ANALYSIS OF PHASE ANGLE AND MAGNITUTE OF CURRENT USING DISCRETE FOURIER TRANSFORM ALGORITHM BASED PMU

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Abstract: The use of advanced technologies necessitates sophisticated instrumentation for the operation, control, restoration, and protection of a rapidly expanding electricity system under normal and abnormal conditions. Currently, phasor measurement unit (PMU) applications are widely found in real-time operation, monitoring, controlling, and analysis of power system networks because it eliminates the various limitations of supervisory control and data acquisition system (SCADA) traditionally used in power systems. PMU data is becoming increasingly important for online and offline analysis. Wide area measurement system (WAMS) is a new technology developed by combining multiple PMUs in a power system. The present paper proposes a model of MATLAB based PMU using Discrete Fourier Transform (DFT) algorithm and evaluation of its operation under different contingencies for analysis of current signals magnitude and phase angles of power system. In this paper, PMU based two bus system having WAMS network is presented as a case study.

Keywords: **DFT- Discrete Fourier Transform, PMU-Phasor Measurement System, PDC-Phasor Data Concentrator, GPS-Global Positioning System, WAMS-Wide Area Monitoring System, IEEE Standard C37.118-2005, Synchronization.**

I. INTRODUCTION

Since many years, phasors have been widely used in power systems for analysing alternating quantities under the assumption o f constant frequency [1]. Currently, a new technique known as synchronised phasor measurement is being developed, which empl oys WAMS for various power system applications via PMU [2]. PMUs measure positive sequence voltage and current, allowing direct access to the state of the power system at any time, which is more advantageous than a traditional SCADA system for a vari ety of power system applications [3].

To supply electricity from power plants to consumers, a reliable, efficient, and, most importantly, affordable transmission network is required. If more power is transmitted per line, the problem of grid congestion, system reliability, and cost increases. However, if these issues predominate, they may cause system instability, blackouts or rolling blackouts, communication failure, and other issues. This is not a desirable situation, and because of the cascading effects, a number of power plants will have to be shut down. During the survey of blackouts, the main reasons discovered were the inefficiency of the system and the operator's response capacity in such a situation. As a result, these blackouts could have been avoided, and immunity to cascading could have been increased. [4-5].

WAMS is becoming more popular in today's cutting-edge technologies for upgrading the traditional electric grid. Modernizing the electricity delivery system is critical all over the world. However, various algorithms were developed in the early period for real-time monitoring of power system networks with working frequency evaluation. A synchronised phasor measurement unit (PMU) was introduced for the first time before the 1990s [6]. These PMUs have become the critical data acquisition technology in wide area measurement systems, with numerous applications currently being developed around the world [7] [8].

Phasor technology is a key and advanced technology on the horizon that holds great promise for improving grid reliability, alleviating transmission congestion, and addressing some of the electric industry's operational challenges. WAMS integrates existing SCADA systems by providing high sub-second resolution and global visibility to meet the new emerging need for wide area grid monitoring while continuing to use existing SCADA infrastructure for local monitoring and control. Timing information is critical for real-time continuous estimations of system parameters, which PMU provides at a very high rate (30 samples per second) from accurately captured snapshots of power system behavior at various events [9]. The main advantage of this methodology is that it can measure actual system states and perform without relying on outdated and inaccurate offline studies and comprehensive system models [10].

The intent of this paper is to present a MATLAB based PMU which uses DFT algorithm and to explore its application for analysis of current magnitude and its phase angle during different fault conditions. The MATLAB platform can process simulated power system WAMS based network. It is proposed that this simulated network will present a hands-on understanding for the algorithms and substitution involved in the phasor measurement process. Finally, the proposed PMU performance is verified under different operating scenarios for the analysis of current phase angle and magnitude of power system.

2. Phasor Measurement Unit (PMU)

Synchrophasor measurements, also known as synchronised phasor measurements, convert a voltage or current phasor to an absolute time reference. The global positioning system (GPS) provides this in the form of a common time signal, which is generated at 1 pulse per second (1 pps) by GPS [11]. The phasor angle has no particular significance with an arbitrary time signal, but by collecting all PMU outputs at the same timing reference, the phase angle difference between phasors is obtained, and it provides an invaluable input to monitoring, protection, and control of the power system network [12]. The first PMU prototypes were built at Virginia Tech, and Macrodyne built the first PMU (model 1690) in 1992 [13] using the 1892 phasor measurement technique.

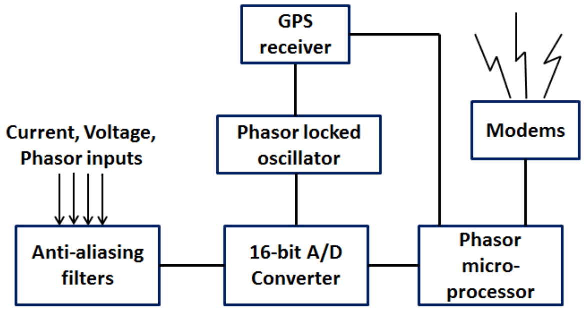

Fig. 2.1 Phasor Measurement Unit (PMU)

Fig. 2.1 depicts the PMU's basic architecture, which includes an anti-aliasing filter, an ADC, a phase locked oscillator, a GPS receiver, a processor, and a modem. All three analogue currents and voltages are obtained in this unit from the secondary of CT and PT transmission lines. The frequency response of the anti-aliasing filters is determined by the sampling rate used in the sampling process. In most cases, less than half the sampling frequency is used to satisfy the Nyquist criterion in all analog-type filters with a cut-off frequency. Using the techniques, the processor calculates positive-sequence components of all current and voltage signals. Whereas frequency and rate of change of frequency are measured locally and can be included in the PMU output.

Finally, the PMU output is a time-stamped measurement that is transferred over communication links via appropriate modems to a higher level in the measurement system hierarchy, such as the PDC, for central monitoring. The IEEE Synchrophasor Standard C37.118-2005 [14] and C37.118-2011 [15] define the requirements for PMU performance. The previous standard only introduced requirements for PMU steady-state performance, but it was later revised to analyze dynamic power system behavior.

3. MATLAB based PMU with DFT algorithm

Discrete Fourier Transform (DFT) is a method of calculating the Fourier transform of a small number of samples taken from an input signal $x(t)$. The Fourier transform is calculated at discrete steps in the frequency domain, just as the input signal is sampled at discrete instants in the time domain [16]. DFT algorithm has been used in phasor measurement unit (PMU) for find out the voltage and current phasor synchronously on real time in the power system. With the help of MATLAB Simulink blocks for find out positive sequence component from the available signals [17][18]. By using DFT algorithm and its relation with Fourier series coefficients gives the phasor representation of the k_{th} harmonics component as follows.
First of all DFT can be described by considering the Pure sinusoidal input signal in the following form :

$$x(t) = X_m \cos(\omega t + \theta) \text{ ....(1)}$$

Where,

ω = frequency of signal (radian per second)
θ = phase angle (radian)
X_m= Peak amplitude of the signal

So, $X_m/\sqrt{2}$ is the RMS value of the signal $x(t)$ and which is helpful to calculate active and reactive power for AC Network.

$$x(t) = Re\left(X_m e^{j(\omega t+\theta)}\right) \text{...........(2)}$$

$$x(t) = \left[\{e^{j\omega t}\} X_m e^{j\theta}\right]$$

From the (2) , avoid the term $e^{j\omega t}$ by considering that the frequency is ω and it can be represented by complex value X in terms of phasor representation.

$$X = X_r + jX_i \text{...........(3)}$$

$$X = (X_m/\sqrt{2})(\cos\theta + j\sin\theta) \text{...........(4)}$$

Now let's take the signal $x(t)$ is sampled N times per period of 50Hz signal to generate the any order of harmonic component is given by,

$$X(k) = \frac{2}{N}\sum_{m=0}^{N-1} x(n)\ e^{-j\,2\pi k\ m/N} \text{ ... ... (5)}$$

Where,
$k = order\ of\ harmonic$
$N = Total\ number\ of\ sample\ per\ window$

$n = n_{th}\ no. of\ smple$

$m = m_{th}\ no. of\ sample = (n-1)_{th}\ no. of\ sample$

$$x\,(n) = \ Discrete\ signal$$

$$\omega = 2\pi f\ \ , f = \left(\frac{1}{T_s\,N}\right), \omega = \frac{2\pi}{T_s N}$$

$$\theta = \frac{2\pi}{NT}\ t\ \ = \ \frac{2\pi\ n}{N}\ \ (where\ t = n\ T)$$

Now, (6) can be expand using (5) and it is rewritten as follow:

$$\mathrm{X\ (k)} = \left[\frac{2}{N}\ \sum_{m=0}^{N-1} x\ (n). \cos\left(\frac{2\pi m}{N}\right)\right] - j\ \left[\frac{2}{N}\ \sum_{m=0}^{N-1} x\ (n). \sin\left(\frac{2\pi m}{N}\right)\right] \text{.........(6)}$$

For the RMS value ,

$$\mathrm{X\ (k)} = \frac{1}{\sqrt{2}}\left[\frac{2}{N}\ \sum_{m=0}^{N-1} x\ (n). \cos\left(\frac{2\pi m}{N}\right)\right] - j\ \left[\frac{2}{N}\ \sum_{m=0}^{N-1} x\ (n). \sin\left(\frac{2\pi m}{N}\right)\right]$$

$$\mathrm{X\ (k)} = \left[\frac{\sqrt{2}}{N}\ \sum_{m=0}^{N-1} x\ (n). \cos\left(\frac{2\pi m}{N}\right)\right] - j\ \left[\frac{\sqrt{2}}{N}\ \sum_{m=0}^{N-1} x\ (n). \sin\left(\frac{2\pi m}{N}\right)\right]\ \text{.......(7)}$$

The RMS value of the phase angle and the amplitude of the voltage or current phasor can be obtained as follows:

$$\text{Phase angle ,}\quad \theta = \ \tan^{-1}\left(\frac{\frac{\sqrt{2}}{N}\ \sum_{m=0}^{N-1} x\ (n). \sin\left(\frac{2\pi m}{N}\right)}{\frac{\sqrt{2}}{N}\ \sum_{m=0}^{N-1} x\ (n). \cos\left(\frac{2\pi m}{N}\right)}\right)\ \ldots..(8)$$

$$RMS\ Amplitude,\ X_{rms} = \ (X_r + X_i)\ /\ 2\ \text{..........(9)}$$

So, (7) gives the fundamental FFT equation to find out the any order harmonic component. PMU can only measure fundamental signals. So take k=1 in the equation 1. Moreover, (6) is the expansion of (5) which gives real and imaginary part of this FFT equation. The (8) gives the angle of measuring signal.

4. TEST SYSTEM, RESULTS AND DISCUSSION

a) Test system

The performance of the overall proposed power system network is investigated through a MATLAB simulation. PMU based 2 bus system represents WAMS network [18]. This system is shown in Fig. 5.1. The PMU functions were programmed in MATLAB Simulink platform. The simulation parameters are shown in Table 1. In this proposed system 11kV Generator is connected with 100kW active load. Transmission line length between two buses is 50km and on each bus PMU is connected. Each PMU is synchronized with GPS and transfers data through communication line.

Table 1. Network Simulation Parameters

Parameter	Value
Voltage Source	11kv
System Frequency	50 Hz
Transmission Line Length	50 km
Fault Timer	[0 0.5]
Fault Resistance	0.001 Ω
RL branch Resistance	0.01 Ω
RL branch Inductance	0.0031 H
Load	100kw
PT ratio	11000/110
CT ratio	1:1
Line Constant	*R0* = 0.01273 Ω (Ω /km); *R1* = 1 0.3864 Ω (Ω /km) *L0* = 0.9337mH (H/Km); *L1* = 4.1264 mH (H/Km) *C0* = 12.74 nF (F/Km); *C1* = 7.751 nF (F/Km)

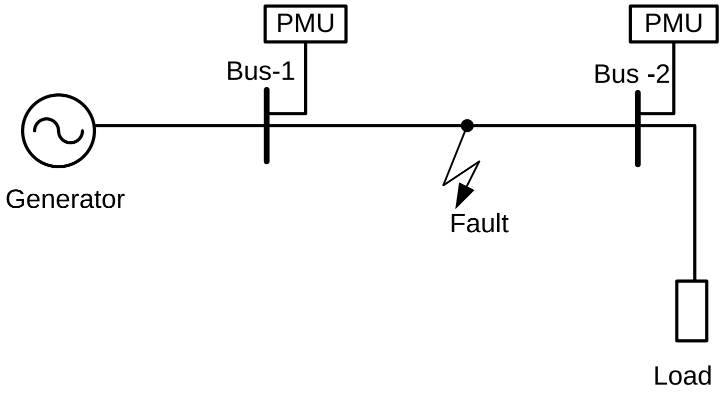

Fig. 4.1 Single Line Diagram of Two Bus Power System Network with PMUs.

In this proposed system, following four contingencies are studied:
1) Current Magnitude and phase angle with reference signal.
2) Current Magnitude and phase angle during single line to Ground fault.
3) Current Magnitude and phase angle during double line to Ground fault.
4) Current Magnitude and phase angle during Three line to Ground fault.

b) Results and Discussion

In the test system, four different contingencies are created to compare the behavior of variation of different parameters.

Case 1: PMU output current phase angle compared with reference signal, SLG fault, DLG fault and TLG fault is shown in figure 4.2 to 4.5.

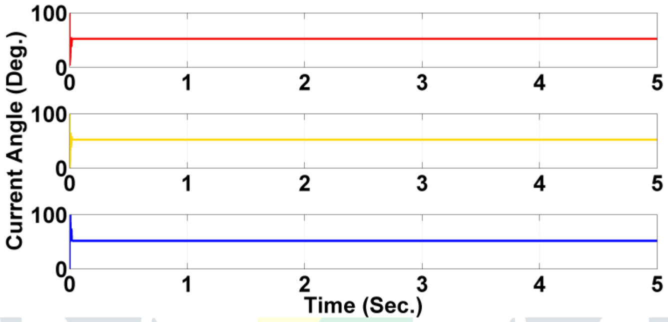

Fig 4.2 Ia,Ib,Ic Current phase angle difference with reference signal without fault.

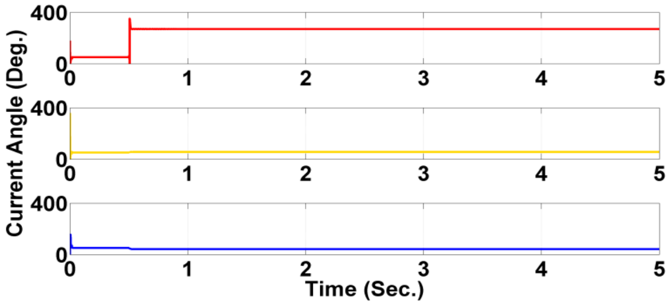

Fig 4.3 Ia,Ib,Ic Current phase angle difference with reference signal during single line to ground fault.

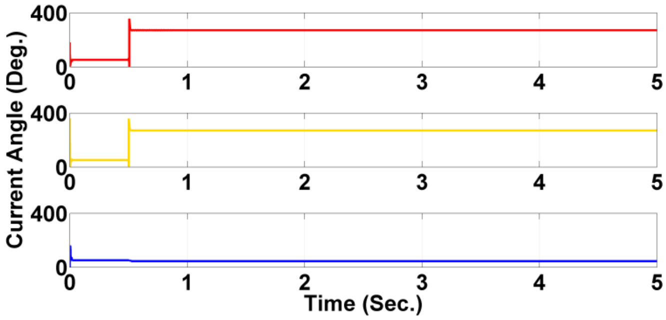

Fig 4.4 Ia,Ib,Ic Current phase angle difference with reference signal during double line to ground fault.

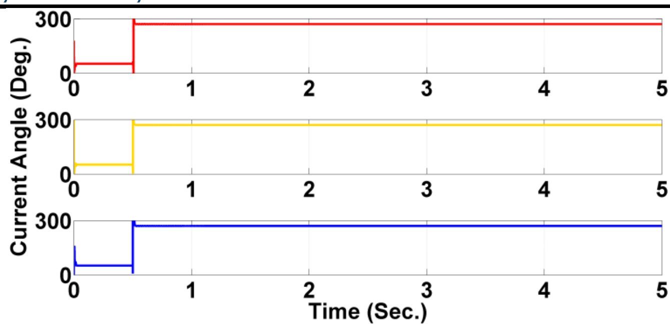

Fig 4.5 Ia,Ib,Ic Current phase angle difference with reference signal during Triple line to ground fault.

From the case study 1, it can be concluded that without fault condition, PMU output current phase angle is perfectly locked with reference signal or almost zero degree phase difference is obtained as shown in figure 4.2. The effect of line to ground fault occurred at 0.5 second can be seen from figure 4.3. Similarly, the effect of double line to ground fault shown in figure 4.4 and triple line to ground fault is shown in figure 4.5 can be observed very easily.

Case 2: PMU output current Magnitude compared with reference signal, SLG fault, DLG fault, and TLG fault is shown in figure 4.6 to 4.9

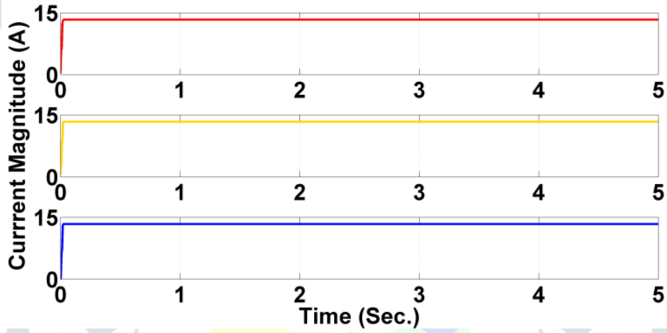

Fig 4.6 Ia,Ib,Ic current magnitude without fault.

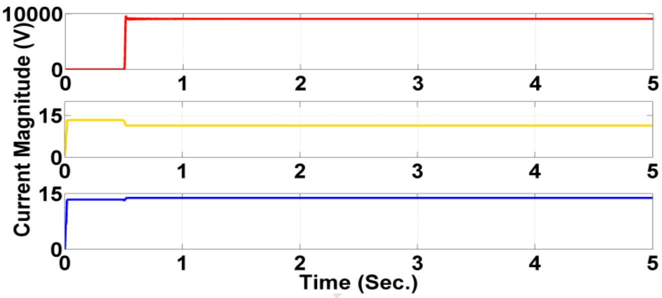

Fig 4.7 Ia,Ib,Ic current magnitude during single line to ground fault.

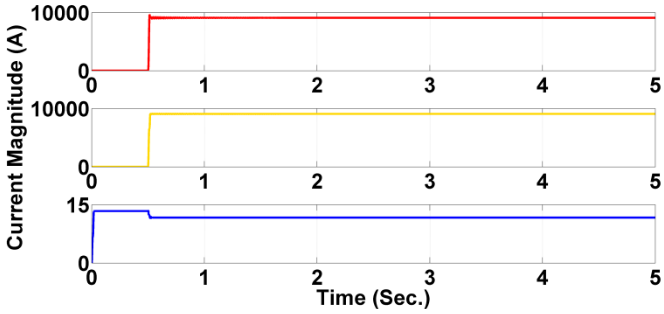

Fig 4.8 Ia,Ib,Ic current magnitude during double line to ground fault.

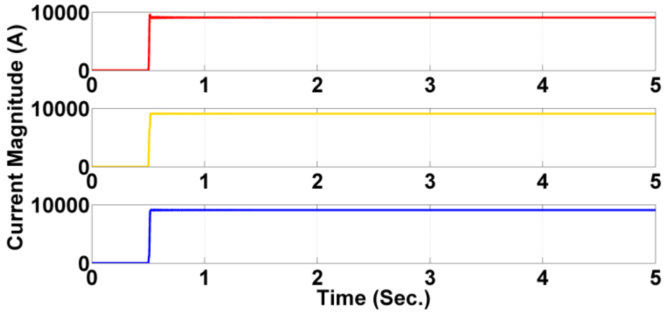

Fig 4.9 Ia,Ib,Ic current magnitude during Triple line to ground fault.

The current magnitude during different contingencies are represented in figure 4.6 to 4.9. Due to single line to ground fault as shown in figure 4.7 the current magnitude of that respective phase becomes thousands of amperes at fault time or at 0.5 second which can be seen. The same results is obtained during double line to ground fault and triple line to ground fault which are shown in figure 4.8 and 4.9 respectively.

5. CONCLUSION

In this Paper, The 11kV source is connected to 100kW load having 50km long transmission line at 50Hz is shown and 30 samples per each cycle for current are taken. Test is carried out for healthy network as well as different fault condition like SLG, DLG and TLG. After this test, current magnitude and their angles are compared with reference signal. After this comparison, it is concluded that DFT based PMU model gives harmonic free fundamental output. The main purpose of this simulation is to explore the function of internal algorithm in the PMU performance under different contingencies. This simulation explores the concept involved in the phasor measurement unit for phasor estimation in wide area measurement system.

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