Design and Development of a Synchrophasor Measurements Unit as per IEEE Standard C37.118.1-2011

Saeed Hassan Khan, *Member, IEEE*, Saba Imtiaz, Hafsa Mustafa, Anabia Aijaz, Dr. Muhammad Ali

***Abstract*—Synchronized phasor measurement is the state of the art technology for Wide Area Monitoring of Electrical Power Systems under both static and dynamic conditions. The measurements are acquired through Phasor Measurement Units (PMUs) installed at selected nodes of the electrical power grid. PMUs are commercially built by various companies across the globe and are used for the measurement of system parameters as well as protection of system equipment. A new version of the PMU standard has recently been published. This project aims to design and implement a PMU in compliance with the new version of the IEEE standard C37.118.1-2011. The measured quantities are limited to the voltage and current phasors, change of frequency and rate of change of frequency of a balanced three phase power system. Algorithm based on a simple DFT technique and symmetrical components are used to obtain the required computations for both nominal and off-nominal frequencies. Arduino Due has been used as hardware platform which has high computing power and faster speed meeting the desired requirements.**

***Index Terms*—Synchrophasor, state estimation, phasor, frequency, change of frequency, rate of change of frequency, anti-aliasing filter, microcontroller, IEEE Standard C37.118.1-2011.**

I. Introduction

With the growth in size of electrical transmission networks and integration of various types and sizes of conventional and alternate power sources with the grid, threat of system failure resulting in huge blackouts has grown [1]-[3]. Wide Area Measurement and Control requirements of such dynamic grids have rendered the state estimation and protection with traditional SCADA systems as slow and insufficient [1]. The necessity of more precise, detailed and high-speed real-time monitoring systems is being acknowledged [4].

A Phasor Measurement Unit (PMU) is a device designed to measure the basic system parameters with optimum accuracy and desired speed. PMU samples the voltage and/or current signals to calculate voltage and/or current phasor(s), deviation from nominal frequency and the rate of change of frequency, with exact time stamp associated with each measurement.

These computations not only facilitate real-time state estimation but also improve protection schemes. Remedial Action Schemes, Adaptive Relays etc. are few such examples [5]-[8]. Several applications of PMUs have been discussed in variety of relevant literature. Some examples are [9]-[14].

Saeed Hassan Khan, Saba Imtiaz, Hafsa Mustafa, Anabia Aijaz and Dr. Muhammad Ali are with the Department of Electrical Engineering, NED University of Engineering & Technology, Karachi 75270, Pakistan.
(E-mails: saeedhassankhan@gmail.com (corresponding author); sabaimtiaz1991@yahoo.com; hafsa_19jun@hotmail.com; anajz99@yahoo.com; alimemon@neduet.edu.pk)

A. Scope

The project aims at the design and development of the Measurement Unit of a PMU as per IEEE Standard C37.118.1-2011. The aspects kept in focus while designing the PMU were that it should be:

1. Low-price; as low as a few hundred dollars.
2. High-speed; as high as 2,500 computations every second.
3. Accurate
4. In accordance with the latest IEEE standard

This project intended to simplify the complex embedded design features of a PMU by focusing on just the essential requirement of accurate computations as per IEEE standard C37.118.1-2011.

Arduino Due, a high-end Microcontroller, known for its high processing speed and wide range applications, has been utilized to keep the design low-price, accurate and with reasonable speed which is required to perform the standard operation expected from a PMU. New and efficient algorithms to carry out the task were designed to optimize the code and memory required for the task.

B. Objectives

The salient objectives of this project are to design and implement the following:

- An interface unit for the analog data inputs
- A network of synchronized Microcontroller Units for each of the three phases to perform three phase sampling
- Improved phasor estimation, frequency, change of frequency (COF) and rate of change of frequency (ROCOF) computation algorithms for a three phase balanced power system

C. Structure of the Report

Section II gives an overview of the Synchrophasor technology and its uses. It describes how it is facilitating the modern power network and mentions some of the leading manufacturers of PMUs throughout the world.

Section III gives deeper understanding of a PMU and explains its structure in detail. This section also describes the

IEEE standard C37.118.1-2011 and its specifics being followed in this project.

Section IV describes the design specifications in depth. Theoretical aspects relating to measurement have also been explained.

Section V discusses the proposed platform and relates it to the requirements of a typical and the designed PMU in particular.

Section VI illustrates the performance of the proposed hardware and evaluates it by comparing it to simulated results and tests proposed by the standard.

Section VII concludes and suggestions for further improvement in the design are given in the end.

II. Modern Power Networks & Synchrophasors

A. Wide Area Measurement System

The technological advancements have increased the usage of electric power resulting in need of larger and efficient power systems. It is necessary to provide accurate means to monitor such networks in order to ensure system stability [15]. A seemingly minor fault can trigger cascading tripping leading to cascading blackouts [16]. To minimize such risks wide area measurement and control strategies are being adopted in the world [17]. Wide Area Measurement System (WAMS) provides synchronized and efficient time scaled measurements of system parameters which enables complete monitoring, protection, and control of the power system [17, 18].

PMU is a component of Wide Area Measurement System. Till date, it has been used mainly for online supervision and recording in WAMS [19].

PMUs are installed at selected nodes of the network from where they collect the data, compute the desired parameters, time-stamp and store them, and send the same to Local Data Concentrators (LDC) or Phasor Data Concentrators (PDC). The PDC acquires the information and uses it for state estimation or to perform other diagnostic tasks. If there are multiple PDCs, they all report to a central Super Data Concentrator [20]. Collectively, all the synchronized PMUs give a snapshot of the whole system at an instant [15].

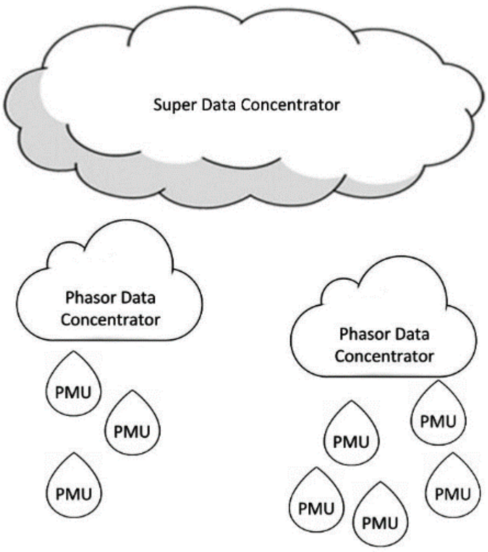

Figure 1 Typical PMU Network

B. Need of PMU

The necessity to monitor the power network’s dynamic characteristics more precisely and efficiently, justifies the importance of synchrophasor data [7, 21, 22, 23]. The need of Phasor Measurement Unit (PMU) was recognized when the occurrence of blackouts became a global phenomenon [1, 2, and 17]. It was then crucial for the power supply companies to predict fault conditions, record disturbances, prevent fault from spreading into healthy part of the system and avoid instability [7, 15, 19, and 24].

The accuracy offered by PMU enables power supply companies to have wide area control [7]. PMUs can be used in conjunction with existing protective devices while sharing system information acquired to enhance fault prevention and/or protection capability of the system [7, 19]. The use of adaptive relaying techniques is possible also due to synchrophasor technology [25].

Synchronized phasor measurements not only help prevent failures but also help improve EMS [4, 26]. The parameters derived from the synchrophasor data facilitate effective utilization of existing electrical installations by identifying their power transfer capability [27].

1) Existing State Estimation Methods

The existing system state estimation makes use of the SCADA (Supervisory Control and Data Acquisition) system to analyze system parameters [28]. Remote Terminal Units (RTUs) are used in SCADA to gather data from meters, transducers etc.

Early state estimators used unsynchronized data acquired from different locations of the network to measure the state. This process involved the assumption that the system is static and does not change during the measurements. However, by the time the computations are performed, the system may not remain same and thus errors are introduced [17].

Synchrophasors have revolutionized the whole state estimation process [19, 29]. Not only the measurements are now synchronized, which give accurate, timely estimates of the system’s current state, but also the time required for computations have been brought down [3, 23].

2) Limitations of SCADA

Traditionally implemented SCADA System possesses two major weaknesses. One is having indirect measurement of parameters using model-based state estimates from SCADA data, and the other is its low resolution since measurements are typically taken once every 1-5 seconds [4, 26]. These two shortcomings may lead a system towards failure. The low resolution results in missing critical data and if the state of the system is changing rapidly, the measured parameters will no longer remain error-free [17].

3) Benefits of Synchrophasor Measurements

PMU technology is often referred to as an MRI of power network, while SCADA merely provides an X-ray [26]. PMUs provide system parameters represented as complex numbers, from which the magnitude and phase angles can easily be deduced [30]. The rate at which the PMU transmits the data can be as high as 10-60 measurements every second. While connected to a critical line or bus, a PMU measures the bus voltages, three-phase line currents and frequency, from which megawatts and megavars can be computed [31].

Since all PMUs in a system are synchronized with a standard clock, typically GPS [15], every measurement made is accurately time-stamped and the error introduced in state estimation by traditional SCADA due to unsynchronized data diminishes [1]. Due to its high sampling rate, it improves the state estimates measured by SCADA to optimize load shedding and remedial action schemes [1, 6].

C. Implementation of PMUs throughout the World

Over the last few years, rapid growth has been observed in the technology of Synchronized Phasor measurements [32]. In the early 1980s, Virginia Tech proposed the prevailing prototype of PMU which was put into operation at few substations of Bonneville Power Administration (BPA), the American Electric Power Service Corporation and the New York Power Authority. Later Virginia Tech in collaboration with Macrodyne manufactured the first commercial PMU. Nowadays, commercial PMUs are being mass-produced, either as a stand-alone application or embedded within a protection device, by different companies and are deployed at power systems throughout the world.

The existing synchrophasor installations are found in North America, China, Europe, India, Russia, Scandinavia, Brazil, etc. Leading Manufacturers

There are several manufacturers spread out globally, producing PMUs for commercial or industrial usage [17]. Some of the major manufacturers are Siemens, ABB, Schweitzer Engineering Laboratories (SEL), Macrodyne, Mehta Tech, General Electric Company (GE) and ALSTOM, etc., a little introduction of which is given as follows.

1) ABB

ABB - RES670 IEC works as a standalone PMU unit increasing transmission capacity with improved operational security of existing power system. The RES521 has PMU functionalities including phasor measurements and communication capabilities according to standard protocols like TCP/IP. The price of RES521 is approx. within 17,000 to 25,000 Euros.

2) Siemens

Siemens designed a SIGUARD Phasor Data Processor that helps control power swings and transients through quick monitoring of current system situation at all times. In addition, the Simeas-R-PMU works as a digital fault recorder with GPS receiver and sync transceiver. The price ranges from 9,584 Euros to 20,852 Euros.

3) National Instruments

The NI Compact RIO Power Measurement System is a 3-phase power measurement hardware with 300Vrms (3 channels), 5 Arms (4 channels) and 50,000 S/s per channel simultaneous waveform acquisition. The cost of the basic design is US$15,522.

4) SEL

SEL has a wide range of synchrophasor products including PMUs, PDCs, satellite synchronized clocks, synchrophasor vector processors etc. The SEL products with PMU functionalities are SEL421 Protection Automation and Control System. It is priced at $6,930. Similarly, SEL351A Protection System has a price of $1,260, SEL451 Protection, Automation and Bay Control System $4,500, SEL487E Transformer Protection Relay $6,750, and SEL487V Capacitor Protection and Control System is being sold at $4,200. The SEL351A Protection System and SEL487E Transformer Protection Relay can be ordered as standalone PMUs.

5) Alstom Grid

The MiCom P847 is a phasor measurement unit having backup protection for the cable application and all overhead lines.

6) General Electric

GE provides solution from power system instabilities through advanced monitoring techniques. Its N60 is a Network Stability and Synchrophasor Measurement System which claims measurements every 16.67ms.

7) NR Electric Co.

NR has built PCS-996A for phasor measurements with accurate time stamping through GPS. It is used for real-time monitoring, stability estimation, remedial control functions and visualization of power system’s state.

D. Cost of PMU - The Major Problem

The PMUs are available in wide range of prices, ranging from $7,000 USD to over $50,000 USD as per their specifications. Furthermore, stand-alone, 3-phase voltage and current channel PMUs can be found for around $20,000. Relays with PMU functionalities or PMU and DFR with 2 voltage and 6 or 8 current channels are being sold for around $30,000 to over $50,000 USD.

The cost for PMU installation, testing and updating existing substations ranges from $100,000 to over $200,000 USD.

These costs are evidently huge and are unaffordable for many second and third world countries. Therefore, an attempt is made to design a cost effective Synchrophasor Measurement Unit in this project.

III. PHASOR MEASUREMENT UNITS

This section is aimed to give the reader a detailed description of PMU module, and the requirements set out in IEEE standard. It describes what a PMU is and the basic components that collectively make a PMU. It also discusses the relevant standard which defines the terms and tasks expected from a Synchrophasor, and guides the manufacturer on how to evaluate the manufactured product.

A. Phasor Measurement Unit

Phasor Measurement Unit (PMU) is a data acquisition device that helps in estimating the state of power network by measuring current and voltage phasors and frequency of a given node. Several PMUs installed at various grid locations use a common time reference thus making whole measurement system time synchronized.

PMUs were first designed in early 1980s at the Virginia Tech, USA [33]. Given all the advantages it offers to power systems, it has become a research focal point, and a lot of manufacturers worldwide are offering their devices meeting the current standards. [17]

IEEE defines Phasor Measurement Unit as a device that produces Synchronized Phasor, Frequency and Rate of Change of Frequency (ROCOF) estimates from voltage and/or current signals and a time synchronizing signal. [31]

One of the key characteristics of PMU measurements is that the data collected is very precisely time-stamped. A standard time source is used for time-tagging the data acquired by real-time, time domain sampling of current or voltage signals. Global Positioning System (GPS) is the generally accepted time source for its accuracy and universal availability at all times.

The time source should be common to all the PMUs connected in a network and data concentrators. This synchronism gives a PMU its characteristic name of Synchrophasor. High precision time-stamping makes transmission speed of measured data less important [20]. Therefore all the PMU measurements with same time-stamp should determine the state of the power system for that instant, at any given time.

B. Major Elements of PMU

A simplified diagram of the PMU structure is given in fig. 2. PMUs are broadly comprised of three basic units:

1. Clock Synchronization Unit
2. Measurement Unit
3. 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 satellites. These signals are later used by the phase-locked oscillators to provide timing signals to the data acquisition system.

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

1. The Interface Unit – consisting of an interface circuit for the analog data inputs, anti-aliasing filters and signal conditioning;
2. Sampling Unit – consisting of Analog-to-Digital Converters;
3. Phasor Computation Unit – comprising of a processor or microcontroller and a storage device.

The Data Transmission Unit retrieves the measured data from the Measurement Unit and transmits it over some suitable communication protocol. The modes of transmission may vary as per requirement or availability of resources. The transmitted data is collected at the Data Concentrator and/or it may be exchanged between other units of PMU for control and protection applications.

C. C37.118.1-2011 – IEEE Standard for Synchrophasor Measurements for Power Systems

IEEE Standard 1344, the first standard describing Synchrophasor, was introduced in 1995 [34]. As this standard considered the performance of PMU on nominal and off nominal frequencies as same, it was later superseded in 2005 by another IEEE Standard C37.118-2005 [35].

Later in 2011, IEEE C37.118-2005 was also replaced, as that standard determined the performance of phasor measurements only under steady state conditions. A revised version, IEEE C37.118-2011, of 2005 standard was introduced in December 2011 which comprised of two subdivisions; C37.118.1-2011 dealing with the phasor estimation and C37.118.2-2011 covering the communication protocols [36].

C37.118.2-2011 - IEEE Standard for Synchrophasor Data Transfer for Power Systems illustrates methods for real-time exchange of synchronized phasor measurements between

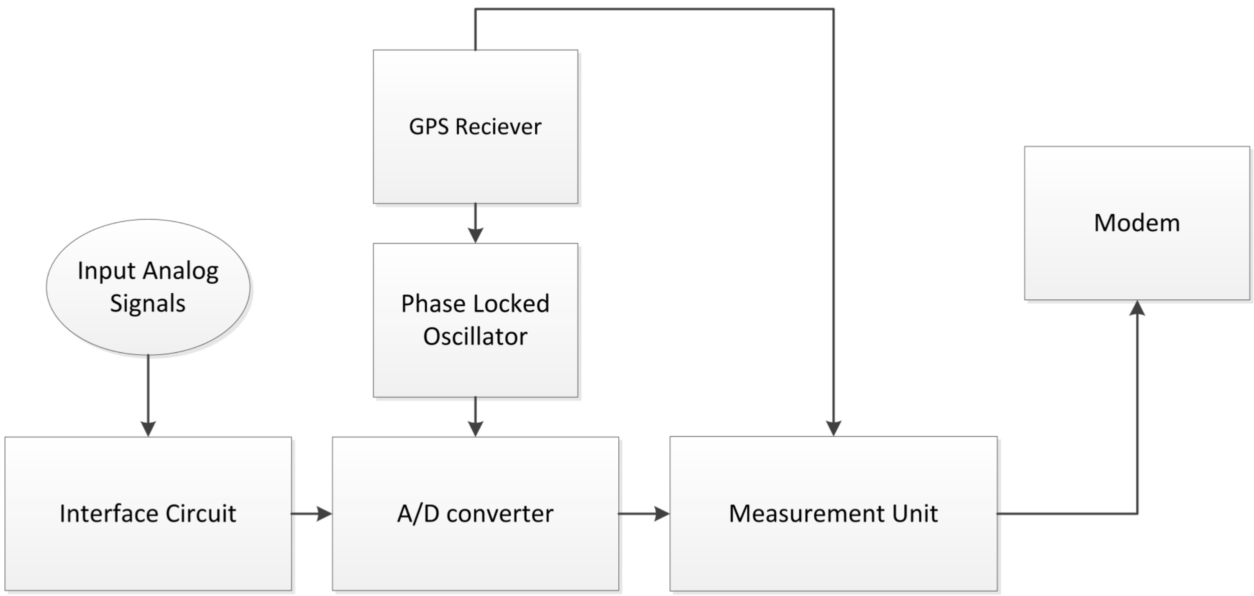

Figure 2 Basic PMU Structure

equipment. The standard specifies messaging that can be used with any suitable communication protocol for real-time communication between phasor measurement units (PMU), phasor data concentrators (PDC), and other applications. It also characterizes message types, contents, and use.

Since the scope of this project is the measurement unit only, therefore IEEE C37.118.1-2011 shall be discussed here in necessary detail. The standard explains phasors, change of frequency and rate of change of frequency measurements, their evaluation and compliance with the standard. It also defines time tag and synchronization requirements, under both static and dynamic conditions.

1) Classification of PMUs

IEEE Standard C37.118.1-2011 classifies PMUs into two classes on the basis of performance as given below:

a) Class P

The letter P refers to the protection of applications that requires fast response with no explicit filtering. This class aims at capturing the dynamic behavior of the system with some relaxed performance parameters.

b) Class M

Class M refers to the applications that do not require very fast response and are affected by the phenomenon of aliasing. The letter M denotes measurements. Hence this class is used in devices for measurement purposes which require high precision but not necessarily require minimum time delay.

2) Reporting Rates

According to standard C37.118.1-2011, the required reporting rates should either be 10, 25 or 50 frames per second for a 50 Hz system, and it may be 10, 12, 15, 20, 30, 60 frames per second for a 60 Hz system. This means that for a 50 Hz system, PMU could be sending out one measurement every power cycle. So the device must be capable enough to perform all sensing and computing operations needed to prepare one measurement within one power cycle.

3) Nyquist Criterion

The standard defines Nyquist criterion which states that the sampling rate must at least be twice the fundamental frequency for an alias-free representation of a signal.

In practical applications over sampling is performed so that the sampling frequency is always greater than half of the system frequency. Typically, sampling frequency is 10-50 times the nominal frequency.

4) Error Calculation

IEEE Standard C37.118.1-2011 also describes error calculation methods, namely Total Vector Error (TVE), Frequency Error (FE) and ROCOF Error (RFE) calculations.

a) Total Vector Error

It is the measure of error between the ideal phasor value of the signal and the phasor estimate given by PMU. Mathematically it can be represented as:

$$TVE = \left|\frac{\boldsymbol{V}_{measured} - \boldsymbol{V}_{ideal}}{\boldsymbol{V}_{ideal}}\right| \text{ x } 100 \quad (1)$$

There can be multiple possible phasors leading to the same TVE, depending upon the variation of proportion of error involved in the magnitude and angle of the phasor. This idea can be understood from fig. 3. The circle encompasses all the possible phasors for a given TVE.

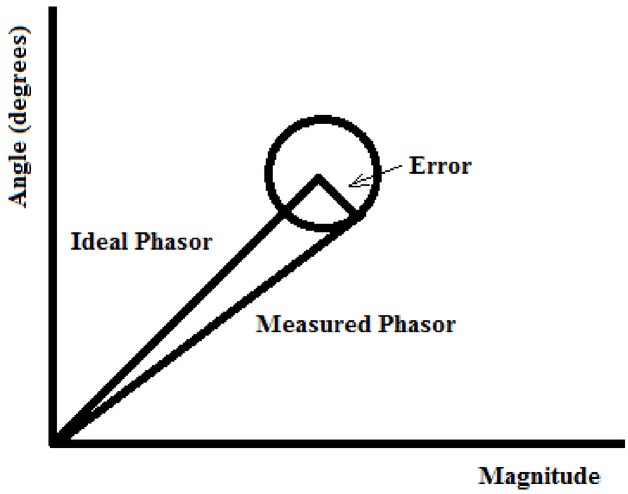

Figure 3 Total Vector Error (TVE)

b) Frequency Error

Frequency error is the difference between the measured and actual frequencies. Mathematically it can be given as:

$$FE = |f_{true} - f_{measured}| = |\Delta f_{true} - \Delta f_{measured}| \quad (2)$$

where f is frequency, and Δf represents change in frequency in Hz.

c) Rate of Change of Frequency Error

Rate of change of frequency error is defined as the difference between measured and theoretical rate of change of frequencies. It may be represented as:

$$RFE = |ROCOF_{true} - ROCOF_{measured}| \quad (3)$$

The compliance requirements under static state as set by the latest standard are given in table 1. From the details given in table 1, it can be easily deduced that a PMU should have high processing speed, fast reporting rate and minimum latency. A PMU should also be checked for errors in the measurements it provides which should remain in specified limits as described above.

IV. Design Specifications

The project aimed at developing an operational PMU which should comply with minimum requirements or better as described in IEEE Standard C37.118.1-2011. The objective of designing a cost effective PMU contained three sub-design-phases, namely:

- Identifying IEEE Standard C37.118.1-2011 requirements;
- Designing necessary modules as per standard requirements;
- Choosing an appropriate hardware platform and implementation of the design.

The first design phase has been described in the previous section. This section will describe the proposed design of a PMU complying with the minimum requirements stated in standards.

Table 1 IEEE STANDARD COMPLIANCE FOR STEADY STATE MEASUREMENTS

Description	P Class		M Class	
	Range	Max TVE (%)	Range	Max TVE (%)
	Steady State Synchrophasor Measurement Requirements			
Signal Frequency Range	±2.0 Hz	1	±2.0 Hz for F_s<10 ±F_s/5 for 10≤F_s<25 ±5.0 Hz for F_s ≥25	1
Signal Magnitude – Voltage	80% to 120% rated	1	10% to 120% rated	1
Signal Magnitude – Current	10% to 200% rated	1	10% to 200% rated	1
Phase Angle	±π radians	1	±π radians	1
Signal Frequency	Steady State Frequency and ROCOF Measurement Requirements			
	Max FE	Max RFE	Max FE	Max RFE
	0.005 Hz	0.01 Hz/s	0.005 Hz	0.01 Hz/s

This section will also cover the related theoretical aspects of designing a PMU.

A. Sampling Unit

Sampling or analog-to-digital conversion of the current and/or voltage signal is performed by using efficient microcontrollers, one dedicated to each phase. These microcontrollers are synchronized with the help of a common clock which is generated by the PMU.

1) Sampling Requirements

The ADC has been selected to work on a sampling rate of 2,500 Hz for the nominal system frequency of 50 Hz. This simply means that there will be 50 samples in each cycle.

The 2,500 Hz sampling frequency fulfills Nyquist criteria as it is greater than twice the system frequency. Hence it is in accordance with the IEEE standard. Additionally, it can accommodate information for up to 25 harmonics.

B. Aliasing

The nominal frequency of the analog data signals is assumed to be of 50Hz. Under off-nominal conditions, however, the frequency may deviate up to ±5 Hz. Usually, the data signals do not just have the fundamental frequency components and may contain harmonics and frequencies of higher order. In calculation, these higher frequency components will erroneously appear as low frequency components and thus induce errors known as 'aliases'.

In order to avoid errors due to aliasing, the bandwidth of the input signal and the sampling rate of ADC must fulfill the Nyquist Criterion.

1) Anti-Aliasing Filter

To band-limit the input data signal, a second-order low-pass RC filter has been chosen with a cut-off frequency equal to half the sampling frequency. In our case, an ADC with a sampling rate of 2,500 samples per second has been selected. Thus, according to the standard, the fundamental frequency of the input signal may not exceed 1250 Hz which is well above the possible system frequency range.

Since we are dealing with a signal of 50 Hz nominal frequency which may deviate in the range of 45Hz to 55Hz, we must design a second order low-pass passive RC filter with a cut-off frequency of 1250Hz which shall pass the desired range of frequencies with a gain of approximately 0dB. The s-domain transfer-function with given specifications turns out to be

$$\text{T.F} = \frac{7860.26^2}{(s + 2\pi x1250)^2} \quad (4)$$

The gain plot at fundamental frequency and design of the second-order low-pass passive RC filter are shown in fig. 4 and 5 respectively.

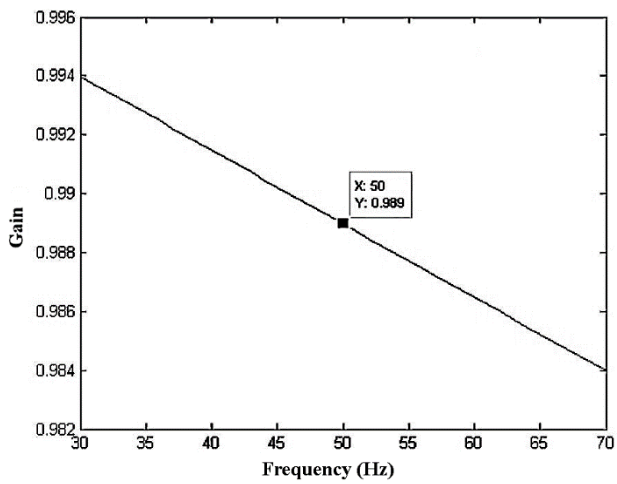

Figure 4 Gain Plot for Anti-Aliasing Filter

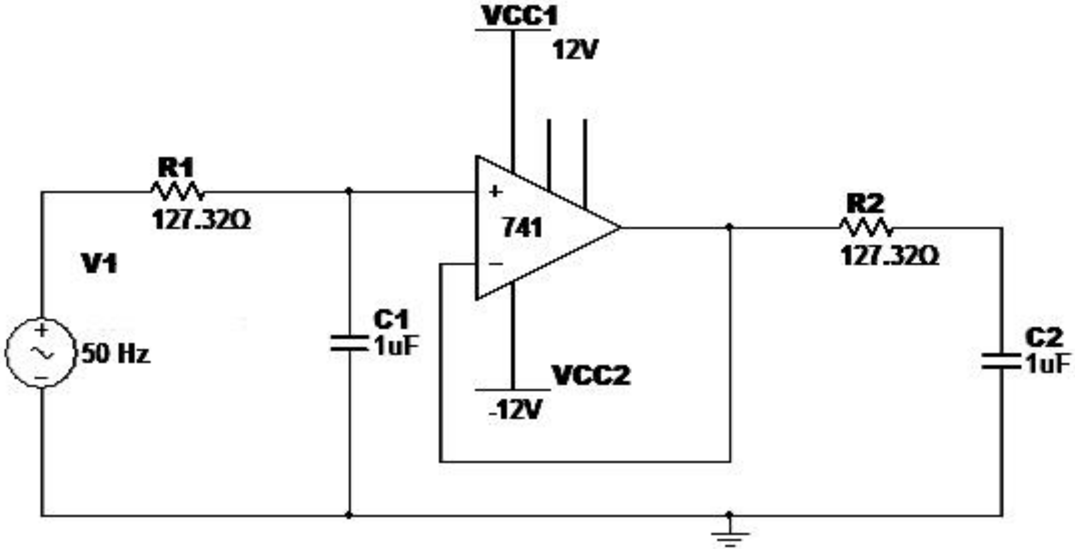

Figure 5 Anti-Aliasing Filter

C. Measurement Unit

The measurement unit should be capable of performing two tasks:

1. Acquire the sampled data and perform all the computations required before the next set of samples are ready for computation.
2. It must calculate:
   a) Voltage and/or Current Phasors (magnitude and angle)
   b) Frequency deviation from nominal (Change of frequency or COF)
   c) Rate of change of frequency (ROCOF)

The theoretical aspects of designing the measurement unit are described in sequence in following sections.

1) Phasor Computation at Nominal Frequency

Assume a balanced three phase system at nominal frequency f0, the sinusoids of which are represented by

$$x_1(t) = X_m \cos(2\pi f_0 t + \emptyset_1) \quad (5)$$
$$x_2(t) = X_m \cos(2\pi f_0 t + \emptyset_2) \quad (6)$$
$$x_3(t) = X_m \cos(2\pi f_0 t + \emptyset_3) \quad (7)$$

where X_m represents the maximum amplitude of the signal, and $\emptyset_1$, $\emptyset_2$ and $\emptyset_3$ are the phase angles $\frac{2\pi}{3}$ radians apart.

Consider the Sampling Unit (SU) samples the three phases at the rate of N samples per cycle, and then the time domain samples can be represented by

$$x_{n1} = X_m \cos\left(\frac{2\pi n}{N} + \emptyset_1\right) \quad (8)$$
$$x_{n2} = X_m \cos\left(\frac{2\pi n}{N} + \emptyset_2\right) \quad (9)$$
$$x_{n3} = X_m \cos\left(\frac{2\pi n}{N} + \emptyset_3\right) \quad (10)$$

where N is integral multiple of f_0 and fulfils Nyquist criterion, and n represents the sample index ranging from 0 to N-1.

The general formula for N-point DFT is given by

$$X = \frac{1}{N}\sum_{n=0}^{N-1} x_n \left\{cos\frac{2\pi n}{N} - j\, sin\frac{2\pi n}{N}\right\} \quad (11)$$

where N is the number of samples in data window, n is the sample number and x_n is the input sample.

The N-point DFT of the signals can thus be calculated as

$$X_k = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} x_n \left\{\cos\left(\frac{2\pi kn}{N}\right) - j\sin\left(\frac{2\pi kn}{N}\right)\right\} \quad (12)$$

where k is the harmonic index.

Since only the phasor of fundamental frequency is of interest, taking k = 0 in equation above gives

$$X_{nom} = X_1 = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} x_n \left\{\cos\left(\frac{2\pi n}{N}\right) - j\sin\left(\frac{2\pi n}{N}\right)\right\} \quad (13)$$

This complex equation may be broken into its real and imaginary constituents as

$$X_r = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} x_n \cos\left(\frac{2\pi n}{N}\right) \quad (14)$$

$$X_i = -\frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} x_n \sin\left(\frac{2\pi n}{N}\right) \quad (15)$$

or

$$X_{nom} = X_r + jX_i \quad (16)$$

The complex quantity X_{nom} actually represents the phasor estimate at nominal frequency input, whose magnitude $|X_{nom}|$ gives the magnitude of the signal. The phase angle can be computed using the trigonometric property

$$\emptyset_{nom} = \tan^{-1}\frac{X_i}{X_r} \quad (17)$$

Three such phasors are computed for the three phase system in consideration i.e. $X_{nom,1}$, $X_{nom,2}$ and $X_{nom,3}$. These phasors, under balanced load condition, will have same magnitude, while $X_{nom,2}$ and $X_{nom,3}$ will be $\frac{2\pi}{3}$ and $\frac{4\pi}{3}$ radians apart from $X_{nom,1}$.

2) Recursive Computation

The phasor estimation using DFT can be computed using N number of samples. This implies that the new phasor can be estimated only after N new samples have been acquired, which is not desirable.

In order to make the system more responsive to instantaneous disturbances, and to make approximation better, the N-point DFT is performed after receiving each new sample. The window comprising of N points thus shifts by one sample, as shown in fig. 6.

It can be observed that this calculation requires recursion of past computations. By keenly observing the process, it can easily be deduced that these recursive calculations can be omitted. The new phasor can be approximated by subtraction of the oldest sample computation from, and addition of the newly received sample to the previously estimated phasor. This method of estimating phasors is called the 'recursive algorithm' [37] and can be shown as

$$X_{new} = X_{previous} + \frac{\sqrt{2}}{N}(x_{new} - x_{oldest})\left\{\cos\left(\frac{2\pi n}{N}\right) - j\sin\left(\frac{2\pi n}{N}\right)\right\} \quad (18)$$

An important observation would be that x_{new} and x_{oldest} will be same since the input signal is a constant sinusoid.

3) Phasor Measurement at Off-nominal Frequencies

When the input frequency f has some difference Δf from nominal, such that

$$f = f_0 + \Delta f \quad (19)$$

The signals can be represented by

$$x_1(t) = X_m\cos(2\pi ft + \emptyset_1) \quad (20)$$

$$x_2(t) = X_m\cos(2\pi ft + \emptyset_2) \quad (21)$$

$$x_3(t) = X_m\cos(2\pi ft + \emptyset_3) \quad (22)$$

The N-point DFT of the new signals can be expressed by

$$X_{off-nom} = PX_{nom}e^{j2\pi(f-f_0)T_s} + QX_{nom}^{*}e^{-j2\pi(f+f_0)T_s} \quad (23)$$

where P and Q are errors introduced in the estimated Phasor [38].

$$P = \left\{\frac{\sin\frac{2\pi N(f-f_0)T_s}{2}}{N\sin\frac{2\pi(f-f_0)T_s}{2}}\right\}e^{j(N-1)\frac{2\pi(f-f_0)T_s}{2}} \quad (24)$$

and

$$Q = \left\{\frac{\sin\frac{2\pi N(f+f_0)T_s}{2}}{N\sin\frac{2\pi(f+f_0)T_s}{2}}\right\}e^{-j(N-1)\frac{2\pi(f+f_0)T_s}{2}} \quad (25)$$

It can be noted that the values of P and Q depend upon the frequency deviation from nominal. PX rotates in counter clockwise direction at the rate of $(\omega - \omega_0)$ and QX* rotates in clockwise manner at a speed of $(\omega + \omega_0)$. Thus the resultant phasor has a frequency of $2\omega_0$. The effect of P and Q on magnitude is very small for ±5Hz deviation in frequency.

Apart from the P and Q errors, the error of *phase-wrap* also exists. Due to difference in the frequency Δf from nominal, the estimated phasor has some offset angle that keeps on adding to the recursively computed phasor (shown in fig.). If the difference in frequency remains same, the phasor will rotate at uniform rate of Δf. The phasor angle will continue to increase to π radians where it will wrap around to –π radians and continue to increase. This error, however, is not considered and the phasor is reported as is. The concept can be illustrated with the help of the fig. 7.

4) Error Correction

Though the error due to second harmonic component can be removed by three point averaging filter, but here the advantage of having a three phase balanced system has been taken. The second harmonic component in the resultant phasor can be removed by finding the positive sequence component of the system. Since the system is balanced, negative and zero sequence components should not be there. The positive sequence component thus calculated represents the true phasor of the principal phase. $\frac{2\pi}{3}$ and $\frac{4\pi}{3}$ radians can be added to the

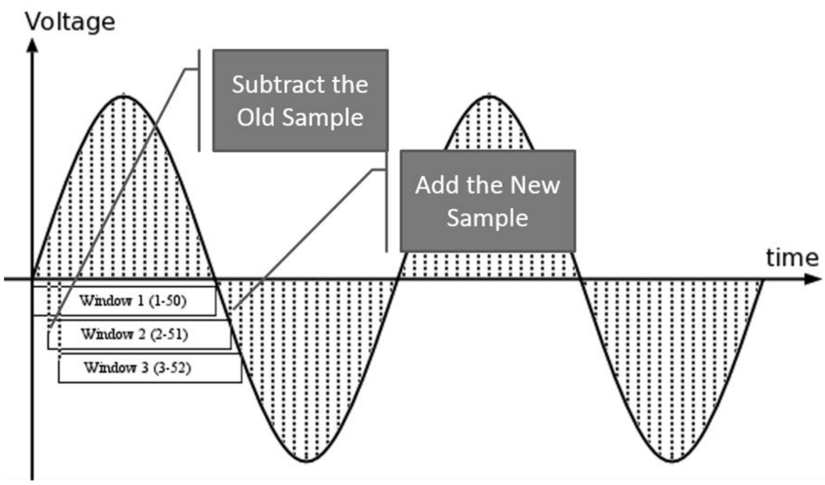

Figure 6 Recursive Measurements

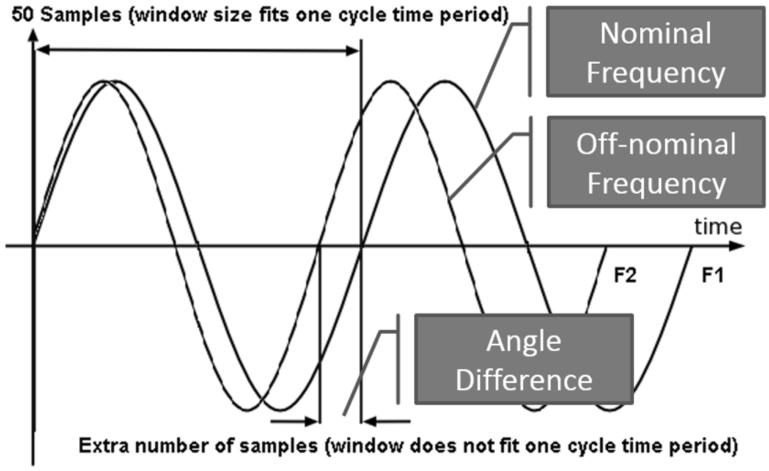

Figure 7 Error due to Off-nominal Frequency

angle of positive-sequence component to get the phasor of second and third phase respectively.

The symmetrical components can be computed as follows:

$$\begin{bmatrix} X_0 \\ X_+ \\ X_- \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix} \times \begin{bmatrix} X_1 \\ X_2 \\ X_3 \end{bmatrix} \quad (26)$$

where X0, X+ and X- represent zero sequence, positive sequence and negative sequence components. X1, X2 and X3 represent the three phase estimated phasors.

5) COF and ROCOF Calculation

The change of frequency and the 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 erroneous but the change in frequency is related to the change in phase angle which remains correct. As the rate of change of phase angle is frequency, the phase angle at any instant can be represented as

$$\emptyset(t) = \int \omega(t)\, dt = \emptyset_0 + \Delta\omega t + \frac{1}{2}\omega' t^2 \quad (27)$$

where ω(t) = frequency in radians $=\omega_0 + \Delta\omega + \omega' t$, ω0 = nominal frequency, $\Delta\omega$ = change in frequency, and ω' represents the rate of change in frequency.

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

$$\begin{bmatrix} \emptyset_0 \\ \emptyset_1 \\ \emptyset_2 \\ \emptyset_3 \\ \vdots \\ \emptyset_{N-1} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & T_s & {T_s}^2 \\ 1 & 2T_s & 2^2{T_s}^2 \\ 1 & 3T_s & 3^2{T_s}^2 \\ \vdots & \vdots & \vdots \\ 1 & (N-1)T_s & (N-1)^2{T_s}^2 \end{bmatrix} \times \begin{bmatrix} \emptyset_0 \\ \Delta\omega \\ \frac{1}{2}\omega' \end{bmatrix} \quad (28)$$

If N = 6, the equation reduces to

$$\begin{bmatrix} \emptyset_0 \\ \emptyset_1 \\ \emptyset_2 \\ \emptyset_3 \\ \emptyset_4 \\ \emptyset_5 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & T_s & {T_s}^2 \\ 1 & 2T_s & 2^2{T_s}^2 \\ 1 & 3T_s & 3^2{T_s}^2 \\ 1 & 4T_s & 4^2{T_s}^2 \\ 1 & 5T_s & 5^2{T_s}^2 \end{bmatrix} \times \begin{bmatrix} \emptyset_0 \\ \Delta\omega \\ \frac{1}{2}\omega' \end{bmatrix} \quad (29)$$

In matrix notation

$$[\emptyset] = [B][\omega] \quad (30)$$

or

$$[\omega] = [BB^T]^{-1}B^T\,[\emptyset] \quad (31)$$

From this equation $\Delta\omega$ and ω' can be computed to give COF (Δf) and ROCOF as

$$\Delta f = \frac{\Delta\omega}{2\pi} \quad (32)$$

and

$$ROCOF = \frac{\omega'}{2\pi} \quad (33)$$

The whole algorithm can be summarized in the following steps:

- Perform real-time three phase sampling at 2,500Hz.
- Accumulate 50 time domain samples of each phase.
- Compute 50-point DFT for each phase.
- Calculate positive-sequence component using the three computed phasors as given in equation (26).
- Compute the magnitude, phase angle, COF and ROCOF using equations (26, 32 & 33)
- Switch to recursive DFT algorithm.

Although this method proves to be highly efficient for a three phase balanced system, however, undesired results are acquired when dealing with an unbalanced system since the second harmonic appears in the positive-sequence component.

V. Arduino Due

A. Proposed Hardware Platform

The design of the synchrophasor suggested above requires that a processing unit having high processing speed is needed. It must be well capable of processing 2,500 samples every second.

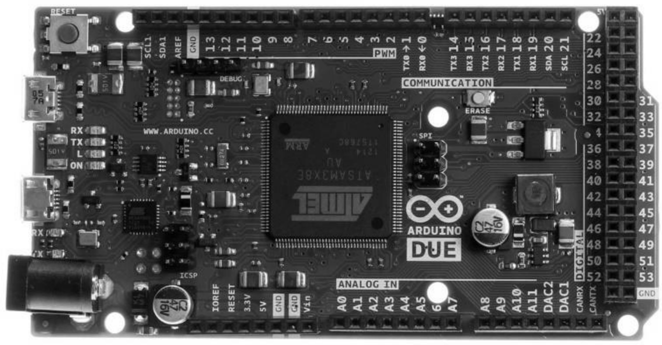

Figure 8 Arduino Due

It must run all the designed algorithms well before the next sample arrives, with maximum accuracy and meeting the standards proposed by IEEE C37.118.1-2011.

All these requirements were observed to be fulfilled by Arduino Due, microcontroller based processing unit, which is cost effective and has suitable processing speed. It also happens to have sufficient memory to store the data required to perform the desired operations. An added advantage of using Arduino Due is its programming language being based on C/C++. The combination of its user friendly interface along with easy programming language makes it appropriate for this project.

B. Arduino Due

Arduino Due with its development replaced the prior 8 bit, 16 MHz Arduino UNO, with a 32 bit, 84MHz microcontroller. It consists of:

- 54 input/output digital pins
- 12 analog input pins
- 84MHz clock
- USB connectivity
- a power jack
- a JTAG header
- 4 UARTs
- 2 Two Wire Interface (TWI)
- A Serial Peripheral Interface (SPI) header
- erase/reset buttons and
- 2 bit digital to analog converters (DAC).

The core of this board is its Atmel SAM3X8E, an ARM Cortex-M3-based processor. The theoretical sampling speed of Arduino Due is 1000 Ksps (kilo samples per second), which is far more than that of its predecessors Arduino UNO, MEGA 2560 and the Leonardo boards (15 Ksps).

C. Key Features

The important features of Arduino Due are given as follows:

1) Speed

The theoretical speed of Arduino Due is 84MHz. This speed is very much sufficient for the synchrophasor being implemented having designed sampling frequency of 2,500 Hz, with 50 samples per cycle.

2) Memory

Arduino Due consists of a Flash memory of two 256KB blocks which together form 512KB of memory which is used for encoding. Other than that it includes a 96KB as SRAM in 2 banks each of 64 and 32 KB. Arduino also includes a feature of erase button with which the current memory can be erased from the microcontroller.

3) Ports

Arduino Due comprises of various ports, each having its own associated registers. Each port consists of different number of pins. Port manipulation allows fast communication and multiple output pins to be called simultaneously. Using this capability the memory of any program can be reduced considerable by using a smaller code with relatively less number of bytes.

There is a register dedicated to each port which controls the port and defines the pin as either input or output. A brief introduction to different ports is given as follows.

a) Port B

Port B consists of both digital and analog pins. It consists of DDRB, PORTB and PINB registers, of which Data Direction Register (DDRB) and Direction Register (PORTB) are read and write enable registers whereas Input Pin Registers (PINB) are read only.

b) Port C

Port C consists of 31 pins out of which 29 are digital. Pin 30 is connected to receiving side of microcontroller (LED 'RX'). It consists of DDRC, PORTC and PINC registers, descriptions of which are similar to that of Port B.

c) Port D

Port D is in control of digital pins 0 to 7. It consists of DDRD, PORTD and PIND registers similar to ports B and C.

4) Programming

The programs or codes written in Arduino's environment are known as 'sketches' and are written in C/C++. In order to program the board, one of the two available USB ports are used. The programming environment is Integrated Development Environment (IDE) written in Java. It is composed of many features including brace matching, automatic indentation, syntax highlighting, along with the ability to compile and upload programs to the board in one click.

D. Applications

Arduino Due is an ideal microcontroller for various sophisticated projects or applications that require very high computing powers. In scientific projects, which need to acquire data quickly and accurately, Arduino Due is popular among digital fabrication community (3d Printers, Laser cutters, CNC milling machines) for achieving higher resolutions and faster speeds with fewer components than that required in the past.

VI. IMPLEMENTATION AND TESTING

A. Hardware Implementation

Hardware implementation of the designed Phasor Computation Unit of PMU is given in this section. The hardware design is based on two presumptions:

The microcontroller has pre-stored sampled data of a static, balanced 3-phase system with nominal frequency of 50Hz, sampled at a rate of 2,500 samples every second.

No harmonic component is present in the signal and thus no interface circuitry, including anti-aliasing filters, is needed.

The section demonstrates the performance of Arduino Due when it is coded with the designed algorithms for 3-phase phasor estimation, change of frequency and rate of change of frequency computations. The algorithm was tested with various signals of nominal and off-nominal frequencies, first on MATLAB and then with Arduino Due. MATLAB results were used for benchmarking and the differences between the two readings are recorded as follows:

1) 220Vrms signal at nominal (50Hz) frequency:

Figure 9 shows the error in magnitude of the voltage/current phasor. As can be observed, this error is within the limits specified by the IEEE standard.

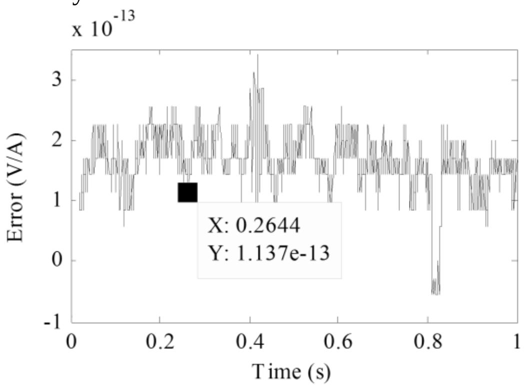

Figure 9 Magnitude Error at 50Hz Nominal Frequency

The following graph (Fig. 10) shows the error in phase computed using the proposed algorithm.

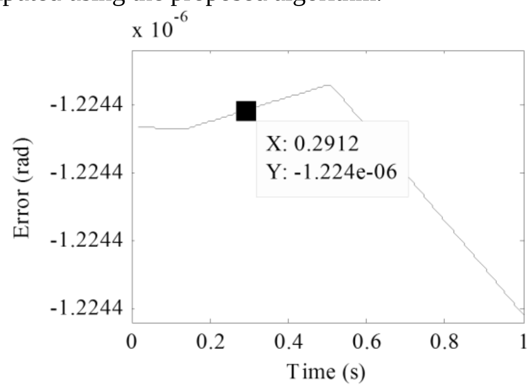

Figure 10 Phase Error at 50Hz Nominal Frequency

Figure 11 shows the error in computed change in frequency as follows.

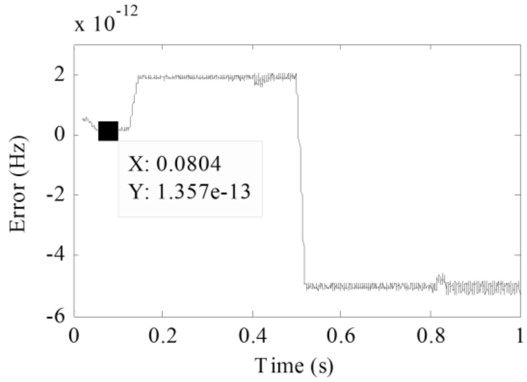

Figure 11 COF Error at 50Hz Nominal Frequency

The graph given in fig. 12 shows the error in ROCOF computation at nominal frequency.

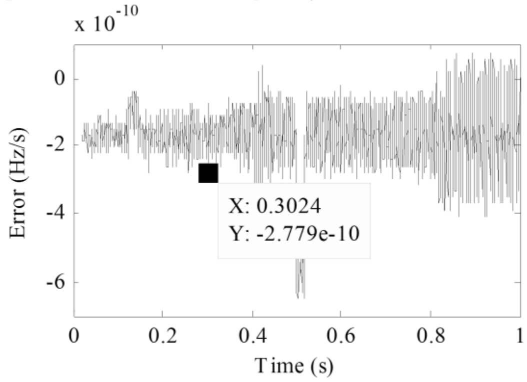

Figure 12 ROCOF Error at 50Hz Nominal Frequency

Similar tests were conducted for off-nominal frequencies of 47Hz and 53Hz. The results are shown in the same order as for nominal frequency above:

2) 220Vrms at off-nominal (47Hz) frequency with 30 degrees phase angle:

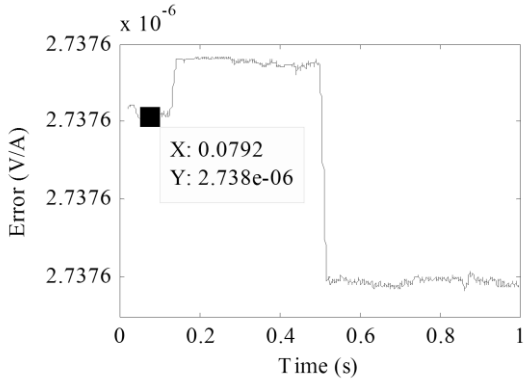

Figure 13 Magnitude Error at 47Hz Off-Nominal Frequency

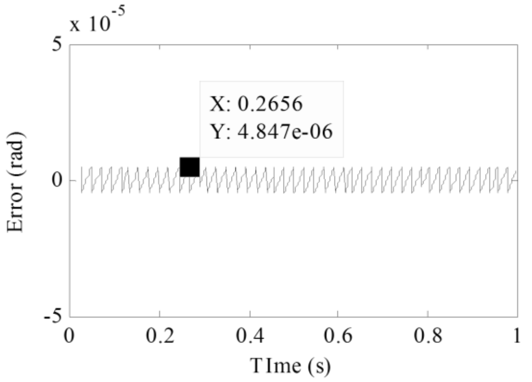

Figure 14 Phase Error at 47Hz Off-Nominal Frequency

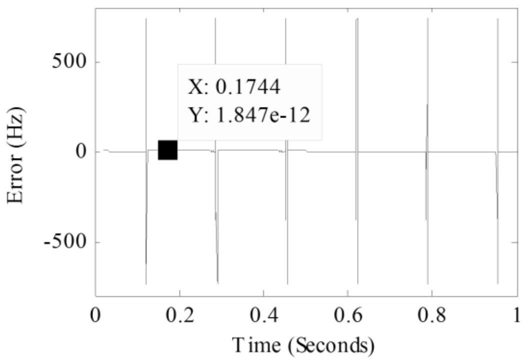

Figure 15 COF Error at 47Hz Off-Nominal Frequency

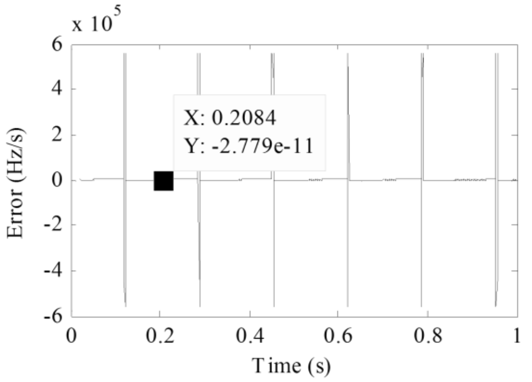

Figure 16 ROCOF Error at 47Hz Off-Nominal Frequency

3) 220Vp at off-nominal (53Hz) frequency with 45 degrees phase angle:

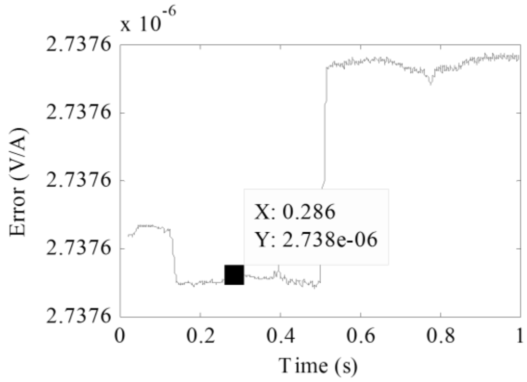

Figure 17 Magnitude Error at 53Hz Off-Nominal Frequency

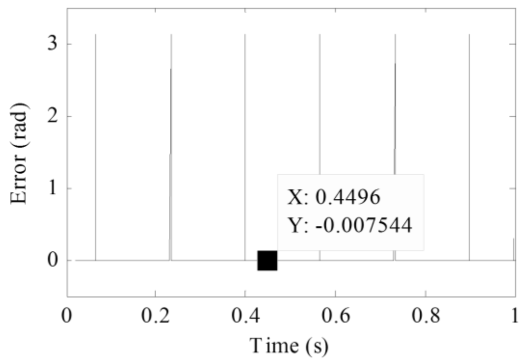

Figure 18 Phase Error at 53Hz Off-Nominal Frequency

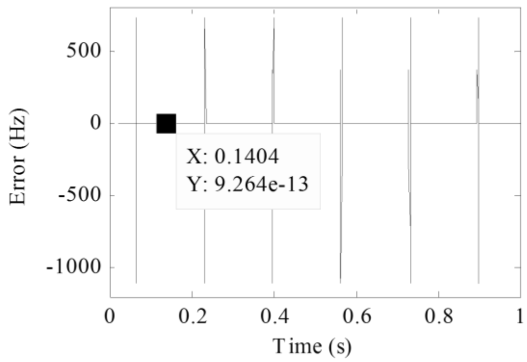

Figure 19 COF Error at 53Hz Off-Nominal Frequency

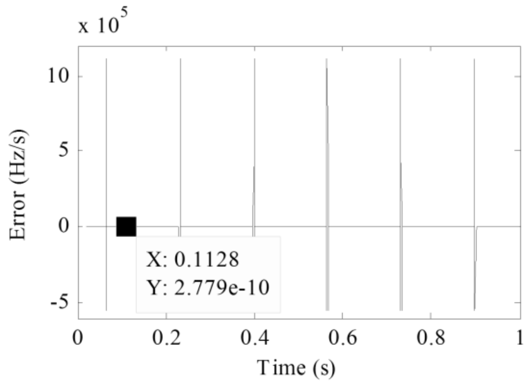

Figure 20 ROCOF Error at 53Hz Off-Nominal Frequency

B. Discussion

The error graphs shown above suggest that the error magnitude in all the cases (nominal and off-nominal frequencies) of a balanced, three phase, static system remains within the compliance boundaries of stated by the IEEE Standard.

The data acquired is precisely time stamped. The average time taken by the microcontroller to give the next reading was calculated to be about 0.000185 second, which is well before the next sample arrives (0.0004 second). This further endorses the possibility of this hardware to be used as a PMU.

However, the methodology of fetching the measured data out of the hardware needs to be reviewed. At present, when the data is fetched through MATLAB, it takes about a few milliseconds for each reading, which seems to be slow. This can be improved by incorporating code optimization techniques and compromising the reporting rate.

The compliance with the standard can be summarized as follows:

Table 2 CHECKLIST FOR COMPLIANCE WITH IEEE STANDARD

Compliance Requirement	Balanced Static System	
	Nominal Frequency	Off-nominal Frequencies
Reporting Rate	✓	✓
Sampling Rate	✓	✓
Magnitude Error	✓	✓
Frequency Error	✓	✓
Time Stamp	✓	✓

VII. CONCLUSION

PMUs are being accepted as the de-facto standard for monitoring the Smart Grid of the future. With growing numbers of live PMUs throughout electric grids, the dream of real-time monitoring at incremental levels of change has not only become viable but, in-fact, would be a reality in the upcoming decade. In order to curtail the predicament of customized and manufacturer-specific standards, IEEE has assumed the arbiter's role and has guided PMU development through its standard C37.118.X.2011.

This project aimed at designing a cost-effective PMU device as per IEEE standard C37.118.1-2011. The theme was to de-mystify hardware implementation of synchrophasor measurement and to push design parameters to such limits that low-cost, micro-controller based implementation may be realized. Balanced 3-phase voltage wave-forms were first simulated in MATLAB and parameters specified by the standard were computed using the recursive DFT algorithm. In the second stage the whole algorithm was ported to C language which was used to program Arduino Due – the micro-controller platform used in this project.

To validate and check synchrophasor output given by Arduino Due, exactly same data was provided to it as used in MATLAB simulation, by internally generating arrays of the 3-phase voltages. The outputs from the micro-controller were then compared with those of the simulation in MATLAB. The results of this experiment were gratifying as the output parameters namely phasor magnitudes, phasor angles, frequency and ROCOF were found to be within error bounds specified by the standard.

Voltage phasor under balanced, steady-state conditions precisely matched the simulation results, however at off-nominal frequency, slight variations and ripples were observed. These were well with-in the bounds of error specified in the standard. Frequency and ROCOF errors were also compared and complied with standard specifications.

The work done in this project has paved way for further development. Currently the hardware meets only one part of the standard i.e. C37.118.1-2011, and needs to conform to the second part C37.118.2-2011 which describes communication methods. Moreover the device needs a GPS synchronized clock to produce synchrophasor data useful for transmission.

The exploration of Arduino Due, as a synchrophasor computer, has also opened up a new venue. With an ARM Cortex M3 controller at its heart, the Arduino Due is running at 84MHz which interestingly is not its optimum clock frequency – it can actually run at 135MHz. By increasing its clock speed, optimizing DFT code and using hardware math features pre-built inside Arduino Due, the system might serve as a complete PMU without additional processor/controller, cutting system design cost and adding more features to the basic PMU.

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