

MODELING OF PHASOR MEASUREMENT UNIT (PMU) USING VARIOUS PHASOR ESTIMATION TECHNIQUES IN MATLAB

A Dissertation submitted in fulfillment of the requirements for the Degree

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in
Electronic Instrumentation & Control Engineering

Submitted by

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DECLARATION

I hereby certify that the work which is presented in dissertation entitled, "Modeling of Phasor Measurement Unit (PMU) using various Phasor Estimation Techniques in MATLAB" in partial fulfillment of the requirements for the award of the degree of Master of Engineering in Electronics (Instrumentation & Control), submitted to Electrical & Instrumentation Engineering Department of Thapar University, Patiala is as authentic record of my own work carried under the supervision of Dr. Sangeeta Kamboj, Assistant Professor, Electrical and Instrumentation Engineering Department, Thapar University, Patiala, Punjab. It refers others researcher's work which are duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in text and references.

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LIST OF ABBREVIATIONS

AC - Alternating Current
ADC - Analog to Digital Convertor
BPF - Band Pass Filter
DC - Direct Current
DFT - Discrete Fourier Transform
DSDR - Digital System Disturbance Recorders
DSP - Digital Signal Processing
EIPP - Eastern Interconnection Phasor Project
FFT - Fast Fourier Transform
GPS - Global Positioning System
IEEE - Institute of Electrical and Electronics Engineers
IPP - Independent Power Producers
ISGW - India Smart Grid Week
LabVIEW - Laboratory Virtual Instrument Engineering Workbench
MATLAB - Matrix Laboratory
MODEM - Modulator-Demodulator
NASPI - North American Synchrophasor Initiative
PLL - Phase Locked Loop
PMU - Phasor Measurement Unit
PPS - Pulse per Second
PSTCL - Punjab State Transmission Corporation Limited
RMS - Root Mean Square
SCADA - Supervisory Control And Data Acquisition
SCDR - Symmetrical Component Distance Relay
SDFT - Sliding Discrete Fourier Transform
UTC - Coordinated Universal Time
WAM - Wide Area Monitoring
WAMS - Wide Area Measurement Systems

ABSTRACT

Present economies are becoming fully dependent on electric power supplies for their routine activities and it becomes an essential condition to have a reliable power system. PMU is the technology used for wide area grid visibility and avoids blackout conditions. Power system monitoring, analysis, protection and control can be done using PMU. Instantaneous voltage and current at a specific node in power transmission system can be measured using a PMU. The delivery of electric power from grids to user is indicated by voltage and current parameter. Global Positioning System (GPS) is used for time stamping of the power signal in PMU. In PMU phasor estimation technique is used to measure phasor value of voltage / current signal. The mechanism involved in the phasor estimation process is necessary for correct phasor data interpretation and analysis, as well as for design of advanced control and protection schemes.

In the work, Modeling of PMU has been done in MATLAB software. The phasor estimation techniques such as zero crossing, DFT (Recursive and Non-recursive) and Sliding DFT has been used to compute magnitude and phase value of input signal. Three cases have been considered to get the output of PMU Model. Also the comparison of results obtained using phasor estimation techniques has been done in the work. The sampling rate upto 6.4 KHz has been taken in modeling of PMU.

1.1 BACKGROUND AND MOTIVATION

Power demand is increasing enormously and the power system is evolving with time. Present economies are becoming fully dependent on electric power supplies for their routine activities and it becomes an essential condition to have a reliable power system. PMU with synchronized measurement is used to measure the status of the large interconnected power system in Wide Area Monitoring (WAM) technology [1, 2]. Wide Area Measurement Systems (WAMS) used Synchronized phasor measurements for power system control, protection and monitoring applications. PMU is one of the Synchrophasor technologies which provides real-time wide-area grid visibility and mitigates blackout conditions [3].

The concept of PMU was originated from Symmetrical Component Distance Relay (SCDR) used in dynamic relay technology. Computation of voltage phase angle was first realized in 1983 by Dr. Phadke and Dr. Thorpe on theoretical basis. Frequency, rate of change of frequency and voltage phasor are the techniques for measurement used at that time [4]. When PMUs became commercially available for the first time in the early 1990s, its applications were limited to be used as digital system disturbance recorders (DSDRs). At that stage, even though their use in protection and control was theoretically established but PMUs were continued to be used only as DSDRs. After the blackouts of 1996 and 2003, PMU technology was highly encouraged for use in protection and control of power system. Due to this Eastern Interconnection Phasor Project (EIPP) also called North American Synchrophasor Project (NASPI) come into existence. In United States the first real-time wide-area monitoring was performed by EIPP [5-7]. PMUs are expensive and their costs depend on the utility, location, and availability of communication channels [8].

Instantaneous voltage and current at a specific node in power transmission system can be measured using a device called PMU. The need for real-time monitoring of power system has led to increased deployment of PMUs. In India, 60 PMUs were installed, including three by

independent power producers (IPPs), out of which 14 PMU pilot project implemented in Northern region [8,9]. In August 2013 the bus voltage changed from 414 kV to 402 kV when the 63 MVAR bus reactor II was installed at the 400 kV Silchar substation. Due to this oscillations in the voltage plot were observed in the north-eastern region. In PMU, phasor estimation technique is used to measure phasor value of voltage/current signal. The mechanism involved in the phasor estimation process is necessary for correct phasor data interpretation and analysis, as well as for design of advanced control and protection schemes. In some of research papers software based PMU simulator and the detail of its phasor estimation using various methods are discussed theoretically. In available literature sampling rate upto 2.88 KHz has been taken to compute phasor of signal.

In the work, Modeling of PMU has been done in MATLAB software. The phasor estimation techniques such as zero crossing, DFT (Recursive and Non-recursive) and Sliding DFT has been used to compute magnitude and phase value of input signal. Three cases have been considered to get the output of PMU Model. Also the comparison of results obtained using Phasor estimation techniques has been done in the work. The sampling rate upto 6.4 KHz has been taken in modeling of PMU.

1.2 Objectives

The objectives of the thesis consist of:

- Modeling of PMU in MATLAB.
- Use of following phasor estimation techniques at different sampling rates to compute magnitude and phase value of given voltage signal :
 - Zero crossing
 - DFT
 - Sliding DFT
- Comparison of phasor estimation techniques to compute magnitude and phase value of simulated/real input signal for cases under studies.

1.3 Thesis Organization

The work consists of six chapters and contents of these chapters are briefly outlined as follows:

- **Chapter 1** covers the introductory part of work carried out in the thesis. Background and motivation, objectives and thesis structure is detailed in the chapter.
- **Chapter 2** presents review on available work for the thesis.
- The introduction of PMU technology and its functioning has been discussed in **chapter 3**. Synchrophasor technology in accordance with IEEE C37.118 Standard, its applications and phasor estimation techniques such as zero crossing, recursive and non-recursive DFT and Sliding DFT has been also discussed in the chapter.
- In **Chapter 4** PMU model has been discussed in detail, an example of sinusoidal signal has been considered to obtain the output of PMU model. Zero crossing, recursive and non recursive DFT techniques has been used to get output of PMU model in the chapter.
- **Chapter 5** considers various cases of input signal for PMU Model. The outputs of Anti-aliasing filter, ADC and measurement unit of PMU model for cases under studies has been presented in the chapter.
- **Chapter 6** presents some concluding remarks of work. Scope for future work has been suggested in the chapter.

CHAPTER-2

LITERATURE SURVEY

Present economies are becoming fully dependent on electric power supplies for their routine activities and it becomes an essential condition to have a reliable power system. PMU with synchronized measurement is used to measure the status of the large interconnected power system in Wide Area Monitoring (WAM) technology. Power system monitoring, analysis, protection and control can be done using PMU. Instantaneous voltage and current at a specific node in power transmission system can be measured using a PMU. Global Positioning System (GPS) is used for time stamping of the power signal in PMU [1,2].

In 2008 S.K. Soonee et. al. member of Power grid corporation of India Limited explained the need of Phase angle measurement for monitoring the security of a wide area grid and also the need of synchrophasor technology in Indian electric Power systems. They explained that the phase angle differences among different nodes are the measures of static stress across the grid and instability. Phase angle can be measured with respect to a predetermined threshold limit. Their approach improved the system visualization and awareness of operations in grid [1].

Bindeshwar Singh et al presented a brief detail on use application of PMU in power system networks in 2011. The authors present the status of research and development in field of applications of PMU and review the applications those are integrated with FACTS controllers in power system control, monitoring and protection [2].

The details of Synchrophasor measurement technology and basic difference between SCADA and PMU measurement technology and its worldwide research, development and applications were explained by Rohini pradip haridas in 2013. In SCADA measurement are taken with analog signal without time synchronization whereas in PMU measurements are taken with digital signal with time synchronization [3].

In 1983 Phadke et. al. introduced the concept of phase estimation and described the DFT computation result for experiments performed in AEP power system simulation laboratory on

theoretical basis. He also describe that the concept of PMU was originated from SCDR as a part of dynamic relay technology [4].

Phadke A.G et. al. (2006) provides the history of PMU that they became commercially available for the first time in the early 1990's, its applications were limited to be used as digital system disturbance recorders (DSDRs). At that stage, even though their use in protection and control was theoretically established but PMUs were continued to be used only as DSDRs [5].

Zhenyu Huang et. al., Phadke et.al. (2008) said that after the blackouts of 1996 and 2003, PMU technology was highly encouraged for use in protection and control of power system. Due to this Eastern Interconnection Phasor Project (EIPP) also called North American Synchrophasor Project (NASPI) come into existence. In United States the first real-time wide-area monitoring was performed by EIPP [6,7].

Overview of synchrophasor projects are described and the areas where the pilot projects are installed and where are going to be installed till December 2013[8]. In India, 60 PMUs were installed, including three by independent power producers (IPPs), out of which 14 PMU pilot project implemented in Northern region. The International Conference and Exhibition on Smart Grids and Smart Cities gets off the ground on 3-5 march as a part of India Smart Grid Week (ISGW) 2015. The three-day event was inaugurated by the chief guest, Mr Devendra Chaudhry, Special Secretary, Ministry of Power. The key objectives of the event was to position India as an important emerging market for smart grid and smart city products and services to the international technology companies and to provide exposure for utilities, regulators and policymakers in the Indian power sector on smart grid technologies, matured solutions and emerging technology trends[9].

In 2009, applications of PMU were widely discussed with the need of Synchrophasor technology for both online and offline time and its deployment in recovery act smart grid program by US department of energy. Online applications are wide area monitoring and visualizing, oscillating detection, frequency stability monitoring, current stability monitoring and state estimation. In

Offline mode PMU perform applications like post event analysis, Data visualization and model validation [10].

G. Gajjar et. al. (2011) provides early explanation for adopting a distributed structural design for PMU. Synchronized phasor measurement were studied and the characterized in detail. The benefits or shortcoming of PMU were incorporated from their different applications. The requirement for expansion of PMU and its functionality was bring out through study of the applications and synchronized phasor measurement characteristic. The PMU was expanded to a distributed system where numerous small functions are working independently and provide functionality of a PMU. The planned substation automation to show the output work on frame work of IEC 61850 process bus [11].

In 2010 international manufacturers offered commercial PMUs which assemble the existing industry standard for Synchrophasor. Synchronized phasor measurements had become a grown-up technology. With the event of major blackouts in power systems around the world, the value of data provided by PMUs had been acknowledged and installation of PMUs on power transmission networks of major power systems become an important activity. De La Ree et. al. provides a brief introduction to the PMU and WAMS technology and discusses the uses of these measurements for improved protection, monitoring, and control of power networks [12].

Kezunovic M. et al (2002, 2010) explains the integration of time correlated information from PMUs, SCADA and non-operational data capture by electronic devices such as protective relays and digital fault recorders as well as their application in fault location, alarm processing and cascading post event analysis. And explains that the data visualization tool that incorporates options for integration of application modules that contains fault location, alarm processing and cascading analysis approaches [13,16].

W.U. Rahman et al (2012) explains how PMU provides new solutions for wide area control, monitoring and protection. Wide-area protection, monitoring and control require communicating a specific-node information to a remote station and all information should be time synchronized

so as to neutralize the time difference between information. It gives a complete instantaneous snap shot of the power system [14].

CIGRE Croatian National Committee listed PMUs applications that provides with the real time working staff with much needed tools to avoid voltage and dynamic instability [15]. To monitor generator responses for irregular excursions considered system frequency. Committee's objective was to spot the benefits of using PMUs for special real time applications and that time ongoing pilot projects i.e. pilot projects in 2006 to give short and long term roadmap for future acts.

Synchronized phasor measurements for power systems was Presented by PMU standards C37.118.1-2011. This IEEE standard defines Synchrophasor, frequency, ROCOF measurement for all operating conditions. It specifies the methods to evaluate the measurements and requirements for observance of the standard under steady-state and dynamic conditions. Time tagging and synchronization requirements were done using GPS. Performance requirements were set with a reference model. The standard PMU can be a stand-alone physical unit[17].

Phadke et. al. (2008) explains the emerging applications and development of the Synchrophasor technology. This will help power system engineers to understand and analyze the basics of "synchronized phasor measurement systems". The technology is bound to users in an phase of power system's improved monitoring, protection, and control. Phadke explains the basic of Synchrophasor and phase difference with GPS and UTC time synchronization [18].

D. Dotta et. al. presented a PMU MATLAB simulator. The aim of the software was to understand the behavior of algorithms to the PMU and to seize key factors affecting their performance under off nominal frequency operation. The PMU simulator was useful for academic and professionals who would like to understand the concepts involved in the phasor estimation process carried out by PMUs. The performance of the simulator was evaluated using simulated and real data from 2.88 kHz measurements. The output of the estimation process was compared with reference traces and phasor from real PMUs[19].

D.G. Hart et. al. (2001) gives the basic architecture of PMU, explain how the PMUs work in the real time with GPS and connect to other GPS with modems. PMU is broadly consists of three basic unit - Clock Synchronization Unit, Measurement Unit, Data Transmission Unit . The Clock Synchronization Unit comprises of GPS receivers and phase-locked oscillators, which provide the sampling clock to the Measurement Unit. The Measurement Unit can be further divided into three basic components- Anti-aliasing filters, Analog-to-Digital, Phasor measurement Unit/ Processor. An anti-aliasing filter is used before signal sampling to satisfy the sampling theorem and to limit the bandwidth of a signal. An analog to digital converter is then used to converts a physical quantity like voltage to a digital number/quantity that represents the amplitude. The Data Transmission Unit retrieves the measured data from the Measurement Unit and transmits it over some suitable communication protocol such as modem [20].

Effectiveness and accuracy for phasor measurement unit's measurement result are directly influenced by measurement unit[21]. The article explains a measurement unit of PMU with the use of a DSP chip as main processor. The DFT phasor measurement algorithms are used. With the hardware circuit and software realization the electric signal can be imported directly with every primal.

Vinay K. Ingle et. al. (2012) explains the implementation of DSP algorithms in MATLAB. It is helpful for programming the code for DSP techniques [23].

Researchers and scientists uses software which suits their work. To do work in the areas of signal analysis and simulation of dynamic systems LabVIEW and MATLAB tools are most commonly used. In 2012 a comparison was made based on practical performed with four comparisons i.e computation with matrices , Bode plot , FFT calculation and DC motor simulation[24]. MATLAB is more efficient tool for evaluating equations.

V. Krishna et. al. explained the design of a Synchronized Phasor Measurement Unit (PMU) based on a Digital Signal Processor. The algorithm used for the implementation of proposed system is Recursive Discrete Fourier Transform (DFT) algorithm. The simulation for the

proposed algorithm in LabVIEW software is explained in this paper and the results are obtained after simulation[25].

Kang H. et. al. (2009) developed a new tool to simulate PMU measurements. The tool provides the capacity to test and study operations offline before they are actually installed. Using the simulation application allow testing of Ethernet to assess traffic load and propagation delay of PMU data [26].

Mark Adamiak examines sensor errors, off-nominal frequency components, timing errors and system harmonics with the issues of implementing measurements. Simulations of the various systems transient are signals and their phasor responses ie output has been presented[27].

A. G. Phadke explains a possible format for transmitting the phasor measurements to remote locations using various methods of synchronizing signals in the paper. The description describes the concept of utilizing time synchronized sampling[28].

Milos Sedlacek explains in the paper the basic idea to find the phasor using zero crossing in the paper. It has been given that in zero crossing phase of a signal can only be compute if a reference signal is provided.

Sourav Mondal et. al. explained the simulation of Non-recursive and recursive DFT phasor estimation algorithm using LabVIEW and compares the result between recursive and non-recursive DFT using a test signal.

Proakis et. al. explained the digital signal processing and its principles, algorithm and application in detail. Discrete Fourier Transform and its implementation to change a signal from one domain to other domain is briefly explained.

Eric Jacobsen et.al. (2003) described a sliding DFT process. To compute the value in SDFT a previous value of SDFT must be known. The computation for computing results is less in Sliding

DFT as compare to DFT. For N point output computations required for SDFT is N as compare to N^2 for DFT.

3.1 Introduction

This chapter describes about the PMU and its basic functioning. Synchrophasor technology in accordance with IEEE C37.118 Standard, its applications and phasor estimation techniques such as zero crossing, recursive and non-recursive DFT and Sliding DFT has been explained in the chapter.

3.2 The Phasor Measurement Unit (PMU)

PMU is a device used to analyze the health of the system in which electric waves on electricity grid are measured. Synchrophasor measurements are the measurements that occur at the same time. PMUs are used to provide synchronization. PMU are installed at various locations in the power system and are synchronized with GPS [10].

Power system monitoring, analysis, protection and control can be done using PMU. Instantaneous voltage and current at a specific node in power transmission system can be measured using a PMU. The delivery of electric power from grids to user is indicated by voltage and current parameter. Global Positioning System (GPS) is used for time stamping of the power signal in PMU. The frequency that does not deviate from its original value ensures the proper operation of power system and its reliability. PMU depends on GPS time signal for accurate time stamping for accurate the power system information [10]. PMU provides measured voltage, current and frequency in form of magnitude and phase as its output. The output of a PMU is the phasor representation of the measured sinusoidal signal with a time stamp [11].

PMU measure the parameters such Positive sequence voltages and currents, Phase voltages and current, Rate of change of frequency synchronously [12].

PMU is used for various applications in power system such as protection, state estimation, fault location of transmission line. PMU have both online (Real-Time) and offline (not real-time) applications. PMU provides solutions for wide area monitoring, wide area interconnected grid protection and control [14].

Online applications are wide area monitoring and visualizing, oscillating detection, frequency stability monitoring, current stability monitoring and state estimation [10-13].

In Offline mode PMU perform applications such as post event analysis, model validation and Data visualization [10,13]. A post event analysis is used to reconstruct the sequence of events after a power system disturbance has occurred. A team of engineers assembles and studies the recordings from various data recorders throughout the grid to understand and reconstruct a timeline of what happened making the job easy and time saving [15]. For integration of application modules that contains Alarm processing, fault location and cascading analysis approaches the data visualization tool is used [16].

3.2.1 Synchrophasor

A phasor is an analytical and time-invariant representation of a sinusoidal wave. It is commonly used for AC power system analysis. A sinusoidal signal is represented as in equation 3.1.

$$x(t) = X_m \cos(\omega t + \varphi) \quad (3.1)$$

This equation can be represented in phasor form as:

$$X = \frac{X_m}{\sqrt{2}} e^{j\varphi} = \frac{X_m}{\sqrt{2}} (\cos\varphi + j\sin\varphi) = X_r + jX_i \quad (3.2)$$

Here, $X_m/\sqrt{2}$ is the root mean square value of the signal and φ is the phase angle. Phasor represent a sinusoidal signal taking into consideration the phase difference of the measured signal with respect to a predefined reference so that two signal are directly compared with respect to the same reference. Synchrophasor use coordinated universal time (UTC) as an

absolute time reference. If UTC is used as a reference for all phasor measurements globally then these measurements can directly be compared irrespective of the locations of sampling [17,18].

The Synchrophasor representation of the signal $x(t)$ in Equation (3.1) is the value X in Equation (3.2) where φ is the instantaneous phase angle relative to a cosine function at the nominal system frequency synchronized to UTC. One pulse per second signal (PPS) generated by some very precise clocks which trace UTC is used as reference for sampling the waveform.

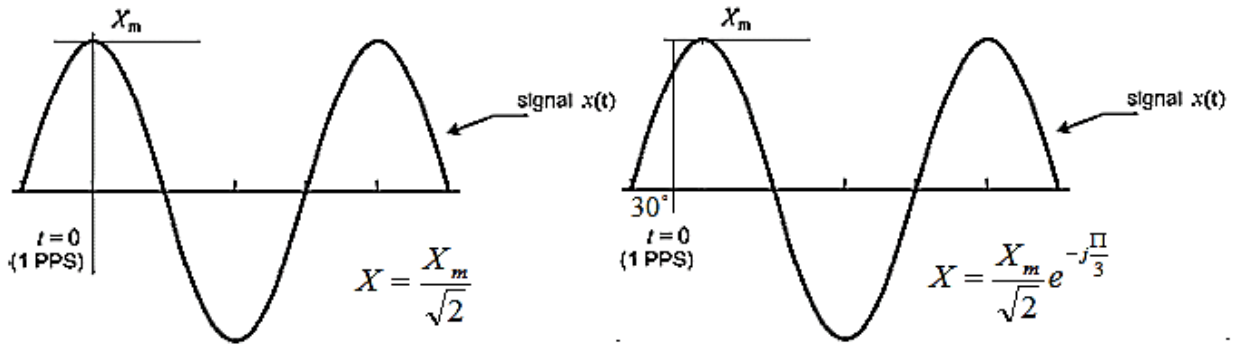


Figure 3.1 Synchrophasor representation

Figure 3.1 illustrates how PPS signal is used as a reference to measure phasor [17]. If the PPS signal coincides with the peak of the measured waveform as shown in first case of the figure, the phase difference is zero hence the phasor representation becomes:

$$X = \frac{X_m}{\sqrt{2}} \quad (3.3)$$

For the second case, where the phase difference between the reference peak and the measured signal peak is 60 degrees, the phasor representation is given by:

$$X = \frac{X_m}{\sqrt{2}} e^{-j\frac{\pi}{3}} \quad (3.4)$$

A power system hardly operates at its fundamental or nominal frequency. If frequency $f \neq f_0$ and $f < 2f_0$, where f_0 is the fundamental frequency of a sinusoidal wave, the observed phasor will

have a constant magnitude. However, the phase angles of the sequence of phasor { $X_0, X_1, X_2, X_3, \dots, X_n$ } will change uniformly at a rate of $2\pi (f - f_0) T_0$, where $T_0 = 1/f_0$ and, as shown in figure 3.2 [17,18].

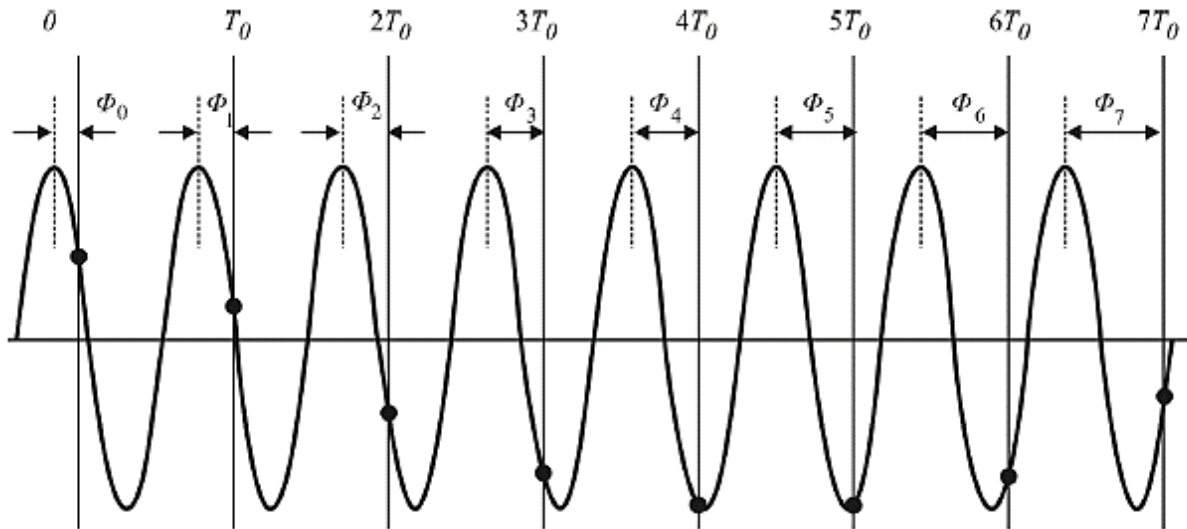


Figure 3.2 A sinusoid signal showing uniform increase in phase angle

3.3 Basic PMU Structure

Synchronized phasor measurement is the state of technology for Wide Area Monitoring of Electrical Power System under both static and dynamic conditions. The measurements are done through Phasor Measurement Units installed at selected nodes of the electrical power grid. PMU is a data acquisition device that helps in estimating the state of power network by measuring current and voltage phasor and frequency of a given node [19,20]. A simplified diagram of the PMU structure is given in figure 3.3 [20].

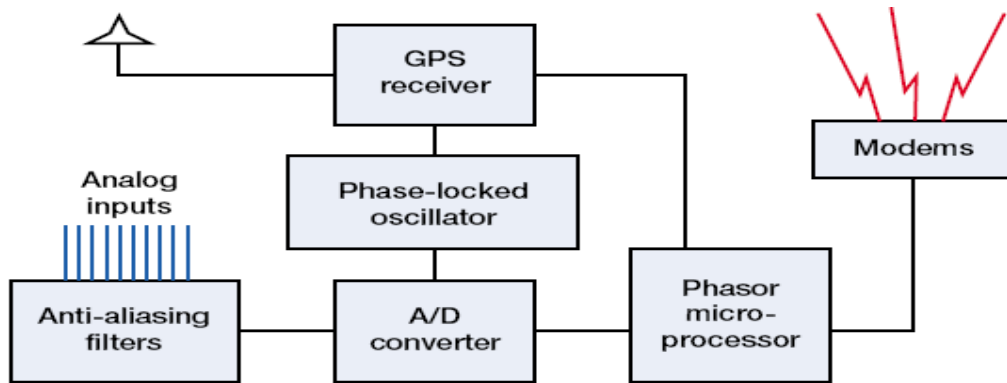


Figure 3.3 Basic PMU Structure

PMU is broadly consists of three basic units:

- Clock Synchronization Unit
- Measurement Unit
- Data Transmission Unit

The Clock Synchronization Unit comprises of GPS receivers and phase-locked oscillators, which provide the sampling clock to the Measurement Unit. The GPS receivers are used to detect 1 pulse per second (PPS) synchronizing signals from GPS source. A GPS reference source along with phase locked oscillator provides the high-speed synchronized sampling with 1 microsecond accuracy [3,20]. A control system that generates an output signal whose phase is related to the phase of an input signal is called PLL. Initially PLL is visualized as an electronic circuit having a variable frequency oscillator and a phase detector. A periodic signal is generated by oscillator. The phase detector compares the phase of the signal with the phase of the input periodic signal. The oscillator is kept to adjust the phases till they matched.

The Measurement Unit can be further divided into three basic components:

- Anti-aliasing filters
- Analog-to-Digital Convertor
- Phasor measurement Unit/ Processor

An anti-aliasing filter is used before a signal sampling to satisfy the sampling theorem and to approximately limit the bandwidth of a signal. As per the theorem the definite interpretation of the signal from its samples is possible only when the power of frequencies above the Nyquist frequency is zero. Real anti-aliasing filters generally not completely satisfy the theorem. They permit some aliasing to occur [3,20]. An anti-aliasing filter is usually a low-pass filter. But this is not a requirement. Nyquist Shannon sampling theorem allows sampling of band limited pass band signals instead of baseband signals. For signals that are bandwidth limited but are not centered at zero, for that signals a band-pass filter can be used as an anti-aliasing filter. To avoid any aliasing errors, the IEEE C37.118 standards make it necessary to use the filter which band limits the input signals to below the of half the sampling frequency chosen [21]. The Butterworth BPF specifically have centre frequency $f_0=50\text{Hz}$ and bandwidth $\Delta f=10\text{Hz}$ is chosen generally due to its maximally flat response in pass-band as compare to other filter as shown in figure 3.4 [22].

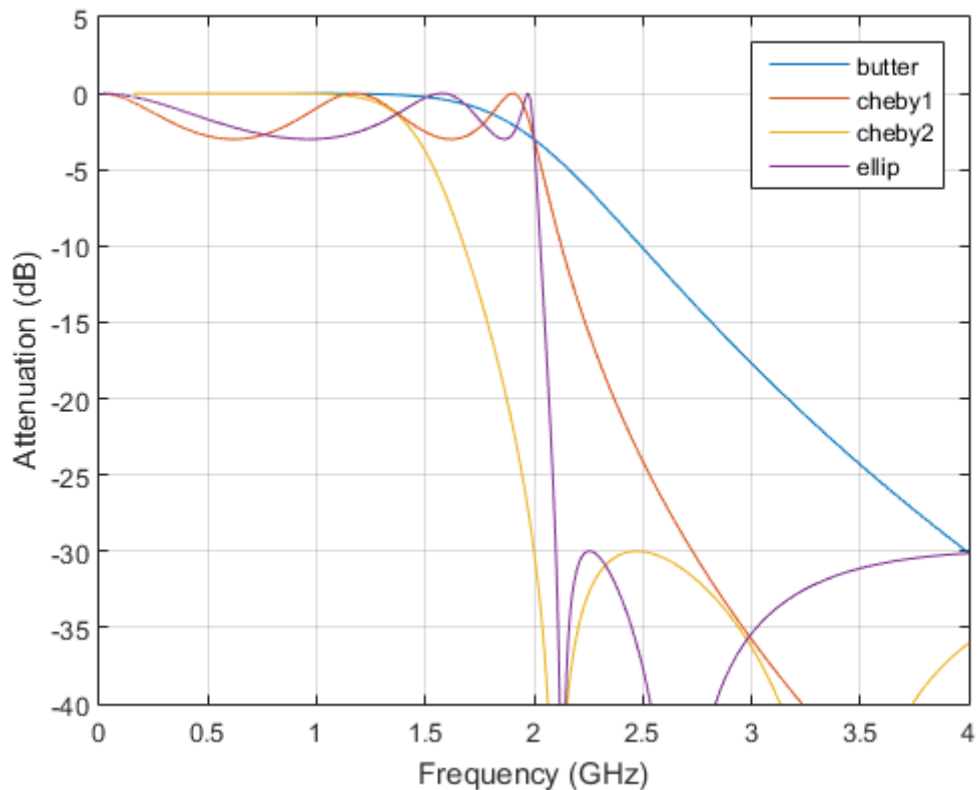


Figure 3.4 Magnitude responses of various filters

The device used to convert a continuous physical quantity usually voltage to a digital number that mainly represents the quantity's amplitude is an analog to digital converter (ADC). Quantization of the input involves in ADC that introduces a small amount of error. The output of ADC is a sequence of digital values that convert a continuous time and amplitude analog signal to a discrete time and discrete amplitude signal. It is therefore required to define the rate at which new digital values are sampled from the analog signal. The rate of new values at which digital values are sampled is called the sampling rate of the converter [3, 20]. Widespread employment of the PMUs for providing both appropriate penetration and redundancy of synchronized measurements is a requirement. Such widespread deployment can be achieved when integrating the PMU function within modern microprocessor based relays similar to the relay integration trend seen with metering, fault recording, and sequence of event re-cording capabilities.

MATLAB software that can be used as a teaching tool and research framework to explore the algorithms involved in the phasor estimation process can be used as PMU phasor measurement processor. Phasor estimation techniques are processed using MATLAB [23]. This software can process simulated and real measured signals. The main idea is to provide a software tool to better understand the phenomena involved in the phasor measurement process. MATLAB is better for computation of equations of phasor estimation and evaluate output [24].

The Data Transmission Unit retrieves the measured data from the Measurement Unit and transmits it over some suitable communication protocol such as MODEM (modulator-demodulator). A device that modulates an analog carrier signal and encodes digital information from the signal and can also demodulate the signal to decode the transmitted information from signal is called modem. The objective of modem is to produce a signal that can be transmitted and decoded to make a replica of the original digital data. Modem can be used with no. means of transmitting analog signals [3,20].

3.4 Phasor Estimation Techniques

Phasor are basically used for ac circuit analysis which is introduced as a mean of representation of steady state sinusoidal signal of power frequency. Measuring these voltage phasor in real time

allows operators to see and respond to approaching grid stability problems. Phasors are often useful in describing the behavior of the power system though the power system is not in steady state. For example, during power swings when the power system is undergoing electromechanical oscillations, the voltages and currents signal are neither in steady state nor is the frequency of the power system at its nominal value. Under these kind of conditions the variations in the voltages and currents are relatively slow, phasors may be used to describe the performance of the network and the variations being treated as a sequence of steady state conditions [21, 25].

To represent a sinusoidal signal, a phasor represents a quantity with magnitude and phase in respect to a reference that is used [26]. A sinusoidal signal and its phasor representation are given in the figure 3.5.

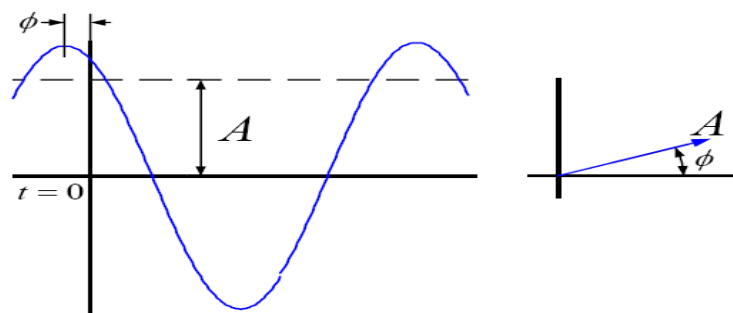


Figure 3.5 Sinusoid signal and its phasor

The length of the phasor is equal to the RMS value of the sinusoidal signal. Depending on the choice of the axis $t = 0$, the phase angle of the phasor is arbitrary. The phase angle is the distance between the sinusoidal signal's peak and a specified reference given and is expressed using an angular measure. The reference is fixed in time (such that time $t = 0$). The phasor length is related to the amplitude of the sinusoidal signal. The word phasor indicates a measurement of both the signal magnitude and the angle [25,27,28].

Here ϕ represents the distance between peak value and signal value at time t in time domain. This ϕ is represented as phase in frequency domain as shown in figure 3.5. If ϕ is to be calculated on right side with respect to peak value then it is $+\phi$ and if it is to be calculated on left side with respect to peak value then it is $-\phi$ [25].

Several methods for phasor estimation are found in the literature are as [19]:

- Zero Crossing
- DFT
- Sliding DFT
- Least Error Squares
- Kalman Filters
- Demodulation
- Phasor measurement angle changing

Out of above given techniques Zero crossing, DFT and Sliding DFT phasor estimation techniques have been used in this work.

3.4.1 Zero Crossing

Zero crossing technique is used with phase difference estimation algorithm. Detections of crossing of a zero level by the measured signal and reference signal is used for phase difference estimation. Signal pre-conditioning is required in practice to prevent additive zero crossings caused by additive noise and signal harmonic components before detection of crossings of zero level [29].

This method is used to multiply the sinusoidal signal by a reference signal. Sinusoid signal must be of same frequency as of the measured signal. This technique is used to find mean value or DC component by this product. This mean value is relative to sine of the phase difference between the measured signal and the reference signal. The phase shift which is considered to be zero gives the real part of the phasor vector of the measured signal. Multiply this signal by sine reference signal i.e. reference signal shifted by 90° in reference to the first one and finding the mean value by low-pass filter give the imaginary part of the phasor x_n of measured signal. Phase difference of measured signal with the reference signal can be found by using $\tan^{-1}(\text{Im } x_n / \text{Re } x_n)$ function. By using the same process for the second measured signal find the phase difference between the second signal and the reference signal. Difference of phase shifts of the two signals

with the reference signal is the measured phase difference. Phase difference of their fundamental harmonic components in case of sinusoidal signals can be distorted by higher harmonic components. The phase difference to be found is given in equation 3.5.

$$\phi = \phi_2 - \phi_1 \quad (3.5)$$

It is one of the methods to measure the phase angle between two buses consisted of generating two synchronized 50 Hz reference signals at two distant stations and to measure at each station the delay between the zero-crossing of the reference and the voltage signal. Phase difference was then computed in a straightforward fashion by sending the measured delays to a central point [29].

3.4.2 DFT

DFT technique for phasor estimation method is widely used. In discrete Fourier transform we can use two algorithms to find out the phase i.e. recursive algorithm or non-recursive algorithm. The algorithm that does not take into account data from previous window and calculate phasor estimate afresh is called non-recursive algorithm [30].

Consider a sinusoidal input signal of frequency ω given by equation 3.6 [29].

$$x(t) = \sqrt{2}X \sin(\omega t + \varphi) \quad (3.6)$$

This signal is conventionally represented by a phasor X in equation 3.7.

$$X = X e^{j\theta} = X \cos \varphi + j X \sin \varphi \quad (3.7)$$

Assuming that $x(t)$ is sampled N times per cycle of the 50 Hz signal to produce the sample set $\{x_n\}$ as given in equation 3.8.

$$x_n = \sqrt{2} \sin\left(\frac{2\pi n}{N} + \varphi\right) \quad (3.8)$$

The Discrete Fourier Transform of $\{x_n\}$ contains a fundamental frequency component given by equation 3.9.

$$X^n = \frac{\sqrt{2}}{N} \sum_{n=0}^{N-1} x_n \cos(2\pi n/N) + j \frac{\sqrt{2}}{N} \sum_{n=0}^{N-1} x_n \sin(2\pi n/N) \quad (3.9)$$

A modified algorithm which saves computation taking into account data from previous window is called as recursive algorithm [30]. The input signal of equation (3.6) gives the fundamental frequency component as given in equation 3.10 [29].

$$X^{n+1} = X^n + \sqrt{2}/N(x_{N+n} - x_n)e^{-jn\theta} \quad (3.10)$$

DFT (Discrete Fourier Transform) is a transform to change the input signal from time domain to frequency domain. The frequency domain contains exactly the same information as the time domain, just in a different form. If one domain is known, other can be calculated. Let $x(t)$ be a sinusoidal input signal in time domain sampled N times per cycle to produce a sample set of $x(n)$. Then DFT of signal can be calculated using equation 3.11 [31].

$$X(k) = \frac{1}{N} \sum_{n=0}^{N-1} x(n) e^{-j2\pi nk/N} \quad (3.11)$$

In frequency domain $X(k)$ consists of two parts i.e. real $\text{Re } X(k)$ and imaginary $\text{Im } X(k)$ with which magnitude and Phase of the signal at each points can be calculated using equation 3.12 and equation 3.13 respectively.

$$\text{Magnitude} = \sqrt{(\text{Re } X(k))^2 + (\text{Im } X(k))^2} \quad (3.12)$$

$$\text{Phase} = \tan^{-1} \frac{\text{Im } X(k)}{\text{Re } X(k)} \quad (3.13)$$

3.4.3 Sliding DFT

Sliding DFT processes have advantage that it requires fewer computations than the DFT for real-time spectral analysis. The sliding DFT (SDFT) algorithm performs an N -point DFT on time samples within a sliding-window. The time window is then advanced one sample and a new N -point DFT is calculated. The values of SDFT are efficiently computed directly from the results of the previous DFT [32]. The method used for the SDFT is known as the DFT shifting theorem or the circular shift property. It is stated that if for a time domain signal $x(n)$ the DFT of a windowed (finite-length) time-domain sequence is $X(k)$, then the DFT of that sequence circularly shifted by one sample is $X(k)e^{j2\pi k/N}$. Then spectral components of a shifted time sequence are the original (unshifted) spectral components multiplied by $e^{j2\pi k/N}$ where k is the DFT bin of interest then the SDFT can be computed using equation 3.14.

$$S_k(n) = S_k(n-1)e^{j\frac{2\pi k}{N}} - x(n-N) + x(n) \quad (3.14)$$

Where $S_k(n)$ is the spectral component and $S_k(n-1)$ is the previous spectral component of Sliding DFT. For the N -point output the computations done is N for the sliding DFT as compare to (N^2) for the DFT and $(N \log (N)^2)$ for the FFT [32].

4.1 Introduction

In the chapter PMU model has been discussed in detail, an example of sinusoidal signal has been considered to obtain the output of PMU model. Zero crossing, recursive and non recursive DFT techniques has been used to get output of PMU model in the chapter.

4.2 PMU Model

Modeling of PMU is done using Simulink toolbox in MATLAB. MATLAB is a software which is used for numerical computing allows plotting of functions and data, implementation of algorithms, simulation of data and interfacing with programs written in languages including C, C++. Though MATLAB is intended primarily for numerical computing, an additional package of toolbox Simulink, adds graphical multi-domain simulation and model-based design for dynamic systems developed by MATHWORKS®.

The following figure 4.1 shows the model of PMU. The main parts of PMU model are as:

- Analog filter
- ADC
- Measurement Unit.

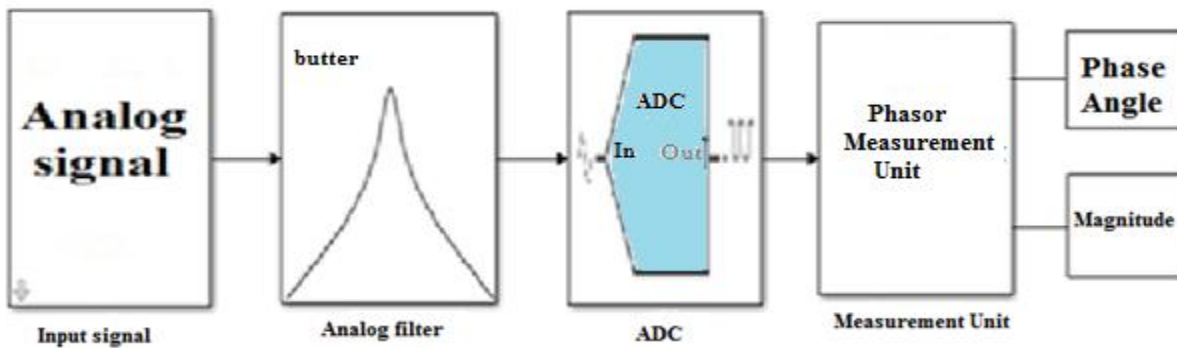


Figure 4.1 PMU Model in MATLAB

Analog Filter

An analog is used to filter out the input frequencies to avoid any aliasing errors. The IEEE C37.118 standard makes it compulsory to use this filter which band limits the input signals. The analog filter is designed to be a band-pass filter with center frequency $f_0 = 50\text{HZ}$ and bandwidth $\Delta f = 10 \text{ Hz}$. The Butterworth band-pass filter is used as analog filter due to its maximally flat response in pass-band. The Butterworth filter of 2nd order is chosen to obtain better results. The 2nd order Butterworth band-pass filter has accurate filter response as compared to 3rd order and 5th order. The 2nd order, 3rd order and 5th order filter response for a signal $x(t) = 220(\sin w_1 t_1 + \sin w_2 t_2 + \sin w_3 t_3)$ having frequency $w_1 = 40 \text{ Hz}$ for $t = 1 \text{ sec}$, $w_2 = 50 \text{ Hz}$ for $t = 0.5 \text{ sec}$, $w_3 = 60 \text{ Hz}$ for $t = 0.5 \text{ sec}$ with center frequency $f_0 = 50\text{HZ}$ and bandwidth $\Delta f = 10 \text{ Hz}$ are shown in figure 4.2, figure 4.3, figure 4.4 respectively.

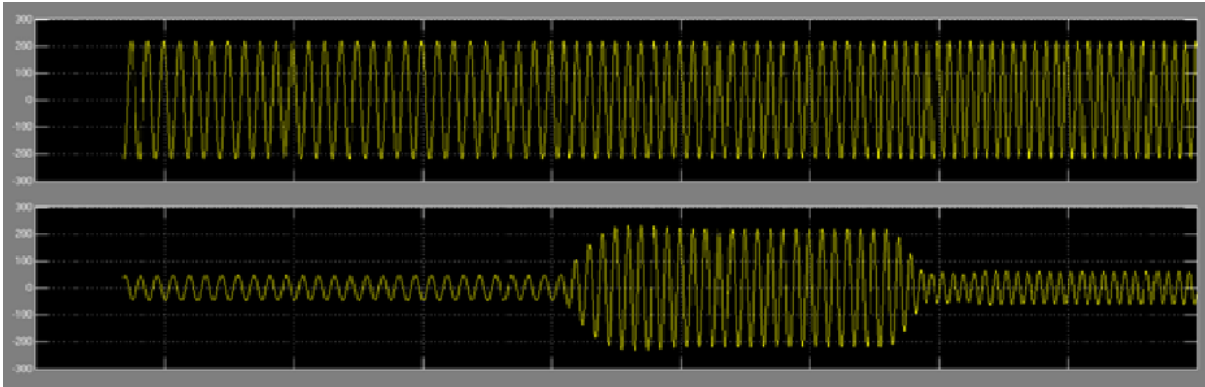


Figure 4.2 Butterworth band pass filter 2nd order

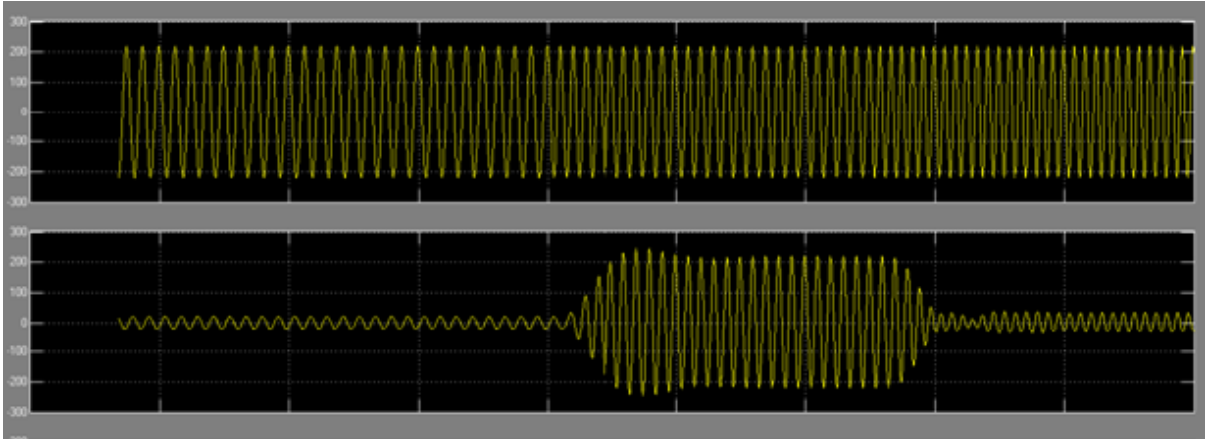


Figure 4.3 Butterworth band pass filter 3rd order

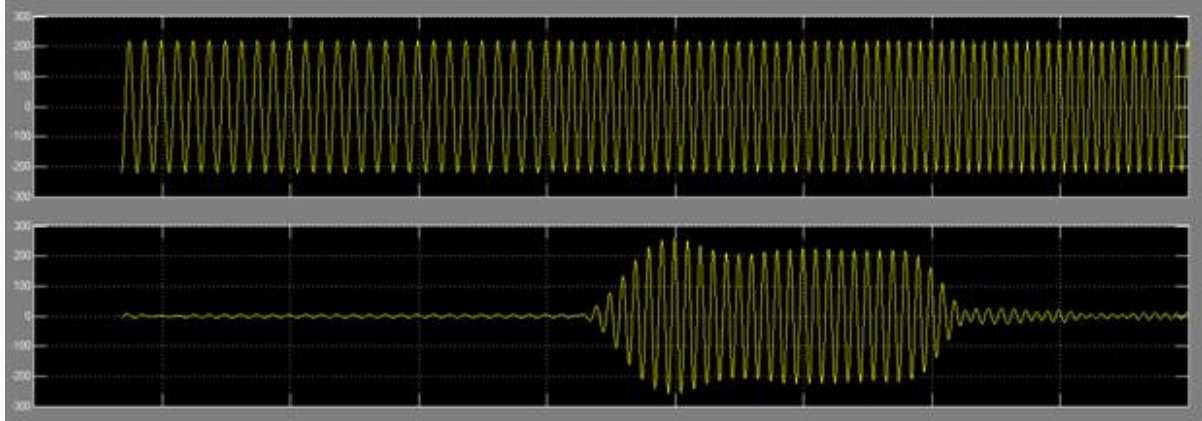


Figure 4.4 Butterworth band pass filter 5th order

Analog to Digital Convertor

In the present work ADC consist of pulse generator, quantizer and sample and hold circuit as shown in Figure 4.5. The sample and hold circuit gives the equivalent result of an Analog to Digital Converters (ADC). Sample and hold circuit converts the input signal into digital signal. In PMU GPS receiver is used for time stamping. In the work pulse generator has been used. Pulse generator generates 1000 pulses for sampling rate of 20 samples/cycle and 6400 pulses for sampling rate of 128 samples/cycle in 1 second as input signal has been sampled in accordance with output of the pulse generator. The quantizer is used to round off error and discretize the input at the interval of 0.5. Sampling in ADC is done for different sampling rates i.e. for 20 samples/cycle and 128 samples/cycle.

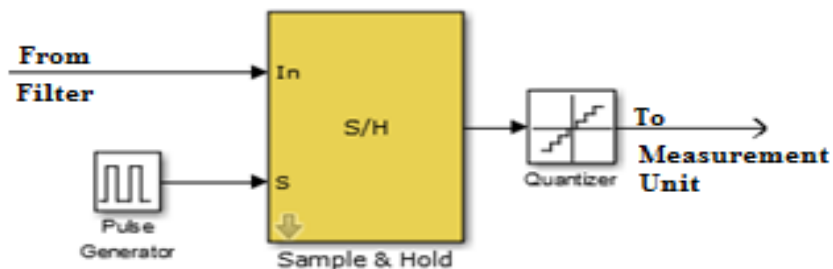


Figure 4.5 ADC using Sample and hold circuit

Measurement Unit

Measurement unit is used to measure Phase and Magnitude of the voltage signal. In measurement unit various phasor estimation techniques such as zero crossing, DFT (Recursive and Non-recursive) and sliding DFT are used to measure Phase and Magnitude of the voltage signal. Different techniques are used to improve accuracy, have useful estimation technique and to increase reliability. To increase efficiency of power system PMU data must be correct and precise.

Consider a sinusoidal signal $x(t) = 220 \sin(100\pi t + \frac{\pi}{4})$ at frequency 50 Hz. The sampling rate is taken at 12 samples per cycle. Thus phasor estimates for first 12 samples using recursive and non-recursive DFT techniques are evaluated as given in table 4.1.

Table 4.1 Recursive and Non-recursive phasor estimates

Sample no.	Sample x_n	Non-recursive Phasor Estimate	Recursive phasor estimate
0	88.388	-54°	36°
1	109.601	-24°	36°
2	141.421	-6°	36°
3	155.563	36°	36°
4	141.421	66°	36°
5	109.601	96°	36°
6	88.388	126°	36°
7	-88.388	-54°	36°
8	-109.601	-24°	36°
9	-141.421	-6°	36°
10	-155.563	36°	36°
11	-141.421	66°	36°
12	-109.601	96°	36°

Figure 4.6 shows the magnitude and phase representation of the given signal using recursive DFT phasor estimation technique.

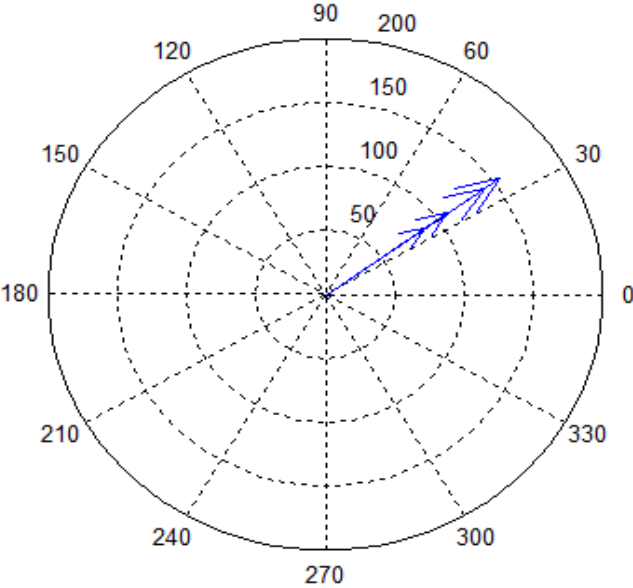


Figure 4.6 Recursive phasor estimation

Figure 4.7 shows the magnitude and phase representation of the given signal using non-recursive DFT phasor estimation technique.

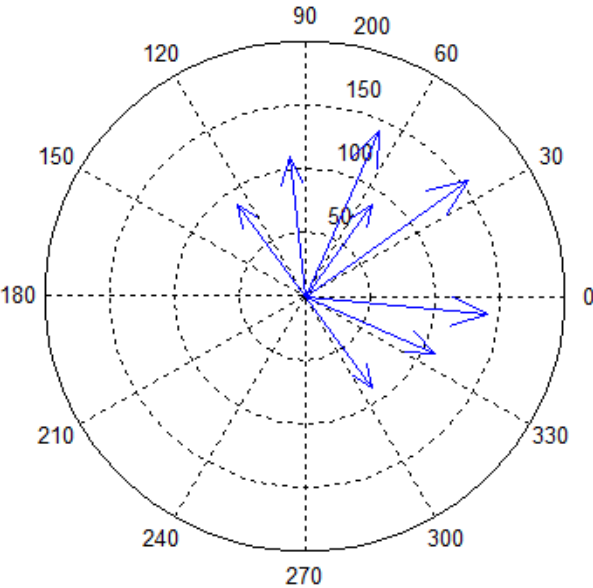


Figure 4.7 Non- recursive phasor estimation

The following figure 4.8 shows an input signal $x(t) = 220 \sin(100\pi t)$ of frequency 50Hz and a reference signal of $x(t) = 220 \sin(100\pi t - \frac{\pi}{4})$ to find phasor output for zero crossing phasor estimation technique.

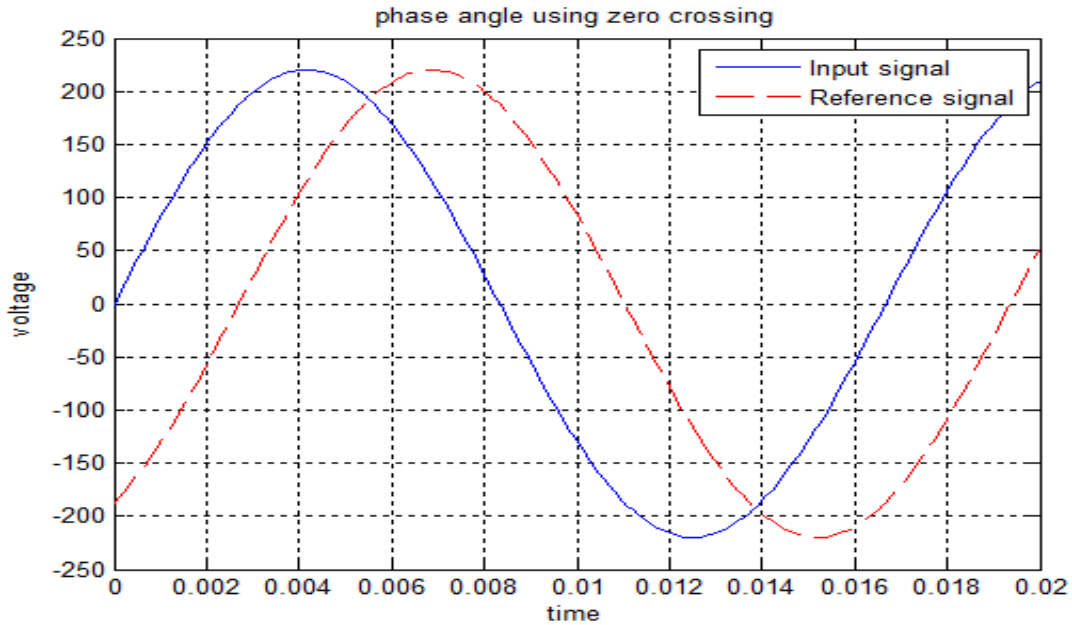


Figure 4.8 Sinusoidal signals for zero crossing phasor estimation technique

Figure 4.9 shows the magnitude and phase representation of the signal $x(t) = 220 \sin(100\pi t)$ and reference signal $x(t) = 220 \sin(100\pi t + \frac{\pi}{4})$ using zero crossing phasor estimation technique.

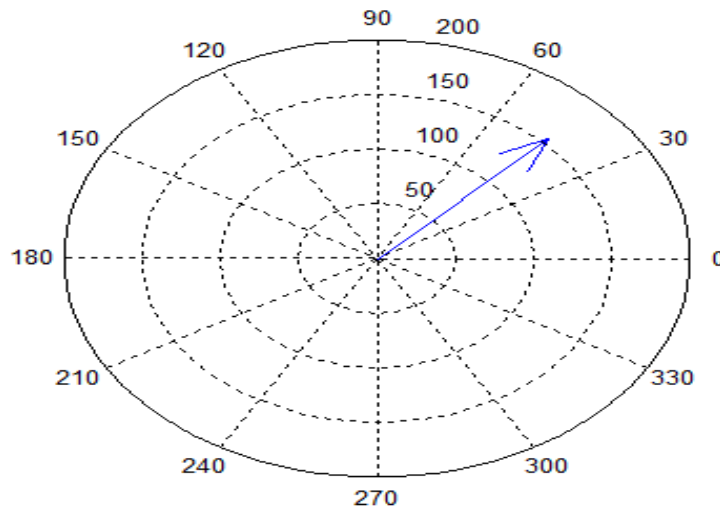


Figure 4.9 Zero crossing phasor estimation

5.1 Introduction

This chapter considers various cases of input signal for PMU Model. The outputs of Anti-aliasing filter, ADC and measurement unit of PMU model for cases under study has been presented in the chapter.

5.2 Case Studies

The following Table 5.1 shows the cases considered as input signal for phasor estimation using PMU model as described in section 4.2.

Table 5.1: Different cases of input for PMU

Cases	Input signal	Signal values
Case 1	Simulated	$x(t) = 220(\sin w_1 t_1 + \sin w_2 t_2 + \sin w_3 t_3)$
Case 2	Simulated	$x(t) = 220 \sin wt_1 + 255 \sin wt_2 + 220\sin wt_3$
Case 3	Real	Data taken from Online Trend Control Project at 400/220kV PSTCL, BHALWAN

5.3 Case 1

5.3.1 Input signal

For phasor estimation of simulated input signal $x(t) = 220(\sin w_1 t_1 + \sin w_2 t_2 + \sin w_3 t_3)$ having frequency $w_1 = 40$ Hz for $t = 1$ sec, $w_2 = 50$ Hz for $t = 0.5$ sec, $w_3 = 60$ Hz for $t = 0.5$ sec is applied to analog filter as can be seen in figure 5.1.

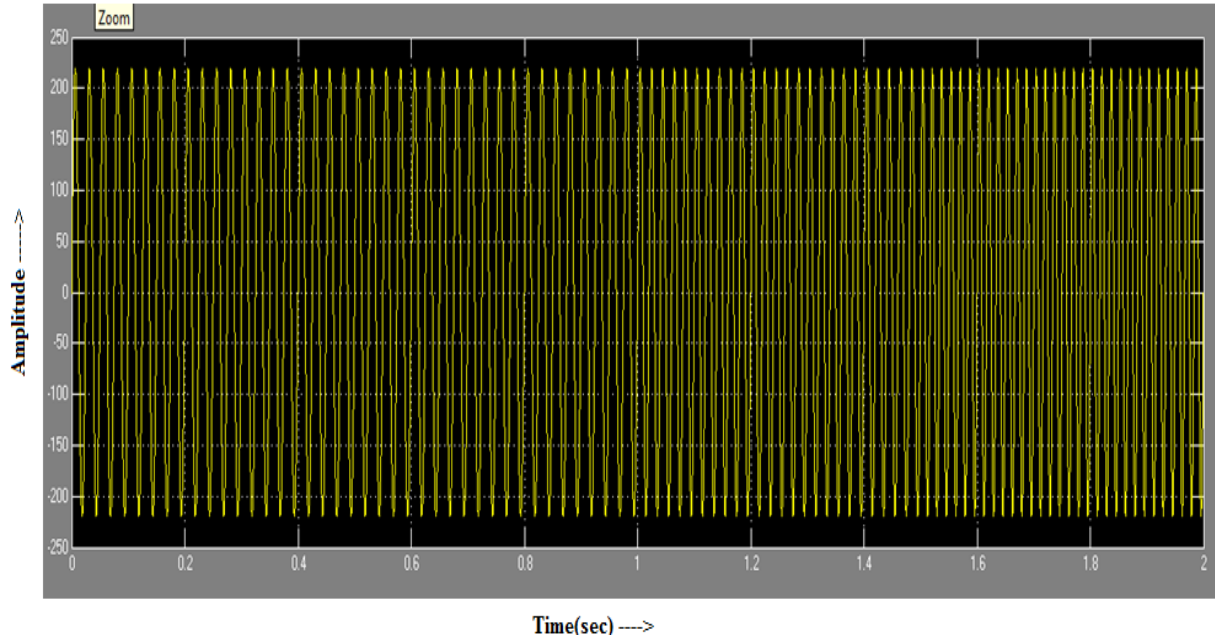


Figure 5.1 Input signal of case 1

5.3.2 Analog Filter Output

Analog filter is a band-pass filter with center frequency $f_0=50\text{Hz}$ and bandwidth $\Delta f = 10 \text{ Hz}$. Figure 5.2 shows the output of the analog filter. Here signal with frequency 50 HZ passes through the filter and signal with frequency 40 Hz and 60 Hz attenuates because as per the band-pass filter parameters only signal of frequency $f= 50\pm 5 \text{ Hz}$ can pass and other attenuates.

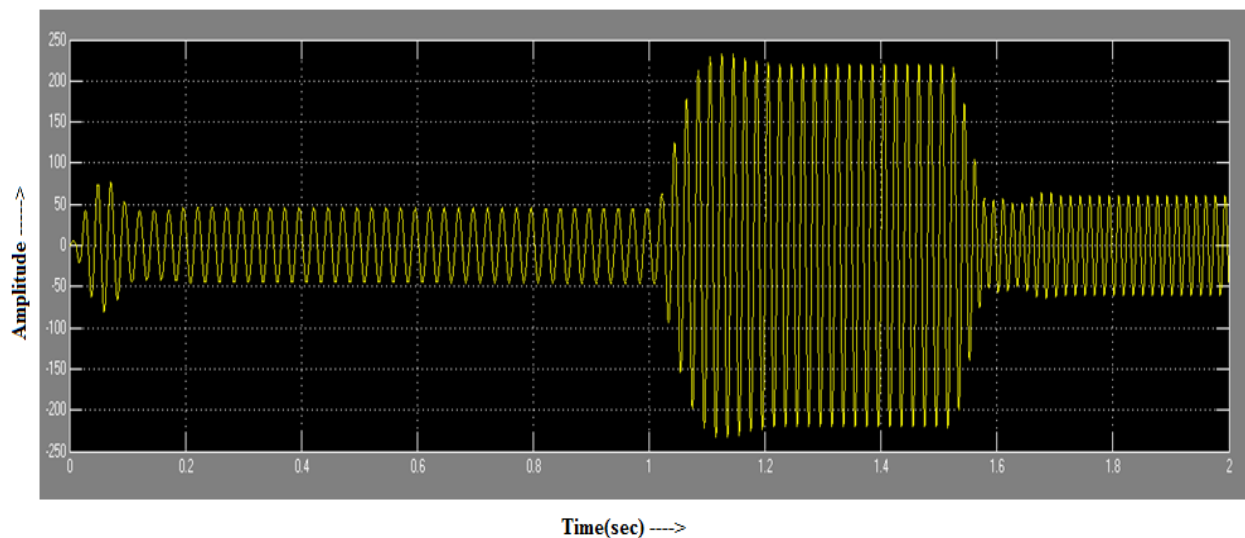


Figure 5.2 Filter Output case 1

5.3.3 Measurement Unit Output

Phasor estimation techniques such as DFT and Sliding DFT are used to measure the phasor of given signal. The window size has been set to 4 points/cycle in DFT and sliding DFT techniques for the estimation. The output of analog signal is sampled using ADC at the sampling rate of 20 samples/cycle and 128 samples/cycle.

The following Figure 5.3 and figure 5.4 presents the output of the measurement unit i.e. magnitude and phase of the signal sampled at the sampling rate of 20 samples/cycle. It has been found that sliding DFT require less computational time as compared to DFT.

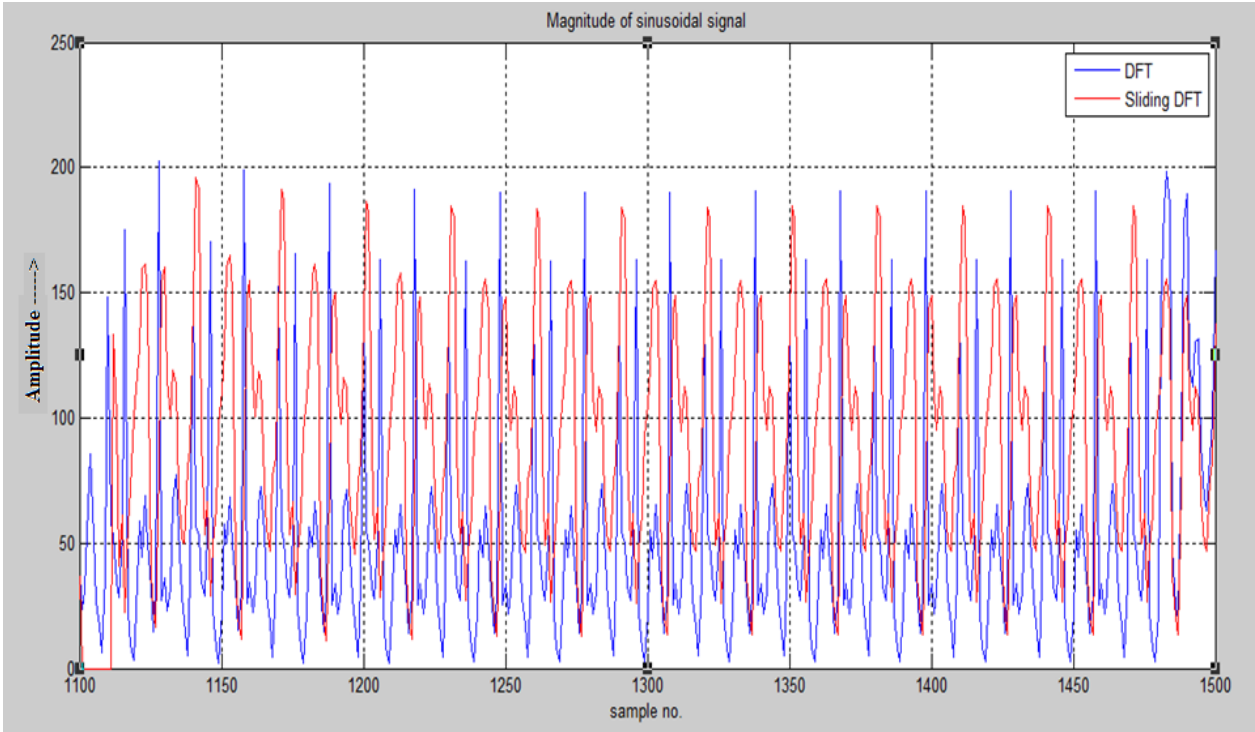


Figure 5.3 Magnitude response of case 1

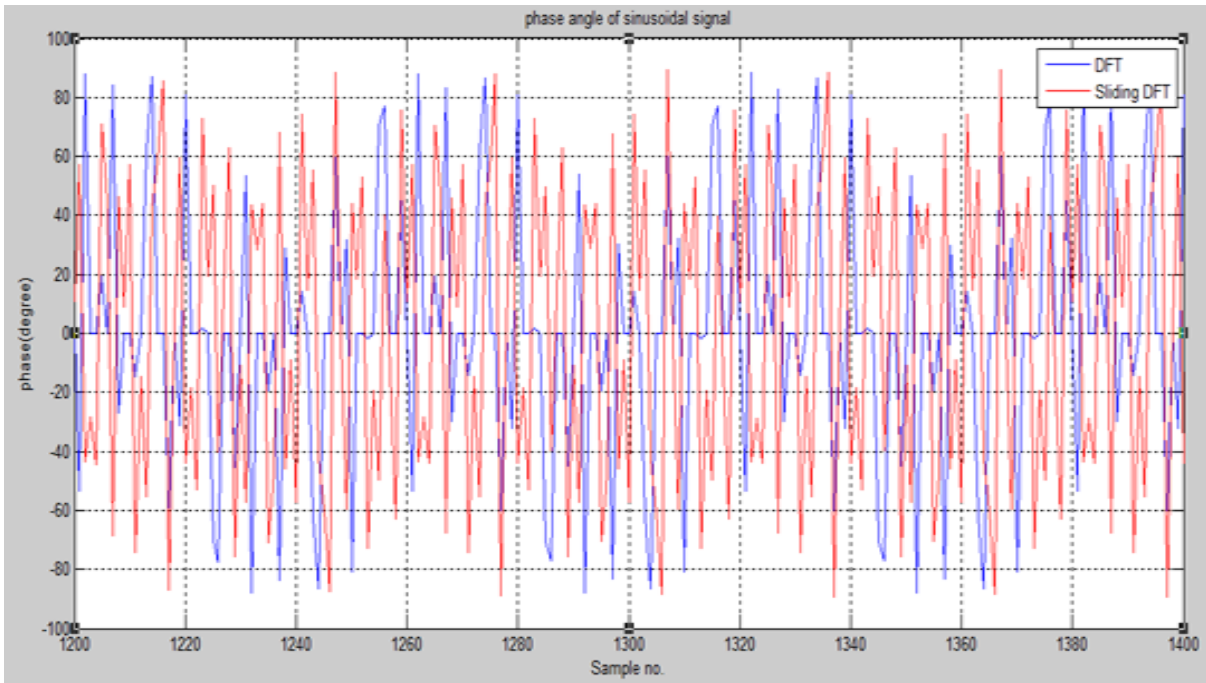


Figure 5.4 Phase response of case 1

Figure 5.5 and figure 5.6 shows the output of the measurement unit i.e. magnitude and phase of the signal sampled at the sampling rate of 128 samples/cycle. It has been observed that more sampling rate improved the results.

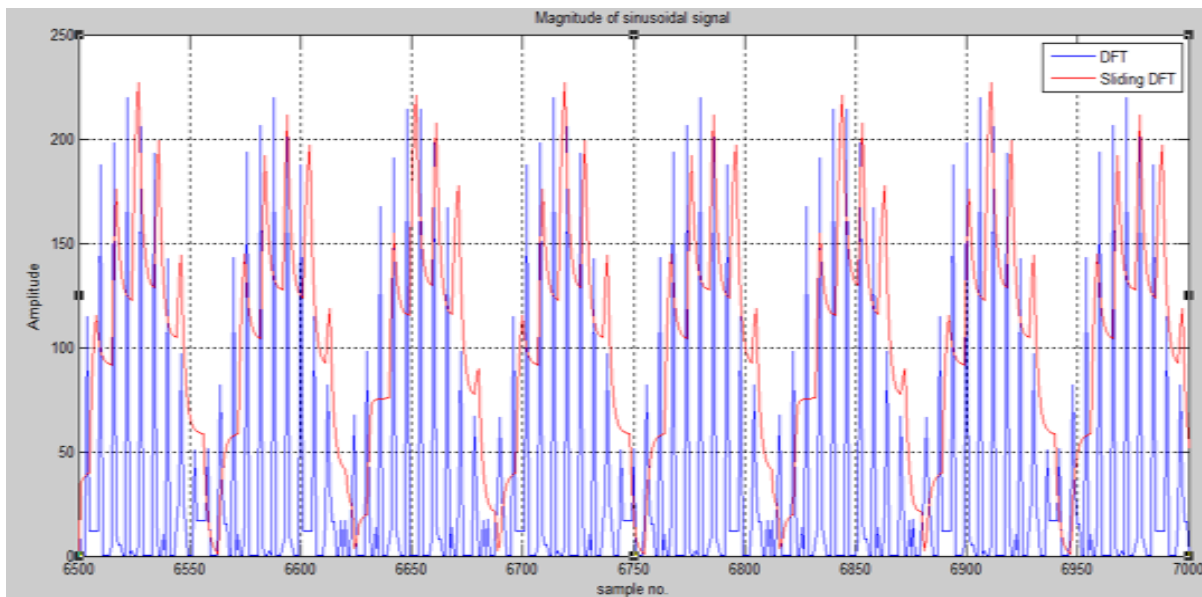


Figure 5.5 Magnitude response of case 1

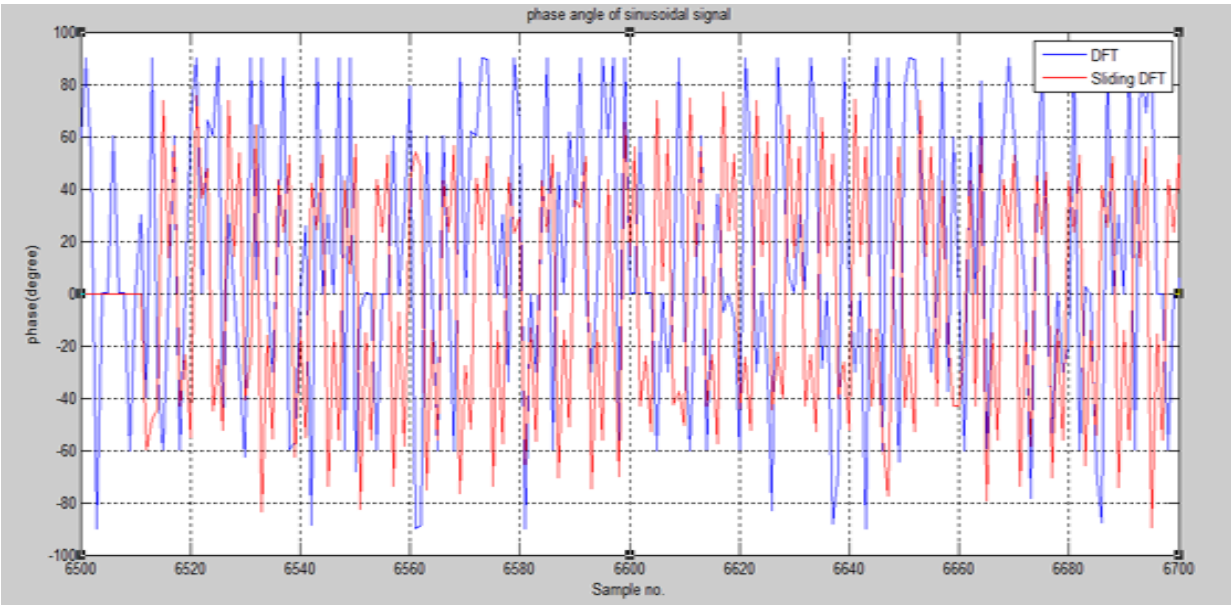


Figure 5.6 Phase response of case 1

5.4 Case 2

5.4.1 Input Signal

For phasor estimation of simulated input signal $x(t) = 220 \sin \omega t_1 + 255 \sin \omega t_2 + 220 \sin \omega t_3$ having frequency $\omega = 50\text{Hz}$ with varying amplitude at time t_2 i.e. for time $t = 1.2$ to 1.25 sec as shown in the following figure 5.7 is applied to analog filter.

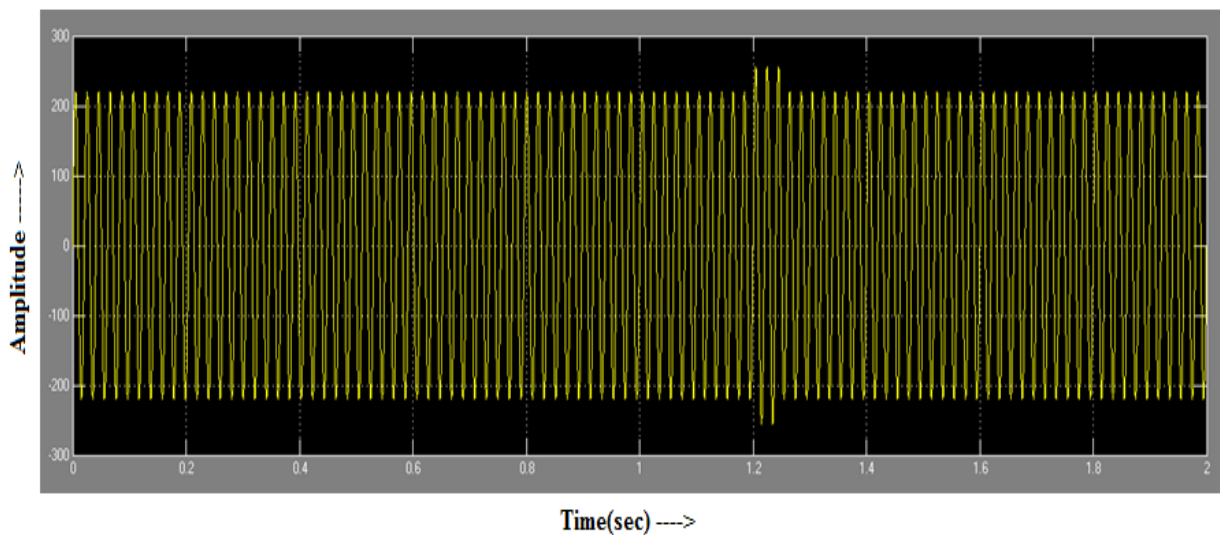


Figure 5.7 Input signal of case 2

5.4.2 Analog Filter Output

As Analog filter is a band-pass filter with center frequency $f_0=50\text{Hz}$ and bandwidth $\Delta f = 10 \text{ Hz}$. Figure 5.8 shows the output of the analog filter. Here signal have constant frequency 50 Hz allows the signal to passes through the filter as the parameter of analog band-pass filter have pass-band frequency of $f = 50 \pm 5 \text{ Hz}$.

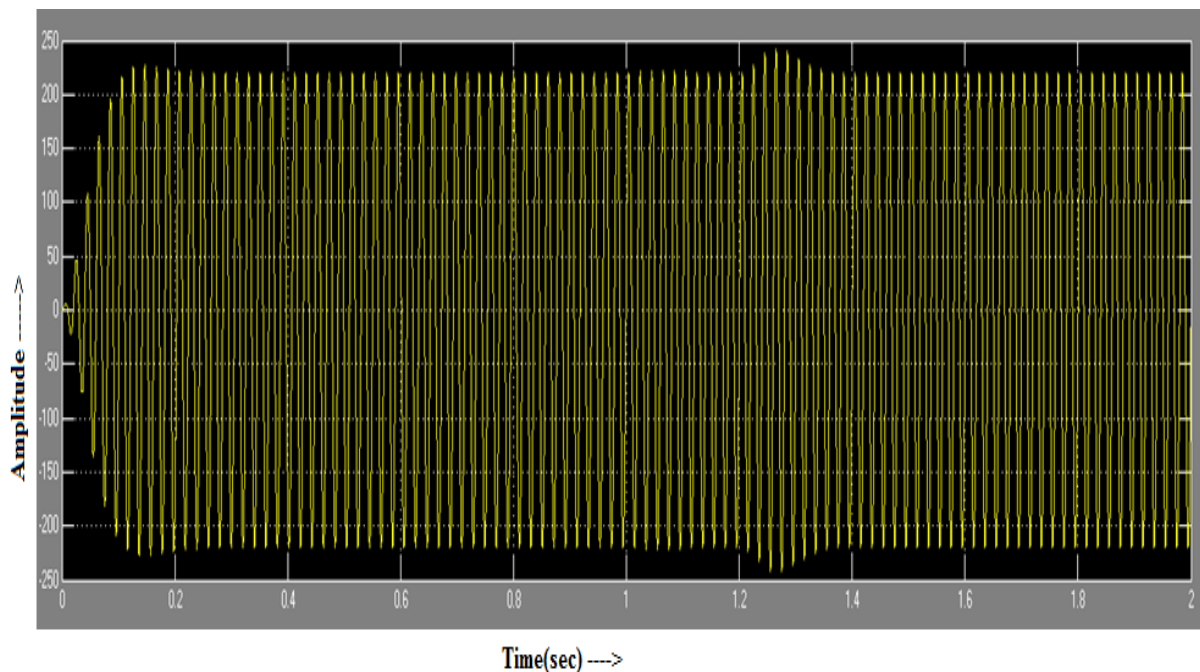


Figure 5.8 Filter Output of case 2

5.4.3 Measurement Unit Output

In measurement unit phasor estimation techniques such as DFT and Sliding DFT are used to measure the phasor of given signal. The window size has been set to 4 points/cycle in DFT and sliding DFT techniques for the estimation. The output of analog filter is sampled using ADC at the sampling rate of 20 samples/cycle and 128 samples/cycle.

The following Figure 5.9 and figure 5.10 shows the output of the measurement unit i.e. magnitude and phase of the signal sampled at the sampling rate of 20 samples/cycle. The slight variation in the magnitude of the signal can be observed in the output.

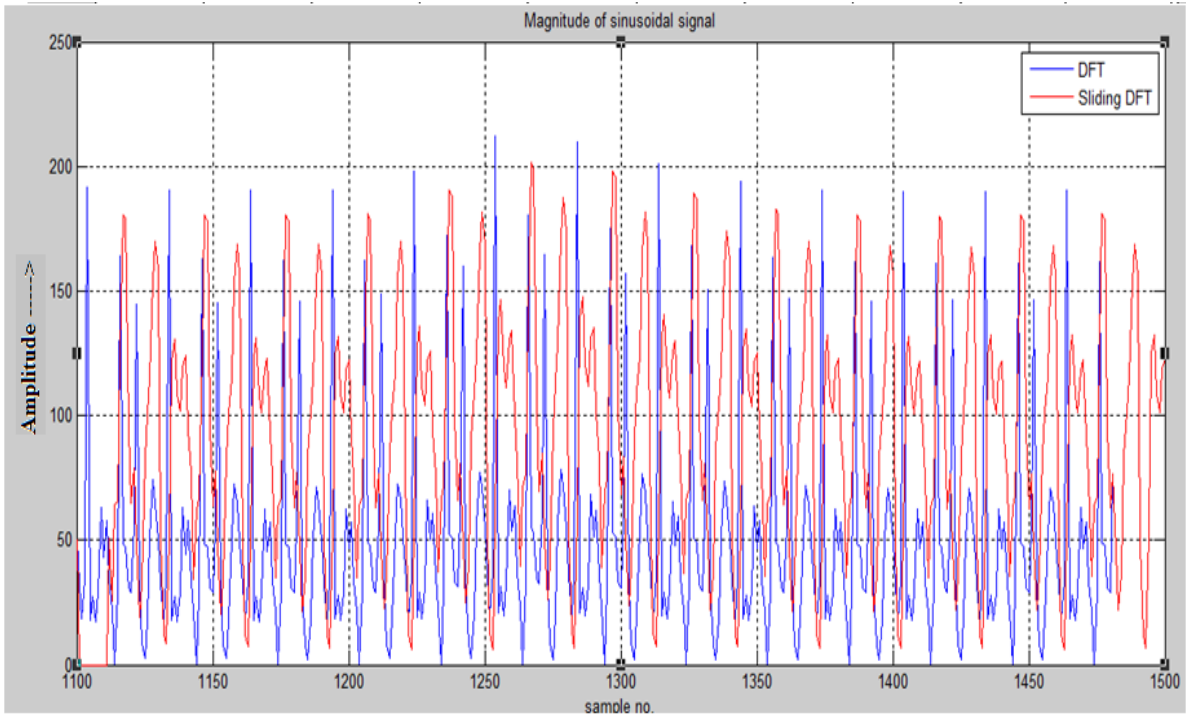


Figure 5.9 Magnitude response of case 2

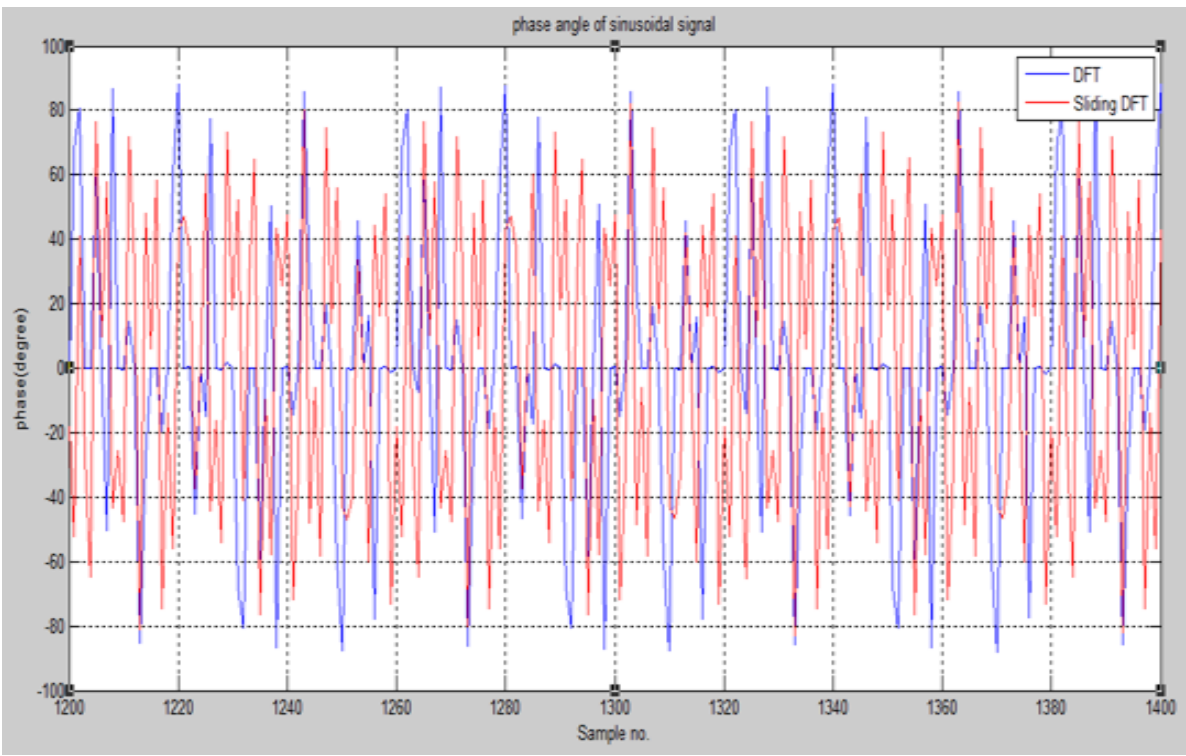


Figure 5.10 Phase response of case 2

Figure 5.11 and figure 5.12 shows the output of the measurement unit i.e. magnitude and phase of the signal sampled at the sampling rate of 128 samples/cycle for input signal. It has been observed that more sampling rate improved the results.

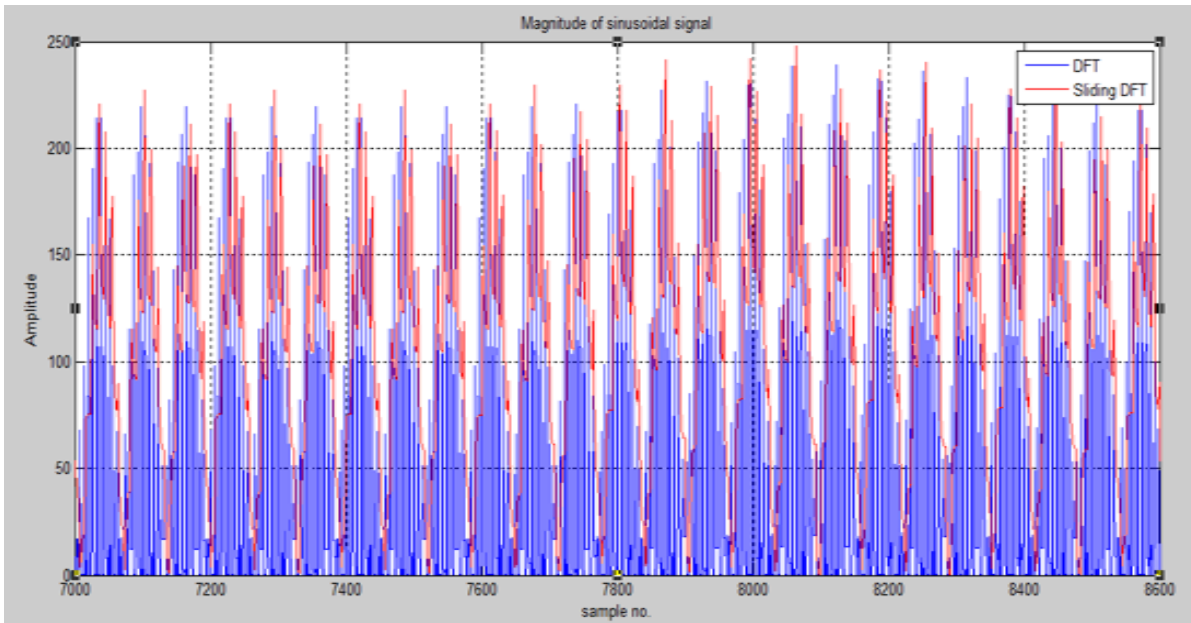


Figure 5.11 Magnitude response of case 2

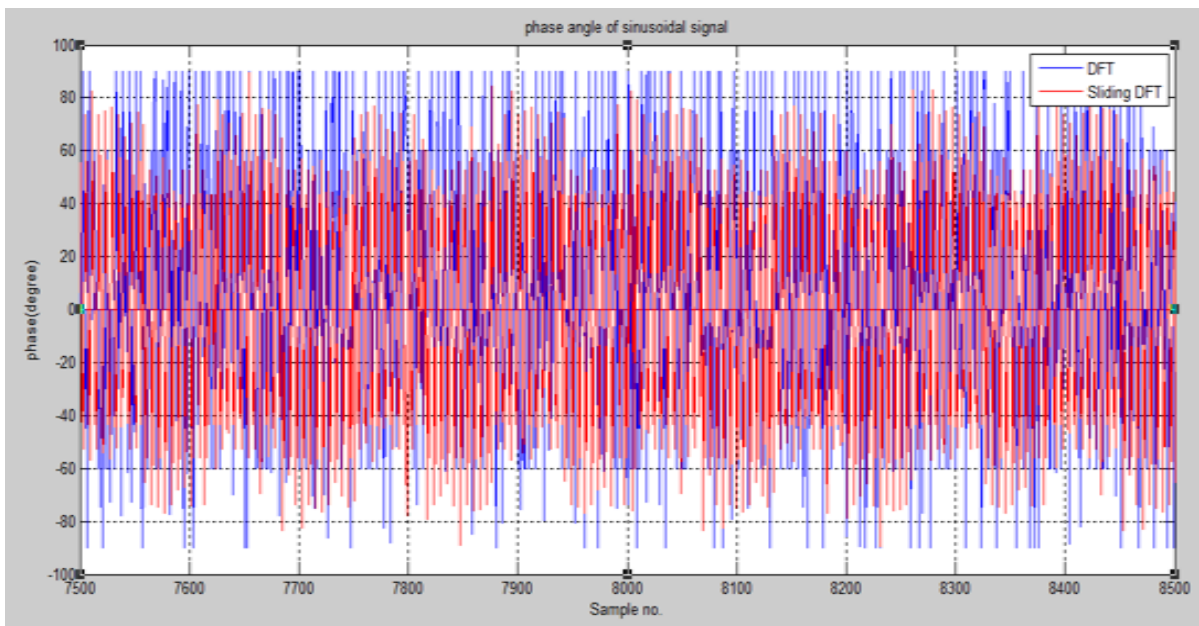


Figure 5.12 Phase response of case 2

As in signal $x(t) = 220 \sin wt_1 + 255 \sin wt_2 + 220 \sin wt_3$ of case 2 variation in magnitude of signal for some time is observed whereas in signal $x(t) = 220(\sin w_1 t_1 + \sin w_2 t_2 + \sin w_3 t_3)$ of case 1 magnitude remains constant. When Synchrophasor estimation is done for signal of case 1 and case 2 simultaneously, the amplitude variation in the signals can be detected as shown in figure 5.13.

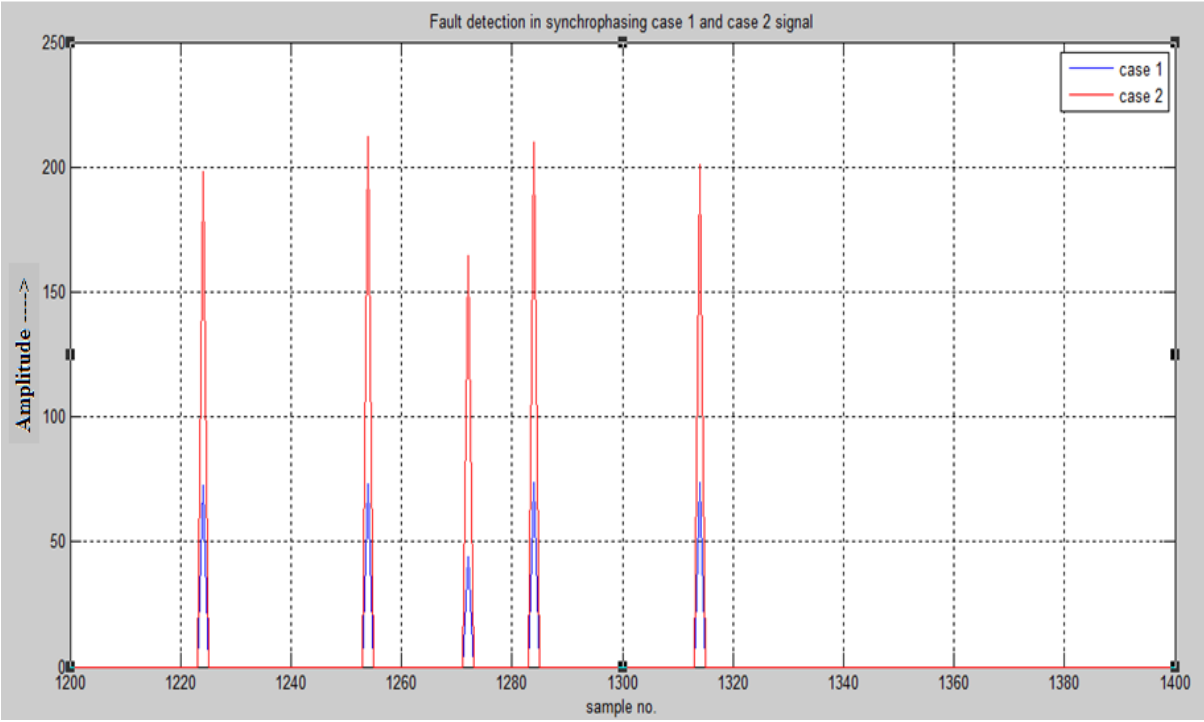


Figure 5.13 Amplitude variations between case1 and case 2

5.5 Case 3

5.5.1 Real Data

The real time signal has been collected at Online Trend Control Project at 400/220kV PSTCL, BHALWAN at frequency of 49-51 Hz for 21 hours as shown in figure 5.14. Two different signals are taken to measure the phasor of the signals synchronously.

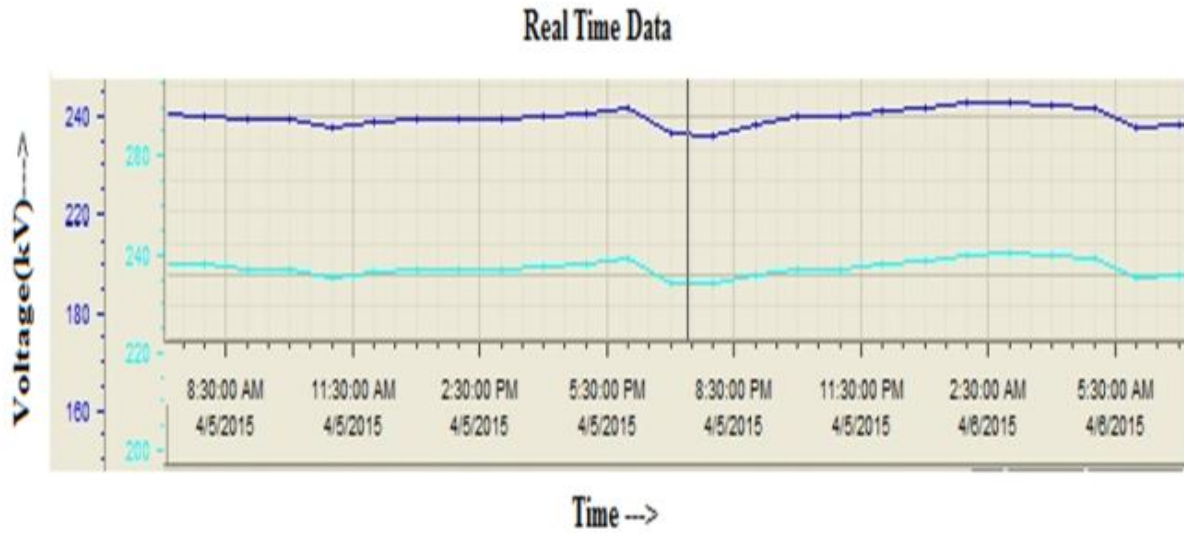


Figure 5.14 Real time input signal of case 3

5.5.2 Measurement Unit Output

The figure 5.15 and figure 5.16 shows the output of the measurement unit i.e. magnitude and phase of the signal. DFT phasor estimation technique is used to measure magnitude and phase response. It has been found that the output results are same for both signals in real time.

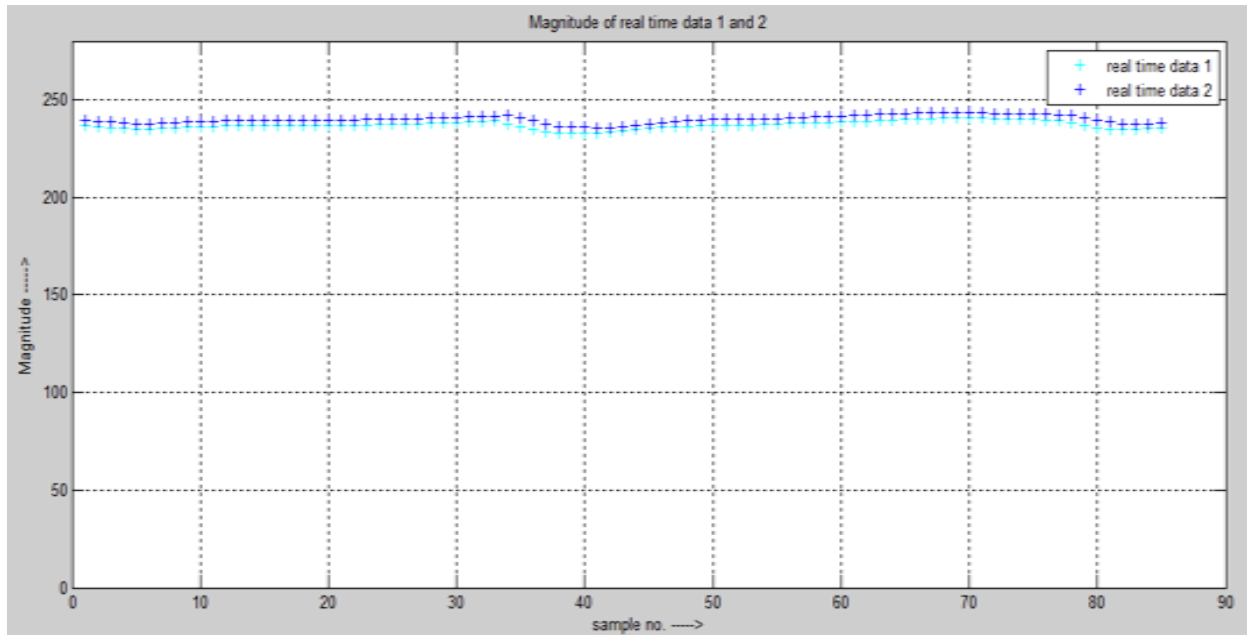


Figure 5.15: Magnitude response of case 3

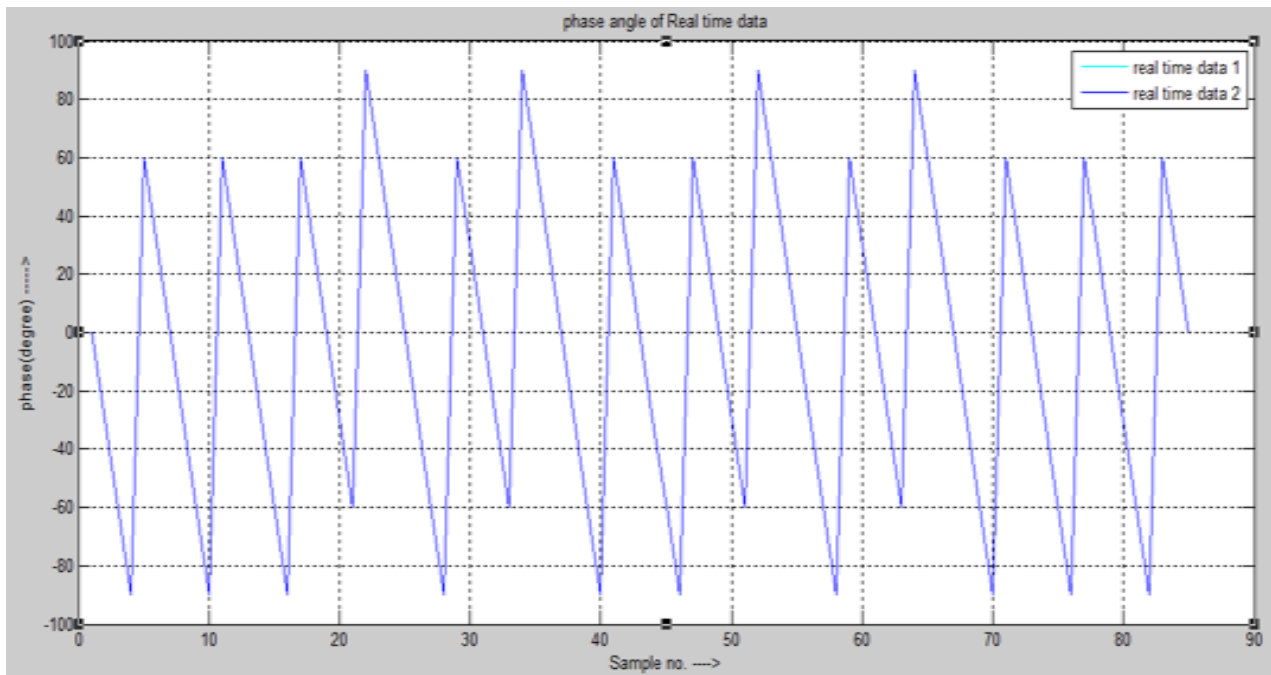


Figure 5.16: Phase response of case 3

6.1 Conclusion

Main conclusions as observed in the present work are summarized as given below:

- Modeling of PMU in MATLAB Simulink toolbox has been done with the use of:
 - 2nd order Butterworth filter
 - Pulse generator giving sampling rate of 20 samples/cycle and 128 samples/cycle.
 - ADC consisting of quantizer and sample/hold circuit
 - Measurement Unit for Phasor Estimation
- Following Phasor estimation techniques has been used in measurement unit of PMU Model:
 - Zero crossing
 - DFT (using recursive and non-recursive)
 - Sliding DFT
- In zero crossing technique reference signal has been required to compute phasor value of given voltage signal.
- Recursive and non-recursive DFT Phasor estimation techniques have been used at sampling rate of 12 samples/cycle for voltage signal $x(t) = 220 \sin(100\pi t + \frac{\pi}{4})$. It has been found that in recursive algorithm phase remains same with every sample where as in non-recursive phase change with every sample.
- Non-recursive DFT technique is more efficient technique for phasor estimation in PMU as compared to zero crossing.
- The phasor estimation technique such as DFT and Sliding DFT having window size of 4 points per cycle has been used. It has been observed that sliding DFT requires less computation time as compared to DFT for cases under studies.

6.2 Future Scope

In the work, phasor estimation technique such as zero crossing, DFT and Sliding DFT has been done in measurement unit of PMU Model. The challenges remained in the work can be expanded in direction as given below:

- Sampling rate can be further increased
- More efficient phasor estimation techniques can be used
- Non uniform sampling can be used

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