HARMONICS AND PHASOR ESTIMATION FOR A DISTORTED POWER SYSTEM SIGNAL

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR

THE DEGREE OF

BACHELOR OF TECHNOLOGY

IN

ELECTRICAL ENGINEERING

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Certificate

*This is to certify that the project entitled, "***Harmonics and Phasor Estimation for a distorted power system signal***" submitted by* ***C V Srinivasa Siddhartha(111ee0431), Gorja Chaitanya Bharath(111ee0199) and Chinmayee Behera(111ee0196)*** *in partial fulfillment of the requirements for the award of Bachelor of Technology Degree in Electrical Engineering at National Institute of Technology, Rourkela is an authentic work carried out by her under my supervision and guidance. To the best of my knowledge, the matter embodied in this Project review report has not been submitted to any other university/ institute for award of any Degree or Diploma.*

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ACKNOWLEDGEMENT

We express our deepest gratitude to our project guide Prof. P.K. Ray whose encouragement, guidance and support from the initial to the final level enabled us to develop an understanding of the subject.

Besides, we would like to thank to Prof. A.K. Panda, Head of the Electrical Engineering Department, National Institute of Technology, Rourkela for providing for providing us with an environment to complete our project successfully.

We are deeply indebted to all faculty members of Electrical Engineering Department, National Institutes of Technology, Rourkela, for their help in making the project a successful one.

Finally, we take this opportunity to extend our deep appreciation our family and friends, for all that they meant to us during the crucial times of the completion of our project.

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Date: 02-05-2015

Place: Rourkela

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ABSTRACT:

The controlling, operating and monitoring of electric devices has been possible because of the knowledge of power system parameters. The relay functionality in power systems is influenced by the two vital power system parameters which are frequency and harmonics. Hence in power systems, phasor estimation is of utmost importance. These computations not only facilitate real-time state estimation, but also improve protection schemes. However, in the presence of power frequency deviation, the phasor undergoes rotation in the complex plane. Interconnection of power grids and distributed generation systems becomes difficult because of this phenomenon. Hence, in this report different algorithms are studied and implemented for the estimation of phasor. The parameters estimated are limited to voltage amplitude and phase, change of frequency and rate of change of frequency.

In this thesis, Singular Value Decomposition (SVD) technique and Recursive Least Square (RLS) algorithms are used to estimate the amplitude and phase for different harmonics present in a distorted power system signal. Simple DFT algorithm is used to estimate the phasor variation, change of frequency and rate of change of frequency when deviated from the nominal frequency.

CHAPTER – 1

1. Introduction

1.1 Background:

With the development of modern power systems, the estimation of phasor becomes one of the most important issues. The presence of power frequency deviation introduces difficulties for grid synchronization. Accurate phasor gives useful information which can be used to protect the systems and to improve power quality [1]–[3]. The presence of Power electronic devices introduces non-linear characteristics in distributed generation systems. The harmonic phasor estimation gives useful information with the help of which power quality can be maintained.

The efficiency, stability and safety of a power system is generally indicated by the power frequency. The power frequency often deviates from its nominal value as a result of power mismatch between generation and load demands. The presence of this deviation results in rotation of the phasor in the complex plane. Thus, the phase angles would vary over time which leads to difficulties in distributed generation systems, interconnection of power grids, identification of power flow direction, and protective relays operation. This problem has resulted in development of the concept of synchronized phasor which helps solve this problem

The whole situation of a system is reflected by the two distinguishing operating parameters which are frequency and harmonics. Hence, in an electrical power system, the frequency and harmonics are required to remain constant. The frequency gives an indication of the dynamic energy balance between load and generating power, whereas the harmonics constitute the state of the system. Hence these parameters are considered as the indices for operating power systems. But, the frequency of an operating system is not constant due to factors such as noise, increasing use of non-linear load, sudden appearance of load-generation mismatches. Hence, the frequency of operation over a small allowable range from its standard value can be taken into consideration depending upon the load condition. The main effect of deviation from system frequency from its nominal value is that it changes the reactance of the component. The reactance in turn influences different relay functionality of power system. Most of the frequency estimation techniques available employ digitalised samples of voltage or current signals. As the voltage signal is less distorted than the line current, it is used more frequently for estimation of system parameters. The power system voltage signal is considered as purely sinusoidal. The time between two zero crossing is given system frequency. However, the measured signals in reality are available in distorted form. Numerous frequency estimation techniques are available. Some of the techniques implemented in this area include Discrete fourier transform (DFT), Kalman filtering, least square error, orthogonal infinite impulse response filtering and zero crossing technique. Genetic algorithm, soft computing technique, and neural network are also some of the techniques used for frequency estimation of power systems.

Harmonics estimation in power system environment is a very important task and has to be accurate. The harmonics estimation has a number of applications which include efficient design of compensatory filter, characterization of electrical device under non sinusoidal conditions, etc. Hence, continuous monitoring is required. The dynamic nature of the source which produce time varying amplitudes in generated signal is the primary source of harmonics in the power system and it is difficult to estimate these harmonics. Accurate, robust and fast estimation of amplitude and phase of the different frequency components is of primary importance. Some of the most widely used classical technology for the estimation of harmonics include the Fast Fourier Transformation (FFT) of a signal and Kalman filtering.

This thesis represented estimation of phasors in terms of amplitude and phase, estimation of frequency and harmonics for a distorted voltage waveform. The distortion of the signal is further enhanced by considering at different situation of power system. The technique used for the estimation of phasor is Singular Value decomposition (SVD),Recursive least square (RLS) algorithm and Discrete Fourier Transform (DFT) Algorithm for the estimation of frequency and harmonics. In this thesis we have also focused on the factor through which magnitude and phase changes that occur because of the changes in the power system frequency due to responses to load generation imbalances.

1.2 Literature Review:

Basic definitions of Phasor, Synchrophasor, Frequency, rate of change of frequency, synchrophasor measurement evalution, Total vector error (TVE) has been described in IEEE Standard for synchrophasor measurements [10]

Singular Value decomposition technique along with the compliance tests were proposed by Cheng-I Chen [4] to estimate the synchrophasor and Auto Regressive (AR) model is used for power frequency tracking for synchronization. Performance evaluation for harmonic synchrophasor estimation is done with benchmark tests for the IEEE standard C37.118-2005 [5].

Development of an effective method to filter out harmonics, decaying offsets and noise from current signal within numerical protective relaying is discussed by Dadash Zadeh,Zhiying Zhang[6]. Phasor estimation algorithm through RMS magnitude estimation and phase angle estimation were proposed by Panut Tavilsup, wanchalermpora [7] using FFT technique.

Maamar Bettayed et al [8] proposed a recursive method for the estimation of power system harmonics. This paper discussed about the use of different variations of the Recursive Least Square (RLS) algorithm for the real time estimation of amplitude and phase of harmonics. The recursive method has the properties of good convergence and easy computation. Because of these properties, the real time estimation of harmonics has become easy for implementation even in noisy environment. In this method, the maximum deviation from nominal value is within 9-10% and the estimation error is within 34%. The performance of this algorithm is better for single frequency estimation and not much satisfactory for multiple frequency estimation because of the presence of larger noise power signal. Hence, the results of RLS algorithm for single frequency system are better.

In the presence of high noise, the harmonics of signals are estimated using singular value decomposition (SVD) method, the results of which are presented by Lobos.T; Kozina.T; Koglin.H.J in a linear least squares method[11]. The SVD method employs the linear least squares solution for calculation. This method is also applicable for the frequency estimation of highly distorted signals.

Importance of positive sequence components in power system, characteristics which accelerates the real time monitoring of positive sequence voltage phasors at the local power sytem bus are discussed by A.G.Phadke, J.S.Thorp, M.G.Adamiak in their research paper[13]. In their research they also included the method regression analysis to determine frequency and rate of change of frequency at the bus using positive sequence voltage phase angle.

Saeed Hassan Khan, Saba Imtiaz, Hafsa Mustafa, Anabia Aijaz, Dr. M.A.Memon [9] proposed a recursive method using recursive computation through simple DFT technique. The measured quantities in the proposed paper are voltage and current phasors, change of frequency and rate of change of frequency of a three phase balanced power system signal.

In the paper presented by Hongga zhao[15], A new model to concern the state variable measured or calculated by PMU as state variable of nodes in the state estimation is reported and this model is able to utilize the PMU's ability of measuring state variables and reduce the scale of estimator. This model also improves the time and convergence speed.

A simple synchrophasor estimation algortithm has been proposed by Sarasij Das and Tarlochan Sidhu [16] in their paper by considering power system steady state, dynamic conditions and protection requirements so that the system can perform satisfactorily during system faults as it is an important requirement for protection applications.

In depth analysis of the effect of off – nominal frequency deviations on single cycle and multi-cycle DFT based synchophasors is presented by David Macii, Dario Petri and Alessandro Zorat in their research paper [17]. Their work provides with some accurate and easily used expressions to keep the total vector error within targeted boundaries.

In the paper published by Masoud karimi-Ghartemani [18], synchrophasor estimation is done by the application of an enhanced phase-locked loop (EPLL) system which gave accurate estimation within off – nominal frequency operation of system. DFT technique is used and some errors are caused due to negative sequence component.

Accuracy of measurement of frequency and rate of change of frequency do not contribute to the performance requirements of PMU in transient conditions. Hence they are not included in the standards. Even after adhering to standard classes of accuracy, different PMUs may give different outputs when subjected to different conditions. Some of the ambiguities that are present are reported in [19] and [20]

Effect of off-nominal frequency deviations on single cycle and multi cycle DFT based synchrophasor estimators, analysis using rectangular window and other windows are reported in [21] and [22].DFT based algorithm for phasor measurement application and its performance for off – nominal frequency conditions, harmonics, inter harmonics and out of band interfering signals was presented in [23] and [24]. Mathematically DFT technique to provide accurate estimation of phasors in off nominal frequency conditions with a three phase balance system is shown in [25] and [26].

A recursive least square algorithm in complex form is presented by abir basak et al [27] to estimate power frequency. A complex signal is derived from three phase signal using transformation. This algorithm has poos convergence rate as the step size is fixed.

Recently, there has been a lot of research going on for the accurate estimation of phase angle, amplitude and frequency for distorted signals and many advanced techniques have been introduced. A two stage solution structure which uses the concept of adaptive linear filtering has been proposed in [28] to track time varying harmonics. A recursive method based on Gauss-Newton algorithm has been presented in [29] for the estimation of fundamental frequency and phasor of a power signal. For the performance of grid synchronization and detection of three phase ac system's positive sequence, numerous phase-locked-loop (PLL) tracking techniques have been illustrated in [30]-[32]. For the detection of positive and negative sequence components of different harmonics and detection of fundamental frequency of three phase input signals, a space vector discrete-time Fourier transform has been proposed in [33]. Also, using the concept of adaptive linear combiner based harmonic estimation algorithm, a hybrid filter is designed in [34] which enhances the noise rejection capability of a digital controller

1.3 Motivation of Project work:

- As discussed before, the frequent usage of nonlinear loads, sudden mismatch of generation load giving rise to reactive power disturbance, presence of harmonics and random noise pollutes the electric power system environment.
- The fundamental frequency deviates from its nominal value because of the presence of nonlinear loads. Also, the harmonics level rises in the power system network which is unwanted. The presence of random noise makes it a difficult task for the exact estimation of harmonics and frequency amplitude and phase.
- Hence, this thesis introduces an estimator using the above mentioned SVD, RLS and DFT techniques which are based on the concept of combination of harmonic components. These estimators provide accurate harmonic phasor under off nominal power frequency condition.

1.4 Objective of the Report:

The objectives of the thesis are as follows:

- To estimate the Phasor in terms of amplitude and phase for a harmonic signal of different power system conditions.
- To estimate the synchronized frequency using the complex RLS algorithm and analyze it for different power system situation.
- To estimate a synchrophasor based on the combination on the combination of harmonic components introduced in the grid synchronization.
- To estimate the attenuation in magnitude and phase during the off nominal frequency condition in comparison with nominal frequency condition.

1.5 Report organization:

Chapter – 1 consists of an introduction of power system parameter and importance of phasor estimation. It also includes a brief literature review on estimation of power system frequency and harmonics and it focus on the motivation and objective of the project.

Chapter – 2 deals with i) mathematical analysis of Singular Value Decomposition (SVD) technique for the phasor estimation, ii) RLS method for the estimation of both frequency and harmonics and iii) simple DFT method to obtain the factors through which amplitude and phase are changing under off nominal conditions.

Chapter – 3 consists of simulation results of SVD, RLS and DFT algorithms to estimate phasors.
Chapter – 4 deals with the conclusion of our work.

CHAPTER – 2

2. Mathematical Analysis

2.1 Proposed Harmonic Synchrophasor Estimation:

The measured signal *y* is sampled and is represented in the discrete-time form *y*(*n*) to characterize power quality disturbances. *y(n)* is of finite length *N* sampled at the time interval Δt by *H* sinusoidal components and can be represented as

$$y(n) = \sum_{h=1}^{H} A_h \cos(n\omega_h \Delta t + \emptyset_h) \qquad (1)$$

Where A_h is the amplitude, φ_h is the initial phase angle, $\omega_h = 2\pi h f_1$ is the harmonic radian frequency, and f_1 is the power frequency.

After obtaining the amplitude and phase angles, the *h*th harmonic phasor Y_h can be represented as

$$Y_h = \left(\frac{A_h}{\sqrt{2}}\right) e^{j\emptyset_h} \qquad (2)$$

Total vector error (TVE) is introduced in order to evaluate the accuracy of phasor estimation. It is defined as the vectorial difference between measured and expected phasor values at a given instant of time (n).

$$TVE\,(n) = 100\% * \frac{|YMEAS|(n) - Y|IDEAL|}{Y|IDEAL|} \qquad (3)$$

TVE is defined only for the evaluation of fundamental component. For phasor with harmonic components, the definition can be extended as

$$TVE_h(n) = 100\% * \frac{|Yh\_\mathrm{MEAS}|(n) - Yh\_|\mathrm{IDEAL}|}{Yh\_|\mathrm{IDEAL}|} \qquad (4)$$

From the above equations (3) and (4), it can be noted that the errors from different sources for timing, magnitude and phase angle are combined in the definition. There will be a significant TVE when the power frequency deviates from its nominal value.

2.2 Combination of Harmonic components for phasor estimation using SVD technique:

Summation of different harmonic components of a power signal has been expressed in (1). By combining these components, the exact phasor information can be extracted. Consider N samples of a power signal y stored in a vector space Y. By the linear combination of elements of S, one may find a set S to span Y the elements of which are lineary independent.

$$span(S) = span(S_1, S_2, \ldots, S_H) \subset Y \qquad (5)$$

The power signal can be decomposed into a set of harmonics because of the linear independency of all the elements of S.

From (1), the measured signal y can be further decomposed as

$$y(n) = \sum_{h=1}^{H} A_h \cos(2\pi h f_1 n\, \Delta t + \emptyset_h)$$

$$= \sum_{h=1}^{H} A_h\, cos\emptyset_h cos2\pi h f_1 n\Delta t - A_h sin\emptyset_h sin2\pi h f_1 n\Delta t$$

$$= \sum_{h=1}^{H} x_{2h-1} cos2\pi h f_1 n\Delta t - x_{2h} sin2\pi h f_1 n\Delta t \qquad (6)$$

If N samples are considered, the power signal can be decomposed and represented in the form of matrix as shown in (7). Here, S is unit reference signal matrix, Y is the signal vector, x is the estimated phasor state vector. The harmonic phasor in (2) can be obtained after computing the *h*th harmonic amplitude and phase angle from (8) and (9).

$$\begin{bmatrix} y(1) \\ y(2) \\ \vdots \\ y(N) \end{bmatrix} = \begin{bmatrix} \cos 2\pi\cdot f_1\cdot\Delta t & -\sin 2\pi\cdot f_1\cdot\Delta t & \cos 2\pi\cdot 2f_1\cdot\Delta t & -\sin 2\pi\cdot 2f_1\cdot\Delta t & \cdots & \cos 2\pi\cdot Hf_1\cdot\Delta t & -\sin 2\pi\cdot Hf_1\cdot\Delta t \\ \cos 2\pi\cdot f_1\cdot 2\Delta t & -\sin 2\pi\cdot f_1\cdot 2\Delta t & \cos 2\pi\cdot 2f_1\cdot 2\Delta t & -\sin 2\pi\cdot 2f_1\cdot 2\Delta t & \cdots & \cos 2\pi\cdot Hf_1\cdot 2\Delta t & -\sin 2\pi\cdot Hf_1\cdot 2\Delta t \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \cos 2\pi\cdot f_1\cdot N\Delta t & -\sin 2\pi\cdot f_1\cdot N\Delta t & \cos 2\pi\cdot 2f_1\cdot N\Delta t & -\sin 2\pi\cdot 2f_1\cdot N\Delta t & \cdots & \cos 2\pi\cdot Hf_1\cdot N\Delta t & -\sin 2\pi\cdot Hf_1\cdot N\Delta t \end{bmatrix} \begin{bmatrix} A_1 \cos\phi_1 \\ A_1 \sin\phi_1 \\ \vdots \\ A_h \cos\phi_H \\ A_h \sin\phi_H \end{bmatrix}$$

$$Y = Sx \Longrightarrow Y = [S_{1cos} \quad S_{1sin} \quad S_{2cos} \quad S_{2sin} \quad \cdots \quad S_{Hcos} \quad S_{Hsin}][x_1 \quad x_2 \quad \cdots \quad x_{2H-1} \quad x_{2H}]^T$$

(7)

$$A_h = \sqrt{{x_{2h-1}}^2 + {x_{2h}}^2} \qquad (8)$$

$$\emptyset_h = tan^{-1} \frac{x_{2h}}{x_{2h-1}} \qquad (9)$$

It can be noted from (7) that an element of basis for power signal vector space Y is represented by each column of matrix S. Hence, it can be concluded that combination of different harmonic components gives the phasor estimate as shown in Fig. 1.

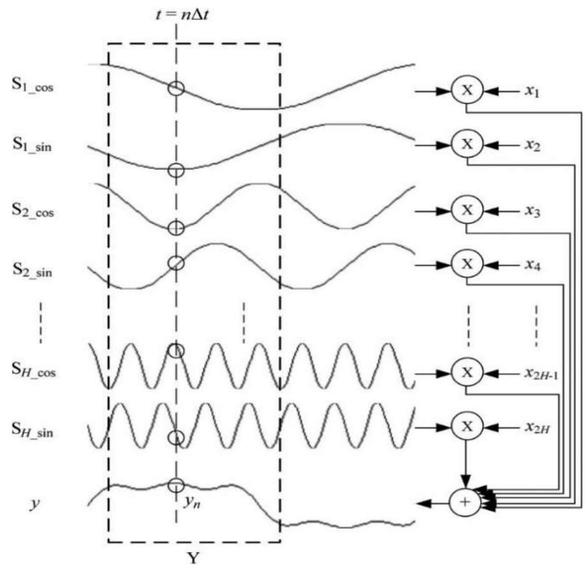

Figure 1 Combination of harmonic components for phasor estimation

The estimation error between actual signal y and estimated signal $\hat{y}$ is defined as in (10). This error should be minimised for accurate estimation of phasor.

$$E = \sum_{n=1}^{N} |y_n - \hat{y}_n|^2 \qquad (10)$$

The phasor estimation becomes an overdetermined problem as for most of the practical situations, the considered number $2H$ is lesser as compared to the number of samples N. Hence, the number of unknows are lesser than the number of equations which makes it difficult for minimizing the estimation error when the pseudo inverse method is applied for solving this problem. Hence, the Singular Value Decomposition (SVD) method is implemented which decomposes the matrix S into three matrices U, Σ, and V^T [10].

$$S = U\Sigma V^T \qquad (11)$$

Here, U and V are orthogonal matrices of dimensions $N \times N$ and $2H \times 2H$, respectively. Σ is a matrix of N x 2H dimension containing singular values in descending order in the diagonal terms. Negligible small singular matrices are omitted from the matrices Σ, U and V to prevent noise interference giving the matrices V_c, Σ_c, and U_c of suitable sizes. The vector x can be estimated according to (12) as

$$X = V_c \Sigma_c^{-1} U_c^T Y \qquad (12)$$

Reciprocal of each singular value gives the matrix Σ_c^{-1}.

2.3 Harmonics estimation using RLS algorithm

A general distorted waveform shown in (13), the continuous signal is discretized as shown in (14) and written in the form of $Y = H(n)X$. In RLS algorithm X (i.e., the sampled signal for 2H+2 harmonics) is updated using (16) to obtain the harmonic signals. This recursive algorithm helps in faster convergence with less deviations from the original magnitude.

General form of waveform is

$$y(t) = \sum_{h=1}^{H} A_h \cos(\omega_h t + \Phi_h) + A_{dc} \exp(-\alpha_{dc} t) + \varepsilon(t) \qquad (13)$$

After discretizing with sampling period Δt, we get expression

$$y(n) = \sum_{h=1}^{H} A_h \cos(\omega_h n\Delta t + \Phi_h) + A_{dc} \exp(-\alpha_{dc} n\Delta t) + \varepsilon(n) \quad (14)$$

Using taylor series for dc decaying term, we get

$$y(n) = \sum_{h=1}^{H} A_h \cos(\omega_h n\Delta t + \Phi_h) + A_{dc} - A_{dc}\alpha_{dc} n\Delta t + \varepsilon(n)$$

$$= \sum_{h=1}^{H} [A_h \cos \Phi_h \cos(\omega_h n\Delta t) - A_h \sin \Phi_h \sin(\omega_h n\Delta t)] + A_{dc} - A_{dc}\alpha_{dc} n\Delta t + \varepsilon(n)$$

$$y(n) = H(n)\, X$$

where $H(n) = [\, \cos(\omega_1 n\Delta t) \;\; \sin(\omega_1 n\Delta t) \;\; \ldots. \;\; \cos(\omega_h n\Delta t) \;\; \sin(\omega_h n\Delta t) \;\; 1 \;\; -n\Delta t\,]^T$

$$X(n) = [X_1(n) \;\; X_2(n) \;\; \ldots\ldots. \;\; X_{2H+1}(n) \;\; X_{2H+2}(n)\,] \qquad (15)$$

X is updated using RLS algorithm as

$$X(n+1) = X(n) + K(n+1)[\, y(n+1) - H(n+1)^T X(n)\,] \quad (16)$$

Gain K is related with covariance of parameter vector using

$$K(n+1) = D(n)\, H(n)\, [\, 1 + H(n+1)^T D(n)\, H(n+1)\,]^{-1}$$

Updated covariance of parameter vector using matrix inversion lemma

$$D(n+1) = [\, I - K(n+1)\, H(n+1)^T\,]\, D(n) \qquad (17)$$

The above equations are initialized by taking some initial values for the estimate at instants *n*, $X(n)$ and *D*. For *D=αI*, where α is a large number and I is the identity matrix of order *(2H+2, 2H+2)* where H is the number of harmonics to be estimated. Equation (15) gives the harmonics that are slightly deviated in amplitude and phase from the original signal.

2.4 Phasor estimation using DFT algorithm

In this method, It is assumed that the sampling clock is a fixed-frequency clock with sampling rates which are multiples of the nominal power system frequency. Using this algorithm phasors are computed at nominal frequency as well as off nominal frequency.

Phasor Computation a Nominal Frequency:

Assuming the balanced three phase system at nominal frequency of f_0, the signal is represented as

$x_1 = X_m cos(2\pi f_0 t + \emptyset_1)$

$x_2 = X_m cos(2\pi f_0 t + \emptyset_2)$

$x_3 = X_m cos(2\pi f_0 t + \emptyset_3)$

Where X_m is the maximum magnitude of the signal, and $\emptyset_1, \emptyset_2, \emptyset_3$ are the phase angles 120^0 apart. Considering a sampling unit that samples the three phases at the rate of N samples per cycle, and the time domain based samples can be represented by

$x_{n1} = X_m cos(\frac{2\pi n}{N} + \emptyset_1)$

$x_{n2} = X_m cos(\frac{2\pi n}{N} + \emptyset_2)$

$x_{n3} = X_m cos(\frac{2\pi n}{N} + \emptyset_3)$

The general formula for N – point DFT is

$$X = \frac{1}{N}\sum_{n=0}^{N-1} x_n \left(cos\frac{2\pi n}{N} - jsin\frac{2\pi n}{N}\right) \qquad (18)$$

Where n represents the sample number

The N – point DFT of signals including the harmonic index k is given by

$$X_k = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} x_n \left(cos\frac{2\pi nk}{N} - jsin\frac{2\pi nk}{N}\right) \qquad (19)$$

Our interest is mainly on the fundamental frequency component i.e., $k = 1$

$X_{nom} = X_1 = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} x_n \left(cos\frac{2\pi n}{N} - jsin\frac{2\pi n}{N}\right)$

$X_{nom} = X_r + jX_i$

Where,

$X_r = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} x_n \cos\left(\frac{2\pi n}{N}\right)$

$X_i = -\frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} x_n \sin\left(\frac{2\pi n}{N}\right)$

The complex quantity X_{nom} represents the phasor estimate at nominal frequency input, whose magnitude $|X_{nom}|$ gives the magnitude of the signal. The phase angle is given by $\emptyset_{nom} = \tan^{-1}(\frac{X_i}{X_r})$

Three such phasors are computed for a three phase system i.e., $X_{nom1}, X_{nom2}, X_{nom3}$. These phasors will be 120^0 apart with the same magnitude.

Phasor measurement at off nominal frequency:

When the input frequency is f has some difference Δf from the nominalf_0, so that $= f_0 + \Delta f$, the balanced three phase system at off nominal frequency of f, the signal is represented as

$x_1 = X_m \cos(2\pi f t + \emptyset_1)$

$x_2 = X_m \cos(2\pi f t + \emptyset_2)$

$x_3 = X_m \cos(2\pi f t + \emptyset_3)$

The N – point DFT of the new signal for off – nominal frequency is expressed by:

$$X_{off-nom} = P X_{nom} e^{j2\pi(f-f_0)T_s} + Q X_{nom}{}^{*} e^{j2\pi(f-f_0)T_s} \qquad (20)$$

Where, $$P = \left\{ \frac{sin\frac{2\pi N(f-f_0)T_S}{2}}{N\, sin\frac{2\pi(f-f_0)T_S}{2}} \right\} e^{j(N-1)\frac{2\pi(f-f_0)T_S}{2}} \qquad (21)$$

$$Q = \left\{ \frac{sin\frac{2\pi N(f+f_0)T_S}{2}}{N\, sin\frac{2\pi(f+f_0)T_S}{2}} \right\} e^{-j(N-1)\frac{2\pi(f+f_0)T_S}{2}} \qquad (22)$$

The values of the P and Q are the factors with which the magnitude and phase of a signal gets attenuated under off nominal frequency conditions which means these are the errors introduced in the estimated phasor.

Error Correction:

An error exists due to the second harmonic component which has to be removed. The advantage of having a three phase balanced system has been taken here. By finding the positive sequence component of the system the second harmonic in the resultant phasor can be removed. Negative and zero sequence components should not be present as balanced system is considered. So, the calculated Positive sequence component represents the true phasor and the symmetrical components can be calculated as follows:

$$\begin{bmatrix} X_0 \\ X_+ \\ X_- \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \times \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} \qquad (23)$$

Where X_0, X_+ and X_- represent zero sequence, positive sequence and negative sequence components. X_1, X_2, and X_3 represent the three phase estimated phasors.

COF and ROCOF calculation:

The change in frequency and rate of change of frequency can be calculated with the help of computed phase angles. COF is defined as the derivative of the phasor estimate and the ROCOF will then be the derivative of COF.

The phase angles although are inaccurate but the change in frequency is related to the change in phase angle which are true. As the rate of change of phase angle is frequency, the phase angle at any instant is represented by (24).

$$\emptyset(t) = \int \omega(t)\, dt = \emptyset_0 + \Delta\omega t + \frac{1}{2}\omega' t^2 \qquad (24)$$

Where ω(t)=frequency in radians = ω_0 + Δω + ω't, ω_0=nominal frequency, Δω=change in frequency, and ω' represents the rate of change in frequency.

If T_s is the sampling time, then the vector of N angle measurements can be given by

$$\begin{bmatrix} \emptyset_0 \\ \emptyset_1 \\ \emptyset_2 \\ \emptyset_3 \\ \vdots \\ \emptyset_{N-1} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & T_s & {T_s}^2 \\ 1 & 2T_s & 2^2{T_s}^2 \\ 1 & 3T_s & 3^2{T_s}^2 \\ \vdots & \vdots & \vdots \\ 1 & (N-1)T_s & (N-1)^2{T_s}^2 \end{bmatrix} \times \begin{bmatrix} \emptyset_0 \\ \Delta\omega \\ \frac{1}{2}\omega' \end{bmatrix} \qquad (25)$$

In matrix notation,

$$[\emptyset] = [B][\omega]$$

Or,

$$[\omega] = \left[BB^T\right]^{-1} B^T[\emptyset] \qquad (26)$$

From this equation (26), Δω and ω' can be computed to give COF (Δf) and ROCOF.

$$\Delta f = \frac{\Delta\omega}{2\pi} \qquad (27)$$

$$ROCOF = \frac{\omega'}{2\pi} \qquad (28)$$

CHAPTER – 3

3. Simulation Results

3.1 Phasor estimation in terms of Amplitude and Phase Using SVD Technique:

Analysis is done for the industrial signal shown in (14) and the plot of signal for a time of 0.04 sec is shown in Fig.2

$$y(t) = 1.5\ \sin(\omega t+80) + 0.5\ \sin(3\omega t+60) + 0.2\ \sin(5\omega t+45) + 0.15\ \sin(7\omega t+36) + 0.1\ \sin(11\omega t+30) + 0.5\ e^{-5t} + 0.01\ randn \qquad (14)$$

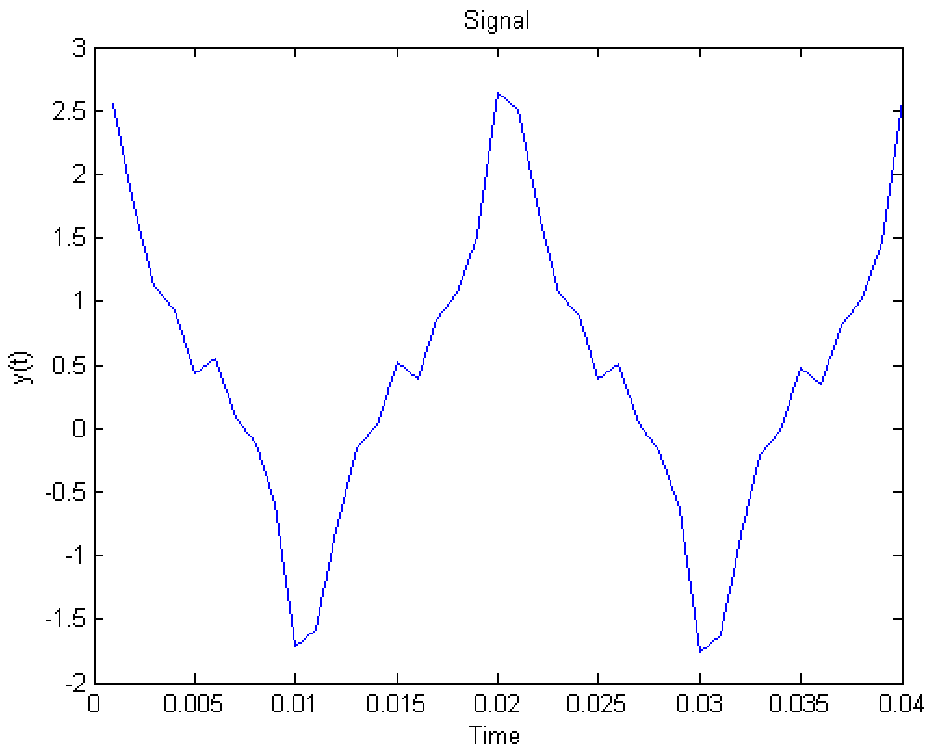

Figure 2 Plot of the assumed signal mentioned in (14)

Constraints:

The Sampling time is fixed constant throughout the analysis. It is taken as 0.001. The analysis is made for 200 samples. The Number of harmonics are user defined. Here the results are shown for 11 harmonics.

The estimated harmonic phase and amplitude of a phasor obtained through the Singular Value Decomposition technique. And the error in amplitude and phase i.e., the deviation from original signal is computed for all the harmonics and tabulated for comparative study are shown in

Table I.

Harmonic	Amplitude	Error in Amplitude	Phase(in degree)	Error in Phase(in degree)
1	1.5032	0.0032	77.7366	2.2634
2	0.0063	0.0063	4.0970	4.0970
3	0.5028	0.0028	54.2349	5.751
4	0.0032	0.0032	7.2994	7.2994
5	0.2023	0.0023	35.6605	9.3395
6	0.0022	0.0022	10.2678	10.2678
7	0.1519	0.0019	23.2491	12.7509
8	0.0018	0.0018	12.7698	12.7698
9	0.0016	0.0016	13.8177	13.8177
10	0.0015	0.0015	14.7246	14.7246
11	0.1014	0.0014	10.2809	19.7191

Table 1 Estimated amplitude and phase using SVD method

Now the estimated phasor can be obtained by substituting the values from Table I in equation (2).

From the Table I, it can be noted that the estimated amplitudes and phase angles comply with the actual values. The even harmonics have an amplitude and phase zero which agree with the estimated values from the table. The error in amplitude decreases while traversing from top to bottom, whereas error in phase angle increases.

3.2 Harmonics estimation using RLS algorithm

1st Harmonic:

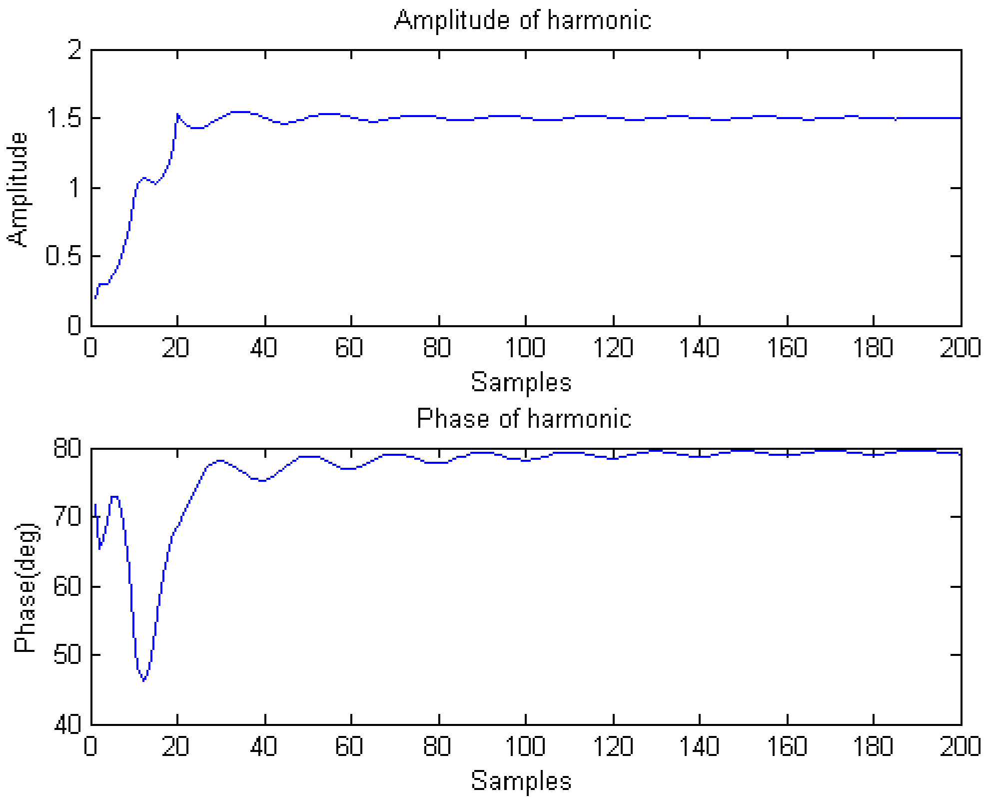

Figure 3: 1st harmonic estimation

From Fig.3, we observe that the amplitude increases initially from around 0.25 and settles at the value of 1.5 after 60 samples. Also, the phase is oscillatory in the beginning but eventually settles at 80^o after 120 samples.

From Fig.4, we observe that the amplitude oscillates initially from 0.2 and settles at the value of 0.5 after 40 samples. Also, the phase is oscillatory in the beginning but eventually settles at 60^o after 30 samples.

3rd Harmonic:

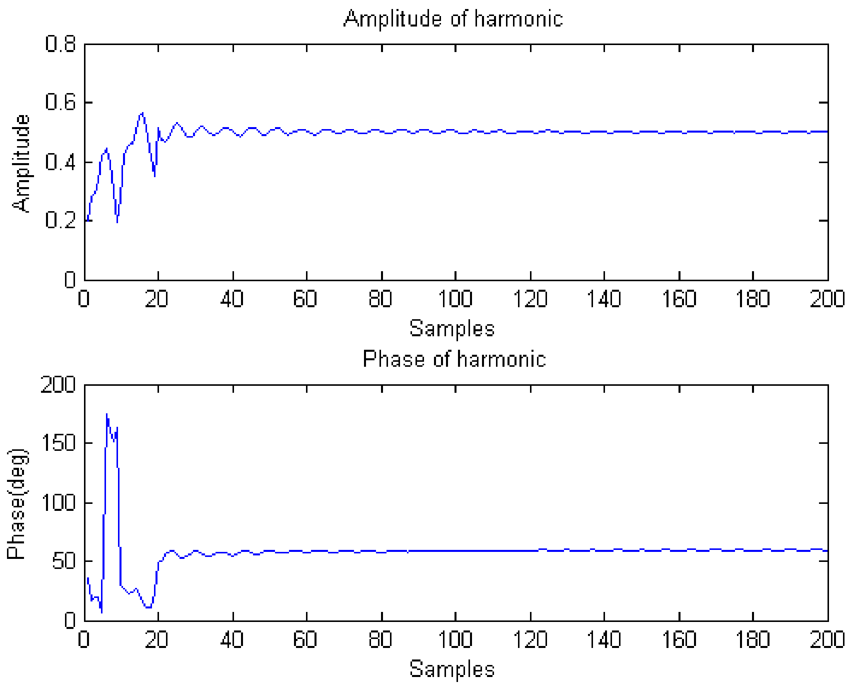

Figure 4: 3rd harmonic estimation

5th Harmonic:

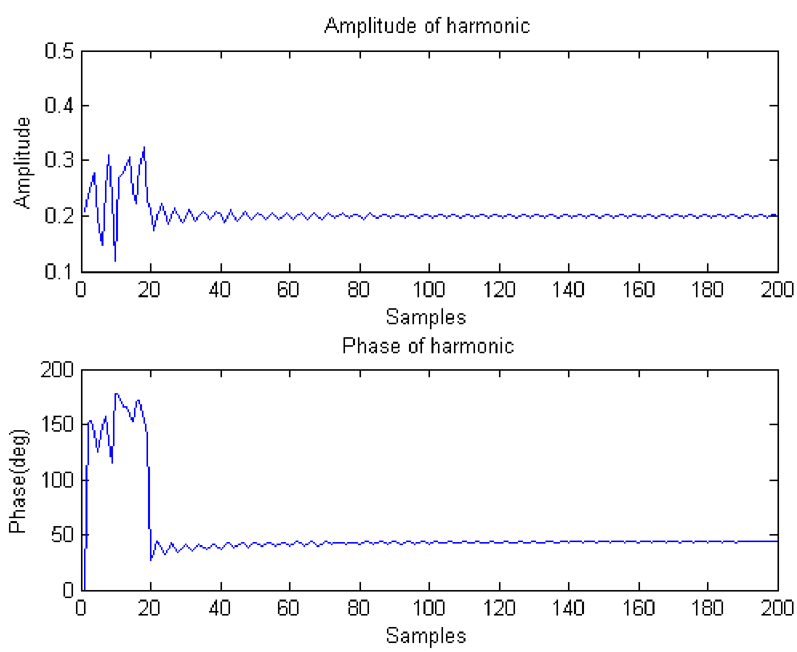

Figure 5: 5th harmonic estimation

From Fig.5, we observe that the amplitude oscillates initially from 0.2 and settles at the value of 0.2 after 40 samples. Also, the phase is oscillatory in the beginning but eventually settles at 45^o after 30 samples.

7th Harmonic:

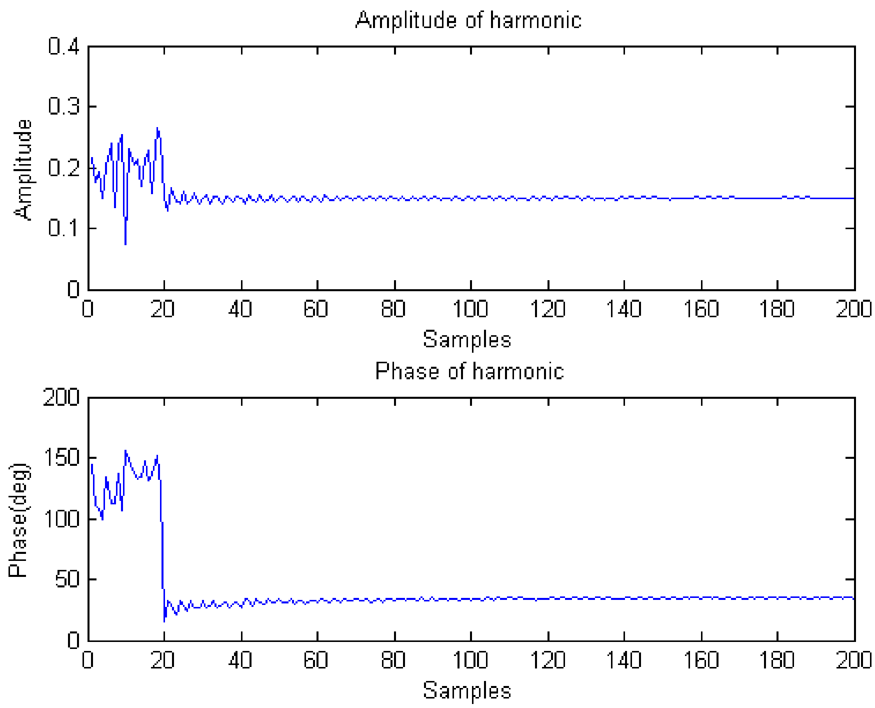

Figure 6:7th harmonic estimation

From Fig.6, we observe that the amplitude oscillates initially from 0.2 and settles at the value of 0.15 after 40 samples. Also, the phase is oscillatory in the beginning but eventually settles at 36^o after 40 samples.

From Fig.7, we observe that the amplitude oscillates initially from 0.23 and settles at the value of 0.03 after 20 samples. This is due to the decaying and noise signals present.

From Fig.8, we observe that the amplitude oscillates initially from 0.43 and settles at the value of 0.1 after 20 samples. Also, the phase is oscillatory in the beginning but eventually settles at 30^o after 40 samples.

9^{th} Harmonic:

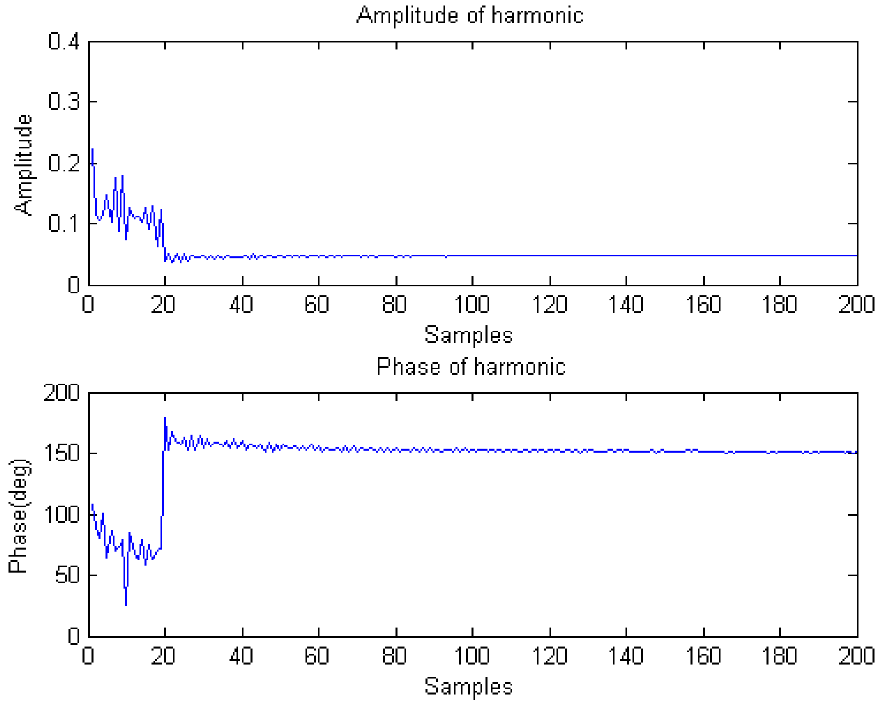

Figure7: 9th harmonic estimation

11^{th} Harmonic:

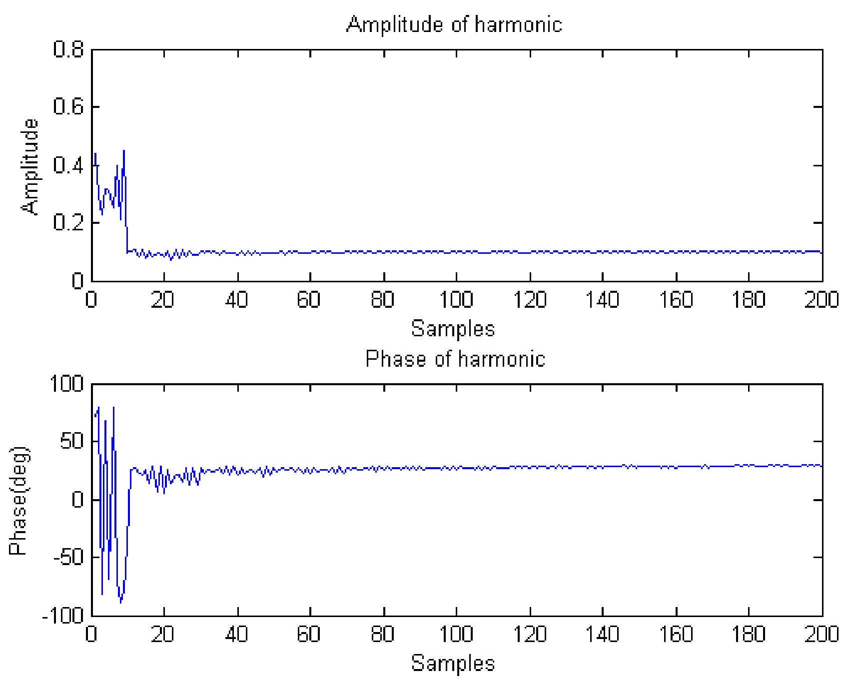

Figure 8: 11th harmonic estimation

3.3 Effect on Phasor during off – nominal frequency condition estimated through DFT Algorithm

In general because of the power system imbalances and changes in the load, the power system frequency may be deviated. Under these conditions, the magnitude and phase of a signal may get varied. In this section, it is focused on the factor through which amplitude and phase gets changed during off nominal frequency when compared with the phasor on nominal frequency conditions.

Table II: Variation of attenuation factor P with frequency deviation.

Δf	|P|	$\angle$P (degrees)
-5	0.9836	-17.64
-4.5	0.9867	-15.876
-4	0.9895	-14.112
-3.5	0.9920	-12.348
-3	0.9941	-10.584
-2.5	0.9959	-8.82
-2	0.9974	-7.056
-1.5	0.9985	-5.292
-1	0.9993	-3.528
-0.5	0.9998	-1.764
0	1	0
0.5	-0.9998	1.764
1	-0.9993	3.528
1.5	-0.9985	5.292
2	-0.9974	7.056
2.5	-0.9959	8.82
3	-0.9941	10.584
3.5	-0.9920	12.348
4	-0.9895	14.112
4.5	-0.9867	15.876
5	-0.9836	17.64

Table III: Variation of attenuation factor Q with frequency deviation.

Δf	$\lvert Q \rvert$	$\angle Q$ (degrees)
-5	-0.0434	29.37
-4.5	-0.0390	27.94
-4	-0.0346	26.5
-3.5	-0.0302	25.06
-3	-0.0258	23.62
-2.5	-0.0215	22.19
-2	-0.0171	20.75
-1.5	-0.0128	19.31
-1	-0.0085	17.87
-0.5	-0.0042	16.44
0	0	15
0.5	0.0042	13.56
1	0.0084	12.12
1.5	0.0125	10.69
2	0.0166	9.25
2.5	0.0206	7.81
3	0.0246	6.37
3.5	0.0285	4.94
4	0.0324	3.5
4.5	0.0363	2.06
5	0.0400	0.62

The errors introduced in the estimated phasor i.e., the dependence of factors P and Q on frequency deviation for a nominal frequency of 50 Hz for a frequency deviation of about ± 5Hz range calculated from equations (16), (17), (18) are tabulated in Table II and III and the variation of the factors in magnitude and phase with frequency deviation are plotted and shown in Figs 9-12.

Plots of Variation of Factor P with frequency deviation:

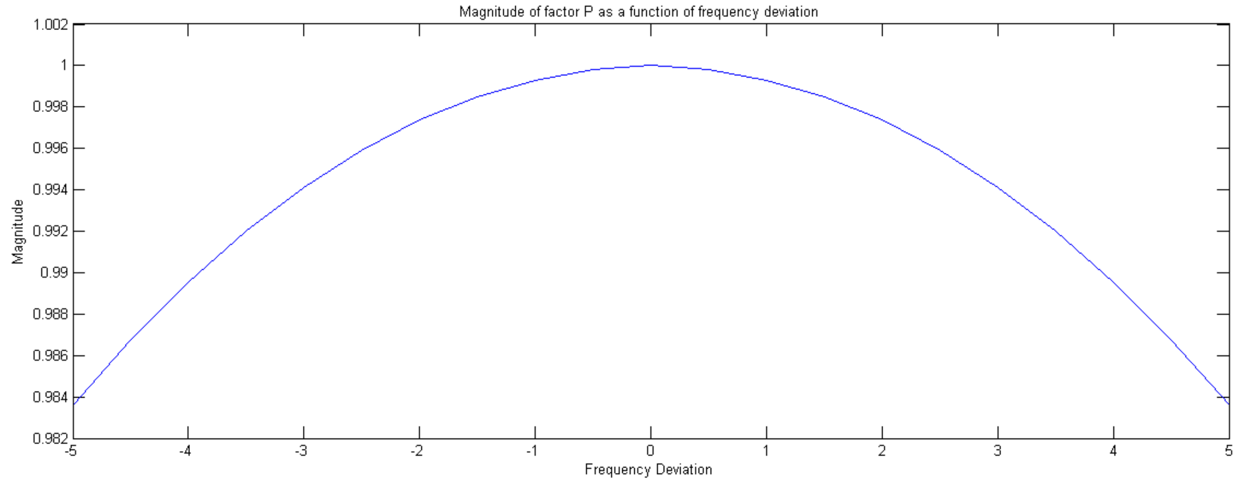

Figure 9: Magnitude of factor P as a function of frequency deviation

Fig.9 shows the plot between frequency deviation and magnitude of P. We can infer from the plot that at a deviation of 5 Hz from nominal frequency, maximum attenuation occurs, being around 98.36%. The effect of factor P can be often neglected as it affects the principal term of the quantity being measured.

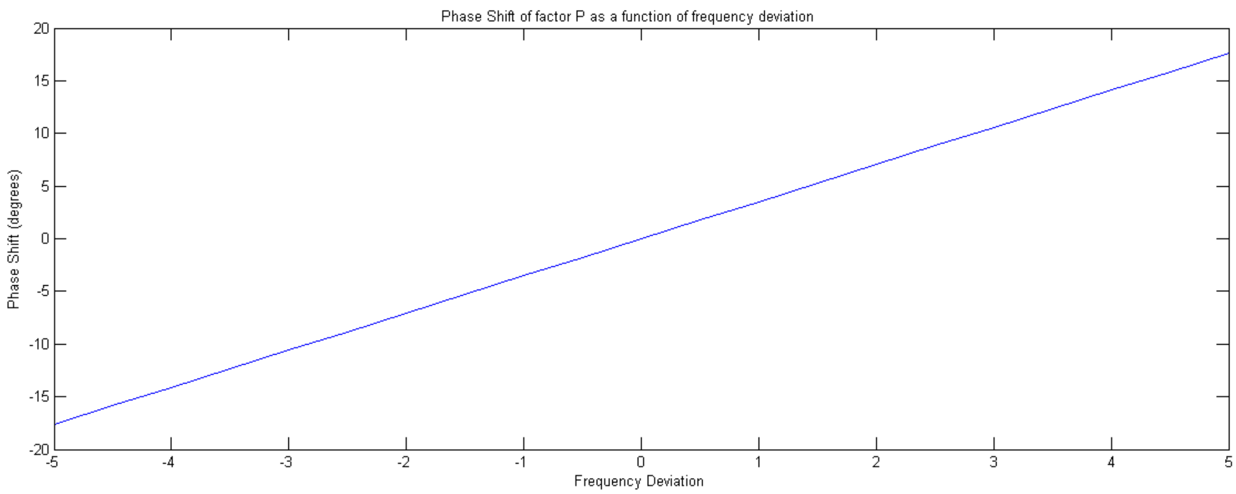

Figure 10: Phase shift of factor P as a function of frequency deviation

Fig.10 shows the plot of phase shift of factor P as a function of frequency deviation. The phase angle varies linearly in the ±5 Hz range and the error corresponds to about 2 degrees per Hz deviation.

Plots of Variation of Factor Q with frequency deviation:

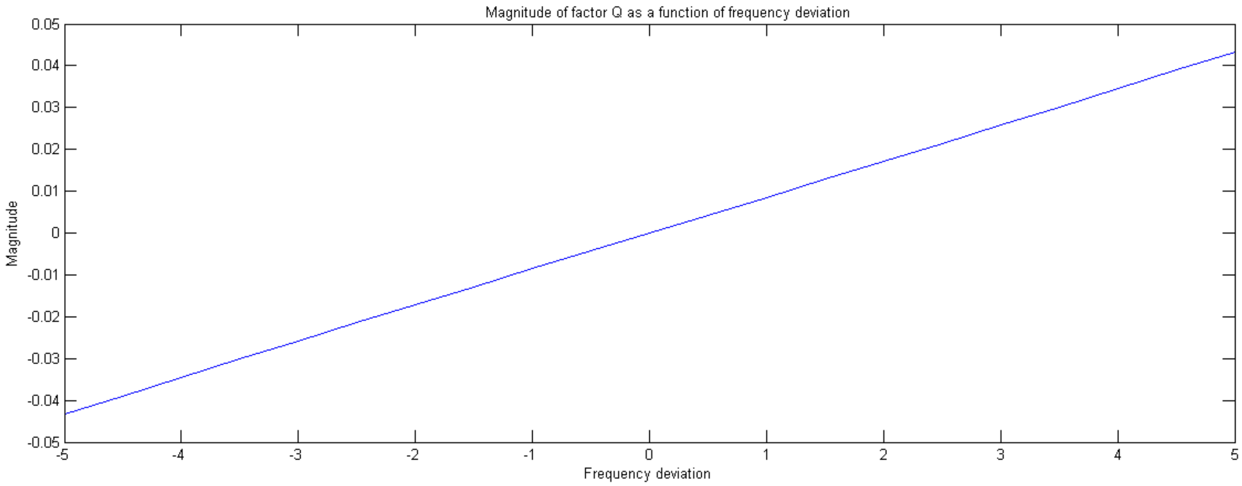

Figure 11: Magnitude of factor Q as a function of frequency deviation

Fig.11 shows the plot between frequency deviation and magnitude of Q. The magnitude of factor Q increases linearly with respect to frequency deviation, the increase being about 0.004 per unit per Hz. The magnitude is 0 at nominal frequency. The absolute value of Q is not plotted as the multiplier also becomes negative at negative frequency deviations.

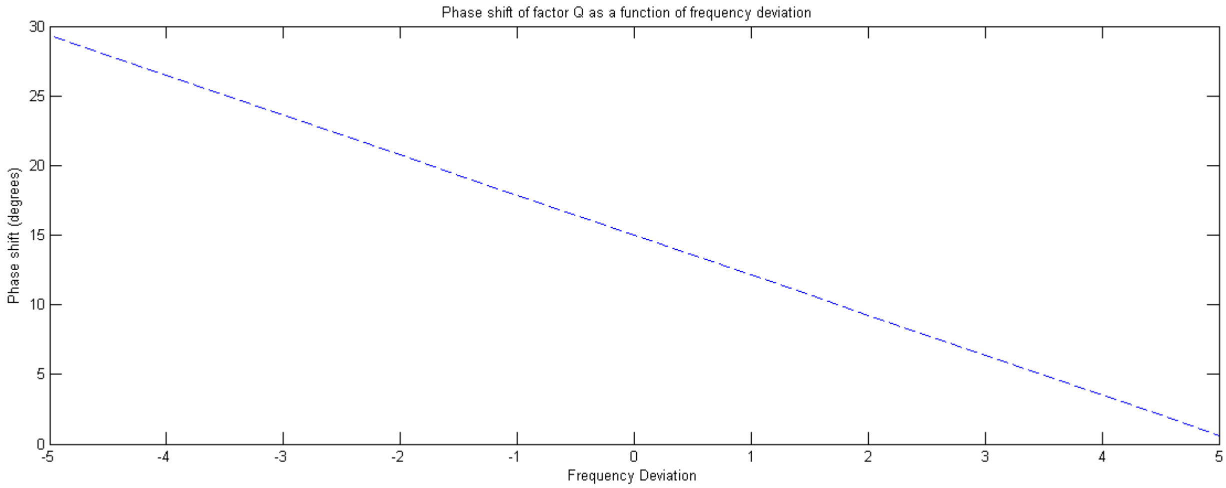

Figure 12: Phase angle of factor Q as a function of frequency deviation

Fig.12 shows the plot between frequency deviation and phase angle of Q. The phase angle is 15 degrees at nominal frequency, and the phase angle varies linearly with respect to frequency deviation.

The positive sequence phasor is estimated from balanced inputs at off nominal frequencies according to equation (19). The plot of magnitude of the estimated positive sequence voltage with respect to time for an off nominal frequency of 51 Hz is shown in Fig.13.

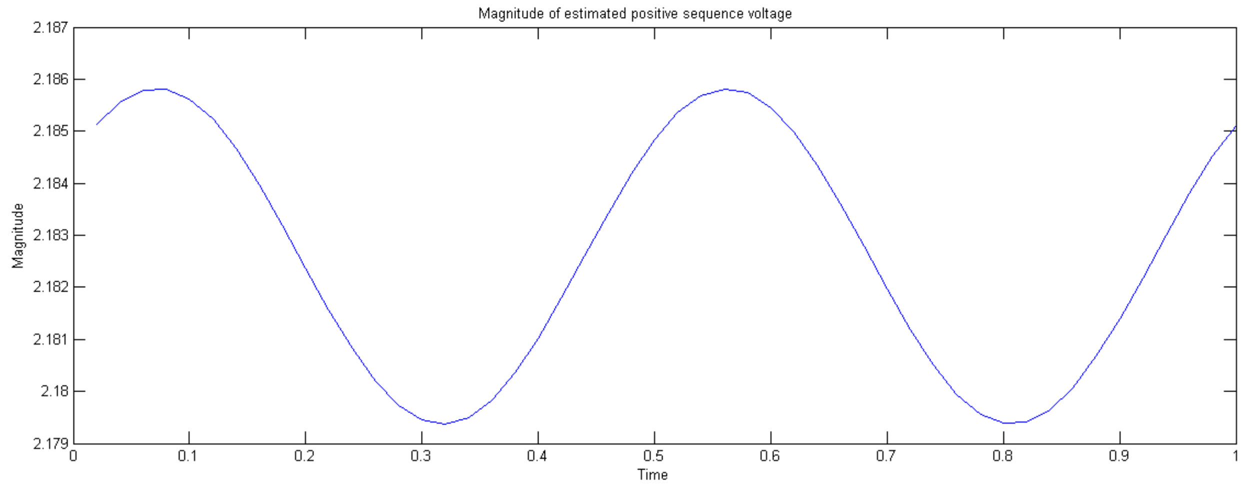

Figure 13: Magnitude of estimated positive sequence voltage for a signal of 51Hz

From the Fig.13, it can be noted that the magnitude oscillates around the value of 2.18. The phase angle of the estimated positive sequence component for an off nominal frequency of 51 Hz is shown in Fig.14.

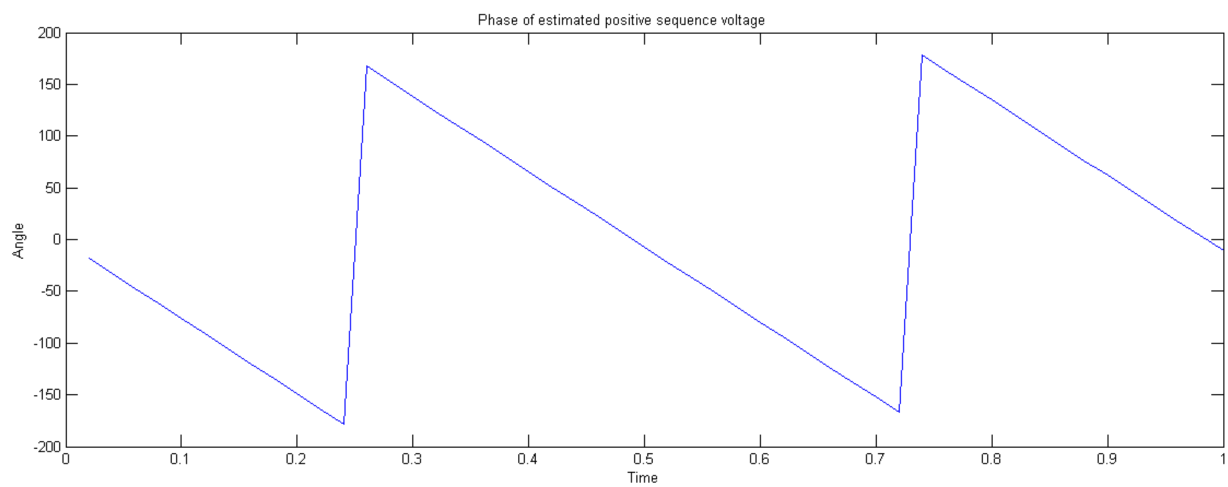

Figure 14: Phase of estimated positive sequence voltage for a signal of 51 Hz

From the Fig.14, it can be noted that the phase is periodic and varies between $-\pi$ to π for an off nominal frequency of 51 Hz.

It is clear from equation (16) that the first and second derivatives of the phase angle of the phasor estimate would provide an estimate of change of frequency $\Delta\omega=(\omega-\omega_0)$, and the rate of change of frequency.

The plot of change of frequency (COF) with respect to time for a signal of off nominal frequency of 51 Hz is shown in Fig.15.

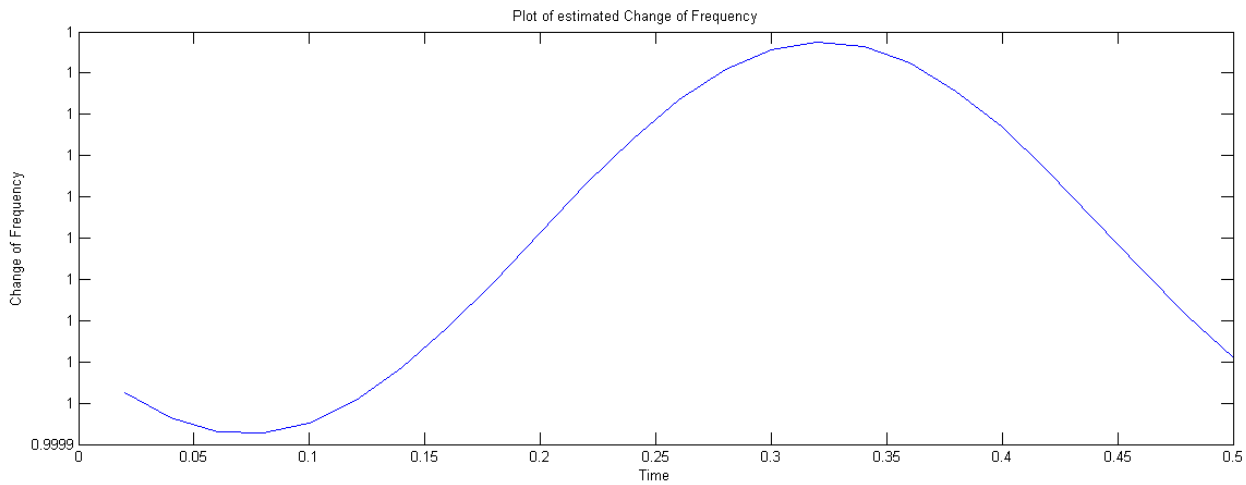

Figure 15: Plot of estimated change of frequency

It can be noted from the figure that the change of frequency is estimated about 1 Hz which agrees with the actual change of frequency (51Hz – 50Hz = 1Hz). The plot of ROCOF with respect to time for an off nominal frequency of 51 Hz is shown in Fig.16.

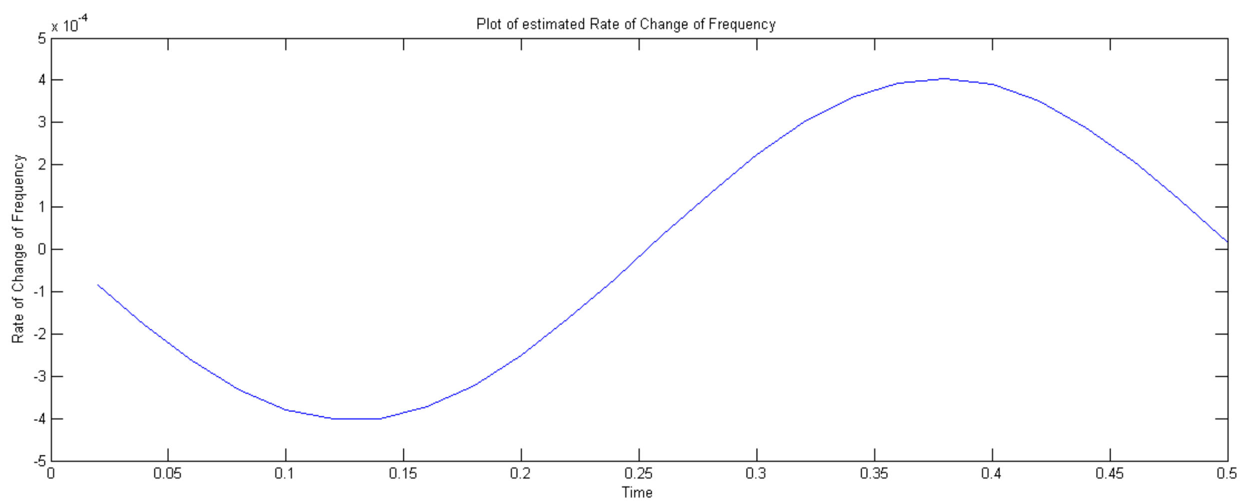

Figure 16: Plot of estimated rate of change of frequency

It can be noted from the figure that the ROCOF is of the order of 10^{-4} for 51 Hz off nominal frequency and oscillates about the zero line.

CHAPTER – 4

4. Conclusion

This project is aimed studying different algorithms for synchrophasor estimation. In the first phase, SVD algorithm was implemented for a given industrial signal with 40dB SNR. The phasors and harmonics of given industrial signal was estimated using the SVD method and the corresponding errors were calculated for all harmonics. In the second stage, RLS algorithm was implemented for estimation of phasor for different harmonics. It is observed that amplitudes and phases of the estimated signal eventually settle at their original values. The deviation and simulation results for estimated harmonics using different algorithms have been presented. In the final stage, the N-point DFT algorithm was implemented to find the variation in amplitude and phase of a signal at off nominal frequency conditions. The errors in the estimated phasor was calculated and plotted. The DFT is generally sensitive and suffers from large errors in the presence of inter-harmonics and out-of-band interfering signals as mentioned by the IEEE standard [5] on synchrophasors. It can be concluded that the error in phase angle and magnitude is a function of many factors like magnitude of frequency deviation $|\Delta f|$, presence of disturbance or noise signals and the starting point of window during recursive computation. It can be inferred that these techniques gives estimates of phasors with small deviation and these algorithms are useful to PMU for analyzing the phasor under fault conditions and can provide safety to the power grid.

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