**	0.0063
MSE	**0.0079**	0.0081	**0**	0	**0**	0.0001
Imaginary Part of Bus 3						
	h = 5		h = 7		h = 11	
Error	EFICA	FICA	EFICA	FICA	EFICA	FICA
MAE	**0.0116**	0.0147	**0.0068**	0.1597	0.0205	**0.0133**
AME	**0.0016**	0.00186	**0.0009**	0.0169	0.0023	**0.0015**
MSE	**4E-06**	5.8E-06	**0**	0.0005	0	**0**

Table 2 Error Analysis at Bus 6

Real Part of Bus 6						
	h = 5		h = 7		h = 11	
Error	**EFICA**	FICA	**EFICA**	FICA	**EFICA**	FICA
MAE	**0.285**	0.316	**0.1811**	0.2434	**0.0847**	0.0314
AME	**0.042**	0.045	**0.0231**	0.029	**0.0127**	0.0051
MSE	**0.003**	0.003	**0.001**	0.0015	**0.0003**	0
Imaginary Part of Bus 6						
	h = 5		h = 7		h = 11	
Error	EFICA	FICA	EFICA	FICA	EFICA	FICA
MAE	**0.443**	0.69	**0.0359**	0.0513	**0.0039**	0.0042
AME	**0.051**	0.082	**0.0047**	0.0061	**0.0006**	0.0005
MSE	**0.005**	0.011	**0**	0.0001	**0**	0

Table 3 Error Analysis at Bus 8

Real Part of Bus 8						
	h = 5		h = 7		h = 11	
	EFICA	FICA	EFICA	FICA	EFICA	FICA
Error					**1.0e-03 ***	1.0e-03 *
MAE	**0.0069**	0.00772	**0.001**	0.002	**0.1449**	0.2946
AME	**0.0008**	0.00087	**2E-04**	3E-4	**0.0162**	0.0333
MSE	**1.0E-6**	1.3E-6	**0**	0	**0**	0
Imaginary Part of Bus 8						
	h = 5		h = 7		h = 11	
Error	EFICA	FICA	EFICA	FICA	EFICA	FICA
MAE	**0.0299**	0.042401	**0.009**	0.012	**0.0012**	0.0098
AME	**0.0054**	0.007745	**0.001**	0.002	**0.0001**	0.0011
MSE	**4.7E-5**	9.5E-5	**0**	0	**0**	0

The comparison of error values for EFICA and FICA algorithms indicate that the error is drastically reduced when EFICA algorithm is applied. However the computation time is about three times that of FICA under identical case studies.

This indicates that a compromise has to be made between memory (computation time) and accuracy when applying independent component analysis technique to any system. The prime aim of the work is to use this analysis further for either the design of mitigation equipment or for penalizing the perpetrators of harmonics with accuracy being more significant for both the applications. With the availability of high processing computers and other processors the implementation of such a scheme may not be a difficult task.

5. Experimental Analysis

A simple three bus system is setup in the laboratory for the purpose of analyzing harmonic state estimation using ICA algorithms. The three bus system is depicted in figure 5.

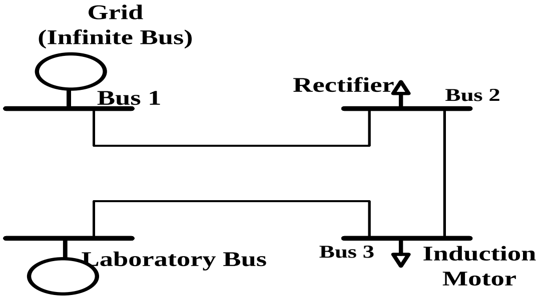


Fig. 5 Laboratory model of the three bus system

Bus 1 represents the grid supply which is connected to bus 2 through a transmission line. A three phase rectifier (TSTR16PB) acts as the non linear load on bus 2 and an induction motor (415 V, 4.7 A, 2.2 kW, 1450 r.p.m., 50 Hz) serves as the non linear load on bus 3. Two power quality analyzers (Fluke 434 and Fluke 435) are mounted at buses two and three to record the sensor readings (harmonic voltages). Bus three is provided with supply through the alternator called as the laboratory bus. The laboratory setup of the system is partly illustrated in figure 6.

Fig. 6 Laboratory Setup for HSE analysis

The power analyzers record only the magnitudes of the electrical quantities. The two non-linear loads represent customer loads which undergo random fluctuations. These random variations are recorded as sensor readings every five minutes at buses two and three respectively. The current magnitude evaluation is done by loading these 288 readings into Microsoft Excel and importing them to MATLAB where the FICA and EFICA algorithms are applied to the interconnected three bus model. The unknown currents are thus determined and portrayed in figure 7 respectively.

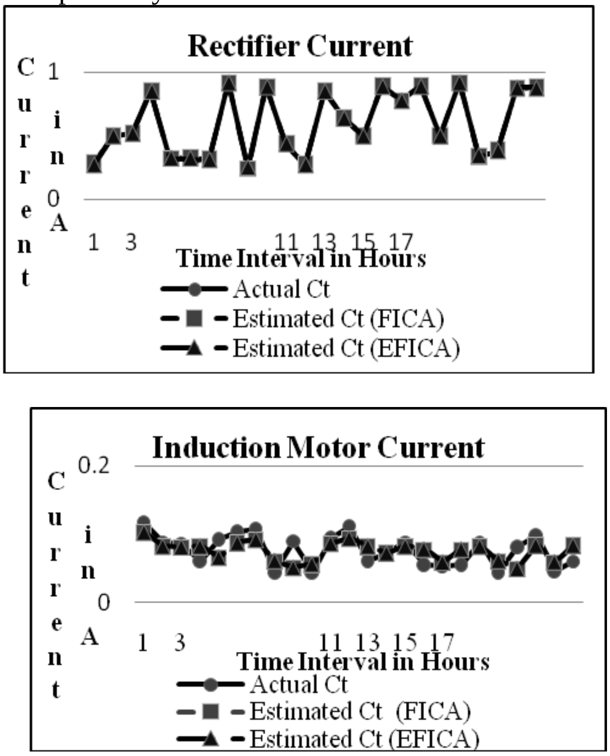


Fig. 7 Current Magnitude at bus 2 and bus 3 at h = 5

The current magnitudes with h = 5 loads agree well with the actual values. The wide difference is observed in the induction motor largely due to the dynamic nature of the load. However, this effect is reduced if more number of samples is considered or when more versatile algorithms are used for current computation. The effect of various errors defined in (13)-(15) for the rectifier load is given in Fig. 8 respectively.

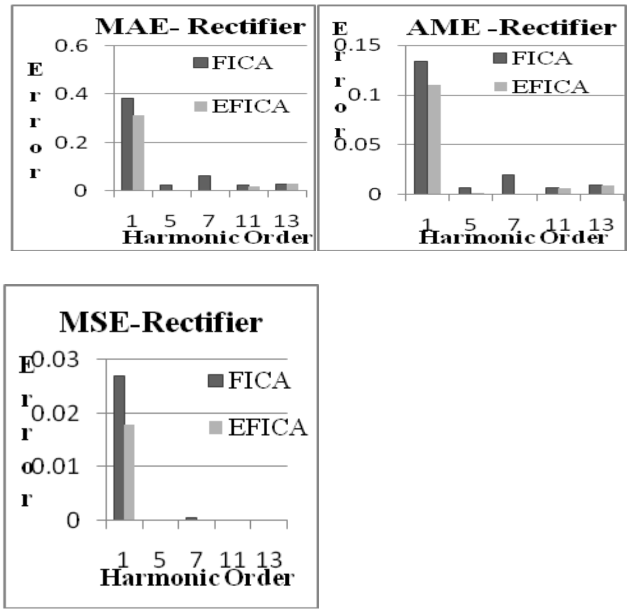


Fig. 8 Bar Chart indicating MAE, AME and MSE for rectifier

A comprehensive study of these bar charts illustrates the performance edge of EFICA algorithm over FICA algorithm.

6. Conclusions:

The harmonic state estimation is implemented on an IEEE 14 bus and on a three bus model using FICA and the more precise EFICA algorithms. Both the results point to the better performance of the EFICA over FICA indicating that most of the loads follow a Gaussian or close to Gaussian probability distribution. Since in the experimental setup also EFICA has higher accuracy than FICA it can be concluded that most of the loads even in real time case follow close to gaussian probability distribution. Harmonic current estimation thus encourages ICA algorithms which can be efficient for such a probability distribution. With larger number of samples better accuracy can be obtained for the experimental setup. The ICA based algorithms can be made more dynamic by integrating with other dynamic models.

References

1. Ekrem Gursoy, Dagmar Niebur: *Harmonic Load Identification Using Complex Independent Component Analysis*.In: IEEE Transactions on Power Delivery,XXIV (2009),No.5, p. 285-292.
2. Supriya.P, T.N.Padmanabhan Nambiar :*Tracking of Harmonic Load Profile using Simultaneous Blind Extraction method*. In Proceedings of the National Conference, RAEPESM-2011, March 2011. Gorakhpur India,Vol.1 P21 1-4.
3. Z. Koldovsky, P. Tichavsky and E. Oja: *Efficient Variant of Algorithm FastICA for Independent Component Analysis Attaining the Cramer-RaoLower Bound*. In: IEEE Trans. on Neural Networks, XVII (2006),No. 5,p. 1265-1277.
4. P. Tichavsky, Z. Koldovsky and E. Oja :*Speed and Accuracy Enhancement of Linear ICA Techniques Using Rational Nonlinear Functions*. In: Proceedings of 7th International Conference on Independent Component Analysis (ICA2007), Sept. 2007. p. 285-292.
5. Supriya.P,T.N.Padmanabhan Nambiar: *Harmonic Current Estimation using Blind Signal Processing Techniques*. In Proceedings of IEEE Conference on Signal Processing(ISCCN 2011) July 21-22. 2011,Kanyakumari, p116-120 .
6. Simon Haykin:Neural Networks and Learning Machines, PHI(India), (2009).
7. Wilsun Xu ,Hermann W. Dommel ,M. Brent Hughes ,Gay W.K. Chang and Le Tan : *Modelling of adjustable speed drives for power system harmonic analysis.* In *:* IEEE Trans Power Delivery, XIV(1999), No.2, p 595-601.
8. K.R.Padiyar : HVDC Power Transmission Systems, Tunbridge Wells, Kent, UK, New Academic Science Limited, Second Edition, (2011).
9. Mohammed Osman Hassan, S. J. Cheng, Zakaria Anwar Zakaria: *Steady-State Modeling of SVC and TCSC for Power Flow Analysis.* In Proceedings of the International MultiConference of Engineers and Computer Scientists 2009 Vol II IMECS 2009, Hong Kong, March 18 - 20, 2009, p1443-1448.
10. Supriya.P,T.N.PadmanabhanNambiar:*Estimation of Harmonic Voltages using Independent Component Analysis.* In Proceedings of International Conference on Sustainable Energy and Intelligent Systems(SEISCON 2011) July 20-22,2011,Chennai,India,p 218-222.
11. R. Abu-Hashim, R. Burch, G. Chang, M. Grady, E. Gunther, M. Halpin,C. Harziadonin, Y. Liu, M. Marz, T. Ortmeyer, V. Rajagopalan, S. Ranade,P. Ribeiro, T. Sim, and W. Xu:*Test systems for harmonics modeling andsimulation*. In : IEEE Trans. Power Delivery, XIV(1999), No. 2, p. 579-587.
12. Enrique Acha,Manuel Madrigal: *Power System Harmonics –Computer Modelling and Analysis,* John Wiley,2001,p.56-60.