# Study of Different Estimation Techniques for a Micro-Phasor Measurement Unit Implementation

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*Abstract:* Distribution power networks are very complex, due to the great number nodes, short distances, and small amplitude and phase angle differences between nodes, faster dynamics and lack of standard documentation. Thus, these complexities have raised the need to develop new Phasor Measurement Unit (PMU) called Micro-Phasor Measurement Unit (µPMU) with high accuracy and high precision. In this work, several estimation techniques have been investigated so far for improving effectiveness and accuracy of this micro-PMU.

*Keywords:* Distribution power networks, µPMU, Discrete Fourier Transform algorithm, Smart discrete Fourier transform.

Received: March 18, 2022. Revised: October 14, 2022. Accepted: November 17, 2022. Published: December 31, 2022.

## 1. Introduction

DISTRIBUTION networks are very complex, due to the great number nodes, short distances, and small amplitude and angle differences between nodes, faster dynamics, and lack of standard documentation [1]. Thus, these complexities have raised the need to develop new monitoring system with high accuracy and high precision that support the achievement of situational awareness in distribution networks and enable the distribution operators to make operational decisions in response to such disturbances [2].

To improve situational awareness and alleviate these complexities, the micro-phasor measurement unit (µPMU) or distribution level PMU (D-PMU) has been developed in distribution networks [3].This unit is capable of measuring the synchronized voltage and current phasors (both magnitude and phase angle) in real-time at higher accuracy, high precision, and high sampling rate, to facilitate a level of visibility into a distribution network [4]. The µPMU reports four fundamental measurements on three phases, so it has 4x3=12 measurement channels. These four measurements are voltage magnitude, voltage phase angle, current magnitude, and current phase angle per phase with the adjustable sampling rate in the range of (10-120) samples per second for a 60Hz system; if the GPS antenna has established satellites, µPMUs also use the GPS clock to ensure precise time synchronization [5]. It has accuracy angle of ±0.01°, total vector error allowance of ±0.05% (precision), angle resolution of ±0.002°, and magnitude resolution of ±0.0002%.

In this work, several signal processing techniques to estimate phasor have been investigated so far for improving effectiveness and accuracy of this micro-PMU. In fact, there are no standard algorithms implemented in a PMU or standard number of cycles used in computing a phasor. Till now, the used algorithms can be divided into two categories DFT algorithms (such as DFT, recursive DFT, smart DFT….) and non-DFT algorithms (such as Kalman filters, weighted least squares, neural networks, least error square….) [6-8].

The conventional and the most commonly used algorithm for amplitude and phase estimations is the discrete Fourier transform (DFT)[6],[7],[8] introduced in two forms: nonrecursive and recursive.

Using the DFT algorithm, researchers have focused their efforts on studying the gain frequency response in terms of suppressing the effect of harmonics included in the AC voltage on phase detection [9], [10]. However, the absolute phase detected by the DFT, especially recursive DFT, may involve considerable error during input signal dynamics and system disturbances, which may be excluded from µPMU.

## 2. Review of Micro-Phasor Measurement Unit ( µPMU)

Several review papers on µPMU have mainly been conducted on its applications in distribution networks, such as monitoring and diagnostic applications, and control applications [11- 13]. In a recent review paper [14], the authors have reviewed the applications of µPMU for emerging active distribution networks. Especially, this work has mainly focused on state awareness and event detection. Figure 1 illustrates the µPMU with related research.

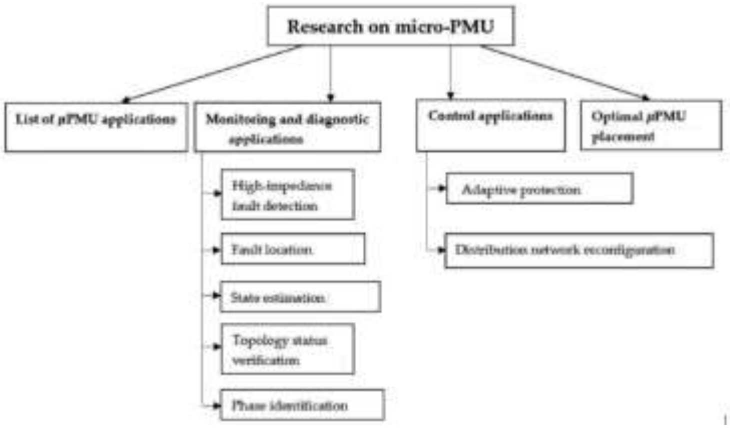


Fig. 1 μPMU with related research [15]

The works in [11, 12] summarize the different applications of μPMU such as diagnostic and control applications, and their objectives. Moreover, the development process of the μPMU network is described in the works.

A recent paper [14] reviews μPMU based applications for emerging active distribution networks. The needs of μPMU at the distribution level are explained and summarized its applications in [15]. A recent report [16] provides a comprehensive list of μPMU applications such as monitoring and diagnostics, planning, and operation and control applications.

The distribution operators can detect the events in real-time, by investigating data from the μPMU installed in the distribution network [17]. For example, using μPMU data, reverse power flow in distribution networks can be easily detected [18]. Upon detection of distribution system frequency event, power mismatch between generation and load demand which can be caused by power system disturbances is estimated at the early stage of the event [19].

Identification of high-impedance fault location with μPMU data is proposed in [20] which uses the synchronized harmonic phasors and focuses on the third harmonic components of pre-fault and post-fault measurements. This shows that only two μPMUs are enough to estimate the location of a high-impedance fault in the distribution network.

Determining accurate fault location can help to reduce the duration of outage and operation cost of distribution networks. Micro-PMU measurements help to improve the accuracy of finding the fault location. In [21], the authors propose a fault location identification algorithm that uses the recorded data of voltage and current phasors before and during the fault from μPMUs installed at two terminals. Another fault location finding method is proposed in [22]. This method consists of two steps:

- The candidate fault locations are found using voltage and current information provided by the μPMU at one terminal by iterating each line segment, and
- the actual fault is found by voltage difference, which is obtained by using the measurements from μPMUs installed at two terminals in the distribution network.

In [23], the authors propose an algorithm to find a fault location in the distribution network and analyzes the characteristics of μPMU noise and its impact on the traditional impedance fault location. According to this work, both μPMU noise and fault location error follow Gaussian distribution. The accuracy of the impedance method is influenced by μPMU noise, and the accuracy of the double-ended impedance method is higher than that of the single-ended impedance method under μPMU measurement error.

In [24], a method to locate the source of events in distribution networks is proposed by using μPMU data. The proposed method is based on the compensation theorem in the circuit theory to generate an equivalent circuit to locate the event by using the voltage and current phasors from the μPMUs. The source of the event can be detected by using the measurements of the two μPMUs.

Observability of a distribution network is necessary to operate securely and efficiently to increase the accuracy and reliability of the network. The location of μPMUs should be carefully considered for system observability. Complete observability is defined as all bus voltages and line currents phasors being uniquely determined. The μPMU measures the voltage phasors of the installed bus and the current phasors of the incident lines to that bus; the voltage phasors of adjacent buses to that bus can be calculated using line parameters and Ohm's law. Hence, all buses connected to that bus where μPMU is installed, are observable.

To obtain the minimum number of μPMUs for complete observability, a graphic theoretic method is proposed in [15]. The proposed method is based on the collection of the set of vertices and edges. The distribution network is converted to a graph by considering the lines as edges, and buses as vertices. The spanning tree consists of two types of vertices: Pendant and cut vertices. The proposed placement method is formulated in two steps:

- Select the pendant vertices, and
- Choose the cut vertices connected to these pendant vertices as the installation locations of μPMUs.

The unobservable vertices are grouped, and the μPMU is installed at vertex that makes each group observable.

As mentioned earlier with μPMU, the reliability and resiliency of distribution networks can be improved by reducing not only the duration of outages but also the number of customers affected by outages. It helps to reduce the time required to restore the service through faster determination of fault location, faster line reclosing, faster forensic analysis, faster black-start, faster island resynchronization, and smoother generation synchronization. The oscillation detection and actions taken to restore the network stability can reduce the interruptions [25, 26]. The number of outages can also be reduced by identifying the potential equipment failures and repairing them before actual failure.

Phase angle can be used to monitor and improve the speed and accuracy of line reclosing and generator synchronization. When the interruptions occur in the distribution network, μPMU data can be used to analyze the events, so that the operator can determine the causes. There are many events in distribution networks, but the conventional models used to monitor distribution networks are not accurate in predicting the network behavior under different network disturbance conditions [27]. If μPMU data are available and are used for model validation, it is expected that better models of each distribution network [28] can be obtained. The use of μPMU data allows operators to identify the events and it mitigate reliability concerns, because the data can be used to accurately find fault locations, perform phase angle monitoring for line reclosing, and verify line flows and network conditions before, during and after the outage. Therefore, the μPMU can help event detection and achieve faster service restoration, which is highly valuable for distribution utility and customers. In [29], the authors present the benefits of μPMU in developing countries. In developing countries, there are a number of unplanned power outages. The duration of unplanned outages can be reduced by finding causes and locations of the outages. Through the case study of Rwanda power system, this work shows that the total unplanned power outages duration can be reduced to 51.7%.

The cost savings by using μPMUs are obtained by equipment savings, labor savings, and other avoided costs. Moreover, the cost is further saved through congestion reduction, and reduction of labor cost associated with reduced forensic event analysis and model validation. These events can frequently occur by using more renewable energies in distribution networks. At the same time, as renewable generators replace fossil fuel-based generators, fuel costs can be saved [30]. In addition, μPMUs can improve the operational tools and the operator's instincts with μPMU-based training and tools, including visualization, alarms, and alerts. μPMU qualities can help the operators reduce outage duration, as well as minimize the effects on customers due to the speedy system restoration time [31].Distribution networks can be efficiently operated resulting in high utilization of the existing distribution assets with μPMUs. Better recognition of active and reactive power needs can improve grid utilization [32]. Therefore, utility company minimizes line losses, delivered energy costs and total generation requirements to provide the same amount of delivered electricity. The increased efficiency can lower the capital costs for distribution lines and generation assets. With μPMU data and analytics, equipment failures can be identified even before they occur, resulting in maintenance costs reduction. This can reduce crew labor costs and enable more cost-effective equipment acquisition and inventory management. Moreover, using μPMU data in distribution networks can reduce crew field time spent on searching for fault location for repairing [33].

# 3. Different Phasor Measurement Techniques

In this work, a number of DFT algorithms are investigated and simulated in accordance with IEEE C37.118 Standard. Then, the performance of the recursive DFT algorithm, which involves fewer calculations than the classical DFT, is studied by computer simulation. Possible numerical recursive DFT accumulation error is addressed. To solve this problem, a reset of the DFT algorithm at appropriate intervals is proposed and evaluated. This paper offers a method that reduces the calculation load and minimizes the errors, while the error accumulation is resetting at a predefined period; its effectiveness is proved by simulation.

The power system phasor, amplitude, phase angle and frequency are decision variable provided by μPMU which may be critical, used by distribution network applications. To estimate phasor parameters, the original analog signal with its harmonics is first sampled; an appropriate mathematical estimation method can then be applied. There are no standard algorithms used in a μPMU or a standard number of cycles used in computing a phasor. The fast and accurate measurements of the phasor are still considered in a contemporary topic of research interest. In literature, there are various methods used in phasor estimation such as the Discrete Fourier Transform (recursive and non-recursive) [5], Newton method [35], Kalman filtering [9], level tracking, least square algorithm [36], Neural networks and others [37].

Out of all the above-mentioned methods for phasor estimation, DFT algorithm is the most popular and widely used method for fundamental and harmonic measuring [38]. Algorithm has been used in the present work for modeling μPMU measurement with the help of Matlab software.

## 3.1 DFT estimation technique

The Discrete Fourier Transform (DFT) algorithm is one of the most important tools for scientific research. It has been applied to many useful applications such as signal modeling, spectral analysis, signal compressions, and power system measurements. It is used when the signals are known only at N instants separated by a sample times T. It converts a time domain signal to frequency domain keeping all the information carried by the input signal unchangeable [6].

DFT is accurate only when it is used in the case of synchronous sampling, and the sampling theorem is satisfied.

Sampling theorem: $T/Ts \geq 2m$; where, m is the highest order of harmonics. Synchronized sampling implies $T/Ts = N$.

Consider a sinusoidal input signal of frequency fo given by:

$$x(t)=X_m \cos(2\pi f0t+\varphi) \quad (1)$$

Where Xm: maximum value of the input signal,

f0: the nominal frequency,

φ : the initial phase angle of the input signal.

The signal has a Fourier series

$$x(t)=ak\cos(2\pi fot)+bk \sin(2\pi fot) \quad (2)$$

or,

$$x(t) \quad \left\{\sqrt{a_k^2+b_k^2}\right\} = \cos(2\pi fot+\varphi)$$

$$\text{where,} \quad \varphi = \arctan\left(\frac{-b_k}{a_k}\right) \quad (3)$$

The signal is conventionally represented by a phasor $\bar{X}$ related to the fundamental frequency component of its DFT,

$$\bar{X} = \frac{X_m}{\sqrt{2}} e^{j\varphi}$$

$=Xe^{j\varphi}$

Where , $Xm=\sqrt{a_k^2+b_k^2}$ (4)

$\bar{X}=X\cos\varphi+jX\sin\varphi$ (5)

Assuming that the periodic signal x(t) is sampled N times (usually 12, 24, 36…) per fundamental period (50Hz or 60Hz with no harmonics n=1), the phasor representation (Fourier transform) is given by

$$\bar{X} = Xc - jXs \quad (6)$$

Where, $X_c = \sum_{k=1}^{N} X_k \cos(\frac{2\pi}{N}k)$

and $X_s = \sum_{k=1}^{N} X_k \sin\left(\frac{2\pi}{N}k\right)$

In some literatures, the definition of DFT with no harmonics is

$$X = \frac{\sqrt{2}}{N}\sum_{k=1}^{N} X_k e^{\frac{-j2\pi}{N}k} \quad (7)$$

Figure 2 shows a signal processing step performed for generating the synchronized phasors provided that the power system frequency is operating at nominal frequency. This is based on the fixed frequency sampling synchronized to an absolute time reference, followed by multiplication of the cosine and sine nominal frequency carrier.

DFT has two types of estimation techniques depending on the use of data from the previous window. These types are recursive and non-recursive DFT.

After calculation of the first phasor, two different algorithms are described to update the phasor for successive windows. The simplest way to update the phasor is to perform calculations freshely each time for the successive windows, a non-recursive algorithm, the other way is a recursive algorithm where only phasor updating is needed instead of new phasor estimation for the new window.

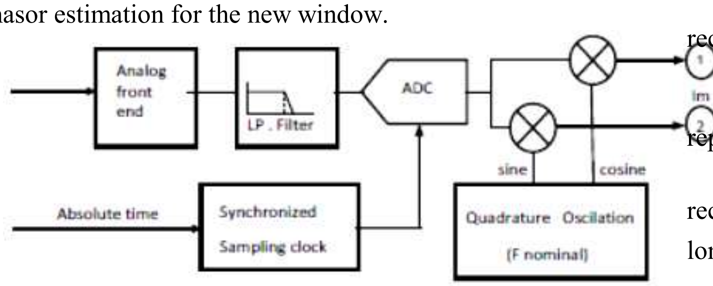


Fig. 2 PMU Phasor signal processing model

## 3.2 Non-recursive DFT algorithm.

The non-recursive DFT algorithm is the simplest procedure to calculate phasor for each and every window where the present output depends only on the present input as time function as shown in Figure 3. General equation for non-recursive update is given in equation (7).

In general, the phasor obtained from a constant sinusoid of nominal power system frequency by this technique will have a constant magnitude and will rotate in the counterclockwise direction by sampling angle θ = 2π/N as the data window advances by one sample [8].

Non-recursive algorithms are numerically stable since they do not take any reference of previous data. But they are somewhat wasteful of computation effort; requires 2N multiplications and 2(N-l) additions to produce the phasor [39].

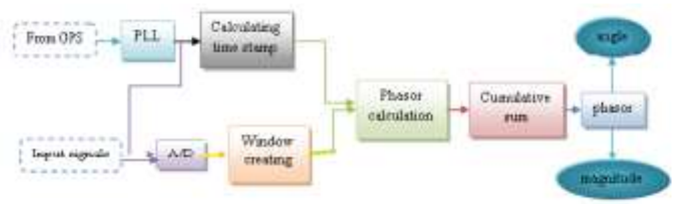


Fig. 3 PMU model for non recursive algorithm

## 3.3 Recursive DFT algorithm.

For recursive phasor estimation, the phasor is calculated for X N-1 only, and then the new phasor XN that is obtained after an elapsed time corresponding to 2π/N radians is obtained by making a recursive update on the old phasor. (N–1) multiplications by the Fourier coefficients are common to the new and old windows, only one sample (x0) is discarded, and one sample (xN) is added to the data set; making this a very efficient computation algorithm. Its formula is given as in Equation (8) [7].

$$\hat{X}^N = \frac{\sqrt{2}}{N}\sum_{k=0}^{N-1} X_{k+1} e^{\frac{-j2\pi}{N}(k+1)}$$

$$\hat{X}^N = X^{N-1} + \frac{\sqrt{2}}{N}(x_N - x_0)\, e^{\frac{-j2\pi}{N}0} \quad (8)$$

Where $e^{\frac{-j2\pi}{N}0} = e^{\frac{-j2\pi}{N}N}$ since N samples span exactly one period of the fundamental frequency.

When the last sample in the data window is (N + r), the recursive phasor estimate is given by

$$\hat{X}^{N+r} = X^{N+r-1} + \frac{\sqrt{2}}{N}(x_{N+r} - x_r)\, e^{\frac{-j2\pi}{N}r} \quad (9)$$

Where r represents the present state and (r-1) represents the past state.

The phasor for a constant sinusoid remains stationary for recursive phasor estimation. Furthermore, $\hat{X}^{N+r} = X^{N+r-1}$ as long as the sample $x_{N+r} = x_r$.

In general, the recursive algorithm is faster, but numerically unstable. If an error occurs in the estimated phasor from one window, it will be present in all the phasor estimates from then on. In other words, the Input signal dynamics and frequency drifts would produce a pattern of accumulated error in the estimated phase and magnitude during real time operation.

Nevertheless, because of its great computational efficiency, it is usually the algorithm of choice in many applications. Unless stated otherwise explicitly.

The difference between the recursive and non-recursive Phasor calculations is illustrated in Figure 4, the non-recursive Phasor rotates in counter-clockwise direction by an angle 2π/N as the sample time advances, whereas the recursive phasor remains stationary. More importantly, the computation implied in the recursive formula (9) involves only two samples: $x_{N+r}$ and $x_r$, whereas the non-recursive formula (6) implies computations with N samples.

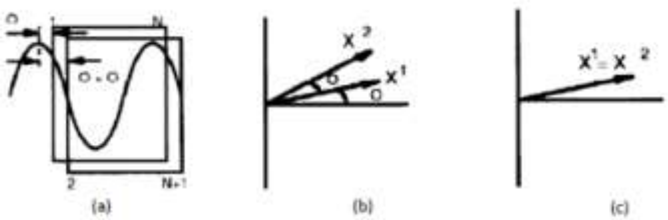


Fig. 4 Phasors from sampled data, (a) Moving window, (b) Non-recursive, and (c ) Recursive computation.

Frequency is be defined as,

$$f(t) = \frac{1}{2\pi}\left(\frac{d\theta(t)}{dt}\right) \quad (10)$$

Where $\theta(t) = \omega t + \varphi$

Rate of Change of Frequency (ROCOF) is defined as,

$$ROCOF = \left(\frac{df(t)}{dt}\right) = \left(\frac{d\left(\frac{1}{2\pi}\left(\frac{d\theta(t)}{dt}\right)\right)}{dt}\right) \quad (11)$$

Total Vector Error (TVE) defines the error between the measured and the theoretical phasors. According to IEEE standard the maximum error permissible in the system is about 1 %. It can be calculated as,

$$TVE = \sqrt{\frac{(V_r(n)-V_r)^2+(V_i(n)-V_i)^2}{V_r^2+V_i^2}} \quad (12)$$

Vr(n) : Real part of the theoretical phasor,
Vr : Real part of the measured phasor,
Vi(n) : Imaginary part of the theoretical phasor and
Vi : Imaginary part of the measured phasor at the instant n.

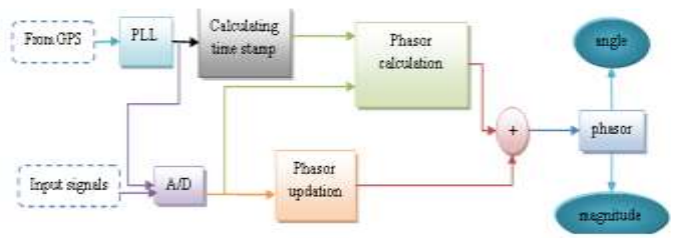


Fig. 5 PMU model for recursive algorithm

### 3.4 Smart DFT algorithm.

Smart discrete Fourier transform (SDFT) is a digital measurement algorithm which is based on DFT, which gets over the faults that arise when frequency offset occurs and keeps all the advantages of the DFT such as fast calculation, immunity to harmonics of fundamental frequency. Moreover, it overcomes the leakage error and even the recursive computing can be used in SDFT [9, 10].

Thus, the development of the algorithm of SDFT is similar to the conventional DFT method. Yet, SDFT relies on frequency estimation obtained by three consecutive DFT fundamental components. By using an estimated frequency; ω=2Π(50+Δf), a phasor can be obtained as xr=Ar+Br

Where

$$A_r = \frac{\bar{x}}{N}\frac{\sin N\theta_1}{\sin\frac{\theta_1}{2}} e^{j\frac{\pi}{50N}(\Delta f(2r+N-1)+100r)} \quad (13)$$

$$B_r = \frac{\bar{x}^*}{N}\frac{\sin N\theta_2}{\sin\frac{\theta_2}{2}} e^{j\frac{\pi}{50N}(\Delta f(2r+N-1)+100(r+N-1))}$$

(14)

By defining

$$\alpha = e^{j\left(\frac{\pi}{50N}(2\Delta f+100)\right)} \quad (15)$$

$$x_{r+1} = A_{r+1} + B_{r+1} = A_r \times \alpha + B_r \times \alpha^{-1} \quad (16)$$

$$x_{r+2} = A_{r+2} + B_{r+2} = A_r \times \alpha^2 + B_r \times \alpha^{-2} \quad (17)$$

After mathematical manipulations, following equation can be obtained,

$$\alpha = \frac{(x_r+x_{r+2}) \pm \sqrt{(x_r+x_{r+2})^2-(4x_{r+1})^2}}{2x_{r+1}} \quad (18)$$

$$f = 50 + \Delta f = \cos^{-1}((\mathrm{Re}(\alpha)) \times \frac{50N}{2\pi} \quad (19)$$

We can estimate phasor after getting exact frequency by the following equations,

$$A_r = \frac{\hat{x}_{r+1}*\alpha-\hat{x}_r}{\alpha^2-1} \quad (20)$$

$$x = Abs(A_r) * \frac{N\sin(\frac{\pi\Delta f}{50N})}{\sin(\frac{\pi\Delta f}{50})} \quad (21)$$

$$\phi = angle(A_r) - \frac{\pi}{50N}\,(\Delta f(N-1)) \quad (22)$$

It is clear that The SDFT algorithm requires additional computational steps compared to the standard DFT, but the benefits of reduced filtering requirements outweigh additional processing expenses [9, 10].

## 4. Why not FFT is in µPMU

The standard method for spectrum analysis in digital signal processing (DSP) is the discrete Fourier transform (DFT), typically implemented using a fast Fourier transform (FFT) algorithm. The FFT is fast or computationally efficient when all the N values of x(n) are needed. However, there are applications that require spectrum analysis only over a subset of the N center frequencies of an N-point DFT. With the FFT being used, the entire DFT-sequence has to be computed, and then all the unwanted values get discarded. Hence for such applications it is more efficient to use other algorithms.

Furthermore, the use of the FFT imposes a restriction on the number of samples required for the data window.

Verification of algorithms in MATLAB

MATLAB model for micro-Phasor Measurement Unit algorithms were developed and compared to get the required phase and magnitude of the signal. test cases have been considered for single phase 311V, x(t)=311 Sin (100wt+□/4) at frequency 50Hz which is sampled at a sampling frequency of 1800 Hz i.e. 36 samples per cycle. The phasor output for non-recursive DFT, recursive DFT and non-recursive smart DFT estimates are shown in Figures 6,7 and 8 respectively.

The same tests have been considered for single phase signal at frequency 51 Hz. The phasor outputs are shown in figures 9, 10 and 11.

In Figure 6, it can be noted that the obtained phasor estimates with non-recursive algorithm maintains a constant magnitude. However, when a new phasor estimate for the given phasor is taken, the phasor rotates anti-clockwise by an angle of 10° from the previous one due to the delay for getting successive samples.

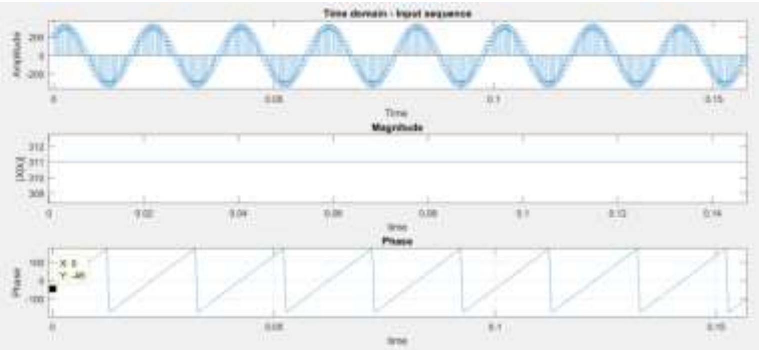


Fig. 6  Phasor output for non-recursive DFT at 50Hz

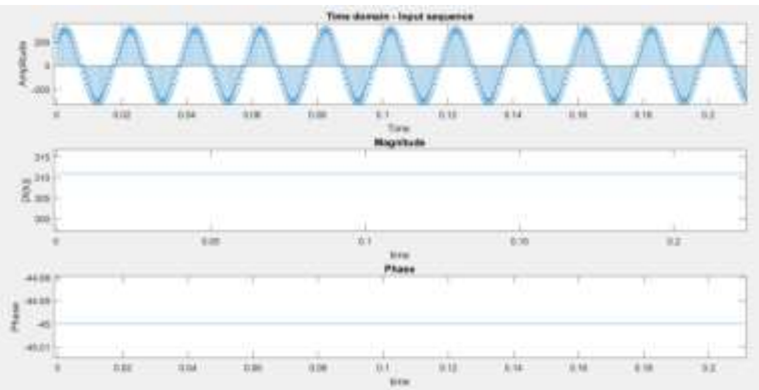


Fig. 7 Phasor output for recursive DFT at 50Hz

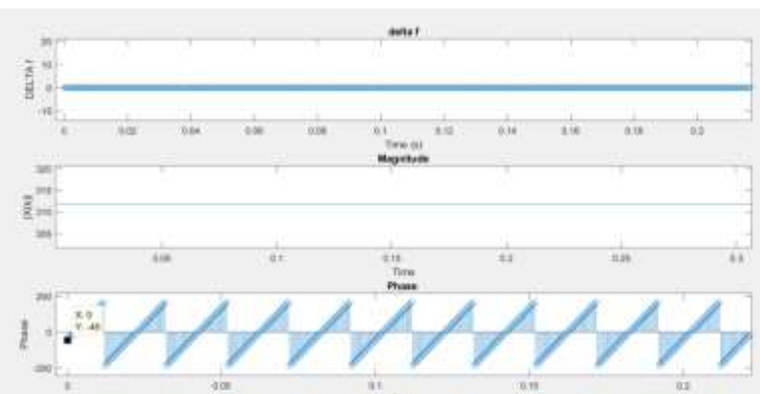


Fig. 8 Phasor output for Smart DFT at 50Hz

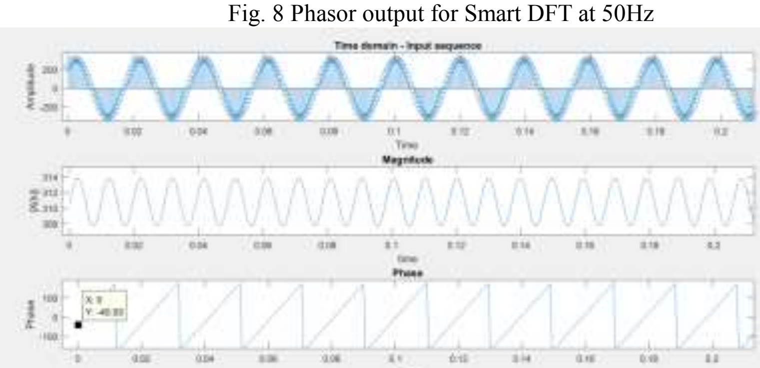


Fig. 9 Phasor output for non-recursive DFT at 51Hz

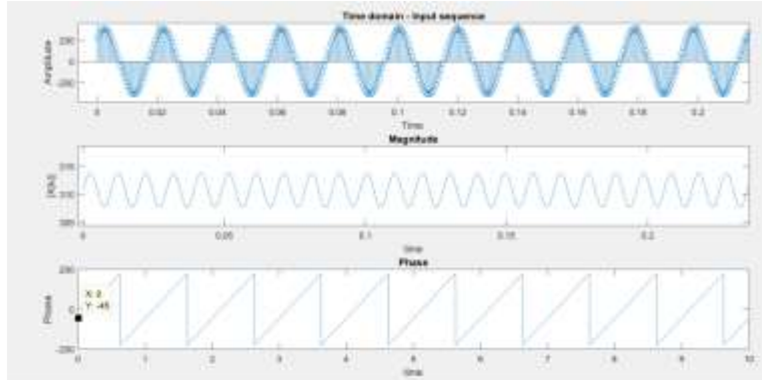


Fig. 10 Phasor output for recursive DFT at 51Hz

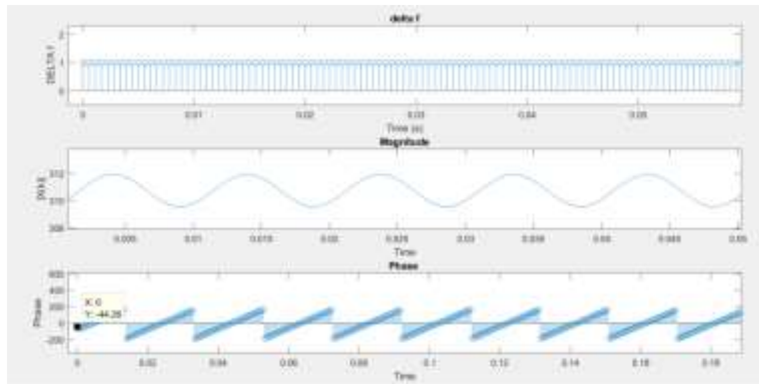


Fig. 11 Phasor output for Smart DFT at 51Hz

Figure 7 shows that with recursive phasor estimation, estimated magnitude and phase of the phasor remains constant over different data windows.

In figure 8, since the smart DFT uses non-recursive DFT algorithm the results are exactly the same as the ones presented in previous figure.

In another hand, when the frequency is changed from 50 to 51 Hz. it is observed that the magnitude of the phasor is oscillating when using any of the three algorithms, but the error using Smart DFT is clearly reduced.  Figure 9 shows that the phase angle when using non-recursive DFT looks like the obtained one when an input signal is applied with a frequency of 50 Hz, except the fact that the starting phase angle is shifted from -45° to -40.93°.

It is also observed in figure 10 that the phase angle using recursive algorithm with a frequency deviation is no longer constant, but it rotates counterclockwise with a period of 1/ delta f.

Figure 11 shows that the results of smart DFT algorithm are similar to the results of non-recursive DFT with fewer errors.

# 5.  Conclusion

From the obtained simulation results, the advantages and drawbacks of all algorithms can be highlighted as follows:

The non-recursive DFT algorithm is stable, with harmonic suppression for stationary signal and is simple to understand, but it requires more number of calculative operations (2N multiplications and 2(N-1) additions) and therefore faces many difficulties in its implementation. Furthermore, when the operating frequency of the system deviates from 50 Hz, the receiving data of PMUs cannot satisfy the condition of integral period sampling, and the frequency aliasing and spectral leakage of DFT method will cause big errors in parameter estimation and reduce the accuracy of the DFT algorithm. To overcome These effects additional filtering is required. However, implementation of these additional filtering requires storing of a large number of signal samples; thus, computationally expensive specifically for real-time implementations such as µPMU.

The recursive DFT algorithm possess all the merits of DFT like easy implementation. However, in the recursive algorithm, only two multiplications are needed to be performed at each new sample time. This property saves a lot of computational time and leads to stationary phasors in the complex plane. Recursive DFT algorithm can also, be used to detect and monitor the third harmonics present in the system. But it has some drawbacks as the problem of instability and accumulation of errors, and hence low accuracy which is not suitable for µPMU implementation.

The smart DFT (SDFT) algorithm is an algorithm based either on recursive or non-recursive DFT with additional computational steps capable of achieving the required accuracy with minimum or no additional filtering. Thus, it can outweigh the additional computational complexity in real-time implementation. It uses the frequency estimates to recalculate the phasor values. In this way, less erroneous results are obtained when frequency deviates from the nominal value. Thus, the last technique may be chosen for implementing a real-time system with high accuracy such as µPMU.

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