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Analysis of Effectiveness of Phasor Measurement for Monitoring Electrical grids

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***Abstract*—Power system is now operating under more severe operating conditions than ever before. With more efficient use of transmission lines, the power system may frequently operate near the limit of voltage stability. As a result, there is a high probability that the system will suffer voltage instability or that a voltage collapse may occur. Voltage security is an important subset of power system stability, and has received increasing concerns in research after several well-known blackouts. Therefore, voltage stability analysis is a major concern in power system planning and operation. Phasor Measurement Units (PMUs) by employing satellite technology, offer a state of Wide Area Monitoring System (WAMS) for improving power system monitoring, control and protection.**

***Index Terms*— Phasor Measurement Unit (PMU), Wide Area Monitoring System, Global Positioning System.**

I. INTRODUCTION

Power systems are operating in a more complicated condition and therefore encounter more challenges. If one part of a power grid becomes seriously out of synchronism with the rest, the whole network can become unstable and blackout may occur. In this regard, we need to use advanced and smart monitoring tools to quickly and reliably observe the changing state of the key electrical parameters in real time, take appropriate corrective measures and isolate faults.

Phasor Measurement Units (PMUs) by employing satellite technology, offer a state of Wide Area Monitoring System (WAMS) for improving power system monitoring, control and protection. Wide Area Monitoring System use a GPS satellite signal to time synchronize from phasor measurement units (PMUs) at important nodes in the power system, send real-time phasor (angle and magnitude) data to a Control Centre. The acquired phasor data provides dynamic information on power systems, which helps operators to initiate corrective actions to enhance the power system reliability.

The potential applications of the phasor measurements include real-time power system monitoring, protection and control. The phasors, measured at the same time instant, provide a snapshot of the power system network and by comparing the snapshots of the consecutive time instants, not only the steady state but also the dynamic states of the critical nodes in the network can be tracked.

It is possible to utilize the bus voltages provided by the SCADA measurements. However, the measurements captured by SCADA system are asynchronous, and are processed by a state estimator to give a system-wide picture of the power network. Conventionally, state estimation programs are run at few minutes interval in modern energy management systems. Hence, SCADA measurements are not suitable for on-line assessment of the impending voltage instability. PMUs, on the other hand, can provide synchronized measurements once per cycle of the system frequency, making the computations possible at a faster rate.

PMUs are the main building blocks in the synchrophasor based WAMS. They provide phasor data with faster refreshment rate. The information provided by them, i.e., the voltage and the current phasors, are processed at the Phasor Data Concentrators (PDCs) to extract the relevant information about the system operating condition.

II. PHASORS AND ITS MEASUREMENT

A. PHASOR

A phasor is a vectorial representation of an ac signal with sinusoidal waveform as shown in Fig.1. It is well known that a sinusoid can be written using the equation. [1]

$$X(t)= X_m \cos(\omega t + \varphi) \qquad (1)$$

In the above equation, ω is the angular velocity φ is the initial angle between a reference point and the positive peak. X_m is the peak amplitude of the waveform. The magnitude of phasor equals to the root mean square (RMS) value of the waveform which is ($X_m / \sqrt{2}$).

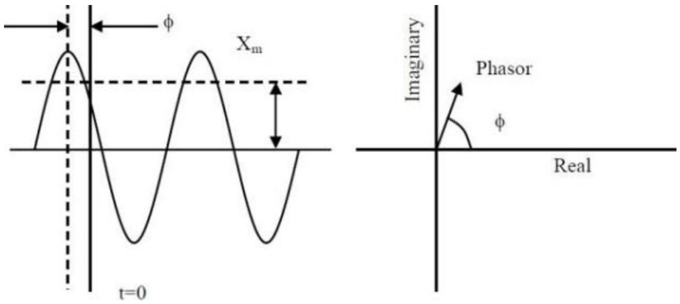

Fig.1 A sinusoid and its phasor representation

B. PHASOR MEASUREMENT UNIT

There is no uniform structure adopted for commercially available PMUs.[2] However, the functional blocks of a typical PMU are generic, and the common components are shown in Fig.2.

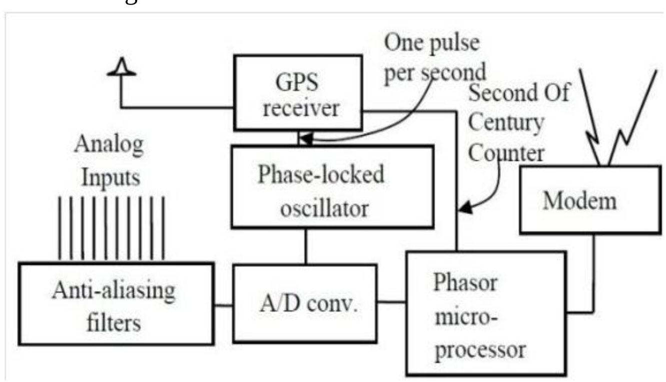

Fig.2. Functional blocks of Typical PMU.

As shown in Fig.2, analogue input signals, which are derived from a scaled signal from voltage and current transformers are initially passed through anti-aliasing filters. A PMU may collect data from different locations in the system on simultaneous basis and normally requires data from all three phases to extract the positive sequence component, which is what is normally of interest and contains information that can be used to assess the state of the power system.

PMUs are synchronized by satellites through a GPS receiver. The time accuracy of such system is typically in the order of a few hundred nanoseconds. Time stamps are created by the GPS receiver as a label of measurement and for future comparison of measurements. The other important function of the GPS receiver is that it can generate a one pulse-per-second signal to a phase-locked oscillator to synchronise and lock the phase of the sampling clock.

Synchrophasors measure voltages and currents at principle intersecting locations (critical substations) on a power grid and can output accurately time-stamped voltage and current phasors. Because these phasors are truly synchronized, synchronized comparison of two quantities is possible, in real time.

C PHASOR NETWORKS

A phasor network consists of phasor measurement units (PMUs) dispersed throughout the electricity system, Phasor Data Concentrators (PDC) to collect the information and a Supervisory Control And Data Acquisition (SCADA) system at the central control facility. Such a network is used in Wide Area Measurement Systems (WAMS). The complete network requires rapid data transfer within the frequency of sampling of the phasor data. GPS time stamping can provide a theoretical accuracy of synchronization better than 1 microsecond. The PDC correlates the data, and controls and monitors the PMUs. At the central control facility, the SCADA system presents system wide data on all generators and substations in the system every 2 to 10 seconds.

III. PHASOR ESTIMATION OF NOMINAL FREQUENCY INPUTS

Consider a constant input signal $x(t)$ at the nominal frequency of the power system $f0$, which is sampled at a sampling frequency $Nf0$. The sampling angle θ is equal to $2\pi/N$, and the phasor estimation is performed.

$x(t)= Xm\cos(2\pi f0t +\varphi)$

The N data samples of this input xn:{$n = 0,1,2,\cdots,N-1$) are

$xn = Xm\cos(n\theta +\varphi)$.

Since the principal interest in phasor measurements is to calculate the fundamental frequency component, we will set $k = 1$ to produce the fundamental frequency phasor obtained from the sample set xn. The superscript ($N-1$) is used to identify the phasor as having the ($N-1$)th sample as the last sample used in the phasor estimation.

$$(Xc)^{N-1} = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} \mathrm{xn}\ \cos(\mathrm{n}\theta)$$

$$= \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} \mathrm{Xm}\cos(\mathrm{n}\theta+\varphi)\cos(\mathrm{n}\theta)$$

$$= \frac{\sqrt{2}}{N} Xm \sum_{n=0}^{N-1}[\cos\varphi\cos 2(\mathrm{n}\theta) - \frac{1}{2}\sin\emptyset\sin(2\mathrm{n}\theta)$$

$$= \frac{Xm}{\sqrt{2}}\cos\emptyset$$

It is to be noted that the summation of the $\sin(2n\theta)$ term over one period is identically equal to zero, and that the average of the $\cos^2(n\theta)$ term over a period is equal to 1/2. The sine sum is calculated in a similar fashion:

$$(Xs)^{N-1} = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} \mathrm{xn}\ \sin(n\theta)$$

$$= \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} \mathrm{Xm}\cos(n\theta + \varphi)\sin(n\theta)$$

$$= \frac{\sqrt{2}}{N} Xm \sum_{n=0}^{N-1} [\frac{1}{2}\cos\emptyset \sin(2n\theta) - \sin\varphi \sin 2(n\theta)$$

$$= - \frac{Xm}{\sqrt{2}} \sin\emptyset$$

The phasor X^{N-1} is given by :

$$X^{N-1} = (Xc)^{N-1} \text{-j } (Xs)^{N-1} = \frac{Xm}{\sqrt{2}} e^{j\emptyset}$$

A. Formulas for updating phasors

Non-recursive updates

Considering that the phasor calculation is a continuous process, it is necessary to consider algorithms which will update the phasor estimate as newer data samples are acquired. When the *N*th sample is acquired after the previous set of samples has led to the phasor estimate given by above equation the simplest procedure would be to repeat the calculations implied in equation for the new data window which begins at $n = 1$ and ends at $n = N$.

$$X^{N-1} = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} \mathrm{x_n}[\cos(n\theta) - \mathrm{j}\sin(n\theta)]$$

$$X^{N-1} = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} \mathrm{x_{n+1}}[\cos(n\theta) - \mathrm{j}\sin(n\theta)]$$

Since the phasor calculations are performed fresh for each window without using any data from the earlier estimates, this algorithm is known as a “non-recursive algorithm”**.** Non-recursive algorithms are numerically stable, but are somewhat wasteful of computation effort.

Recursive Updates

The formulas for calculating the $(N – 1)$th and (N)th phasors by the non-recursive algorithm are:

$$X^{N-1} = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} \mathrm{x_n}\, e^{-jn\theta}$$

$$X^{N-1} = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} \mathrm{x_{n+1}}\, e^{-jn\theta}$$

The multipliers for a given sample are different in the two computations.

It should be noted that samples xn:{n = 1,2,…,N – 1) are common to both windows. The second window has no $x0$, so that it begins with $x1$, and it ends with xN, which did not exist in the first window. If one could arrange to keep the multipliers for the common samples the same in the two windows, one would save considerable computations in calculating XN. If we multiply both sides of the second equation by $e^{-j\theta}$, we obtain the following result:[1]

$$X^N \quad = e^{-jn\theta} X^N = \frac{\sqrt{2}}{N}\sum_{n=0}^{N-1} \mathrm{x_{n+1}}\, e^{-j(n+1)\theta}$$

$$= X^{N+1} + \frac{\sqrt{2}}{N}(\mathrm{x_n} - \mathrm{x_{0)e^{-j(0)\theta}}}$$

Where use has been made of the fact that $e^{-j(0)\theta} = e^{-jN\theta,}$ since N samples span exactly one period of the fundamental frequency. Only a recursive update on the old phasor needs to be made to determine the value of the new phasor. This algorithm is known as the “recursive algorithm” for estimating phasors.

IV. SIMULATION STUDIES

Consider the 60-Hz signal $x(t) = 100 \cos(120\pi t + \pi/4)$ sampled at the rate of 12 samples per cycle, that is, at a sampling frequency of 720 Hz. The non-recursive and recursive phasor estimates obtained beginning with sample no. 12. The phasors obtained by recursive and non-recursive algorithm are shown in fig 3a and 3b respectively. As expected the non-recursive phasor estimate produces a phasor of magnitude 100/√2 with an initial angle of 45 degrees and then for each successive estimate the angle increases by 30 degrees.

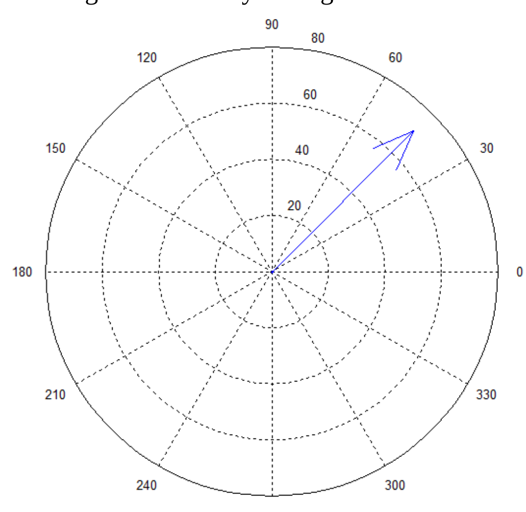

Fig. 3a)Recursive Phasor Estimation

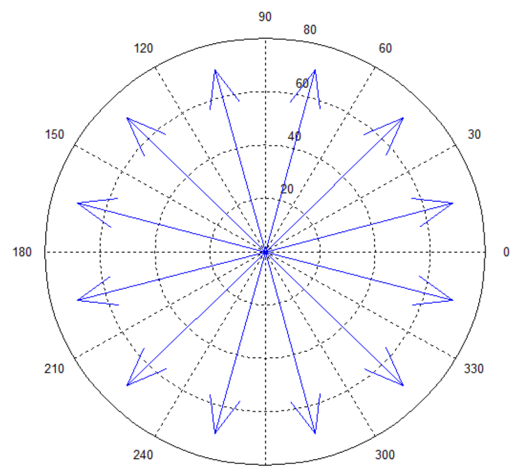

Fig.3b) Non- Recursive Phasor Estimation

For the experimental study a Phasor Measurement Unit is simulated in Matlab/Simulink environment. Figure below shows a three phase system with PMU connected at the source side. In this system 415V,50 Hz three phase source is feeding a three phase R load. PMU is connected at the source side. Since the source and load are balanced PMU measures a three phase balanced load and the phasor obtained is as shown below.

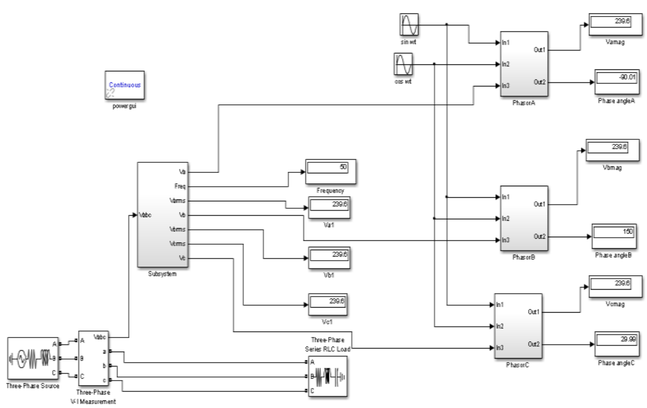

Fig.3. Simulink Model of a three phase system with PMU connected at source side

The output obtained is as shown below:

Phasor A is 239.600000 < -90.000000

Phasor B is 239.600000 < 150.000000

Phasor C is 239.600000 < 30.000000

Frequency is 50.000000 Hz

The phasor obtained is as shown in the compass plot given below:

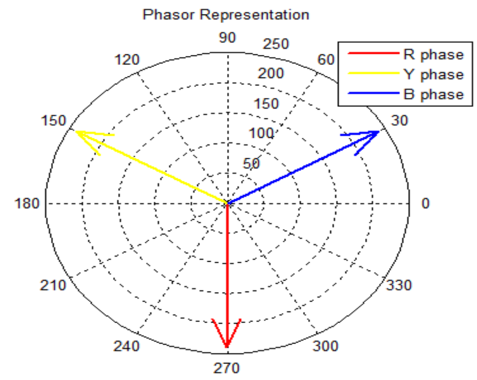

Fig.4. Phasor representation of balanced three phase input.

V.CONCLUSION

From the experimental studies we can conclude that PMU can clearly capture the status of the system behavior. Various algorithms for updating phasor were also considered here. With the help of PMU data, an operator can take early actions to avoid any abnormalities in the system thereby it can increase the reliability of the supply.

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