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Enhancement of Harmonic State Estimation Using Harmonic Prediction

[1] Hussam M. M. Alhaj, Nursyarizal Mohd Nor, Vijanth S.Asirvadam and M. F. Abdullah

[1] Department of Electrical and Electronic Engineering, Universiti Teknologi PETRONAS, Malaysia
E-mail: [1]hussamalhaj13@hotmail.com

ABSTRACT

The world wide increasing using nonlinear loads, mostly consisting of power electronics devices in many applications that bring a great concern about power quality problems caused by these nonlinear loads, harmonics pollution is main concern of power quality issues due to its harmful effect on power system network, several harmonic state estimation "H.S.E" methods have been devolved to estimate the harmonic magnitude level and to identify the harmonic sources ,This paper presents a concept, method and function of harmonic state estimation and implementation of the singular value decomposition "S.V.D" algorithm on power system harmonic state estimation for partially observable systems with harmonic prediction method to compensate the loss of the observation and maintain the redundancy of the measurements. The result shown that the proposed harmonic prediction method can compensate the loss of the measurement and therefore; enhance the performance of "S.V.D" algorithm when the loss of observation occurs.

Keywords: *harmonic state estimation, observablity, singular value decomposition "S.V.D" algorithm, harmonic prediction*

1. INTRODUCTION

The presence of voltage and current waveform distortion is generally expressed in terms of harmonic frequencies which are integer multiples of the fundamental frequency [1].The main sources of the harmonics are the nonlinear loads such as arc furnace, fluorescent lighting and adjustable speed drives and other power electronic equipment that have been used in transmission and generation level such as Flexible AC Transmission System ("F.A.C.T.S") devices and static switch. When a source of sinusoidal voltage is applied to a nonlinear device or load, the resulting current is not perfectly sinusoidal. In the presence of system impedance this current causes a non-sinusoidal voltage drop and, therefore, produces voltage distortion at the load terminals [2].

The major adverse effects of the harmonics are the heating of the induction motors, transformers , capacitors and the over loading of neutrals and so on , Many techniques have been developed to mitigate the distortion (harmonic) and to avoid its harmful effect on power system network (such as active and passive filter). To do any action related to the mitigation of the harmonics the network has to be monitored and the harmonics level known in the network. Due to the size, complexity and high cost of power quality meters the system is not fully monitored, hence there is need for estimation. The main goal of harmonic state estimation is, therefore, to economically generate the best estimation of the harmonic magnitude and the source location at unmonitored bus bars from limited measurements [3].

This problem of harmonic state estimation first was introduced by Heydt in 1989[4] he used least square estimation to estimate the harmonic state and identifying the harmonic source and the problem of harmonic state estimation handled as an inverse of harmonic power flow. In [5, 6] adopting the traditional normal equation that use for fundamental frequency state estimation which require the system to be fully observable. To solve the problem of the observability the authors separate the observability analysis to determine solvability of the measurement equation first.

Reference [7] classified the bus bars to tow sets which Source of harmonic and non source of harmonic and used the information of non source to improve the observability. The singular value decomposition algorithm was introduced in [8,9] instead of normal equations to solve the underdetermined system and found this method more robust, however, it need higher computational cost and by inspection of the null space vectors gives the observability and particular solution can be determined. Harmonic state estimation via sparsity maximization to transform the system from unobservable to observable system under proper measurement arrangements Proposed in [10]. Artificial neural networks to provide initial estimates of the harmonic sources (pseudo – measurements) based on the measured harmonics and fundamental load flows and then improve the estimates by State estimation introduced in [11,12] .

Total least (TLS) square method to estimate the harmonic measurement errors with parameters errors presented in [13]. A new approach to harmonic state estimation is proposed by firstly classifying the network nodes into four types in [14].Utilization of Evolutionary Strategy advantage such as its modeling facilities as well as its potential to solve fairly complex problems presented in [15]. Although these efforts in harmonic state estimation, it is still challenge to estimate reliably all the network state variables in the system-wide or even in moderate size network when the measurements fewer than the state variables. Usually the harmonics measurements installed in the gird and via communication channel the harmonic information sent to the control unit where all the calculation and estimation done using computerize tools but sometimes this information been lost in random fashion due to communication error and this loss effect the performance of harmonic state estimation due to few numbers of measurements. Most of the works done in harmonic state estimation focusing in harmonic state estimation method or algorithm itself. In this paper the problem of harmonics information loss addressed and prediction method based on Finite Impulse Response ("F.I.R") Adaptive Filters with least mean square and Weights Update Based Error Displacement ("W.U.E.D") introduced to predict the future harmonics that can compensate the observation loss

The paper is organized as follows: first, the art of harmonic state estimation explained and the "S.V.D" and harmonic prediction methods were described and then Results and conclusion were discussed respectively.

2. BACKGROUND

2.1. State estimation

The general form of the state estimation which related the measurement set data vector z to the state variables vector x and the system topology is

$$z = H(x) + \varepsilon \qquad (1)$$

Where z is a $(m \times 1)$ vector of known measurements and x is a $(n \times 1)$ vector of state variables (unknown quantities) for which the equation must be solved. $H(x)$ Is a $(m \times n)$ measurement function relating the known measurements to state variables and ε is measurement error with standard deviation σ.

Equation (1) is widely solved as weighted lest square (WLS) which involves finding the $n-$ vector x that minimizes the index $j(x)$ where

$$j(x) = 1/2[(z - Hx)]^T W(z - Hx) \qquad (2)$$

Where

$$W = R_z^{-1} = 1/\sigma_i^2 \qquad (3)$$

R_z Is the measurement covariance matrix where σ_i^2 is the variance of the measurement error. W, can be used to represent meter accuracy or reliability. Engineering judgment is normally needed for the selection of W, and if measurement error is unknown, W is typically assumed to be a unit matrix, assuming that all measurements are equally accurate [16].

Differentiating $j(x)$ yields the first-order optimal conditions.

$$G\check{x} = H^T Wz \qquad (4)$$

Where $\check{x}$ is the state estimate and $G = H^T WH$ is the state estimation gain matrix.

$$H^T WH\check{x} = H^T Wz \qquad (5)$$

The equation (5) will be calculated usually using standard techniques such as "L.U" decomposition, back-substitution, Cholesky decomposition or Gauss-Jordan elimination. [17] State estimation problem can be classified to three situations. Over-determined system when the number of equations (m) greater than the number of unknown state variables (n) which $m > n$, completely determined system when the number of equations (m) equal to the number of unknown state variables (n) which $m = n$ and Under-determined system when the number of equations (m) less than the number of unknown state variables (n) which $m < n$.

The system is said to be observable if all state variables (x) can be determined from the measurement information (z) sometimes the system is not observable hence, Virtual measurements and pseudo – measurement are used to improve the observabiltiy, Virtual measurements are type of information does not need metering and pseudo – measurements is a kind of information we can get from historical dada. [16].

In the traditional state estimation which fundamental frequency state estimation the system is Over-determined or completely determined and full or partial observable due to abundant measurements devices such as revenue meters , therefore, a unique solution can be obtained by using standard techniques such as "L.U" decomposition, back-substitution, Cholesky decomposition or Gauss-Jordan elimination. However, in harmonic state estimation the technical challenge is to solve the measurements equations for underdetermined system, that is, systems with more unknowns than equations, $n > m$ due to the limit number of harmonics measurements and information. In these systems, a unique solution may not exist [16].

2.2. Singular value decomposition ("S.V.D")

Equation (1) in harmonic state estimation represent as

$$V(h)Y(h) = I(h) \qquad (6)$$

Where $I(h)$ representing the harmonic injection currents in each bus, $V(h)$ harmonic voltage in each bus, $Y(h)$ the system bus admittance matrix and (h) denote the harmonic order for instance at fundamental frequency $h = 1$.

Equation (5) in harmonic state estimation is usually underdetermined system due to limited harmonic measurements therefore, the matrix of the equation being singular and the solution by standard technique which normal equation cannot obtained however ("S.V.D") algorithm can provides stable and unique solution for partial observable system.[9] "S.V.D" is based on a theorem from linear algebra which says that a rectangular matrix A can be decomposed into product of three matrices , an orthogonal matrix U ,a diagonal matrix S and the transpose of an orthogonal matrix V . [18]

The theorem is usually presented something like this:

$$A_{m\times n} = U_{mm} S_{mn} V_{nn}^T \qquad (7)$$

Where the columns of U are orthonormal eigenvectors of AA^T , the columns of V are orthonormal eigenvectors of $A^T A$, and S is a diagonal matrix containing the square roots of eigenvalues from U or V in descending order which are called singular values [18].The columns of U correspond to the non-zero singular values and the columns of V correspond to the zero singular values are the column space and null space of A respectively[9].In underdetermined system while most traditional techniques fail, "S.V.D" is able to provide a particular solution and a null space vector for each singularity

$$[x] = [x_P] + \sum_{i=1}^{n-\mathrm{rank}\,A} k_i\,[x_{ni}] \qquad (8)$$

Where $[x_P]$ is a particular solution, $[x_{ni}]$ is null space vector and k_i constant .The another advantage of SVD is that From the null space vector the system island can be determined observable or not by inspection the element of the null space vector if the element is zero this meaning null space element will not alter the particular solution and therefore observable otherwise the null space element can alter the solution and in this case unobservable [9].

3. RESULT AND DISCUSSION

3.1. SVD implemented in harmonic state estimation

The "S.V.D" harmonic state estimation algorithm has been developed and implemented in the system with data found in reference [19].

The system shown in Fig.1 Consist of 8 bus bar, 4 harmonic current measurements and 3 harmonic voltage measurements to estimate the rest of harmonic voltage from this information and the admittance matrix

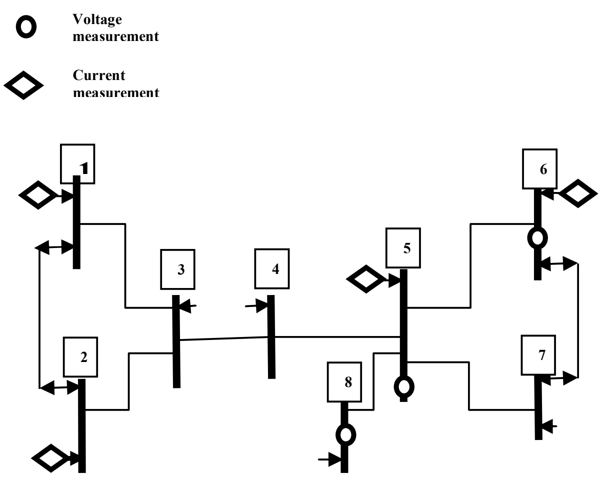

Fig.1 8 Bas bars system

Based on the harmonic voltage in buses number (5, 6, and 8) and the harmonic current in (1, 2, 5, and 6) and the admittance data of the system, the harmonic voltage in bus number (1, 2, 3, 4, and 7) was calculated by ("S.V.D"). The harmonic order assumed to be one just to explain how ("S.V.D") method works in harmonic state estimation. The information of this system given in tables below as fellow:

Table I the system impedance data

Bus No.	Bus No.	R P.u	X P.u	1/2B P.u
1	2	0.00099	0.00820	0.02600
1	3	0.00020	0.00800	0.00000
2	3	0.00010	0.01200	0.00000
3	4	0.03000	0.18700	0.30000
4	5	0.00080	0.01200	0.05000
5	6	0.00100	0.02000	0.03000
6	7	0.00150	0.05200	0.04000
5	7	0.00956	0.05498	0.09092
5	8	0.01000	0.06000	0.10000

Table II Harmonic voltage measurement

Bus No.	Harmonic volt
5	0.00232+j*0.00073
6	0.00225+j*0.00067
8	0.00253+j*0.00003

Table III Harmonic current measurement

Bus No.	Harmonic current
1	0.0045+j*0.0021
2	0.0049+j*0.0009
5	0.0071+j*0.0071
6	0.0063+j*0.0136

All the passive elements are considered to behave linearly with frequency [20].

$$R = constant \qquad (9)$$
$$X_L(h) = jhX_L \qquad (10)$$
$$X_c(h) = -j\frac{X_c}{h} \qquad (11)$$

$$\begin{bmatrix} I_h^1 \\ \vdots \\ I_h^N \end{bmatrix} = \begin{bmatrix} Y_h^{1,1} & \cdots & Y_h^{1,N} \\ \vdots & \vdots & \vdots \\ Y_h^{N,1} & \cdots & Y_h^{N,N} \end{bmatrix} \begin{bmatrix} V_h^1 \\ \vdots \\ V_h^N \end{bmatrix} \qquad (12)$$

Where the current I_h^N is the phasor current at frequency h injected at node,N ,i.e $I_h^N = |I_h^N| < \theta_h$, $Y_h^{N,N}$ is the equivalent admittance at frequency h at node N, V_h^N is the phasor voltage at frequency h injected at node N and N is number of the nodes of the electrical network . Using the information above the ("S.V.D") harmonic state estimation implemented as shown in Fig. 2.[19]

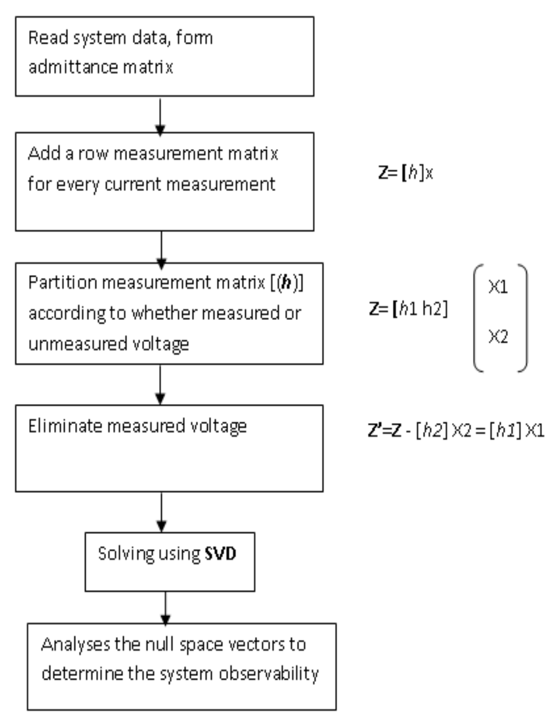

Fig.2"S.V.D" implementation

The result of estimated harmonics voltage from "S.V.D" as in table IV below

Table IV "S.V.D" estimated harmonic voltage

Bus No.	Real	Image	Magnitude	Angle (Deg.)
1	0.000006	0.000012	0.000013	114.48232
2	0.000003	0.000019	0.000019	100.38569
3	0.000009	-0.000031	0.000032	-73.78603
4	0.002283	0.000777	0.00242	18.558
7	0.002780	0.000815	0.002897	16.34612

But when the loss of the observation due to any error occur the result will diver from the actual result. For instance if the current measurement in bus No1 and 6 lost the SVD result of harmonic voltage will change as shown in tables below .(all the underlined value changed)

Table V harmonic voltage estimation when, current information lost in bus1

Bus No.	Real	Image	Magnitude	Angle (Deg.)
1	0.000001	0.000010	0.000010	-86.47639
2	0.000002	0.000016	0.000016	96.13432
3	0.000001	-0.000006	0.000007	-80.06974
4	0.002283	0.000777	0.00242	18.80749
7	0.002780	0.000815	0.002897	16.34612

Table VI harmonic voltage estimation when, current information lost in bus6

Bus No.	Real	Image	Magnitude	Angle (Deg.)
1	0.000006	0.000012	0.000013	114.48232
2	0.000003	0.000019	0.000019	100.38569
3	0.000009	-0.000031	0.000032	-73.78603
4	0.002733	0.000970	0.002900	19.54524
7	0.000608	0.000146	0.000625	13.49526

From the results of these tables random observation loss due to any error such as communication error, instrument calibration etc…, significantly deteriorate the performance of "S.V.D" harmonic state estimation so one step ahead harmonic prediction may compensate the random observation loss and maintain the measurements redundancy and therefore; enhance the performance of "S.V.D" when the information lost.

3.2. Harmonic prediction

To predict one step ahead real time harmonics to compensate the loss of harmonics observation due to the communication error in harmonic state estimation, The Finite Impulse Response "F.I.R" Adaptive Filters with least mean square and Weights Update Based Error Displacement "W.U.E.D" utilized. "W.U.E.D" used to eliminate the effect of the output error on the predictor performance when random losses to the observation (measurement) happen

3.3. The Finite Impulse Response "F.I.R" Adaptive Filters

May be understood as a self-modifying filter that adjusts its coefficients in order to minimize an error function. This error function, also referred to as the cost function, is a distance measurement between the reference or desired signal and the output of the adaptive filter [21]. The basic configuration of an adaptive filter, operating in the discrete-time domain k is shown in Fig. 3.

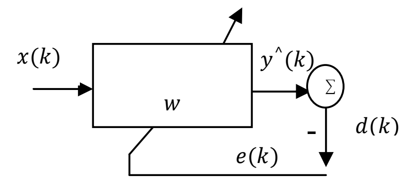

Fig. 3 Adaptive filter

The input signal is given by x(k) the reference signal or desired signal d(k) or y(k) represents the desired output signal (that usually includes some noise component), and $y^{\wedge}(k)$ is the output of the adaptive filter, and hence the error signal is defined as:

$$e(k) = d(k) - y^{\wedge}(k) \qquad (13)$$

3.4. Least Mean Square Algorithm ("L.M.S")

It is a celebrated algorithm and is widely used due to simplicity, low computational complexity and robustness. The simplicity of ("L.M.S") comes from the fact that it does not require matrix inversion and the update of kth coefficient requires only one multiplication and one addition [22].The "L.M.S" algorithm for Nth-order ("F.I.R") adaptive filters shown in steps below [22].

Parameters: M= filter order, μ= step size
Initialization: w_0=0
Computation: for k =0, 1, 2…

(a) $y^{\wedge}(k) = w^T x(k)$ (14)
(b) $e(k) = d(k) - y^{\wedge}(k)$ (15)
(c) $W(k) = w(k-1) + \mu e(k) x(k)$ (16)

Where the step size μ

$$0 < \mu < \frac{2}{\lambda_{max}} \qquad (17)$$

λ_{max} is the largest eigenvalue of the input signal due to the difficulty of determination of the step size μ that is a trade-off between the steady-state excess error and the speed of convergence.[9].

3.5. Weights Update Based Error Displacement ("W.U.E.D")

The output error is one of the most effective factors in the convergence of the weights, since it determines in which direction the weights will step parallel to the received observation, as well as it contributes in the length of the step[23]. In general when the presented training data to the predictor is consistent and continuous the output error decreases until the weights attain the optimal values, then the weights will be frozen. But when the observations are lost in random fashion the output error doesn't direct the weights optimally to the to the solution region due to the random losses of the predictor input."W.U.E.D" reduces the negative

effects of the output error by controlling the weights update based on error displacement (“D.e”). Shown by the following steps.
Step 1: Computing the value of the error displacement:

$$\mathrm{De_k} = \left|\frac{y_k - \hat{y_k}}{y_k}\right| \qquad (18)$$

Step 2: Checking whether the error displacement is smaller than a threshold (δ):

$$\mathrm{De_k} < \delta \qquad (19)$$

Step 3: If the error displacement is smaller than the threshold, the weights are updated:

$$w(k) = w(k-1) + \mu e(k)x(k) \quad (20)$$

Otherwise the weights are frozen:

$$w(k) = w(k-1) \quad (21)$$

3.6. Model of Instantaneous Current Harmonics.

As mentioned above the harmonics are represented as integer multiples of the generated frequency.

$$i_t = \sum_h (A_h)_t \cos\left(2\pi h f_0\, t + (\theta_h)_t\right) + \mathcal{E}_t \quad (22)$$

$$h \in [1,3,5,7,\dots]$$

$(A_h)_t$ is harmonics time- varying amplitude
f_0 is the fundamental frequency
h is harmonics order
$\mathcal{E}_t$ is random noise
$(\theta_h)_t$ is the harmonics order phase angles
$t = 0{:}\,\nabla t$: number of points
$\nabla t = 1/f_s$
f_s = sampling frequency
For simple mathematical calculation ∇t used instead of t
Using the Trigonometry in Eq. 23

$$\cos(A+B)\ \cos A \cos B - \sin A \sin B \qquad (23)$$

Eq. 22 will be in the following form:

$$y_t = w_t \emptyset_t^T + \mathcal{E}_t \quad (24)$$

Where

$$\emptyset_t^T = \left[(A_1)_t\cos(\theta_1)_t, (A_1)_t\sin(\theta_1)_t \dots (A_N)_t\cos(\theta_N)_t, (A_N)_t\sin(\theta_N)_t\right] (24)$$

$$w_t^T = [\cos(w_1\Delta t), -\sin(w_1\Delta t), \dots, \cos(w_N\Delta t), -\sin(w_N\Delta t)] \quad (25)$$

To predict any harmonic order magnitude and phase angle

$$y_t = \cos(w_h\Delta t)\,(A_h)_t\cos(\theta_h)_t - \sin(w_h\Delta t)\,(A_h)_t\sin(\theta_h)_t + \mathcal{E}_t (26)$$

Model the individual harmonic order for instance if the harmonic order is third Eq. (26) will be as

$$y_t = \cos(w_3\Delta t)\,(A_3)_t\cos(\theta_3)_t - \sin(w_3\Delta t)\,(A_3)_t\sin(\theta_3)_t + \mathcal{E}_t (27)$$

Using the historical information of $(A_h)_t\cos(\theta_h)_t$ and $(A_h)_t\sin(h)_t$ in Eq.26 to predict the future value of harmonics where $\cos(w_h\Delta t)$ and $\sin(w_h\Delta t)$ are constant.

The prediction of $(A_h)_t\cos(\theta_h)_t$ and $(A_h)_t\sin(\theta_h)_t$ done in parallel for each harmonic order which Eq. (26) dealt as tow equation and then the magnitude and phase angle for each predicted harmonic order can be calculated as

$$|I_h| = \sqrt{(A_h)_t\cos(\theta_h)_t^{\,2} + (A_h)_t\sin(\theta_h)_t^{\,2}} \; (28)$$

$$\theta_h = tan^{-1}\frac{(A_h)_t\sin(\theta_h)_t}{(A_h)_t\cos(\theta_h)_t} \qquad (29)$$

The frame work of “L.M.S” and (“W.U.E.D”) harmonic predictor as shown in figure below:

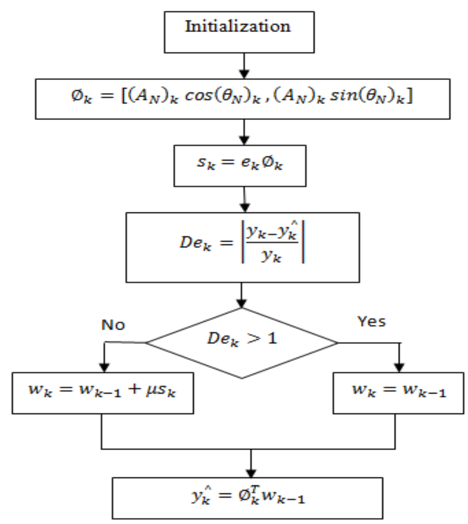

Fig .4(“L.M.S” and “W.U.E.D”)

The historical data collected by fluke 43B analyzer from tow power supplies one supply 15 personal computers desktop (“P.C”) and the other supply 33 computers desktop working independently as single loads harmonics source and the fundamental frequency, sample frequency equal to 50Hz, 51200Hz respectively and the number of points is 1024 while the noise added to data has standard deviation equal to 0.1 and zero mean the dada number used to train the predictor was 1000, the step size of least mean square taken as 0.05 for 14 PC data and 0.1 for 33 “P.C” data . The results are shown in Tables and figures below:

Table VII Mean Square Error for harmonic prediction (14P.C)

Harmonic order	Mean Square Error for 14 PC	
	$(A_N)_t\cos(\theta_N)_t$	$(A_N)_t\sin(\theta_N)_t$
3	0.0176	0.0211
5	0.0171	0.0174
7	0.0161	0.0164

Table VII Mean Square Error for harmonic prediction (33P.C)

Harmonic order	Mean Square Error for 33 PC	
	$(A_N)_t \cos(\theta_N)_t$	$(A_N)_t \sin(\theta_N)_t$
3	0.0563	0.0488
5	0.0451	0.0310
7	0.0216	0.0216

Five Amperes of the fundamental current added to the actual and predicted harmonics order to show the shape of predicted harmonics for 14 "P.C" data and (25) Amperes added to 33 "P.C" data.

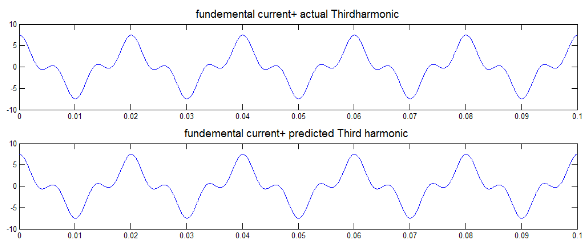

Fig.5 Third harmonic predicted (14 "P.C")

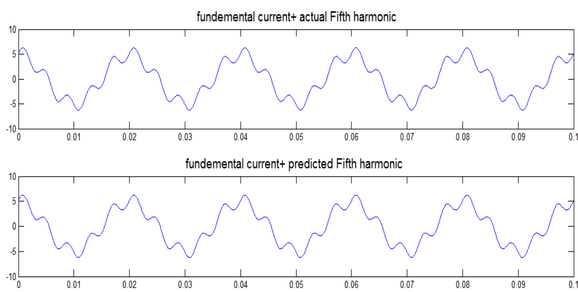

Fig.6 Fifth harmonic predicted (14 "P.C")

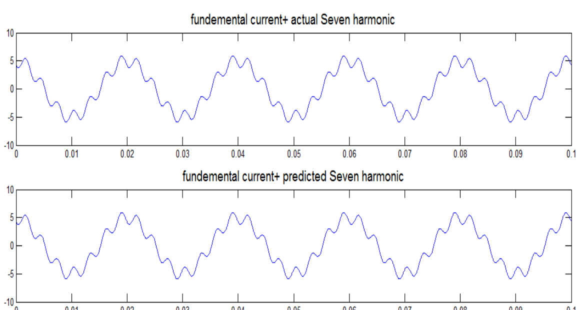

Fig.7 Seven harmonic predicted (14 "P.C")

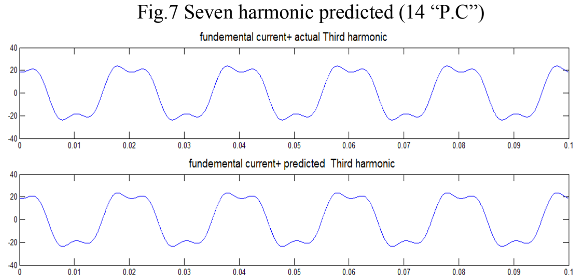

Fig.8 Third harmonic predicted (33 "P.C")

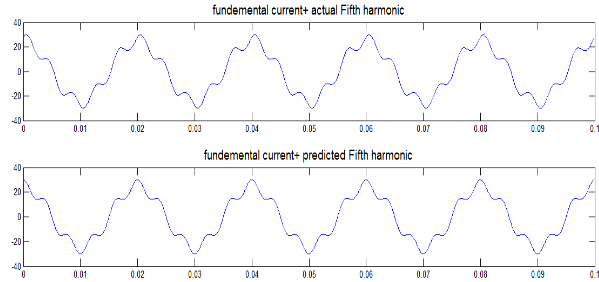

Fig.9 Fifth harmonic predicted (33 "P.C")

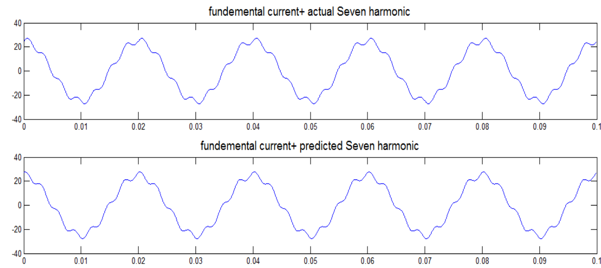

Fig.11 Seven harmonic predicted (14 "P.C")

From the tables and figures the presented methods able to predict one step ahead future harmonics with small mean square error this can compensate the loss of harmonics measurements in harmonic sate estimation.

4. CONCLUSION

Harmonic State Estimation is vital tool for monitoring and determining the harmonics level and sources of the system, due to the cost of harmonic measurements the system is in underdetermined and the traditional algorithm such as "L.U" decomposition, back-substitution, Cholesky decomposition for over determined system fail to give solution but "S.V.D" able to give solution . Harmonic State Estimation is real time implementation using communication channels and computerizes tolls usually in the control center unit due to complexity of acquiring harmonic information from the network sometimes the information lost in random fashion and therefore; affect the performance of the estimator. Prediction of future harmonic may compensate the loss of harmonic information and enhance the estimator when the loss happens.

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Hussam Mubarak M. Alhaj was born in Sudan. He has been working towards PhD Degree in Electrical Engineering emphasis on Power Systems from Universiti Teknologi PETRONAS Malaysia. His current research interest includes power system harmonic state estimation, harmonic prediction, frequency estimation and adaptive Signal processing algorithms.

Ir. Dr. Nursyarizal Mohd Nor obtained his PhD in Electrical Engineering from Universiti Teknologi PETRONAS (UTP), Malaysia in year 2009. In year 2001 he obtained his MSc in Electrical Power Engineering from The University of Manchester Institute of Science and Technology (UMIST), UK. His areas of specialization are 'Analysis and optimization of large scale power systems' and 'State estimation'. He has several publications at his credit. His research interests are in Power Economics Operation and Control, Power Quality, Renewable Energy and Power System Analysis

Dr. Vijanth S. Asirvadam is from an old mining city of Malaysia called Ipoh. He studied at the University of Putra, Malaysia for the Bachelor Science (Hon) majoring in Statistics and graduated in April 1997 before leaving to Belfast Queen's University Belfast to do his Masters where he received his Master's Science degree in Engineering Computation with a Distinction. He later joined the Intelligent Systems and Control Research Group at Queen's University Belfast in November 1999 where he completed his Doctorate (Ph.D.) researching Online and Constructive Neural Learning methods. He took previous employments as a System Engineer and later as a Lecturer at the Multimedia University Malaysia and also as a Senior Lecturer at the AIMST University. Since November 2006, he serve as a Senior Lecturer and later as Associate Professor at the department of Electrical and Electronics Engineering, Universiti Teknologi PETRONAS. His research interest includes linear and nonlinear system identification, model validation and application of computing system in signal and image processing. Dr Vijanth is member of Institute of Electrical and Electronics Engineering (IEEE) and also a member of Institute of Engineering Technology (IET) . He has over 100 publications in proceedings and journals in the field of computational intelligence, control, signal and image processing.

M. F. Abdullah completed his Master of Electrical Engineering from Universiti Tenaga Nasional (UNITEN) in 2006 and now pursuing PhD at Universiti Teknologi PETRONAS (UTP). He is currently a senior lecturer at UTP since 2009. Prior to that, he was working with utility company Tenaga Nasional Berhad (TNB) since 1989 and serving distribution Division for 12 years and transmission division for 8 years. His experience in distribution Division includes planning, construction, maintenance, metering and protection. In transmission division, he was working in maintenance department that responsible for Substation, lines, cables, protection, Telecontrol and technical support. He is a Professional Engineer (Board of Engineers Malaysia), Competent Engineer (Energy Commission), member of The Institute of Engineers, Malaysia (IEM) and member of The Institute of Electrical and Electronics Engineers (IEEE)