Comparative Study of Phasor and Frequency Estimation Algorithms for Distribution Networks

Article *in* Recent Advances in Electrical & Electronic Engineering (Formerly Recent Patents on Electrical & Electronic Engineering) · August 2022

DOI: 10.2174/2352096515666220722114705

Md. Tanvir Shahed
Bangladesh University of Engineering and Technology

REVIEW ARTICLE

Comparative Study of Phasor and Frequency Estimation Algorithms for Distribution Networks

Md. Tanvir Shahed[1,2,*]

[1]*Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh;* [2]*Department of Electrical and Electronic Engineering, Uttara University, Dhaka-1230, Bangladesh*

ARTICLE HISTORY

Received: March 28, 2022
Revised: May 18, 2022
Accepted: May 24, 2022

DOI:
10.2174/2352096515666220722114705

Abstract: Next-generation phasor measurement units (PMUs) are critical for proper distribution network monitoring in future smart grids. In the highly dynamic environments of future distribution systems, more advanced algorithms for detecting amplitude, phase, and frequency changes in power waveforms will be required. In this context, the goal of this study is to discuss the advantages and disadvantages of commonly used PMU algorithms. Many commonly used approaches for power system phasors and frequency estimation algorithms for distribution networks are reviewed and evaluated in this work from the perspective of phasor and frequency identification. According to various performance criteria, e-IpDFT (Enhanced Interpolated Discrete Fourier Transform) and DDPE (Dictionary-based Dynamic Phasor Estimator) provided the best performance among the algorithms. This study provides some insights into the shortcomings of current phasor estimation algorithms and will be useful in the development of future estimation techniques.

Keywords: Smart grid, distribution network (DN), discrete fourier transform (DFT), empirical wavelet transform (EWT), harmonic detection, phasor measurement unit (PMU), phasor estimation, e-IpDFT, DDPE, Fast TFM (taylor-fourier multifrequency).

1. INTRODUCTION

Harmonic analysis is a major problem for power-system control and protection. Because harmonics are largely fixed in comparison to other power quality disturbances, the examined signals are often translated from the time domain to the frequency domain using the discrete Fourier transform, which can be effectively performed using the fast Fourier transform (FFT). Other sophisticated approaches, such as wavelet and Hilbert-Huang transforms, which span the examined signals with non-Fourier bases, are often unsuitable for harmonic analysis due to the additional computations required for interpreting altered parameters. Consequently, the harmonic estimating methods presented in this study are mostly those having a Fourier basis. Some frequency estimate methods for detecting harmonic frequencies are also addressed.

With the rising penetration of converter-interfaced distributed energy resources, electric cars, active loads, bidirectional power flow, and so on, distribution networks are getting more sophisticated and contaminated with harmonics. The distribution networks face some challenges in emerging microgrid scenarios, including 1) At the distribution level, the signal is normally single-phase, with a very slight phase-angle fluctuation that necessitates a more complex measurement apparatus, 2) The presence of distributed energy sources in large concentrations imparts dynamics into the signal, 3) The usage of power electronic converters exacerbates power quality issues at the distribution level, and 4) At the distribution level, the measurements are noisier. To address the new challenges in distribution grid monitoring, planning, control, management, and protection, Distribution Management System (DMS) would now require dynamic network monitoring *via* measuring devices such as distribution-level PMUs (D-PMUs), which should be able to accurately estimate the fundamental as well as harmonic phasors, as well as a good power quality detection capability. As a result, it is regarded as a critical component of the Smart Grid system. Furthermore, the power system frequency may fluctuate from its nominal value due to a power imbalance between generation and load demand. When using FFT directly for spectrum analysis, these issues would result in errors owing to leakage and picket fence effects [1, 2]. As a result, many approaches for estimating power system harmonics and interharmonics have been presented in recent years. Batch signal processing and recursive (adaptive) approaches are the two broad categories of spectrum estimating techniques. In general, the recursive approach is a parametric technique that requires a greater understanding of the examined signal's spectrum [3]. As a result, the parametric tech-

*Address correspondence to this author at the Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh; Tel: +8801556341680
E-mail: tanvirshahed1996@gmail.com

2352-0965/xx $65.00+.00

niques must select a suitable model, estimate the model's parameters, and then replace these estimated values with the signal's spectral expressions.

The main goal of this paper is to review the relevant research work that has already been attempted by various research personnel and to provide a comparative study between the phasor and frequency estimation techniques for distribution networks. This research will be useful in selecting the optimal phasor and frequency estimation algorithm for a specific application in accordance with IEEE C37.118 Standard [4, 5].

This paper is organized as follows. Section II examines some recently utilized approaches in the literature for power system harmonics and interharmonic estimation. Section IV shows performance discussions based on frequency identification to provide advice for selecting the optimal approach for a certain application. Section V concludes the paper.

2. REVIEW FOR HARMONIC AND FREQUENCY ESTIMATION METHODS

The sinusoidal models are most suited for characterizing harmonic and interharmonic disturbances. The discrete-time form y(n) of a power signal y sampled at the time period t can be expressed with H sinusoidal components in noise as:

$$y(n) = ah \cos (n\omega h\Delta t + \varphi h) + w(n) \quad (1)$$

where ah is the amplitude, φh is the initial phase angle, $\omega h =$

$2\pi fh$ is the harmonic or interharmonic frequency in radius,

and $w(n)$ represents the additive white noise. Alternatively, the model (1) can also be expressed in the complex form

$$y(n) = Ahe^{jn\omega h\Delta t} + w(n) \quad (2)$$

where $Ah = a_h e^{j\varphi h}/2$ is the complex amplitude. In the following, several spectral analysis methods are reviewed to estimate the important parameters of the distorted power.

2.1. Fast TFM Algorithm

Table **1** shows the sequence of processing stages that comprise the method. A fine frequency grid made of P N points replaces the continuous frequency range [-(1/2Ts), +(1/2Ts)] [6]. A vector unknown encompassing all candidate frequencies is built as follows:

$$\underline{\mathbf{P}} = [P_{-PN/2}.^T \dots . P_0{}^T \dots P_{+PN/2}{}^T]^T \quad (3)$$

From (3), after some modifications, Matrix **D** can be formed as

$$\mathbf{D} = [D_{-PN/2}{}^K \dots . D_0{}^K \dots D_{+PN/2}{}^K] \quad (4)$$

where $D_{m,l}{}^k$ denotes the kth order derivative of the Dirichlet kernel.

In decreasing order of calculation time, the most difficult elements of fast-TFM are the search for peaks within zero-padded waveform spectra and the computation of TF (Taylor-Fourier) coefficient estimations. The former involves just a basic search, but a very big collection of values, whereas the latter necessitates the inversion of a relatively large matrix. Both processes may be repeated. A suitable algorithm implementation can provide a continuous reporting rate of 50 Hz while operating on sample sequences with an overlap of 80%. If a field-programmable gate array implementation is examined, further gains can be realized.

2.2. Empirical Wavelet Transform

Fig. (**1**) depicts the design of the Distribution-level PMU (DPMU) based on the Empirical Wavelet Transform, which consists of two major phases. In Step 1, a unique frequency estimator is created, which includes SVA for real-time signal frequency estimation and resampling of the signal based on frequency deviation. Step 2 of the proposed D-PMU employs, at its core, EWT to extract all of the frequency components independently, including the fundamental and harmonic phasors. This approach does not handle interharmonics or out-of-band interference in the signal. The D-efficacy PMUs have been tested and demonstrated for several test scenarios, including MATLAB simulated signals in accordance with IEEE Std C37.118.1a-2014 [4] harmonic distorted signals in various cases in accordance with the European standard EN-50160 [7, 8], distribution-level field signals collected from our Institute substation, and hardware implementation results. The suggested method operates at a reporting rate of Fs (= 50) and an overlapping window of 1 cycle (20 ms for a 50 Hz signal), adding one new data point and deleting the very first data point in a specified window every 1 = fs seconds (0:15625 ms for a 6400 Hz signal).

2.3. Dictionary-Based Sparse Representation of Signals

This technique is based on a dictionary-based sparse signal representation. As demonstrated in the following Equation (5), the phasor estimator attempts to estimate the phasor of the signal (1), which is often contaminated by the presence of noise, harmonics, and decaying dc components [9].

$$r(t) = Rmsin(2\pi fot + \theta) + \gamma e^{\frac{-t}{\tau}} + N(0, \sigma^2) + \sum_{k=2}^{10} Rk\, sin(2\pi fot + \theta_k) \quad (5)$$

Where γ, t is the magnitude and time constant of decaying dc component, k is the harmonic order, Rk, θ_k are the peak amplitude and phase angle of the harmonic signal, N is a Gaussian noise present in the signal.

The suggested phasor estimate technique is divided into two parts: "Coarse and Fine stages." To get an approximate estimate of a signal's phase angle, the signal's samples are first projected on the components of a primary dictionary matrix (P), then a secondary dictionary matrix (S) is used to fine-tune the predicted phase angle.

The suggested Dictionary-based algorithm's performance and resilience have been effectively tested and confirmed in accordance with the test criteria provided in the IEEE C37.118.1a-2014 standard, as well as on a modified two-area test power system. The hardware findings from an experimental radial power network with a constructed PMU prototype based on the proposed algorithm correctly predicted the phasor under transient conditions with an accuracy of TVE (Total Vector Error) less than 3% using just 10 samples per cycle. The experiment on the performance of the suggested

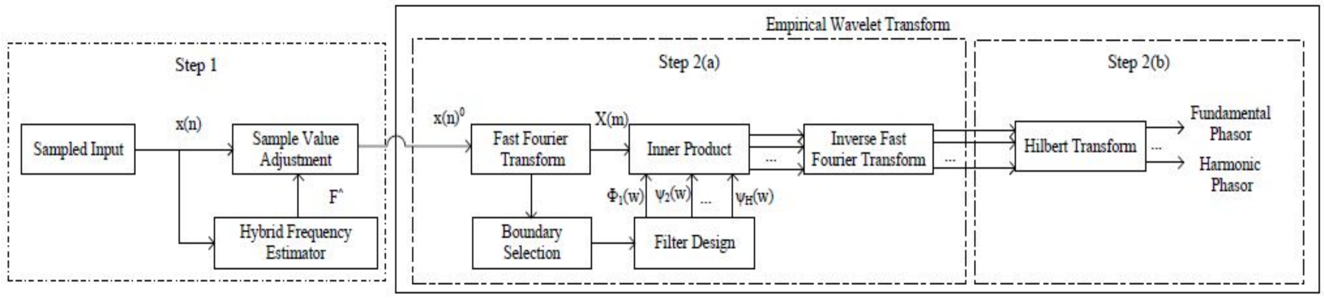


Fig. (1). Structure of proposed D-PMU algorithm.

Table 1. Fast-TFM Algorithm Execution Flow.

INITIALIZATION	
1	Initialize algorithm parameters; N, target SRR (Signal to residual error), zero-padding (fine grid) factor P
2	Pre compute matrix D
3	Set minimum number of interharmonics for peak search
4	Optionally, provide an upper bound on phasor frequency (if lower than 1/2Ts) and/or indicate the maximum number of harmonic components for peak search
FIRST ITERATION	
1	Acquire N waveform samples, forming vector x
2	Apply Hann window, zero pad x to length NP, and compute DFT
3	Locate the fundamental phasor and determine the frequency-dependent threshold
4	Search for local peaks
5	Find TF coefficient, P
6	Determine residue, calculate SRR and check with the target value.
SECOND ITERATION	
1	Apply Hann window, zero pad residue to length NP and compute DFT
2	Determine threshold and search for local peaks
3	Form index set and recompute TF coefficient

estimating approach demonstrates its importance, *i.e.*, minimal complexity, high accuracy, and resilience. Because of these benefits, the suggested technique is appropriate for estimating the phasor corresponding to the basic component using a P-class PMU for protective applications. In terms of cost efficiency, the PMU using the suggested method for phasor estimate might be a solid solution, and it can find applications in monitoring and protecting microgrid or distribution networks integrated with renewable energy sources.

2.4. Enhanced Interpolated Dynamic DFT (e-IpD^2FT)

e-IpD^2FT is a unique synchrophasor estimator designed specifically for distribution networks, where the second harmonic contributes the most uncertainty. The IpD^2FT 's adaptive equivalent filters are utilized to determine optimum frequencies. Because just a few cycles are utilized, the e-IpD^2FT provides a quick reaction and can fulfill P-class response time criteria. Furthermore, its accuracy is great, and it can match the majority of M-class accuracy criteria merely during a three-cycle observation window, even when oscillation, substantial-frequency deviation, and harmonic distortions occur concurrently in a voltage/current signal.

Fig. (**2**) summarizes the steps of the e-IpD^2FT method. To remove second harmonic interferences in frequency deviation circumstances, the fundamental frequency should be determined first, followed by adaptive modification of the three DTFT (Discrete-Time Fourier Transform) frequencies. As a consequence, the estimated fundamental frequency is used not only in the construction of signal models but also in the change of DTFT frequencies. Three rounds were employed to alter the fundamental frequency and hence the DTFT frequencies for great accuracy [10].

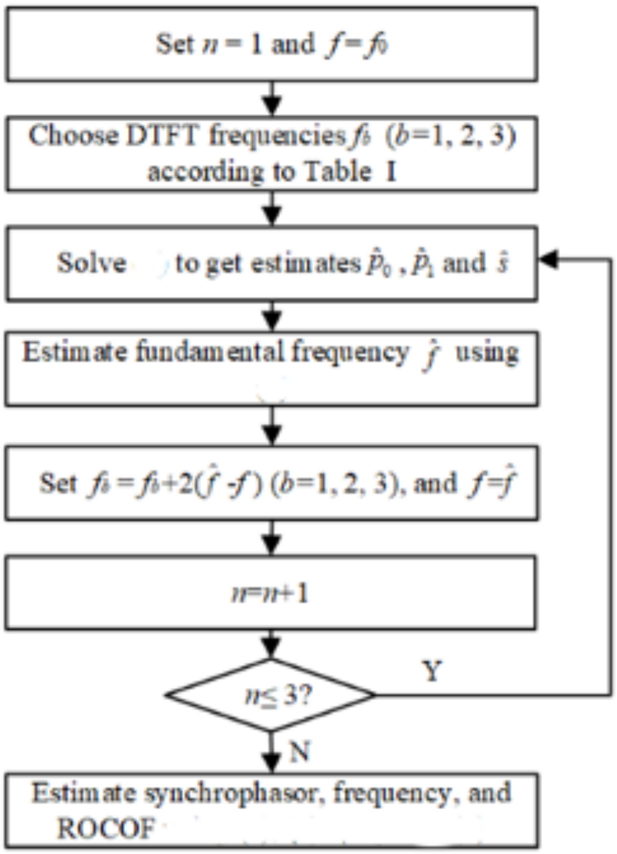


Fig. (2). Steps for implementing the e-IpD^2FT.

2.5. Dynamic Discrete Fourier Transform Based

When the amplitude, frequency, and phase angle of the voltage and current indicate dynamic circumstances, such as low-frequency oscillation, the accuracy of the commercial DFT method declines dramatically [11, 12]. To overcome the issue, the approach uses a dynamic calibration factor to correct the traditional DFT algorithm under fixed interval and high-frequency sampling settings. This technique overcomes the disadvantages of traditional algorithm measurement accuracy rapidly declining in the presence of power supply frequency variation or dynamic measurement. Because the international distribution network waveform data has a high sampling rate, the traditional phasor is used to represent the theoretical phasor, and its value is changed to get the result closer to the theoretical value. The phasor measurement software simulation platform is built in MATLAB/Simulink on the algorithm's principle, providing a simulation environment for researchers to verify the phasor measurement algorithm of the distribution network and the fault location, state estimation, or other advanced applications. The benefit of this approach is its high accuracy and minimal computation; nevertheless, the window function interception length fluctuates, resulting in poor real-time performance.

2.6. Hilbert Transform Plus Interpolated DFT

Synchrophasor estimation is generally performed by means of a spectral analysis algorithm which is based on the DFT. Traditional DFT techniques, on the other hand, suffer from various uncertainties due to the stationarity assumption, spectrum leakage effects, and finite-grid resolution. This Hilbert Transform plus Interpolated DFT technique tackles these constraints by combining the Hilbert transform (HT) and the interpolated DFT (IpDFT) technique. Specifically, the HT suppresses spectral leakage caused by the negative image of the tones being analyzed, whereas the IpDFT decreases the impacts of spectrum granularity and, thus, reduce significantly the window length up to 40 ms. In this way, the algorithm aims at providing high-accuracy estimates of synchrophasor, frequency, and ROCOF (Rate of change of frequency) associated with the fundamental component, as well as minimizing the measurement reporting latency [13].

In greater depth, the algorithm is made up of three phases that must be completed in a specific order. Using the HT, it first computes the analytic signal associated with the acquired waveform. The Hanning weighing function is then used. Finally, the fundamental amplitude, frequency, and beginning phase are estimated using a three-point interpolation approach. As a result, the approach is known as HT-interpolated DFT (IpDFT), and it takes into consideration both leakage suppression and finite resolution correction. Based on the results, the use of HT provides a viable approach for SE since it allows for a relaxation of the reporting latency limitations as well as a reduction in computing complexity. With the exception of harmonic distortion (1%) and phase step testing, an IpDFT-based solution ensures compliance with all IEEE Std standards for both M and P classes [13].

2.7. Improved DFT-Based Phasor Estimation Algorithm Using Down-Sampling

The existence of a fading dc component (ddc) in fault current signals reduces the accuracy of DFT-based approaches. This technique offers an extra signal created by down sampling the fault current to compensate for the adverse effect of ddc. In addition to DFT, the basic phasor is properly approximated using auxiliary signal sample-summation and fault current signal sample-summation. The simulation results suggest that this approach outperforms the previous understudied phasor estimation algorithms in the following ways:

- Faster convergence time,
- Superior performance in the presence of ddc, harmonics, noise, numerous ddc components, and off-nominal frequency situations,
- Less reliance on ddc value;
- Reduced computational complexity.

These advantages make this algorithm appropriate for digital relaying [14].

2.8. Voltage Phasor and Local System Frequency Estimation by Newton Type Algorithms

The topic of voltage phasor and local system frequency estimation was considered an unconstrained optimization problem in this technique. A collection of in voltage samples, given a sinusoidal voltage model, represents a system of m highly nonlinear equations to be solved. The authors developed a very efficient adaptive algorithm capable of estimating the voltage phasor and local system frequency over a wide frequency range by employing Newton's well-known iterative procedure for solving a system of nonlinear equations (in the power engineering practice commonly used in Load-Flow studies). The technique achieved great measurement accuracy throughout a wide frequency range, as demonstrated by computer-simulated and empirically collected data records. Once started, the suggested technique demonstrated strong resilience and excellent dynamic responsiveness. The concept is straightforward and simple to implement with today's hardware technologies. The findings demonstrated that the technique may be a valuable tool in a variety of power engineering applications, such as shaft speed monitoring [15].

2.9. Conditional Maximum Likelihood of Three-Phase Phasor Estimation Method

To solve the phasor parameters in the distribution network, a new approach for simultaneous phasor estimate based on CML (conditional maximum likelihood) is suggested. After identifying the parameter, the maximum likelihood estimated value may be calculated by solving the vector orthogonal to the eigenvector of the parameter covariance matrix. This approach employs the geometric edges and inner angles to calculate the amplitude and phase, decreasing the amount of computation [16].

MSE validates CML performance and tests signals under harmonic, noise, and frequency offset conditions. The findings satisfy the standards of IEEE C37.118, and the approach has a lower computation load for PMU than DFT. The CML technique is dynamically tested, and the impedance of the distribution network model is solved using the CML method's phasor estimate findings. The simulation demonstrates that the impedance estimate performance based on the CML measurement value is met. Because of its numerical stability and estimation precision in a quasi-steady-state situation, the phasor measurement technique may be used for fault identification, state estimation, and other advanced applications in distribution networks. The CML technique can increase phasor estimate precision and balance three-phase effects. Future studies will concentrate on the enhanced application of PMU in distribution networks [16].

2.10. Interpolated Dynamic DFT (IpD^2FT) Synchrophasor Estimator

A discrete Fourier transform (DFT)-based algorithm based on a dynamic phasor model (referred to as the interpolated dynamic DFT-based synchrophasor estimator) is used in this algorithm to estimate not only the amplitude and phase of the collected waveforms but also their frequency and rate of change of frequency (ROCOF) [17].

Several simulation findings indicate that if the synchrophasor Taylor's series is trimmed to the second-order and a suitable MSL window is chosen, the majority of the M-class criteria of IEEE C37.118.1-2011 may be satisfied with four-cycle observation intervals. The major sources of uncertainty impacting synchrophasor parameter estimate accuracy are harmonics (especially second-order harmonics), wideband noise, and out-of-band interferers (frequency and ROCOF estimation are particularly sensitive to these kinds of disturbances). Their effects, however, can be successfully minimized by extending the observation period time. This is especially critical when out-of-band interferers are present. However, this option has a negative impact on 1) responsiveness in the case of rapid amplitude or phase shifts and 2) accuracy when amplitude or phase variations occur [17].

3. PERFORMANCE DISCUSSION

3.1. Computational Complexity

Profiling of execution times for MATLAB 2012b code on a 2.6-GHz Intel Core i7 processor using the Fast TFM algorithm [6] shows that, even with non-optimized code, the average fast-TFM processing time is TP 18 ms for N = 500, up to ten harmonics/interharmonics, and a frequency search range up to 600 Hz. In another study [7] using the EWT algorithm, the approximate number of operations for 4 selective harmonic phasor estimations at off-nominal frequency are 9930 multiplications and 13710 additions. So, it takes a huge number of multipliers and adders. Thus, we can say that with respect to computational complexity, the EWT algorithm is not good as the computational burden is much in this algorithm. The Dictionary-based Dynamic Phasor Estimator (DDPE) [9] can estimate the phasor of a signal in 0.308 ms, but other approaches such as HDPE (Hilbert transform-based dynamic phasor estimator), CDPE (Convolution-based dynamic phasor estimator), SDPE (Shank’s dynamic phasor estimator), and LDPE (Least square approximation based dynamic phasor estimator) take longer.

In a study [10], it is shown that the computation time of the e-IpD^2FT will be longer than the IpD^2FT. Table II lists the major computations of the two approaches. The main computations of the e- IpD^2FT and IpD^2FT are generating matrices ($\mathbf{W}$, $\mathbf{Y}$) and equation (6).

$$\mathrm{WP} \approx \mathrm{Y} \tag{6}$$

Where W is a function related to the derivative order k of raw synchrophasor (with k = 0,1…K); P is a column vector consisting of the raw synchro phasors; Y is a column vector containing the windowed DTFT of x[n] at the three-bin frequencies [10].

Assume the observation window has Nw samples, the iteration number is n, and the Taylor truncation order is K = 2. So, from Table **2**, we can see that the computational efficiency is better in IpD^2FT algorithm.

The response time of the amplitude step test in the Discrete Fourier transform-based Phasor Measurement method [11] is 20 ms, and the response time of the frequency step test is 16 ms, which is substantially faster than the conventional 30 ms, indicating that the algorithm has a rapid reaction speed. The HT-IpDFT algorithm requires 32 multipliers, and 61 adders in accurate type simulations in MATLAB whereas in fast type simulations it requires 12 multipliers and 21 adders [13]. So, this algorithm requires lesser computations which makes it a faster algorithm.

Improved DFT-Based Phasor Estimation Algorithm using Down-Sampling [14] provides lower computational complexity compared to conventional DFT-based approaches

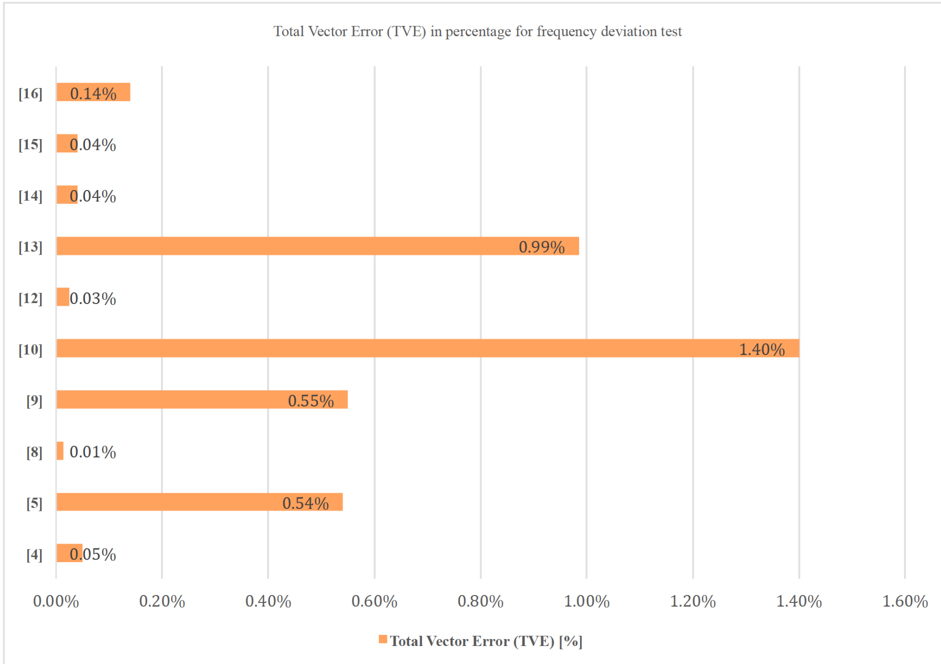


Fig. (3). Total vector error (TVE) in percentage for frequency deviation test. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

Table 2. The computational complexity of the e-IpD^2FT and IpD^2FT. The computation types + and × represent complex addition and multiplication, respectively.

Method	Comp.	Comp. Type		
		+	×	Exp.
e-IpD^2FT	W	6n ($N_w - 1$)	6n N_w	6n N_w
	Y	3n ($N_w - 1$)	3n N_w	3n N_w
	(6)	130n	412n	----
IpD^2FT	W	6n ($N_w - 1$)	6n N_w	6n N_w
	Y	3($N_w - 1$)	3 N_w	3 N_w
	(6)	130n	412n	----

which require more than 12% mathematical operations than this algorithm. For the Newton Type Algorithms, the computations burden-related data was not available [15]. In the Conditional Maximum Likelihood (CML) of the Three-Phase Phasor Estimation method [16], it takes lesser computation than DFT-based approaches but it did not provide the statistical data regarding computation. In Interpolated Dynamic DFT (IpD^2FT) based algorithm [17], the algorithm requires limited computational burden due to its small number iterations and limited matrix size (*i.e.*, 3 × 3) without providing statistical data regarding this algorithm.

Among these algorithms, it can be said that HT-IpDFT based algorithm is one of the computationally efficient algorithms. But due to the data unavailability of some of thealgorithms, it is not possible to decide which is the best computationally efficient algorithm of this type.

3.2. Total Vector Error (TVE)

The total vector errors of the discussed algorithms are given in the following bar chart: TVEs are defined according to the IEEE Std specifications as:

$$\text{TVE} = \frac{\|S - P\|2}{\|P\|2} \tag{7}$$

where S and P represent the estimated phasor and synchrophasor, respectively. The IEEE measurement standard [5] employs total vector error (TVE) to define phasor measurement accuracy, whereas the Chinese standard synchronous phasor measurement device detection specification for power system uses amplitude error and phase angle error [18, 19].

1) Frequency Deviation Test: In the above Fig. (**3**), TVE has been compared according to the frequency deviation test. For this test, steady-state frequency is slightly varied to check its performance at off-nominal frequency. From the chart, we can see that the dictionary-based dynamic DFT phasor estimation DDPE) algorithm provides the best output among the phasor estimation algorithms and the TVE of almost all the algorithms are within the IEEE standard (1%) except the dynamic DFT algorithm.

2) Frequency Ramp Test: Again, according to the frequency ramp test, harmonic distortion test, amplitude test, phase test, and modulation test, a full comparison could not be performed due to data unavailability of several papers.A few studies have performed the frequency ramp test [7, 9, 10, 13, 17]. For the frequency ramp test, the reference signal is used as, x(t) = $R_m$cos (2π f t +π$R_f t^2$), where, R_f is ramp rate in Hz/s, R_m is the nominal magnitude, and f is the off-nominal frequency. The simulation is run for 1s with a ramp rate of 1 Hz/s. A summary of the frequency ramp test of the different algorithms is given in Table **3**.

Table 3. Frequency Ramp test comparison of max TVE values among different phasor estimator algorithms.

Method	Max TVE (%)
EWT [7]	0.04285
DDPE [9]	0.8
e-Ip$\boldsymbol{D}^2$FT [10]	0.0
HT Plus IpDFT [13]	0.05
Ip$\boldsymbol{D}^2$FT [17]	0.0

From the above Table **3**, we can see that a few methods [10, 17] give the best results regarding TVE in the frequency ramp test. Also, all the methods comply with the IEEE Synchrophasor Standard which requires the TVE value below 1%.

3) Harmonic Distortion Test: Another type of test *i.e.*, the Harmonic Distortion test is used to predict the harmonic estimator efficiency. In this test, different harmonics are added to determine the algorithm efficiency in the presence of harmonic distortion. In this case, also, a full comparison could not be made due to the data unavailability of a few papers. In the following Table **4**, the results of TVE for different algorithms are given.

We can see from Table IV that all the methods give the TVE value below 1%. So, they all comply with the IEEE Synchrophasor Standard [4]. Among the methods, another study [7] gives the best results according to this test.

4) Step Change Test: Step change tests *i.e.*, Amplitude Step Change, and Phase Step Change are also done to evaluate the performance of the synchrophasor estimator algorithm. Step mutation primarily replicates voltage and current signal changes induced by a grounding fault, short circuit, or major disturbance in the distribution network. The step test consists mostly of the amplitude step test and the frequency or phase step test, which verify the algorithm's response time in the case of signal mutation. Mainly, it gives the transient performance of the algorithm. According to this test, the comparison among the discussed algorithms is given in Table **5**. Results of some of the algorithms are missing as they did not conduct this test in their works.

Table 4. Harmonic Distortion test comparison of max TVE values among different phasor estimator algorithms.

Method	Max TVE (%)
Fast TFM [6]	0.85
EWT [7]	0.0
DDPE [9]	0.05
e-Ip$\boldsymbol{D}^2$FT [10]	0.09
HT Plus IpDFT [13]	0.01
Ip$\boldsymbol{D}^2$FT [17]	0.05

Table 5. Step Change test comparison of max TVE (%) values among different phasor estimator algorithms.

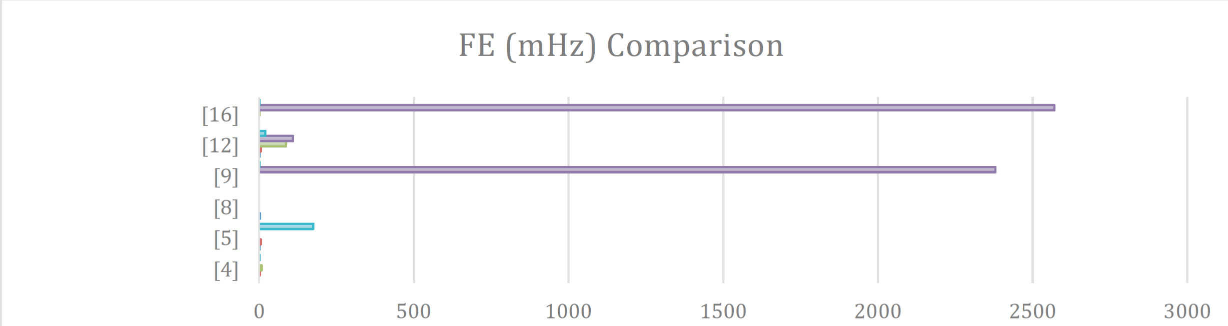
Method	Amplitude Step Change	Phase Step Change
EWT [7]	5	9
DDPE [9]	0.04	0.04
e-Ip$\boldsymbol{D}^2$FT [10]	0.82	1.60
HT Plus IpDFT [13]	10	>10
Ip$\boldsymbol{D}^2$FT [17]	0.82	0.95

According to the IEEE Standard, the max TVE value for this test is 2%. From Table **5**, it is obvious that the TVE values [7, 13] are above the IEEE Standard. Among these methods, a study [9] provides the best performance according to this test.

5) Modulation Test: Another type of test is the Modulation test. Rotor angle oscillations in synchronous machines are caused by strained tie-lines, bulk load fluctuations, alternator outages, and transmission line failures, which can cause power swings in the system. Such voltage fluctuations can cause the protective relays in transmission networks to malfunction, resulting in cascaded outages of lines and system blackouts. In general, power swings may be mathematically expressed as the modulated sinusoidal signal, as shown in the equation below:

$$r5(t) = R_m\,(1 + Kx \sin(2\pi f_m t + \theta)) \times \sin(2\pi f_0 t + Ka \sin(2\pi f_m t) + \theta) \quad (8)$$

where Kx and Ka are the modulated amplitude and phase coefficients respectively, f_m is the modulation frequency,



	[4]	[5]	[8]	[9]	[12]	[16]
Modulation Test	2	175.2		0.02	20.1	0.02
Step Change				2380	110	2570
Harmonic Distortion	8	0		0	86.5	0.01
Fre. Ramp	2.4	5.3		0	5.44	0
Fre. Deviation		0.06	3.6	0	2	0

Fig. (4). FE (mHz) comparison. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

and f_0 is the nominal frequency. A comparison among the discussed according to this test is given in the following:

Table 6. Modulation test comparison of max TVE values among different phasor estimator algorithms.

Method	Max TVE (%)
EWT [7]	0.5443
DDPE [9]	6
e-Ip$\boldsymbol{D}^2$FT [10]	0.03
HT Plus IpDFT [13]	0.93
Ip$\boldsymbol{D}^2$FT [17]	0.01

According to the IEEE Standard, the max TVE value for this test is 3%. From Table **6**, it is obvious that the TVE value [9] is above the IEEE Standard. Among these methods, another study [17] provides the best performance according to this test.

3.3. Frequency Error (FE)

The frequency error (FE) is calculated using the following formula:

$$F = F_1 - F \tag{9}$$

where F_1 and F represent the estimated frequency and frequency associated with the fundamental component, respectively.

1. Frequency Deviation Test: According to the Frequency Deviation test, the frequency error (FE) (mHz) comparison among the algorithms is given in the following Fig. (**4**). From the chart, we can see that a few [10, 17] algorithms provide the best performance among the algorithms according to frequency error (FE) performance. Due to data unavailability o [6, 11, 14, 15], we could not evaluate the performance of these algorithms. The IEEE standard FE value for this test is 5 mHz. It can be observed that all the algorithms maintain the IEEE Standard.

2. Frequency Ramp Test: An FE summary of the frequency ramp test of the different algorithms is given in the following chart. The IEEE Standard FE value for this test is 10 mHz. So, all the FE values of the algorithms are below that. A few studies [10, 17] provide the least FE value among the algorithms so, they have good transient behavior. A comparison of some of the algorithms could be done as they did not conduct this test in their works.

3. Harmonic Distortion Test: According to this test, a few studies [7, 10] provide the best performance. So, they are more reliable in a harmonic frequency environment. The IEEE Standard FE value for this test is 30 mHz. So, from the above chart, it is obvious that another study [13] failed to maintain the IEEE Standard according to this test. Some of the data of other methods are missing as they did not conduct this test in their works.

4. Step Change Test: The IEEE standard FE value for this test is 4500 mHz. So, a few studies [10, 13, 17] maintain the IEEE Standard. Another study [13] provides the least FE according to this test. In this case, also, several data of other methods are missing as they did not provide the results of this test.

5. Modulation Test: The IEEE Standard FE value for this test is 300 mHz. So, all of the algorithms maintain the IEEE Standard. Among the algorithms, two studies [10, 17] give the least FE value.

3.4. Rate of Frequency Error (RFE)

The rate of change of frequency error (RFE), also known as ROCOF, is calculated using the following formula:

$$RFE = \frac{\partial F_1}{\partial t} - \frac{\partial F}{\partial t} \tag{10}$$

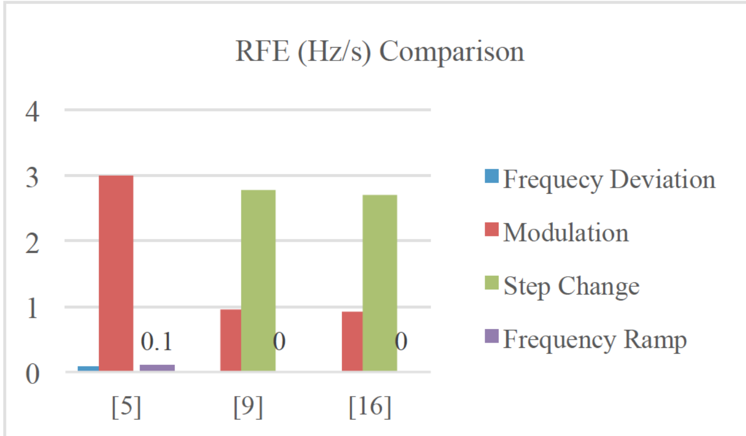


Fig. (5). RFE (Hz/s) comparison. (*A higher resolution / colour version of this figure is available in the electronic copy of the article*).

Where ∂t represents the time change of the frequency error. The RFE values of some of the algorithms have been found. Other algorithms did not provide the results. The results mainly have come from the harmonic distortion test. From Table **7**, we can see that only a few studies [6, 7, 10, 17] provided this data in their works. Among the algorithms, Chauhan *et al.* [7] provide the lowest RFE value in their works. In this case, also, the performance of other methods could not be evaluated due to data unavailability in the paper.

Table 7. Harmonic Distortion test comparison of max RFE (Hz/s) values among different phasor estimator algorithms.

Method	Max RFE (Hz/s)
Fast TFM [6]	6
EWT [7]	0.00
e-Ip$\boldsymbol{D}^2$FT [10]	0.06
Ip$\boldsymbol{D}^2$FT [17]	1.73

Among the algorithms, only a few studies [7, 10, 17] have performed other types of tests like Frequency Deviation Test, Modulation Test, Step change Test, and Frequency Ramp Test. A brief comparison of these tests is given in Fig. (**5**).

All the tests' data are within the IEEE standard. For the Frequency Deviation test, the lowest RFE value is provided in a few studies [7, 10, 17]. For the modulation test, a study [17] gives the lowest RFE value. Then, for the Step Change test, a study [17] offers the best performance. AFinally, for the Frequency Ramp test, both studies [10, 17] display the best performance. So, from the above study, an appropriated algorithm can be selected for a specific application based on the given criteria.

CONCLUSION

A thorough study of the literature from international and national publications reveals that several researchers have already begun work on various estimating methodologies involved in the acquisition of phasor values of data gathered using PMU. These strategies will include PMU smart technology in our current electricity grid. The current study may be described as a review effort that considers PMU as well as phasor measuring methodologies. The phasor estimation techniques [6, 7, 9-11, 13-17] have been briefly discussed. Among the algorithms, e-IpDFT, and DDPE provides the best performance whereas others also provide good performance according to different performance criteria. The advancement of PMU, as well as other constituent parts such as a smart meter, distributed generation, and a communication system (ICT), is required for the current grid to be upgraded to Smart Grid [20].

The current challenges that can be summarized from the review study can be taken up for future research. Future research on phasor estimation techniques can be conducted in the following directions:

1. By raising the sampling rate.
2. Non-uniform sampling can be employed.
3. Other than the ones discussed here, new phasor estimation techniques may be more efficient.

LIST OF ABBREVIATIONS

DMS = Distribution Management System

FFT = Fast Fourier transform

TVE = Total Vector Error

CONSENT FOR PUBLICATION

Not applicable.

FUNDING

None.

CONFLICT OF INTEREST

The authors declare no conflict of interest financial or otherwise.

ACKNOWLEDGEMENTS

Declared none.

REFERENCES

[1] C.I. Chen, "Virtual multifunction power quality analyzer based on adaptive linear neural network", *IEEE Trans. Ind. Electron.,* vol. 59, no. 8, pp. 3321-3329, 2012. http://dx.doi.org/10.1109/TIE.2011.2151811

[2] C.I. Chen and G.W. Chang, "An efficient prony-based solution procedure for tracking of power system voltage variations", *IEEE Trans. Ind. Electron.,* vol. 60, no. 7, pp. 2681-2688, 2013. http://dx.doi.org/10.1109/TIE.2012.2196896

[3] S.M. Kay, *Modern Spectral Estimation: Theory and Application.* Prentice Hall, 1988.

[4] "C37.118.1a-2014 IEEE standard for synchrophasor measurements for power systems - amendment 1: Modification of selected performance requirements", *IEEE Std C37.118.1a-2014 (Amendment to IEEE Std C37.118.1-2011), 30 Apr, 2014,* 2014, pp. 1-25. http://dx.doi.org/10.1109/IEEESTD.2014.6804630

[5] K.E. Martin. "Synchrophasor measurements under the IEEE standard C37. 118.1-2011 with amendment C37. 118.1 a *IEEE Trans. Power Deliv.*, *2 Mar 2015,* vol. 30, no. 3, pp. 1514-22, 2015.

[6] C. Narduzzi, M. Bertocco, G. Frigo, and G. Giorgi, "Fast-TFM - Multifrequency phasor measurement for distribution networks", *IEEE Trans. Instrum. Meas.,* vol. 67, no. 8, pp. 1825-1835, 2018. http://dx.doi.org/10.1109/TIM.2018.2809080

[7] K. Chauhan, M.V. Reddy, and R. Sodhi, "A novel distribution-level phasor estimation algorithm using empirical wavelet transform", *IEEE Trans. Ind. Electron.,* vol. 65, no. 10, pp. 7984-7995, 2018. http://dx.doi.org/10.1109/TIE.2018.2801837

[8] "EN 50160:1999 - Voltage characteristics of electricity supplied by public distribution systems", *European Standard,* 1999. Available from: https://standards.iteh.ai/catalog/standards/clc/f332a3d0-5ddf-40d9-b654-eb6c0dd3f87e/en-50160-1999 (Accessed Feb 11, 2022).

[9] S. Affijulla, and P. Tripathy, "Development of dictionary-based phasor estimator suitable for P-class phasor measurement unit", *IEEE Trans. Instrum. Meas.,* vol. 67, no. 11, pp. 2603-2615, 2018. http://dx.doi.org/10.1109/TIM.2018.2824545

[10] L. Chen, W. Zhao, F. Wang, Q. Wang, and S. Huang, "Enhanced interpolated dynamic DFT synchrophasor estimator considering second harmonic interferences", *Sensors (Basel),* vol. 18, no. 9, pp. 1-18, 2018. http://dx.doi.org/10.3390/s18092748 PMID: 30134587

[11] Z. Zhou, R. Lin, L. Wang, Y. Wang, and H. Li, "Research on discrete fourier transform-based phasor measurement algorithm for distribution network under high frequency sampling", *Energies,* vol. 11, no. 9, 2203, 2018. http://dx.doi.org/10.3390/en11092203

[12] S. Jian, Z. Bing and W. Yun, "Methods for improvement of dynamic performance of PMU", *Power Syst. Prot. Control,* vol. 43, no. 19, pp. 89-94, 2015.

[13] G. Frigo, A. Derviškadić and M. Paolone, "Reduced leakage synchrophasor estimation: Hilbert transform plus interpolated DFT", *IEEE Trans. Instrum. Meas.,* vol. 68, no. 10, pp. 3468-3483, 2019. http://dx.doi.org/10.1109/TIM.2018.2879070

[14] B. Jafarpisheh, S.M. Madani, and S. Jafarpisheh, "Improved DFT-Based phasor estimation algorithm using down-sampling", *IEEE Trans. Power Deliv.,* vol. 33, no. 6, pp. 3242-3245, 2018. http://dx.doi.org/10.1109/TPWRD.2018.2831005

[15] V.V. Terzija, M.B. Djuric and B.D. Kovacevic, "Voltage phasor and local system frequency estimation using newton type algorithm", *IEEE Trans. Power Deliv.,* vol. 9, no. 3, pp. 1368-1374, 1994. http://dx.doi.org/10.1109/61.311162

[16] J. Li, W. Wei, S. Zhang, G. Li, and C. Gu, "Conditional maximum likelihood of three-phase phasor estimation for μpMU in active distribution networks", *Energies,* vol. 11, no. 5, 2018. http://dx.doi.org/10.3390/en11051320

[17] D. Petri, D. Fontanelli, and D. Macii, "A frequency-domain algorithm for dynamic synchrophasor and frequency estimation", *IEEE Trans. Instrum. Meas.,* vol. 63, no. 10, pp. 2330-2340, 2014. http://dx.doi.org/10.1109/TIM.2014.2308996

[18] D.N. Zhang, H. Liu, T.S. Bi, Y.L. Hu, and X.L. Zhang, "Comparison of the PMU static and dynamic standards and evaluation methods between Chinese standards and IEEE", *IEEE Power Syst. Prot. Control.,* vol. 41, pp. 140-145, 2013.

[19] G. Benmouyal, E.P. Schweitzer and A. Guzmán. A China Standard Press, Synchronized phasor measurement in protective relays for protection, control, and analysis of electric power systems", In 57th Annual Conference for Protective Relay Engineers, *1 Apr 2004, 2012*, College Station, TX, USA, 2012, pp. 419-450.

[20] D. Gagwari, and R.S. Bhatia, "A brief analysis of recent developments in smart grid", In *2015 IEEE Int. Conf. Signal Process. Informatics, Commun. Energy Syst. SPICES, 19 Feb 2015,* Kozhikode, India, pp. 1-5, 2015. http://dx.doi.org/10.1109/SPICES.2015.7091529