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PHASOR MEASUREMENT UNITS IN POWER SYSTEM NETWORKS - A REVIEW

Mr. K.S. Chandragupta Mauryan
Assistant Professor,
Sri Krishna College of Technology,
Coimbatore, Tamilnadu, India

Mr. V. Ramkumar
PG scholar,
Sri Krishna College of Technology,
Coimbatore, Tamilnadu, India

***Abstract—* This paper presents a review of the Phasor Measurement Units employed in the Modern Power Systems. Synchronized phasor measurements have advanced the power system monitoring, controlling, protecting and operating standards in the recent decades. Its potential can be used effectively in the process of upgrading the current power grids into smart grids. With these ideas in mind, a review on PMU is presented here describing PMU's historical development, working principle, applications along with a brief note on optimal placement techniques. As all the potentials of PMUs are discussed in this review, it may serve people working in the field of smart grid.**

***Keywords—* Phasor measurement unit (PMU), Symmetrical component distance relay (SCDR), Global positioning system (GPS), Anti-aliasing filter (AAF), Phase locked oscillator (PLO), Symmetrical Component Discrete Fourier Transform (SCDFT).**

I. INTRODUCTION

Phasor is a way of representation of the sinusoidal signals. Its amplitude, frequency and phase angle are time invariant. For example, consider the sinusoidal signal given by,

$$V(t) = X_m \cos(\omega t + \varphi) \quad \_\_\_\_\_\_\_\_\_\_ (1)$$

Where φ is the phase angle, ω is the frequency, and Xm is the peak amplitude of the signal. This pure sinusoidal signal can be represented by a complex number, as shown in fig.1, with its magnitude equal to RMS value($X_m/\sqrt{2}$) of the signal and with its phase angle equal to the phase angle(□) of the signal [1] which is the phasor representation 'X' of the sinusoid signal in (1) is given by,

$$X = (X_m/\sqrt{2})e = (X_m/\sqrt{2})e[\cos\varphi + j\sin\varphi] \quad \_\_\_\_\_\_\_\_\_\_ (2)$$

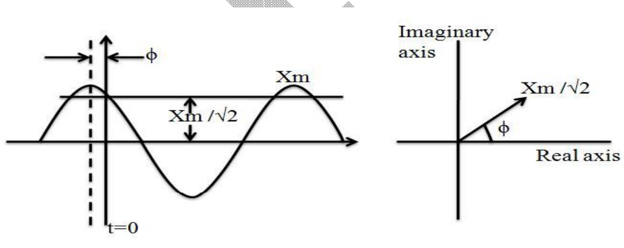

Fig.1 : Phasor representation of sinusoidal signal (a) Sinusoidal signal (b) Phasor representation

It is customary to neglect the ω component in the phasor representation with the understanding that frequency of the signal is constant in that particular representation, leading to the constant phasor representation of the signals. Hence in a single phasor diagram all phasors will be having the same frequency and can be distinguished from each other only by their phase angle and their magnitude. The positive phase angles of the phasors are measured in the counter clockwise direction from the real axis.

In practice a waveform is often corrupted by other signals having different frequency. So in such cases, it is necessary to Extract a single frequency component which is usually the fundamental frequency component and then represent it by a phasors. This extraction is done with 'Fourier Transform' calculation. In sampled data systems, 'Discrete Fourier Transform (DFT)' is used.

This form of representation is extremely useful in Electrical Engineering studies. For instance, Phasors form an efficient method of analyzing the AC circuits when the frequencies are same (but amplitudes need not to be). Because when the frequencies are same then two sinusoidal waveforms can be represented just by two vectors with phase angle difference of $\varphi_d = \varphi_1 - \varphi_2$ in the complex plane. So Power, Voltage, Current and Impedance in the electrical circuits can be represented by phasors and calculations could be made, just by using the magnitude of the phasor and its relative phase angle difference with the other phasor quantities, in a constant frequency system.

It is obvious that the measurement of phasors at different nodes in the Power System forms the crucial part in analyzing the Power System. Phasor Measurement Units (PMU) is the modern technological device built in late 1980's to measure phasors of sinusoidal electrical quantities in the Electric Power Grid. The beauty of this device lies in its synchronized measurement of phasors at multiple remote measurement points in the power grid. Synchronization is achieved by using timing signals from Global positioning system for the

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same-time sampling of Voltage and Current waveforms at different measuring nodes.

II. HISTORICAL DEVELOPMENT

In the mid 1960s, to make the power systems secure, researches were encouraged in the field of power system operation. PMU was one of the effective outcomes initiated by those researches. The important stages in the development of PMU [2] are as follows

2.1 Invention of symmetrical component distance relay(SCDR)

After the initiation of researches, algorithms for computer relaying for the protection of power systems were developed. In the process the symmetrical component distance relay for the protection of high voltage transmission line were invented. In this relay, the relaying algorithm was based upon the measurement of positive, negative and zero sequence voltages and currents at the transmission line terminal. This relay proved to be advantageous, in the fact that to find the fault location for all types of faults in the power system, processing of only one equation is good enough. This led to the development of recursive algorithm know as the Symmetrical Component Discrete Fourier Transform (SCDFT), for calculating the symmetrical components of voltages and current. It necessitated the synchronous measurement of phasors across the power grid. This led to the next stage of development.

2.2 Synchronisation of sampling clock

The sampling clocks used in sampling the voltage and current signals at different remote measuring units were synchronized subsequently. With this synchronization, absolute time of sampling process are recorded which enables the time stamping of the measured data. By aligning the time stamped measured data, we can obtain simultaneous positive sequence measurements. This provides phasor measurements on a common reference axis. With the advent of Global positioning system(GPS), precise synchronization of sampling clocks were made possible with synchronization accuracies of 1µs or even better.

2.3 Development of prototype and commercial PMU

In 1988, Virginia tech research team developed the first prototype PMU. Based on this prototype Macrodyne Co. started manufacturing PMU on a commercial basis with several innovations included in it. A notable development in this regard was the IEEE standard 1344 "Synchrophasor" defining the output data format for the PMUs.

2.4 Field installations

Virginia tech team initially installed its PMU unit in three utilities in U.S namely Bonneville Power Administration, American Electric Power and New York Power Authority which were in the pursuance of the funded research projects. Next series of installations of PMUs were that of macrodyne units when Macrodyne Co. began manufacturing PMUs. Over the years many PMU units were installed world-wide and other manufacturers also began manufacturing PMUs.

2.5 Early application research

Application research were first led by virginia tech and cornell university. Initial applications of PMU were conceived in the field of state estimation. This technology made possible the determination of steady state of power system accurately. PMU also find its application, in using phasors for feedback in control system and in devising adaptive relaying systems. User friendly display for power system operators of the data provided by PMUs was another subject of research. Over these three decades, researches has widen the application prospects of PMU

III. PMU WORKING PRINCIPLE

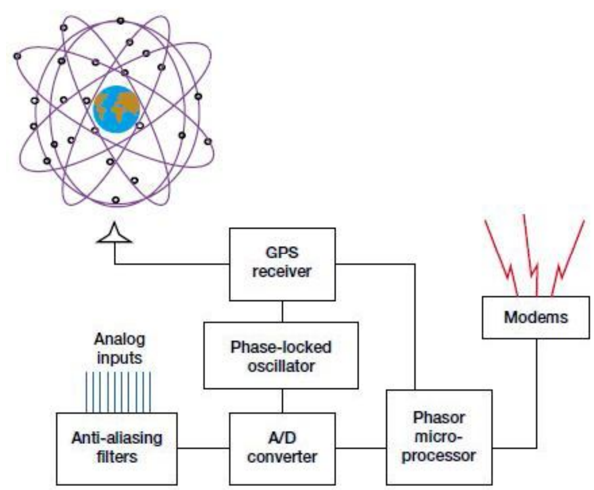

Fig.2 : Basic block diagram of PMU

The Voltages and currents in their analog form are derived from the potential and current transformer secondaries which are then fed to Anti-Aliasing filter. The surge isolation stages have omitted in this block diagram although they must be included in the practical measurement system meeting the IEEE Surge Withstand Capability standard, C37.9 1 [4]

3.1 Anti-aliasing filter

As per Nyquist-Shannon sampling theorem, to reconstruct a signal after sampling, sampling frequency must greater than twice the maximum frequency of the signal to be sampled. If lower sampling rates are used then the original signal's information may not be completely recoverable from the sampled signal and they may appear as aliases. So to avoid this effect, Anti-aliasing filter is used which restricts the bandwidth of the signal to approximately satisfy the sampling theorem, for the fixed sampling frequency of the system. Need for anti-aliasing is discussed in [5],[6] and a patented model of anti-aliasing filter is cited [7].

3.2 GPS

Global positioning system is a satellite based navigation system which gives information about location and time irrespective of weather conditions. It consists of a network of 24 satellites orbiting in 6 geo-synchronous orbits such that at any given instant 4 satellites are visible from any point on the earth surface. All technical details of GPS are reviewed [8].GPS provides accurate information about location and time (could be local time or Universal Time Coordinate) of the GPS receiver's location. Along with it satellite is capable of transmitting common access 'one pulse per second' with an identifier, which is accurate about 1µs at any location on earth. This pulse combined with time-tag is crucial for the application considered here.

3.3 Phase locked oscillator

Usually in PMU, the pulse signals from the satellite are phase locked with the sampling clock. This job is accomplished by phase lock oscillator. The Phase locked oscillator system is analyzed in [9]. PLO divides the one pulse per second signal from GPS into required number of pulses per second for sampling. At present in most systems, this is 12 per cycle of fundamental frequency [4]. The sampling instant could be identified, as the pulse number within one second interval is identified by the GPS time tag.

When the phasors are time tagged then they are referred as synchrophasors. New IEEE Standard C37.118-2005 [10] (In 2011, it was divided into two parts with one describing the standards of phasor measurements and the other describing standards of communication channel) describes the exact format of the time tagging and the measurement of synchrophasors.

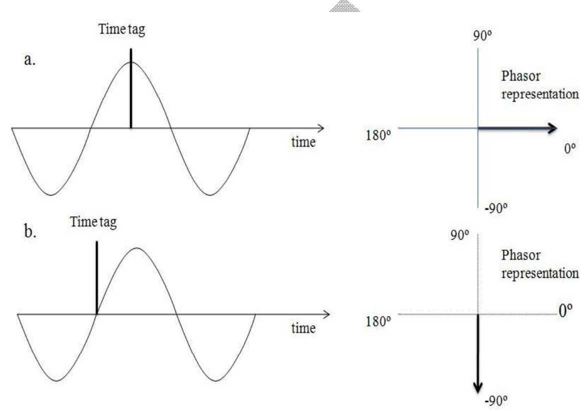

Fig.3 : Synchrophasor definition and angle convention

Using the synchronized clocks as a reference, a PMU creates the phasor representation (complex number) of a constant sinusoidal signal as shown in fig.3. The time tag, representing the reporting instant, forms the reference for the phasor representation of the measured sinusoidal signal. The relationship between the time tag and the phasor representation is such that the phase angle of the phasor is equal to the angular separation between the time tag and the peak of the sinusoid. For instance, in Fig.3.a the peak of the signal coincides with the time tag producing an angle measurement of 0º, whereas in Fig.3.b the signal crosses zero at the time tag producing an angle measurement of -90º as per the synchrophasor standards.

If the phasors are determined with respect to arbitrary time signals the phase angle by itself has no particular significance. So when all PMUs in the power system use the same time reference, their measurements are comparable and the phase angle differences between the phasors are accurate.

3.4 A/D Converter

The Analog to digital converter digitizes the analog signal, from the AAF,at sampling instants defined by the sampling time signals from PLO. These digitized samples are then fed to the phasor microprocessor.

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3.5 Phasor microprocessor

It is programmed to calculate the positive sequence components from the digitized sampled data by using an recursive algorithm which is usually Discrete Fourier Transform (DFT) as described in [11]. This calculated phasor is time-tagged. All the measured data are transmitted to the remote location through a proper communication channel using modems.

3.6 PMU utilization in power system

The phasor measurement units installed at various buses in the power system network provides with a pool of time-tagged phasor measurement data at various nodes in the network. These data are gathered by the device called phasor data concentrator which synchronises the measurement taken at every time instant independent of when the data was received. Then these time synchronized datas are fed to the advanced application software for the analysis of power system. Based on this analysis, system control, protection and various other functions are guided. Phasor data concentrator has been detailed discussed in [12].

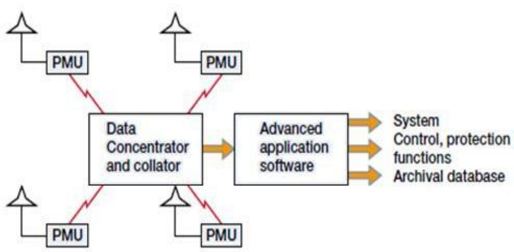

Fig.4 : PMU utilization in power system

IV. OPTIMUM PLACEMENT OF PMU

Observability of the system is necessary for better monitoring, control, operation and protection of the system. In simple context, the system is said to be observable if all the state vectors of the system can be estimated or measured directly or indirectly to the required accuracy. The concept of system observability is defined in two ways [13] namely, Numerical observability and Topological observability. It is obvious, that installing PMU at every bus will prove to be uneconomical. So, Measurements that can used for observability estimation are listed in [13] as of three types namely,

(i) ***Direct measurements:*** They are the voltage and incident current phasor values at the buses where PMUs are located.

(ii) ***pseudo measurements:*** These are the current and voltage phasor values calculated from direct measurement data through ohm's law.

(iii) ***Extended measurement:*** They are the current and voltage phasors which are calculated at the zero injection bus. This extended measurement is defined only in two cases. First,in the case of a bus where all the incident current are known except one. Hence, the unknown current value can be inferred from the kirchoff's law. Second, in the case of a bus where all the incident bus voltages are known, hence the voltage of that bus can be inferred from the kirchoff's law.

Optimal placement of PMUs in the system topology fulfilling the objective of complete observability of the system is necessary. This objective has been a subject of research in many papers[13],[14],[15],[16]. The task of analyzing power system observability is equivalent to the task of building measurement spanning tree. According to the network topology, identified by the system adjacency matrix, pseudo and extended measurements are obtained from the direct measurements. In turn, by using this calculated measurements, new pseudo and extended measurements at adjacent buses or nodes are calculated to we fail to find new measurements.

As a result of this, a measurement spanning tree will be built and if it included all of the buses in the system then the system is said to be observable in the topological sense. Though this technique is basic one, several methods have been adopted in above cited research papers in determining the optimal placement of PMUs in the system for its complete observability such as binary search algorithm, incomplete observablity, observability factor analysis, hybrid genetic algorithm and simulated annealing, to name a few.

V. APPLICATIONS

Phasor measurement unit encompasses high potential to be effectively utilized by the power system utilities to advance the overall existing technology. Considering its accuracy and speed in the measurement of the phasors and other parameters, it will materialize as a fundamental component in smart grids. A survey on its applications is presented below

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5.1 Early applications

During early times at the introduction of commercial PMUs, due to low availability and high cost of communication channels, post-event monitoring were the only application of PMUs. At this stage they were essentially used as digital system disturbance recorders. The frequency and phasor measurement data provided by PMUs showed interesting informations and expanded their application scope in the power system.

5.2 State estimation

Voltage and phase angles at different buses describe the state of the system. Usually in the traditional state estimation, the line flow measurements of real and reactive power were used to estimate the voltage and phase angle at all the buses in the system. In other words, the state of the system was just inferred from the unsynchronized power flow measurement. But with the advent of PMU, 'state measurement' instead of 'state estimation', is made possible. In other words, state of the system is obtained through direct measurements from PMUs rather than estimating from various available data in the system

5.3 Power system protection

Synchronized phasor measurements helps in advancing the power system protection techniques. PMUs enable the early fault detection in the system, allowing for the quick isolation of the faulted segment preventing the power outages. Synchronised phasor measurement provides us with time track of the state variables and several of their derivatives over an observational interval, so it makes simpler to predict the instabilities or outcome of a power swing or transients or any other disturbance using relatively good and simplified models. With these predictions, appropriate protection decisions can be taken by the operator. This leads to the concept of adaptive relaying, where the protection functions changes according to the changing power system conditions. Time tracking and prediction of state variables is picturised in fig.5.

5.4 Power system control

Power system control elements such as Facts devices, generation excitation systems, etc.. uses a local feedback to achieve control objective. But often the control objective is based on remote occurrence. During such operations mathematical model based calculations are used in the control functions. To the extent that the assumed model is not valid under the prevailing conditions, control function may not be effective.

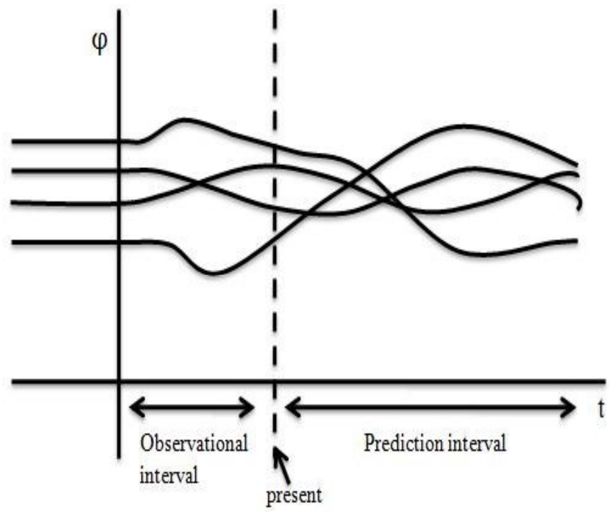

Fig.5 : Time tracking and prediction of state variables

With synchronous phasor measurements, it is possible for direct feedback of system parameters from remote locations to the controllers. Experience shows that improved control performance is achieved with PMUs based controllers, than the model based controllers. Also the frequency data are representative of the transient stability, electromechanical oscillation and certain overload phenomenon, which certainly helps in advanced control of power system.

PMUs enable wide area measurement, protection and control in the whole area of regional transmission networks and local distribution grids. Power quality can be increased by precise analysis and automated correction of power sources based on the feedback from the PMUs. Various applications of PMU are detailed in [17],[18],[19].

VI. RELIABILITY ISSUES WITH PMU

The problems associated with PMUs include clocking system failures and inaccuracies, communication channel problems, instrument transformer problems, filter instabilities and inaccuracies, calibration errors, component failures, software errors, etc.. These problems affect the phasor measurement applications of monitoring, controlling and protecting power system. The reliability of the PMUs must be ensured for its effective application in the power system.

Corresponding Author: Mr. K.S. Chandragupta Mauryan, Sri Krishna College of Technology, Coimbatore, Tamilnadu , India

VII. CONCLUSION

This paper presented a brief review on the phasor measurement unit and its application in the power system. For detailed analysis, appropriate references were cited. Currently, researches are carried out in integrating more functional components into the existing PMU and extend its application capabilities in the power system. Also, a number of pilot projects are being carried out in many countries and utilities to install PMUs and analyze its possible advantages in their existing systems. There is no exaggeration in saying that PMU is one of those technologies which has revolutionized the way of power system operation in the recent decades. PMU proves to be a promising component for the Smart girds for its advanced measurement, monitoring, control, protection, reliability and automated decision supporting objectives. In the coming years, we can witness the extensive use of PMU world over.

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Corresponding Author: Mr. K.S. Chandragupta Mauryan, Sri Krishna College of Technology, Coimbatore, Tamilnadu , India