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Novel PMU Model for Dynamic State Disturbance Analysis with Effective Data Handling System

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ABSTRACT- In this paper a hybrid DFT phasor calculation method is presented. This method is used to calculate the fundamental component phasor value of the harmonic signal without any physical filter. With this method the computational time for each phasor value calculation is reduced and the calculated phasor value has the constant magnitude and rotating phase angle. This calculated phasor values are used for the disturbance or fault identification in the power system based on Total Vector Error (TVE). The %TVE-based fault identification is more effective, because the TVE value is calculated with reference phasor value. If any fault/disturbance occurs or frequency changes then %TVE value changes. This change in TVE value is reflected in the calculation of the next sample (1/f.*N sec), giving the advantage to this method as compared to the other magnitude-based fault identification systems. Normally with the phasor calculation large data is produced, which requires large memory for the storage of this data and makes the analysis difficult. To avoid large data storage system conditional-based data storage system is proposed, where the data is stored during only the disturbance conditions or at every one second. With this technique, the data to be stored is reduced and the analysis of this data also becomes simpler for the post disturbance and for future load prediction. The performance of the proposed method is evaluated in terms of accuracy of calculation and its implementation ability. The simulation results are as per the IEEE C37.118.1a2014 for the power system monitoring and fault identification.

Keywords: Phasor; Recursive DFT; Non-Recursive DFT; Hybrid DFT; Harmonics; TVE; Effective data storage.

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1. INTRODUCTION

In modern days the electrical energy plays very important role. Without electrical energy there is no development in the industries and in day-to-day life. Every day topological changes are coming in the power system to meet the electrical energy generation and load demand, which requires large number of interconnections and long-distance power transmission lines.

In the olden days the generation and load demand were satisfied locally. But, now in the recent years to increase the reliability of the power system large numbers of interconnections are being made and power is transmitted over long distances. To monitor this type of long and large power systems Wide Area Monitoring System (WAMS) is required. In the WAMS technology Phasor Measurement Unit (PMU) plays very important role. Because PMUs produce the phasor values with time synchronization, which are useful for the dynamic state power flow studies and to know state of the system in dynamic state [1]. The commercially available PMUs produce the large data [2], approximately 2GB per day. The storage and analysis of this large data become very difficult. Initially, the PMUs were developed to monitor the power system parameters in the transmission lines [3]. But in the recent years, the PMUs are deployed in the distribution systems also [4]. In the distribution systems, more chances are there for the faults or disturbances, for which, PMUs are useful for their identification [5]. But economic data handling of distribution PMUs is very challenging [6]. Fault identification in the distribution system is very difficult when fault current is low or fault impedance is high [7]. The conventional distance relays cannot identify the high impedance faults due to their pick-up value setting ranges [8]. The problems with the relays to detect the fault condition resulted in the blackout in India on June 30, 2012 and in many other blackouts across the world [9]. To avoid the blackouts' accurate fault identification and classification are required [10]. In most of the cases, the faults are identified based on the impedance calculation [11]. Instead of impedance-based fault calculation, signal analysis methods are better for fault detection and identification [12]. Different signal analysis methods are presented [13] to monitor and detect the faults in the dynamic state. The conventionally available PMUs use the Discrete Fourier Transform (DFT), and Taylor approximation [14] is used for the Phasor calculation. For better accuracy and fast calculation of phasor, a new DFT-based technique is required and the generated data from this also should be stored in an effective way.

This paper presents the introduction and importance of the new phasor measurement technique in the *Section 1*. The signal representation and different calculation methods are presented in the *Section 2*. The new method for the phasor calculation which is suitable for the dynamic state monitoring is presented in the *Section 3*. The effective data storage system and the fault identification are presented in the *Section 4*. *Section 5* presents the conclusion of the work.

2. SIGNAL REPRESENTATION AND PHASOR CALCULATION METHODS

In the real time, any voltage signal can be represented in time domain as:

$$V(t)=V_{1m}\sin(\omega_1 t+\varphi_1)+V_{3m}\sin(\omega_3 t+\varphi_3)+V_{5m}\sin(\omega_5 t+\varphi_5) \quad (1)$$

In the real time the signal may contain harmonics, this harmonic, which may be present due to many factors. But among the entire components, only the fundamental component is useful for the work and the remaining all components will create extra losses in the system or these are not useful for the work. So, for the work done calculation purpose, only the fundamental component need to be considered. Generally, to obtain the fundamental component, different types of active or passive filters are used. Due to ageing effect or improper design of filter components only the fundamental component may not be extracted. For this, in the DFT-based technique, filters are used based on computational technique. A sinusoidal signal represented in time domain (discrete) and frequency domain is shown in *figure 1*.

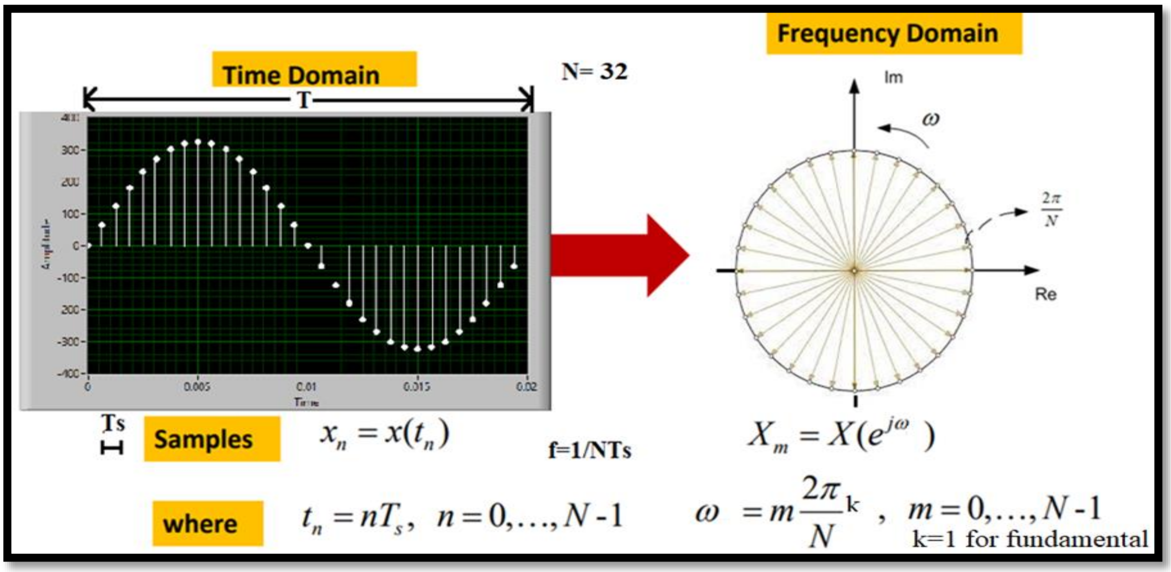

Figure 1: Sampled signal representation in time and frequency domain

The fundamental component extraction from *equation (1)* is

$$V_{real}=\frac{\sqrt{2}}{M}\sum_{n=0}^{(M)-1}\left(V_m\cos\frac{2\pi nk}{M}\right) \quad ...(2)$$

$$V_{imag}=\frac{\sqrt{2}}{M}\sum_{n=0}^{(M)-1}\left(V_m\sin\frac{2\pi nk}{M}\right) \quad ....(3)$$

For the calculation of Fundamental phasor component, different Recursive and Non-Recursive DFT techniques are popularly used.

The Recursive DFT calculates the fundamental component value accurately with less computational time, but it always gives the phasor value with constant magnitude and constant phase angle [15-16]. With constant magnitude and phase angle representation live pictorial representation of the signal is not possible.

The Non-Recursive DFT calculates the fundamental component value accurately and generates the phasor value with constant magnitude and variable phase angle. But it takes more time for each computation [17-18]. Thus, it gives real time visualization of the signal but not suitable for the dynamic state monitoring [19].

3. HYBRID DFT PHASOR CALCULATION WITH LESS COMPUTATIONAL TIME

The real time signal, represented in *equation (1)* in continuous and discrete format, is shown in *figure 1*. For the calculation of the fundamental component phasor value and phase angle in an effective way, the developed flow chart is shown in *figure 2*.

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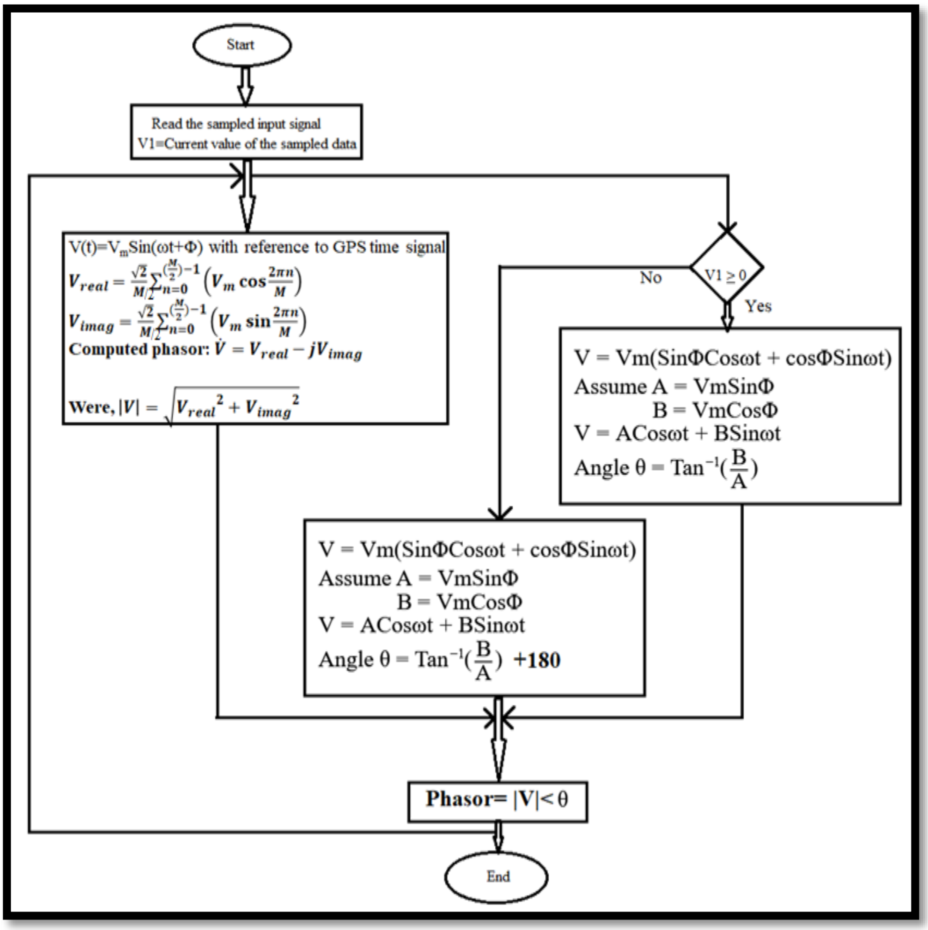

Figure 2: Flow chart of the hybrid DFT technique phasor calculation

From the developed flow chart, the following equations are derived to calculate the fundamental component phasor value with less computational time,

$$V_{real} = \frac{\sqrt{2}}{M/2}\sum_{n=0}^{(\frac{M}{2})-1}\left(V_m \cos\frac{2\pi nk}{M}\right) \quad ...(4)$$

$$V_{imag} = \frac{\sqrt{2}}{M/2}\sum_{n=0}^{(\frac{M}{2})-1}\left(V_m \sin\frac{2\pi nk}{M}\right) \quad ....(5)$$

For fundamental component k=1

Where, $|V| = \sqrt{V_{real}{}^2 + V_{imag}{}^2}$

The fundamental component of equation (1) can be represented as

$V=V_m(\mathrm{Sin}\Phi\mathrm{Cos}\omega t+\mathrm{Cos}\Phi\mathrm{Sin}\omega t)$

Assume $A=V_m\mathrm{Sin}\Phi$; $B=V_m\mathrm{Cos}\Phi$

$V=A\mathrm{Cos}\omega t+B\sin\omega t$

Angle $\theta= \mathrm{Tan}^{-1}(B/A)$

Computed Phasor $|V|<\theta$

The calculated phasor value in the presence of harmonics is shown in *figure 3*.

	Time	Instantaneous Value	Magnitude	Phase angle
	7/25/2022 21:25	0	-	-
	7/25/2022 21:25	63.45697	-	-
	7/25/2022 21:25	124.4753	-	-
	7/25/2022 21:25	180.7102	-	-
	7/25/2022 21:25	230.0004	-	-

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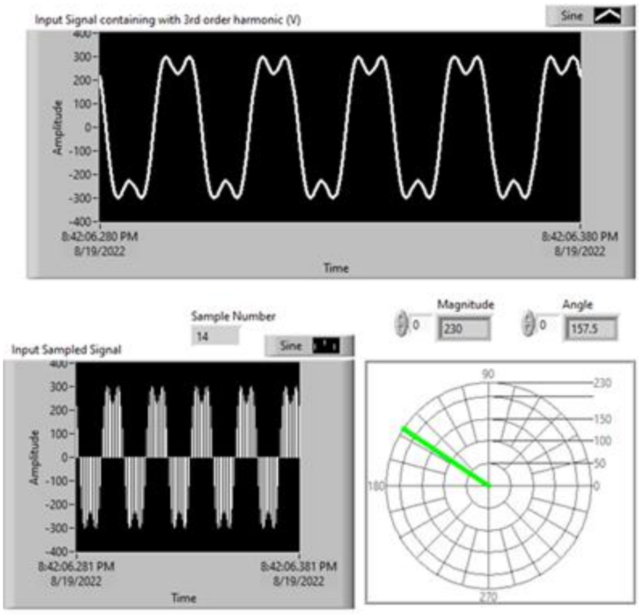

7/25/2022 21:25	270.4519	-	-
7/25/2022 21:25	300.51	-	-
7/25/2022 21:25	319.0197	-	-
7/25/2022 21:25	325.2697	-	-
7/25/2022 21:25	319.0197	-	-
7/25/2022 21:25	300.51	-	-
7/25/2022 21:25	270.4519	-	-
7/25/2022 21:25	230.0004	-	-
7/25/2022 21:25	180.7102	-	-
7/25/2022 21:25	124.4753	-	-
7/25/2022 21:25	63.45697	-	-
7/25/2022 21:25	0	230.0004	180
7/25/2022 21:25	-63.457	230.0004	191.25
7/25/2022 21:25	-124.475	230.0004	202.5
7/25/2022 21:25	-180.71	230.0004	213.75
7/25/2022 21:25	-230	230.0004	225
7/25/2022 21:25	-270.452	230.0004	236.25
7/25/2022 21:25	-300.51	230.0004	247.5
7/25/2022 21:25	-319.02	230.0004	258.75
7/25/2022 21:25	-325.27	230.0004	270
7/25/2022 21:25	-319.02	230.0004	281.25
7/25/2022 21:25	-300.51	230.0004	292.5
7/25/2022 21:25	-270.452	230.0004	303.75
7/25/2022 21:25	-230	230.0004	315
7/25/2022 21:25	-180.71	230.0004	326.25
7/25/2022 21:25	-124.475	230.0004	337.5

Figure 3: Hybrid DFT Phasor Calculation under Harmonics

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The calculated phasor values with different techniques are presented in the *table 1*. In the table it is presented that the time taken for the first phasor calculation and further phasor sample calculation and phasor values.

Table 1: Phasor calculation comparison table

Recursive DFT [21]				Non-Recursive DFT [22]				Hybrid DFT Phasor Calculation			
Date: 8/19/2022 Time	Instantaneous Value	Magnitude	Phase angle	Date: 8/19/2022 Time	Instantaneous Value	Magnitude	Phase angle	Date: 8/19/2022 Time	Instantaneous Value	Magnitude	Phase angle
8:28:16:0006 AM	0	-	-	7:49:13:0006 AM	0	-	-	7:20:08:0006 AM	0	-	-
8:28:16:0012 AM	63.4569	-	-	7:49:13:0012 AM	63.4569	-	-	7:20:08:0012 AM	63.4569	-	-
8:28:16:0018 AM	124.475	-	-	7:49:13:0018 AM	124.475	-	-	7:20:08:0018 AM	124.475	-	-
8:28:16:0025 AM	180.710	-	-	7:49:13:0025 AM	180.710	-	-	7:20:08:0025 AM	180.710	-	-
8:28:16:0031 AM	230.000	-	-	7:49:13:0031 AM	230.000	-	-	7:20:08:0031 AM	230.000	-	-
8:28:16:0037 AM	270.451	-	-	7:49:13:0037 AM	270.451	-	-	7:20:08:0037 AM	270.451	-	-
8:28:16:0043 AM	300.510	-	-	7:49:13:0043 AM	300.510	-	-	7:20:08:0043 AM	300.510	-	-
8:28:16:0050 AM	319.019	-	-	7:49:13:0050 AM	319.019	-	-	7:20:08:0050 AM	319.019	-	-
8:28:16:0056 AM	325.269	-	-	7:49:13:0056 AM	325.269	-	-	7:20:08:0056 AM	325.269	-	-
8:28:16:0062 AM	319.019	-	-	7:49:13:0062 AM	319.019	-	-	7:20:08:0062 AM	319.019	-	-
8:28:16:0068 AM	300.510	-	-	7:49:13:0068 AM	300.510	-	-	7:20:08:0068 AM	300.510	-	-
8:28:16:0075 AM	270.451	-	-	7:49:13:0075 AM	270.451	-	-	7:20:08:0075 AM	270.451	-	-
8:28:16:0081 AM	230.000	-	-	7:49:13:0081 AM	230.000	-	-	7:20:08:0081 AM	230.000	-	-
8:28:16:0087 AM	180.710	-	-	7:49:13:0087 AM	180.710	-	-	7:20:08:0087 AM	180.710	-	-
8:28:16:0093 AM	124.475	-	-	7:49:13:0093 AM	124.475	-	-	7:20:08:0093 AM	124.475	-	-
8:28:16:0100 AM	63.4569	-	-	7:49:13:0100 AM	63.4569	-	-	7:20:08:0100 AM	63.4569	-	-
8:28:16:0106 AM	0	-	-	7:49:13:0106 AM	0	-	-	7:20:08:0106 AM	0	230	180
8:28:16:0112 AM	-63.4569	-	-	7:49:13:0112 AM	-63.4569	-	-	7:20:08:0112 AM	-63.4569	230	191.25
8:28:16:0118 AM	-124.475	-	-	7:49:13:0118 AM	-124.475	-	-	7:20:08:0118 AM	-124.475	230	202.5
8:28:16:0125 AM	-180.710	-	-	7:49:13:0125 AM	-180.710	-	-	7:20:08:0125 AM	-180.710	230	213.75
8:28:16:0131 AM	-230.000	-	-	7:49:13:0131 AM	-230.000	-	-	7:20:08:0131 AM	-230.000	230	225
8:28:16:0137 AM	-270.451	-	-	7:49:13:0137 AM	-270.451	-	-	7:20:08:0137 AM	-270.451	230	236.25
8:28:16:0143 AM	-300.510	-	-	7:49:13:0143 AM	-300.510	-	-	7:20:08:0143 AM	-300.510	230	247.5
8:28:16:0150 AM	-319.019	-	-	7:49:13:0150 AM	-319.019	-	-	7:20:08:0150 AM	-319.019	230	258.75
8:28:16:0156 AM	-325.26	-	-	7:49:13:0156 AM	-325.26	-	-	7:20:08:0156 AM	-325.26	230	270

8:28:16:0162 AM	-319.019	-	-	7:49:13:0162 AM	-319.019	-	-	7:20:08:0162 AM	-319.019	230	281.25
8:28:16:0168 AM	-300.51	-	-	7:49:13:0168 AM	-300.51	-	-	7:20:08:0168 AM	-300.51	230	292.5
8:28:16:0175 AM	-270.451	-	-	7:49:13:0175 AM	-270.451	-	-	7:20:08:0175 AM	-270.451	230	303.75
8:28:16:0181 AM	-230.000	-	-	7:49:13:0181 AM	-230.000	-	-	7:20:08:0181 AM	-230.000	230	315
8:28:16:0187 AM	-180.710	-	-	7:49:13:0187 AM	-180.710	-	-	7:20:08:0187 AM	-180.710	230	326.25
8:28:16:0193 AM	-124.475	-	-	7:49:13:0193 AM	-124.475	-	-	7:20:08:0193 AM	-124.475	230	337.5
8:28:16:0200 AM	-63.4569	-	-	7:49:13:0200 AM	-63.4569	-	-	7:20:08:0200 AM	-63.4569	230	348.75
8:28:16:0206 AM	0	230	-90	7:49:13:0206 AM	0	230	101.25	7:20:08:0206 AM	0	230	0
8:28:16:0212 AM	63.4569	230	-90	7:49:13:0412 AM	63.4569	230	112.5	7:20:08:0212 AM	63.4569	230	11.25
8:28:16:0218 AM	124.475	230	-90	7:49:13:0618 AM	124.475	230	123.75	7:20:08:0218 AM	124.475	230	22.5
8:28:16:0225 AM	180.710	230	-90	7:49:13:0825 AM	180.710	230	135	7:20:08:0225 AM	180.710	230	33.75

From the *table 1* it is identified that the required time for the first phasor value calculation is less. The computation time for each phasor calculation is also less in the proposed method. From this method the obtained phasor values phase is changing with sampling phase angle. It is useful to visualize the signal in real time orientation. But with this sampling rate (1600 samples/sec) large data is produced, which makes the data analysis quite complex.

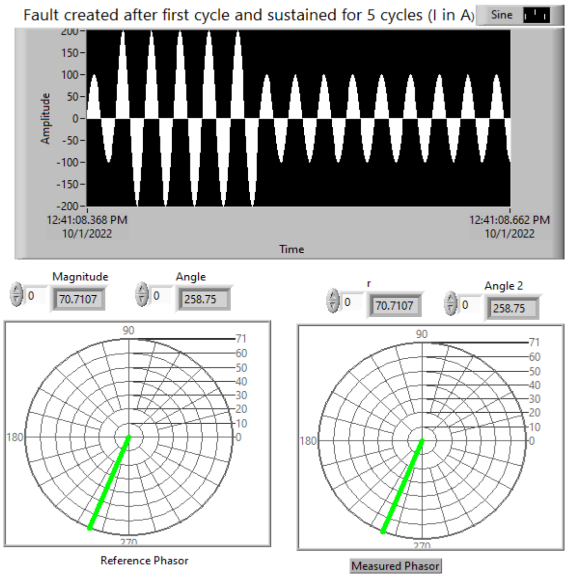
4. FAULT IDENTIFICATION AND EFFECTIVE DATA STORAGE SYSTEM

Due to the less computational time of the phasor value faults can identified with less time. For the analysis purpose the fault is created after one cycle (20 msec). This fault is identified after 1.25 msec from the fault-initiated time. The simulation results are shown in *figure 4*. The fault is calculated based on the Total Vector Error (TVE)

$$\%TVE = \sqrt{\frac{(V_r^e - V_r^a) + (V_i^a - V_i^a)}{(V_r^a)^2 + (V_i^a)^2}} * 100$$

Here, V_r^e, V_i^e are the calculated/estimated phasor real and imaginary values. V_r^a, V_i^a are the real/true phasor real and imaginary values. When the fault/ disturbance occurs, then %TVE is greater than zero. Based on the %TVE calculation (>5%) the fault is identified. With this method the identification of fault condition is more effective [23] than current magnitude or fault impedance-based fault identification. Tue to the fast identification of fault, it is possible to protect the system in the dynamic state without damage of system.

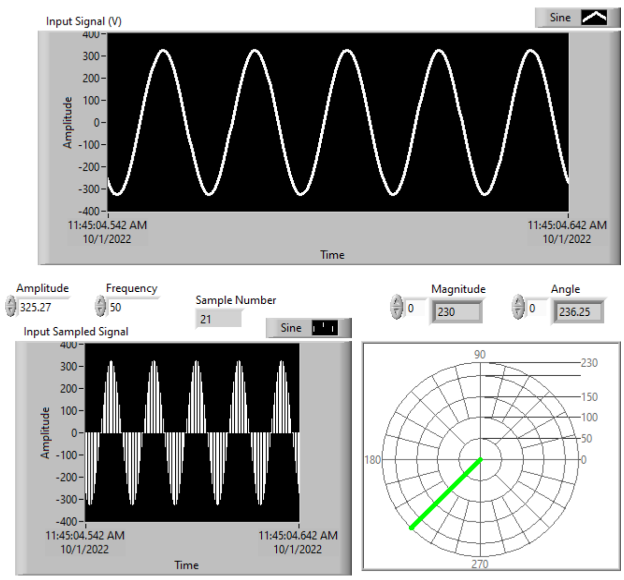
	Time	Instantaneous value	Magnitude	Phase angle	%TVE
	10/1/2022 12:41	0			
	10/1/2022 12:41	19.509032			
	10/1/2022 12:41	38.268343			
	10/1/2022 12:41	55.557023			
	10/1/2022 12:41	70.710678			
	10/1/2022 12:41	83.146961			
	10/1/2022 12:41	92.387953			
	10/1/2022 12:41	98.078528			
	10/1/2022 12:41	100			
	10/1/2022 12:41	98.078528			



10/1/2022 12:41	92.387953			
10/1/2022 12:41	83.146961			
10/1/2022 12:41	70.710678			
10/1/2022 12:41	55.557023			
10/1/2022 12:41	38.268343			
10/1/2022 12:41	19.509032			
10/1/2022 12:41	0	70.710678	180	0
10/1/2022 12:41	-19.509032	70.710678	191.25	0
10/1/2022 12:41	-38.268343	70.710678	202.5	0
10/1/2022 12:41	-55.557023	70.710678	213.75	0
10/1/2022 12:41	-70.710678	70.710678	225	0
10/1/2022 12:41	-83.146961	70.710678	236.25	0
10/1/2022 12:41	-92.387953	70.710678	247.5	0
10/1/2022 12:41	-98.078528	70.710678	258.75	0
10/1/2022 12:41	-100	70.710678	270	0
10/1/2022 12:41	-98.078528	70.710678	281.25	0
10/1/2022 12:41	-92.387953	70.710678	292.5	0
10/1/2022 12:41	-83.146961	70.710678	303.75	0
10/1/2022 12:41	-70.710678	70.710678	315	0
10/1/2022 12:41	-55.557023	70.710678	326.25	0
10/1/2022 12:41	-38.268343	70.710678	337.5	0
10/1/2022 12:41	-19.509032	70.710678	348.75	0
10/1/2022 12:41	0	70.710678	0	0
10/1/2022 12:41	39.018064	70.710678	11.25	0
10/1/2022 12:41	76.536686	71.067213	22.5	2.438629
10/1/2022 12:41	111.114047	72.50165	33.75	7.191069

Figure 4: Fault identification with %TVE value

For the post disturbance analysis purpose only data during disturbance condition (%TVE>1%) is stored. Under normal operating condition all the data is visualized, but only a half cycle data is stored for the future reference for every one second. This data handling is shown in *figure 5*. In the normal operating condition, if total data is stored, then it requires 2GB memory for one hour. But with effective data storage system the required memory is only 200MB for one hour, this is very less as compared to conventional PMU data storage system [24]. Also, the future analysis is simple with this data.



Time	Instantaneous value	Magnitude	Phase angle	Frequency	%TVE
10/1/2022 11:45	0			-	
10/1/2022 11:45	63.456971			50	
10/1/2022 11:45	124.475325			50	
10/1/2022 11:45	180.710163			50	
10/1/2022 11:45	230.000411			50	
10/1/2022 11:45	270.451871			50	
10/1/2022 11:45	300.510018			50	
10/1/2022 11:45	319.019734			50	
10/1/2022 11:45	325.2697			50	
10/1/2022 11:45	319.019734			50	
10/1/2022 11:45	300.510018			50	
10/1/2022 11:45	270.451871			50	
10/1/2022 11:45	230.000411			50	
10/1/2022 11:45	180.710163			50	
10/1/2022 11:45	124.475325			50	
10/1/2022 11:45	63.456971			50	
10/1/2022 11:45	0	230.00	180	50	0
10/1/2022 11:45	270.451871	230.00	56.25	50	0
10/1/2022 11:45	300.510018	230.00	67.5	50	0
10/1/2022 11:45	319.019734	230.00	78.75	50	0
10/1/2022 11:45	325.2697	230.00	90	50	0
10/1/2022 11:45	319.019734	230.00	101.25	50	0
10/1/2022 11:45	300.510018	230.00	112.5	50	0
10/1/2022 11:45	270.451871	230.00	123.75	50	0
10/1/2022 11:45	230.000411	230.00	135	50	0
10/1/2022 11:45	180.710163	230.00	146.25	50	0

	10/1/2022 11:45	124.475325	230.00	157.5	50	0
	10/1/2022 11:45	63.456971	230.00	168.75	50	0
	10/1/2022 11:45	0	230.00	180	50	0

Figure 5: Effective data storage system under healthy operating conditions

5. CONCLUSION

In this paper the phasor values are calculated with the hybrid DFT technique. Using the proposed model, the phasor value of the fundamental component has been calculated accurately even in the presence of voltage variations and harmonics, which satisfies the IEEE C37.118.1a2014 standard for the power system monitoring and fault identification. With the hybrid DFT technique the computational time for each phasor calculation is less (0.625msec), which makes this technique suitable for the dynamic state monitoring of the power system. With the hybrid DFT technique the calculated phasor has the constant magnitude (RMS) value and rotating phase angle, so that it shows the live picture of the power system. The disturbance conditions in the power system are calculated based on the %TVE value. The %TVE based disturbance or fault identification is more effective than current magnitude-based disturbance or fault monitoring. By providing the conditional based data storage system, the required memory for the data storage is reduced to 1/100th of the normal data storage. With the reduced data, analysis is simple for post disturbance analysis or for future load prediction.

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