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Non-Recursive DFT Based Model of Synchrophasor Unit

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Abstract*: The Synchrophasor Unit or commonly called Phasor Measurement Unit (PMU) is the essential component in the modern power grid which plays a significant role in monitoring, control and protection of the power system. PMU offers synchronized measurements of voltage, current and frequency on a real-time basis. Therefore, it is necessary to install Phasor Measurement Devices in the power grid, which can provide a complete state of each bus system. In this paper, Non-recursive based Discrete Fourier Transform (DFT) approach is implemented for the modelling of PMU due to its stable nature. The entire work is done using the NI LabVIEW software, and the results obtained from the model are validated with mathematical analysis.

Keywords: NI LabVIEW, Non-recursive Discrete Fourier Transform, Phasor Measurement Unit (PMU), Smart grid.

I. INTRODUCTION

A modern power system needs more accurate, reliable measurements to control and monitor the whole power system network. Wide Area Monitoring Systems (WAMS) is one of the modern monitoring systems where Phasor Measurement Units are the key components used to control, monitor and protect the whole components of the grid network. PMU is a real-time measuring device which gives the synchronized values of both voltage and current signals with their magnitude and phase values at the installed bus locations. As it gives the synchronized time stamped data of voltage and current measurements that's why it is also known as Synchrophasor Unit. PMU gives GPS time-stamped phasor values to make the large area of the power network fully observable. Real-time monitoring is necessary for the stable operation of the power grid. Therefore, to ensure a stable operating grid, PMU is one of the best options to implement at particular bus locations to make the system completely observable by measuring voltage and current phasors at that particular installed position along with its connected branch locations.

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Due to the high cost along with the installation cost of PMU, it is not feasible to place PMUs at every bus location. That's why to overcome this type of placement problem; several optimization techniques have been proposed to place PMUs optimally for complete observability of the entire grid.

The basic components, along with their phasor estimation techniques, are explained in [1]. Reference [2] described about different design approaches for testing frequency adaptive PMU algorithms. In [3], modelling of PMU using MATLAB software is analyzed. In [4], the application of FACTs controllers with PMU is presented. The fault identification and classification technique using phase angle measurements are described in [5] for smart power grids.

Currently, the monitoring task is performed by using the SCADA system in a remote terminal unit. But, SCADA has some following limitations.

- Due to slow duty cycle and telecommunication problem, it shows the delay in taking measurements at the same time instant.
- Close monitoring during large disturbance could not be possible because of slow changes in the magnitude of voltage, active power and reactive power.
- It is only focused on monitoring and controlling a local network.
- The dynamic behaviour of the power system could not be performed due to the unavailability of high-speed synchronized data.

PMU's overcome the above limitations to give the synchronized value of voltages and currents along with their phasor values.

The main aim of this work is to implement the PMU model using Non-recursive DFT technique using the NI-LabVIEW software. The paper organized as follows: the section II describes about the PMU and section III presents about the Non-recursive DFT approach for implementation of PMU. In section IV, the modelling and simulation study of PMU is described. Section V presents the simulation results and validation with the mathematical analysis and Section VI includes the conclusion of the entire work.

II. PHASOR MEASUREMENT UNIT

According to IEEE, the Phasor Measurement Unit (PMU) is defined as "a device which can able to measure the time-synchronized phasor values along with its magnitudes of both voltage and current signals". It is a microprocessor-based device which can measure 50/60 Hz AC signals (voltages and currents) at a rate of 48 samples per cycle. A phasor is a rotating vector of complex quantity with magnitude and phasor angle of a sinusoidal waveform.

The phasor representation of a sinusoidal signal is given in Fig. 1. Mathematically a sinusoidal wave can be represented as below.

$$x(t) = X_m \cos(\omega t + \phi) \quad (1)$$

Where X_m = the magnitude of the signal, ω= frequency in rad/sec, and ϕ= phase angle.

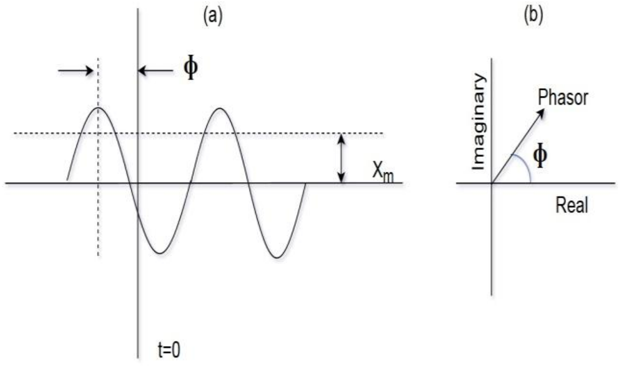

Fig. 1. Phasor representation of a sinusoidal waveform

The RMS value of the above sinusoidal signal can be written as below.

$$X = \frac{X_m}{\sqrt{2}} \angle \phi = \frac{X_m}{\sqrt{2}} e^{i\phi} = \frac{X_m}{\sqrt{2}} (\cos\phi + i\sin\phi) \quad (2)$$

There are various techniques for phasor estimation such as Discrete Fourier Transfer, zero crossing, least error square which are described in [1]. In this paper, the DFT based non-recursive algorithm is implemented to calculate the phasor values of a given signal due to its stable nature.

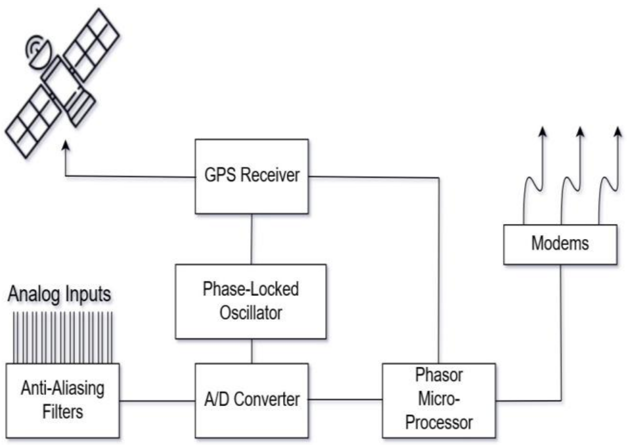

Fig. 2. Block diagram of the Phasor Measurement Unit [6]

A typical block diagram of a PMU is shown in Fig 2. The PMU devices which are placed at different bus locations collect the three-phase voltage and current data from the voltage and current transformers simultaneously to extract the positive sequence component of the signal which can be used to access the state of the power system network. As these analogue signals consist of harmonics, so it is required to filter out those harmonics by using the antialiasing filters. Butterworth Band Pass Filter is used in this purpose as it gives a flat signal from the AAF filter sampled by the analog to digital converter as shown in Fig.2. As the PMUs are installed far away from each other; GPS is used for synchronization of PMU data [7]. Further, the data received at PDC again transmitted those measurements to the local control centres for the processing of acquired data.

III. NON-RECURSIVE BASED DFT APPROACH

The DFT technique is divided into recursive and non-recursive method of phasor estimation. In Non-recursive type, all the phasor values are collected from the new window, and the reference data are not considered from the previous window value [8].

A sinusoidal waveform can be written as

$$\text{x(t)} = \sqrt{2} X \sin(\omega t + \phi) \quad (3)$$

The phasor representation of the above sinusoidal wave can be written as:

$$X = X_m e^{i\phi} = X_m (\cos\phi + i\sin\phi) \quad (4)$$

For N number of samples per cycle, the phasor estimation can be represented as:

$$x_n = \sqrt{2}\sin\left(\frac{2\pi n}{N} + \phi\right) = \sqrt{2}\sin(\theta n + \phi) \quad (5)$$

Where $\theta = \left(\frac{2\pi}{N}\right)$ is taken as the sampling angle.

The phasor estimation for the two consecutive windows nth and (n-1) th can be represented as below.

$$x_n = \frac{\sqrt{2}}{N} \sum_{n=0}^{N-1} x_{n+1} \cdot e^{-i\theta n} \quad (6)$$

$$x_{n-1} = \frac{\sqrt{2}}{N} \sum_{n=0}^{N-1} x_n \cdot e^{-i\theta n} \quad (7)$$

Here the Non-recursive DFT technique is used to calculate the phasor value of the sinusoidal input signal. The first step of Non-recursive technique indicates the sampling of the input signal at the sampling frequency, i.e. the product of the number of samples and the fundamental frequency [9]. Then these samples are collected and calculated to obtain the phasor values. For example, let the number of the sample be taken as 12, the angle θ can be found out by θ=2π/N which is equal to 30°. The angle for the next window can be considered as (ϕ+θ) which are equal to 60°and so on. The final phasor value is calculated by taking the average of all the phasor values. It shows that in Non-recursive DFT technique the magnitude remains constant, only the phase value changes in an anticlockwise direction.

IV. MODELLING OF PMU USING LABVIEW

LabVIEW is a programming language based on structured data flow interfacing with graphical models provided by National Instrument [10]. The programs which are designed using LabVIEW known as Virtual Instruments (VI). There are two-panel windows named as Front panel and Block panel. Logical operations are performed by connecting VI in the Block panel.

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The front panel is used to control the programs, and the output is also viewed from the Front Panel. LabVIEW, along with NI ELVIS provides the real-time implementation of algorithms, standard library VI and user-defined VI provides to construct LabVIEW models. Several options, like system analysis signal manipulation, arithmetic and comparison operations can be performed using LabVIEW. In this paper, the input signal is given from the Virtual Instruments library. Here, the LabVIEW modeling of PMU is presented in Fig. 3. The real-time input signal can be provided from the data acquisition system by interfacing NI ELVIS with LabVIEW. The input signal is then converted into digital to obtain the discrete values and stored using an array. Here 12 samples are considered for each data window. The phasor values are obtained by performing the appropriate arithmetic operation. The complex value of phasor estimation is converted into polar form and displayed as output. This algorithm is repeated for subsequent data samples. For the next phasor estimation, the phasor rotates in an anticlockwise manner with the delay of one sampling angle (θ).

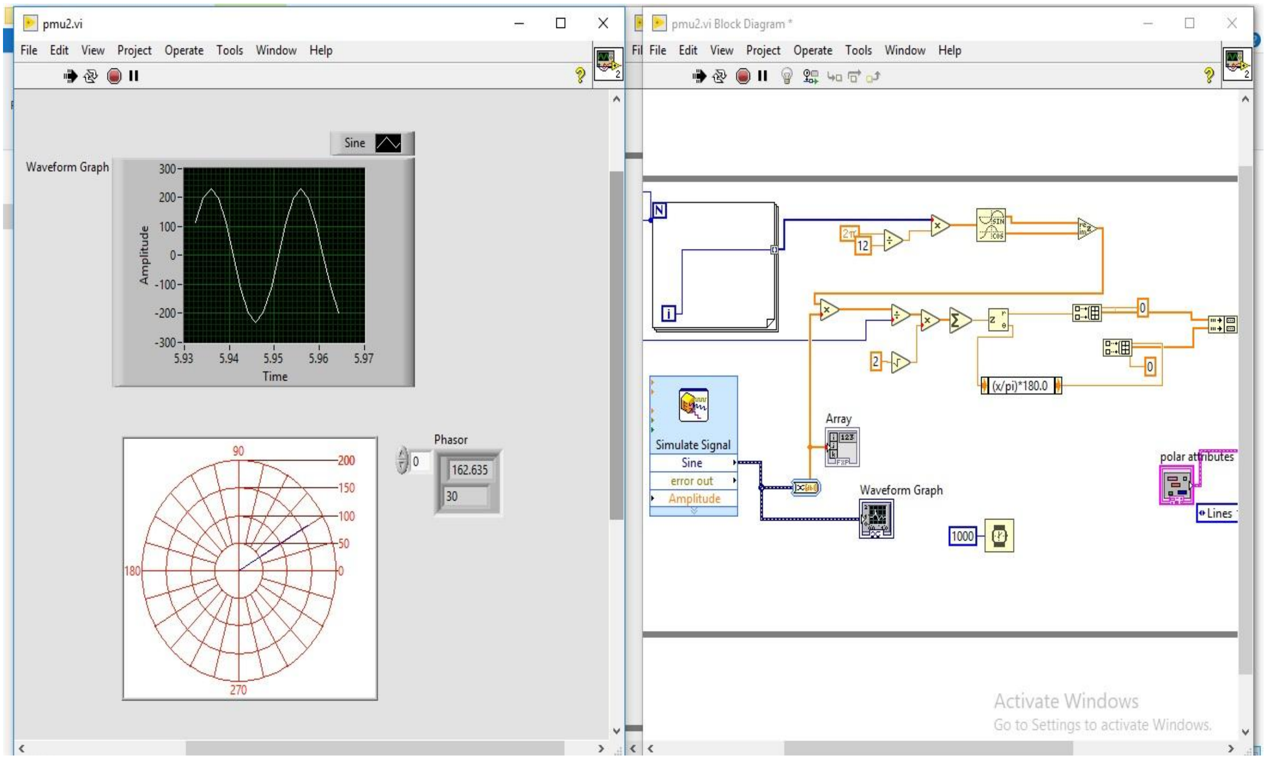

Fig. 3. Lab VIEW modelling of PMU

V. RESULTS AND DISCUSSION

A signal of 230 cos (100πt+π/6) is taken for the result validation with the mathematical analysis. Here the sampling frequency and no of samples per cycle are taken as 600 Hz and 12 respectively. The first cycle completes with a phasor value of 162.672∟30° as given in Table I. It can be seen from Table II that the first 20 samples obtained by simulating the model and phasors are calculated using Eqs. (6) and (7). The phasor can be evaluated using the non-recursive algorithm after completion of one cycle. Table 2 shows that the magnitude and angle of the first 12 samples are constant, and after 12th samples angles are changing in an anticlockwise manner with constant magnitude. The simulation results obtained from PMU LabVIEW model are shown in Fig. 4 and 5. Fig. 4 indicates the polar plot of the first sample window and the 30° anticlockwise phase shifting is shown in Fig. 5.

Table-I: Phasor estimation for the first sample

Sample No	Sample (V_n)	√2 * V_n*e^(-jnθ)
0	199.186	281.689 + i 0.000
1	115	140.84 – i 81.316
2	0	0
3	-115	0.000 + i 163.633
4	-199.186	140.844 + i 243.943
5	-230	281.681 + i 162.633
6	-199.186	281.689 + i 0.000
7	-115	140.84 – i 81.316
8	0	0
9	115	0.000 + i 162.633
10	199.186	140.844 + i 243.943
11	230	281.681 + i 162.633
	Sum	1690.108 + i 976.786
	Average	140.842 + i 81.399 = 162.672∟30°

Table-II: Phasor estimates for sampling window

Sample no	Sample	Phasor estimated by Non-recursive DFT	Remarks
0	199.186	$162.634\angle 30^o$	The first 12 samples calculated using the non-recursive DFT
1	115	$162.634\angle 30^o$	
2	0	$162.634\angle 30^o$	
3	-115	$162.634\angle 30^o$	
4	-199.186	$162.634\angle 30^o$	
5	-230	$162.634\angle 30^o$	
6	-199.186	$162.634\angle 30^o$	
7	-115	$162.634\angle 30^o$	
8	0	$162.634\angle 30^o$	
9	115	$162.634\angle 30^o$	
10	199.186	$162.634\angle 30^o$	
11	230	$162.634\angle 30^o$	
12	199.186	$162.634\angle 60^o$	After 12th sample, the magnitudes remain constant, but the angle changes anticlockwise
13	115	$162.634\angle 90^o$	
14	0	$162.634\angle 120^o$	
15	-115	$162.634\angle 150^o$	
16	-199.186	$162.634\angle 180^o$	
17	-230	$162.634\angle 210^o$	
18	-199.186	$162.634\angle 240^o$	
19	-115	$162.634\angle 270^o$	

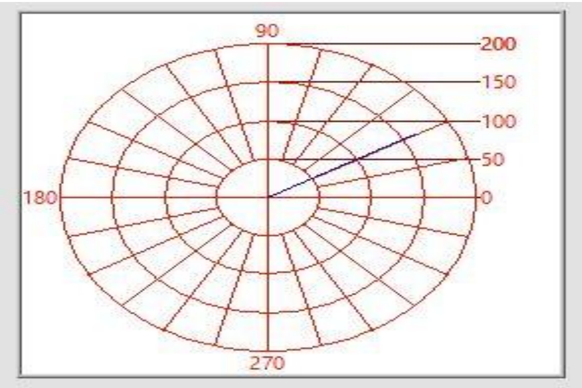

Fig. 4. : Polar plot for first window

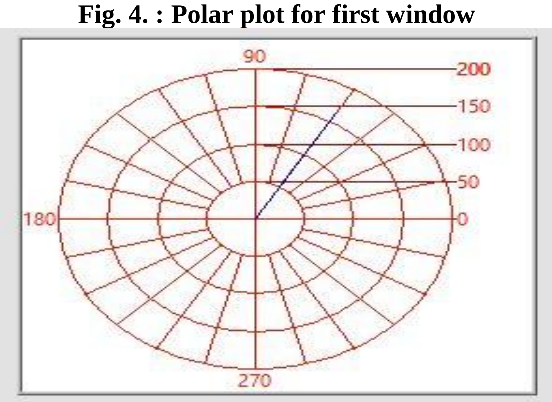

Fig. 5. : Polar plot for second window

VI. CONCLUSION

The non-recursive DFT based approach is used in this paper to model the Synchrophasor Unit or the PMU using NI LabVIEW software. The results obtained from the PMU model are found to be similar while comparing with the mathematical analysis for phasor calculation. This can bring a proper insight for future real-time implementation of PMU in smart grid prototype.

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