# SYNCHROPHASOR TECHNIQUE FOR POWER SYSTEM MONITORING

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*Abstract:* **The concept and definition of Synchrophasors dates back to 1980, the combination of 2nd generation IED platforms and power system needs has brought the technology into high visibility in the electric power industry. As synchrophasor technology has matured, nuances of the measurement of a synchronized phasor have been identified and the details of "how" a phasor is defined, synchronized to absolute time, reported, and communicated have subsequently been re-codified in the recently revised IEEE standard: Synchrophasors for Power Systems – C37.118. This paper reviews the concept of the synchronized phasor and its measuring device like phasor measurement unit and its application in power system.**

*Keywords:* **Synchrophasor, Phasor Measurement Unit (PMU), IEEE Standard C37.118-2005, Synchronization.**

## 1. INTRODUCTION

The electric power grid continues to expand and as transmission lines are pushed to their operating limits, the dynamic operation of the power system has become more of a concern and has become more difficult to accurately model. In addition, the ability to effect real-time system control is developing into a need to prevent wide scale cascading outages. For decades, control centers have estimated the "state" of the power system (the positive sequence voltage and angle at each network node) from measurements of the power flows through the power grid. It is very desirable to be able to "measure" the system state directly and/or augment existing estimators with additional information.

Alternating Current (AC) quantities have been analyzed for over 100 years using a construct developed by Charles Proteus Steinmetz in 1893[1] known as a phasor. In the power system, phasors were usedforanalyzing AC quantities assuming a constant frequency. A relatively new variant of this technique that synchronizes the calculation of a phasor to absolute time has been developed [2], which is known as synchronized phasor measurement or synchrophasors. In order to uniformly create and disseminate these synchronized measurements, several aspects of phasor creation had to be codified [3]. The following text spells out the definitions and requirements that have been established for the creation of synchronized phasor measurements.

The earliest modern application involving direct measurement of phase angle differences was reported in three papers in early 1980s. These systems used LORAN-C, GOES satellite transmissions, and the HBG radio transmissions (in Europe) in order to obtain synchronization of reference time at different locations in a power system. The next available positive-going zero-crossing of a phase voltage was used to estimate the local phase angle with respect to the time reference. Using the difference of measured angles on a common reference at two locations, the phase angle difference between voltages at two buses was established. Measurement accuracies achieved in these systems were of the order of 40 μs.

Single-phase voltage angles were measured and, of course no attempt was made to measure the prevailing voltage phasor magnitude. Neither was any account taken of the harmonics contained in the voltage waveform. These methods of measuring phase angle differences are not suitable for generalization for wide-area phasor measurement systems and remain one-of-a-kind systems which are no longer in use.

It was soon recognized that the positive- sequence measurement (a part of the symmetrical component calculation) is of great value in its own right. Positive-sequence voltages of a network constitute the state vector of a power system, and it is of fundamental importance in all of power system analysis. The first paper to identify the importance of positive-sequence voltage and current phasor measurements, and some of the uses of these measurements, was published in 1983 [4], and this last paper can be viewed as the starting point of modern synchronized phasor measurement technology. The Global Positioning System (GPS) [3] was beginning to be fully deployed around that time. It became clear that this system offered the most Effective way of synchronizing power system measurements over great distances. The first prototypes of the modern "phasor measurement units" (PMUs) using GPS were built at Virginia Tech in early 1980s. The prototype PMU units built at Virginia Tech were deployed at a few substations of the Bonneville Power Administration, the American Electric Power Service Corporation, and the New York Power Authority. The first commercial manufacture of PMUs with Virginia Tech collaboration was started by Macrodyne in 1991 [4]. At pre- sent, a number of manufacturers offer PMUs as a commercial product, and deployment of PMUs on power systems is being carried out in earnest in many countries around the world. IEEE published a standard in 1991 [3] governing the format of data files created and transmitted by the PMU. A revised version of the standard was issued in 2005. Concurrently with the development of PMUs as measurement tools, re- search was ongoing on applications of the measurements provided by the PMUs.

## 2. SYNCHROPHASOR DEFIANTION

An AC waveform can be mathematically represented by the equation:

$$\mathrm{Xt} = \mathrm{Xm}\cos(\omega t + \phi)$$

Where,

Xm= magnitude of the sinusoidal waveform

$\omega = 2 * \pi * f$ where f is the instantaneous frequency

$\phi$ =Angular starting point for the waveform

Note that the synchrophasor is referenced to the cosine function. In a phasor notation, this waveform is typically represented as:

$$\bar{X} = X_m \angle \emptyset$$

Since in the synchrophasor definition, correlation with the equivalent RMS quantity is desired, a scale factor of 1/√2 must be applied to the magnitude which results in the phasor representation as:

$$\bar{X} = \frac{X_m}{\sqrt{2}} \angle \emptyset$$

Adding in the absolute time mark, a synchrophasor is defined as the magnitude and angle of a cosine signal as referenced to an absolute point in time as shown in figure 1.

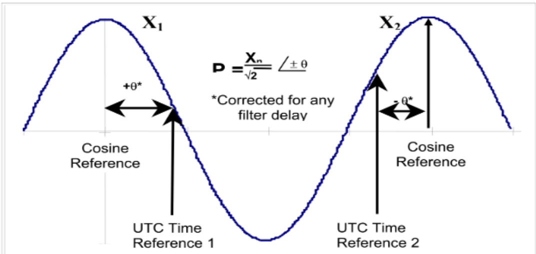


Fig. 1: Details of Synchrophasor

In fig. 1, time strobes are shown as UTC Time Reference 1 and UTC Time Reference 2. At the instant that UTC Time Reference 1 occurs, there is an angle that is shown as "+$\theta$" and, assuming a steady-state sinusoid (i.e. – constant frequency), there is a magnitude of the waveform of X1. Similarly, at UTC Time Reference 2, an angle, with respect to the cosine wave, of "-$\theta$" is measured along with a magnitude or X2. The range of the measured angle is required to be reported in the range of $\pm\pi$ . It should be emphasized that the synchrophasor standard focuses on steady-state signals, that is, a signal where the frequency of the waveform is constant over the period of measurement.

In the real world, the power system seldom operates at exactly the nominal frequency. As such, the calculation of the phase angle $\theta$, needs to consider the frequency of the system at the time of measurement. For example, if the nominal frequency of operating at 59.5Hz on a 60Hz system, the period of the waveform is 16.694ms instead of 16.666ms – a difference of 0.167%.

The captured phasors are to be time tagged based on the time of the UTC Time Reference. The Time Stamp is an 8- byte message consisting of a 4 byte "Second of Century – SOC", a 3-byte Fraction of Second and a 1-byte Time Quality indicator. The SOC time tag counts the number of seconds that have occurred since January 1, 1970, as an unsigned 32-bit Integer. With 32 bits, the SOC counter is good for 136 years or until the year 2106. With 3-bytes for the Fraction of Second, one second can be broken down into 16, 777,216 counts or about 59.6 nsec/count. If such resolution is not desired, the C37.118 standard allows for a user-definable base over which the count will wrap (e.g. – a base of 1,000,000 would tag a phasor to the nearest microsecond). Finally, the Time Quality byte contains information about the status and relative accuracy of the source clock as well as indication of pending leap seconds and the direction (plus or minus). Note that leap seconds (plus or minus) are not included in the 4-byte Second of Century count.

### 2.1 SYNCHRONIZED PHASE REPORTING

The IEEE C37.118 revision of the IEEE 1344 Synchrophasor standard mandates several reporting rates and reporting intervals of synchrophasor reporting. Specifically, the proposed required reporting rates are shown in Table 1 below.

Table:1 Synchrophasor Reporting Rates

| System Freq. | 50Hz | | 60Hz | | | | |
|---|---|---|---|---|---|---|---|
| Reporting Rates: | 10 | 25 | 10 | 12 | 15 | 20 | 30 |

A given reporting rate must evenly divide a one second interval into the specified number of sub-intervals. This is illustrated in figure 2 where the reporting rate is selected as 60 phasors per second (beyond the maximum required value, which is allowed by the standard). The first reporting interval is to be at the Top of Second that is noted as reporting interval "0" in the figure. The Fraction of Second for this reporting interval must be equal to zero. The next reporting interval in the figure, labeled $T_0$, must be reported1/60 of a second after Top of Second – with the Fraction of Second reporting 279,620 counts on a base of 16,777,216

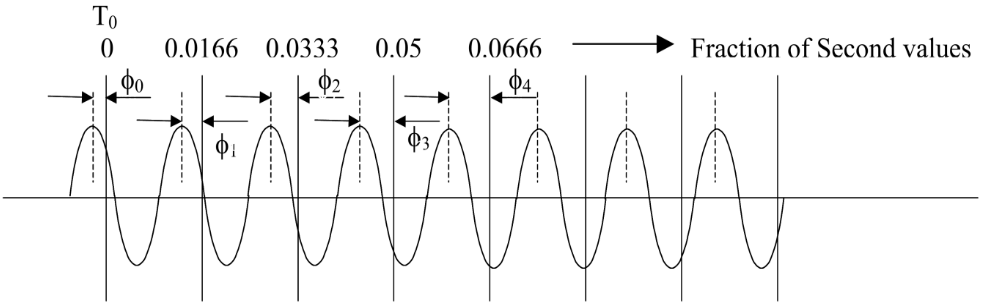


**Figure 2: Synchrophasor definition**

### 2.2. PERFORMANCE CRITERIA

The measurement of a synchrophasor must maintain phase and magnitude accuracy over a range of operating conditions. Accuracy for the synchrophasor is measured by a value termed the Total Vector Error or TVE. TVE is defined as the square root of the difference squared between the real and imaginary parts of the theoretical actual phasor and the estimated phasor – ratioed to the magnitude of the theoretical phasor and presented in percent equation.

$$\varepsilon = \left(\sqrt{\left[\left((X_r(n) - X_r)^2 + (X_i(n) - X_i)^2\right)/\left({X_r}^2 + {X_i}^2\right)\right]}\right) * 100$$

Where: Xr and Xi represent the theoretical exact synchrophasor and Xr(n) and Xi(n) represent the estimated synchrophasor.
In the most demanding level of operation (Level 1), the synchrophasor standard specifies that a Phasor Measurement Unit (PMU) must maintain less that a 1% TVE under conditions of ± 5 Hz off-nominal frequency, 10% Total Harmonic Distortion, and 10% out-of-band influence signal distortion. The next section examines the issues that result from implementation of the phasor measurement using the classical Discrete Fourier Transform.

## 3. THE IEEE STANDARD ON SYNCHROPHASORS

PMUs are becoming among the most useful instruments used in WAMS applied to power networks. They allow the measurement of the synchrophasors defined in [3]. The standard [3] provides the measurement convention to determine accuracy limits and requirements for measurement performance under steady state conditions . In particular the standard considers the UTC as reference time and specifies that the synchronizing source shall have sufficient availability, reliability and accuracy to meet power system requirements.

$a(t) = \sqrt{2}A\cos(2\pi ft + \phi)$ is the complex value given by:

$$A = A \cdot e^{j\emptyset} = A \cdot (\cos\emptyset + j\sin\emptyset)$$

Where, A is the rms value of the signal a(t) and φ is its instantaneous phase angle relative to a cosine function at nominal system frequency synchronized to UTC.

As for the accuracy, [3] defines the TVE as a vectorial difference between the measured and expected value of the phasor, expressed as a fraction of the magnitude of the theoretical phasor.

Considering the synchrophasor representation A=Ar+jAi of the signal a(t), it results:

$$TVE = \sqrt{\frac{(A_r(n) - A_r)^2 + (A_i(n) - A_i)^2}{{A_r}^2 + {A_i}^2}}$$

Where, at the instant of time n of measurement, Ar (n) and Ai (n) are the measured values, given by the measuring device, and Ar and Ai are the theoretical values of the input signal. The standard [3] requires TVE to be maintained below the limit value 1 %. The standard allows for two levels of accuracy compliance: level 1 and level 0. Both call for TVE below 1 %, but level 1 is more stringent by imposing more challenging test reference conditions.

## 4. THE GENERIC PMU

The PMUs manufactured by different manufacturers differ from each other in many important aspects. It is therefore difficult to discuss the PMU hardware configuration in a way which is universally applicable. However, it is possible to discuss a generic PMU, which will capture the essence of its principal components.

Figure 3 is based upon the configuration of the first PMUs built at Virginia Tech. Remember that PMUs evolved out of the development of the “symmetrical component distance relay”. Consequently, the structure shown in Figure 3 parallels that of a computer relay. The analog inputs are currents and voltages obtained from the secondary windings of the current and voltage transformers. All three- phase currents and voltages are used so that positive-sequence measurement can be carried out. In contrast to a relay, a PMU may have currents in several feeders originating in the substation and voltages belonging to various buses in the substation. All elements of the PMU except for the GPS receiver are to be found in computer relays as well.

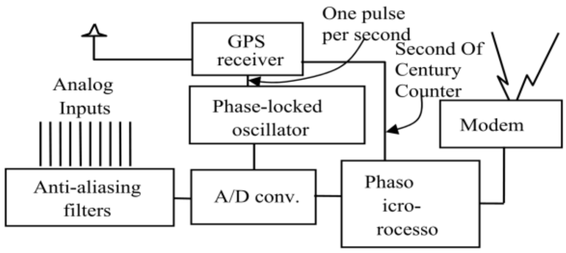


**Fig. 3 Major elements of the modern PMU**

As in many relay designs [5] one may use a high sampling rate (called oversampling) with corresponding high cut-off frequency of the analog anti-aliasing filters. This step is then followed by a digital 'decimation filter' which converts the sampled data to a lower sampling rate, thus providing a 'digital anti-aliasing filter' concatenated with the analog anti-aliasing filters. The advantage of such a scheme is that the effective anti-aliasing filters made up of an analog front end and a digital decimation filter are far more stable as far as aging and temperature variations are concerned. This ensures that all the analog signals have the same phase shift and attenuation, thus assuring that the phase angle differences, and relative magnitudes of the different signals are unchanged.

As an added benefit of the oversampling technique, if there is a possibility of storing raw data from samples of the analog signals, they can be of great utility as high bandwidth "digital fault recorders". The sampling clock is phase-locked with the GPS clock pulse (to be described in the following section). Sampling rates have been going up steadily over the years – starting with a rate of 12 samples per cycle of the nominal power frequency in the first PMUs to as high as 96 or 128 samples per cycle in more modern devices, as faster analog-to-digital converters and microprocessors have become commonplace. Even higher sampling rates are certainly likely in the future leading to more accurate phasor estimates since higher sampling rates do lead to improved estimation accuracy [5].

The microprocessor calculates positive sequence estimates of all the current and voltage signals using the techniques. Certain other estimates of interest are frequency and rate of change of frequency measured locally, and these also are included in the output of the PMU. The timestamp is created from two of the signals derived from the GPS receiver. For the moment, it is sufficient to say that the timestamp identifies the identity of the "universal time coordinated

Finally, the principal output of the PMU is the time-stamped measurement to be transferred over the communication links through suitable modems to a higher level in the measurement system hierarchy.

## 5. THE GLOBAL POSITIONING SYSTEM

The GPS was initiated with the launch of the first Block I satellite in 1978 by US Department of Defense.1 By 1994 the complete constellation of 24 modern satellites was put in place. (In 2007 there are 30 active satellites in orbit, the extra satellites providing for greater accuracy in estimation of spatial coordinates of the receivers. Block I and II satellites have been re- tired.) These are arranged in six orbital planes displaced from each other by 60° and having an inclination of about 55° with respect to the equatorial plane (see Figure 4). The satellites have an orbital radius of 16,500 miles and go around the earth twice for one day. They are so arranged that at least six satellites are visible at most locations on earth, and often as many as 10 satellites may be available for viewing. The most common use of the GPS system is in determining the coordinates of the receiver, al- though for the PMUs the signal which is most important is the one pulse- per-second. This pulse as received by any receiver on earth is coincident with all other received pulses to within 1 microsecond. In practice much better accuracies of synchronization – of the order of a few hundred nano- seconds – have been realized.

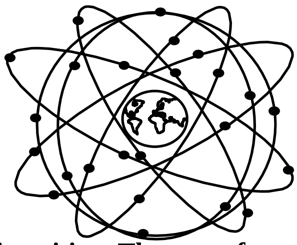

**Fig.4 Representation of the GPS satellite disposition. There are four satellites in each of the six orbits, which orbit around the earth with a period of half a day**.

The GPS satellites keep accurate clocks which provide the one pulse per second signal. The time they keep is known as the GPS time which does not consider the earth's rotation. Corrections to the GPS time are made in the GPS receivers to account for this difference (leap-second correction) so that the receivers provide UTC clock time. The identity of the pulse is defined by the number of seconds since the time that the clocks began to count (January 6, 1980). It should be noted that the PMU standard uses UNIX time base with a "second-of-century" (SOC) counter which began counting at midnight on January 1, 1970. At present there are a number of GPS-like systems being deployed by other nations, with similar goals. It is expected that the GPS system will remain the principal source of synchronization for PMUs for the foresee- able future.

## 6. FUNCTIONAL REQUIREMENTS OF PMUS AND PDCS

**The evolution of "Synchrophasor" standard:**

In order to achieve interoperability among PMUs made by different manufacturers, it is essential that all PMUs perform to a common standard. Reference [6] is the current IEEE standard which defines requirements for compliance.

A short account of the development of this standard may be of interest. The "Synchrophasor" standard was first issued in 1995 [7]. PMUs of early manufacture based on this standard were tested for interoperability, and it was discovered that their performance at off-nominal frequencies was not identical [8]. From the point of interoperability of equipment, this was not acceptable. It was soon recognized that the then existing standard [8] was not very clear on the topic of performance requirements for PMUs at off-nominal frequencies. A working group of the Power System Relaying Committee of IEEE undertook the revision of the standard, and the result is the current standard [3] which clarified the requirements for PMU response to off-nominal frequency inputs. The requirements for off- nominal frequencies can be explained with the help of Figure 5. The definition of a phasor is independent of its frequency; thus, if the input signals connected to the PMU are pure sinusoids of any frequency and the phasor estimate is reported at the time-tag as shown in Figure 5 the output phasor must have a magnitude equal to the rms value of the signal, and its phase angle must be θ, the angle between the reporting instant and the peak of the sinusoid. Note that the PMUs in general contain a number of filters at the input stage.

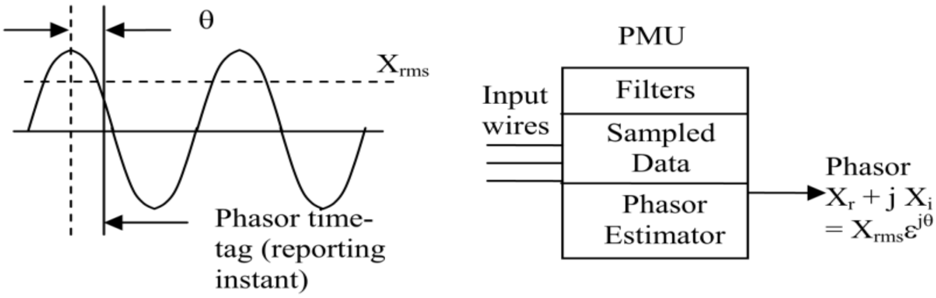


**Fig. 5 PMU performance requirements for input signals of any frequency. (a) Input signal connected to the PMU terminals, and (b) the required output phasor estimate.**

The phase delays caused by these filters must be compensated for before the phasor estimate is re- ported. Also, whether the input is balanced or unbalanced, the positive sequence provided by the PMU must be correct at all frequencies. As a practical matter, the PMU Standard calls for this specification to hold over a frequency deviation of ± 5 Hz from the nominal frequency. Other new features of the standard specify the measurement accuracy requirements for two classes of PMUs, and a standardized reporting time for phasors which is phase-locked to the GPS 1 pps, and is at intervals which are multiples of nominal power frequency periods. It is also important to note that the standard does not specify the requirements for response of PMUs to power system transients. No doubt this will be covered in forthcoming revisions of the standard

**File structure of 'Synchrophasor' standard:**

The file structure for "Synchrophasors" is like that of COMTRADE [9], which defines files for transient data collection and dissemination. COMTRADE standard has been adapted by International Electrotechnical Commission (IEC) and is now the principal international file format stan- dard being used by computer relays, digital fault recorders, and other producers and users of power system transient data. Synchrophasor standard defines four file types for data transmission to and from PMUs. Three files are generated by PMUs: Header files, Con- figuration files, and Data files. One file, the "Command File", is for communicating with the PMUs from a higher level of the hierarchy – such as a PDC. All files have a common structure as shown in Figure 6. The first word of 2 bytes is for synchronization of the data transfer. The second word defines the size of the total record, the third word identifies the data originator uniquely, and the next two words provide the "second of century" (SOC) and the "fraction of a second" (FRACSEC) at which the data is being reported. The length of the Data words which follow FRACSEC de- pends upon the specifications provided in the Configuration file. The last word is the check sum to help determine any errors in data transmission.

The Header file is a human readable file, with pertinent information which the producer of data may wish to share with the user of the data. The Configuration and Data files are machine readable files with fixed formats. Configuration file provides information about the interpretation of the data contained in the data files. In practice the Header and Configuration files are sent by the PMU when the nature of the data being transferred is defined for the first time.

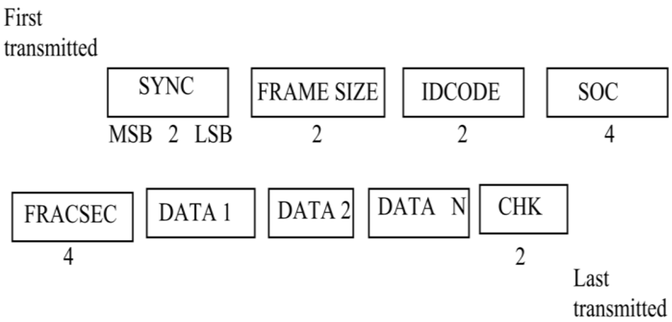

**Fig. 6 Format for files transmitted from and to PMUs. The numbers below the boxes indicate length of the word in bytes.**

The data files contain phasor data (and certain other related measurements such as frequency and rate of change of frequency) which is the principal output of the PMUs. Phasor data may be communicated in rectangular or polar form. Command files are used by higher levels of the hierarchy for controlling the performance of the PMUs. Several commands have been defined and are available at this time, with several reserved codes for commands which may be needed in the future. Finally, it must be mentioned that this summary of the "Synchro- phasor" standard is meant to give the reader an idea of how the standard evolved to its present form, and the general structures of its files. One must go to the Standard document for additional details of the file structure and definitions.

**PDC file**

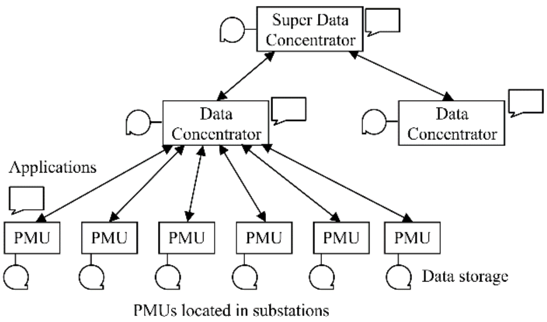


**Fig. 7 Hierarchy of the phasor measurement system and levels of phasor data concentrators.**

The PDC and the super PDC (SPDC) of Figure 7 are important elements of the overall PMU system organization. Their principal functions are to collate data from different PMUs with identical time-tags, to create archival files of data for future retrieval and use, and to make data stream avail- able to application tasks with appropriate speed and latency. Yet there are no industry standards for the PDC data files. However, it is generally understood that PDCs will have file structures similar to those of PMUs. There are not commercially available PDCs at this time. Most existing PDCs have been custom built by researchers or manufacturers of PMUs. As wider implementation of PMU technology takes place, the industry will no doubt work toward creating standards for these important components of the overall PMU infrastructure.

## 7. APPLICATIONS OF SYNCHROPHASORS

Following are a number of applications that demonstrate how synchrophasors may be used to improve system operation. Ap- plications may be implemented to address localized or system- wide issues.

### 7.1. State Estimation

State estimation is a process that determines the state of the power system to allow the system operator to make better decisions aimed at maintaining power system security in the face of various contingencies. Improvement in the accuracy of the state estimation of the power system network is one of the most im- mediate benefits of PMU application.

The state estimation technology currently in use evolved in the 1960s. It uses measurements that do not require a common reference: power system active power and reactive power flow measurements, voltage magnitude, etc., collected over a fairly long interval, to estimate the power system state. The process combines the measurements with the network model to find the variables of interest by solving nonlinear equations by numerical iterations. The process may take several minutes or longer to converge to a solution, is prone to errors in the network parameters, and often diverges during those evolving disturbances when a good state estimation is needed most. The industry is constantly developing methods to improve state estimation accuracy.

The application of a sufficient number of time-tag synchronized PMUs across the system will improve state estimation solutions to the point that the process becomes one of state measurement. Consider the placement of PMUs at busses G, J and S on the power system shown in Figure 8.

The PMU at bus S measures the voltage phasor (amplitude and angle), and current phasors and having these phasor quantities and an accurate system model, the voltage phasors at the remote busses M, P, R, and T can be directly calculated with linear equations ("indirectly measured"). These buses are therefore defined as "observable" to bus S, the PMU location. Similarly, the placement of PMUs at busses J and G define regions X and Y where the state is accurately measured either directly or indirectly. The remaining buses E, N, L and Q are not considered "measurable" with the current PMU placement. The number of adjacent busses that are not measurable (directly or via calculations with linear equations) defines the "depth of non-observability" for a system with partial PMU coverage. It is optimum to place the PMUs in such a way to maintain a uniform depth of "non observability." For this configuration the depth of non-observability is one and state voltage and current quantities at the unobservable busses can be estimated by linear interpolation with reasonable accuracy.

Power system state-vector determination from PMU measurements offer the most precise method yet for obtaining real- time static and dynamic information about the condition of the network [10].

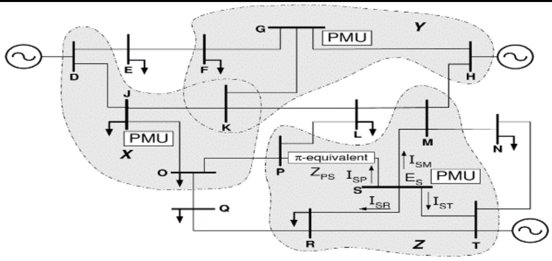


**Figure 8: PMU coverage of the power system network**.

### 7.2. Line Parameter Calculation

PMUs deployed at both ends of a transmission line and measuring both currents and voltages facilitate online tracking (measurement) of line parameters. Performed continuously, such measurement accounts for seasonal and temperature changes. With enough natural unbalance, or when performed during faults, the measurement will yield not only the positive-sequence impedance, but negative- and zero-sequence impedance as well.

More sophisticated line models can also be applied with the synchronized measurements so that the voltage profile across the line may be determined [11].

Direct measurement of line impedances allows detecting errors in databases used by short circuit, state estimation and other application packages, as well as improved fault location accuracy.

### 7.3. Transmission Line Thermal Monitoring

Loading of transmission lines is often constrained by thermal limits rather than stability concerns. There is a chance that changes in the line resistance that reflect conductor heating and sagging can be accurately measured using synchronously measured voltages and currents at both ends of the line (see previous subsection).

A PMU-based approach may complement or replace existing devices that measure the transmission line's thermal capacity to provide an early warning in case of overload, dynamically control transmission line capacity, and provide indirect estimation of line sagging [12].

### 7.4. Real-Time Control and Protection Systems

Synchrophasors provide an ideal measurement for real-time, wide-area control applications. As discussed previously, they provide a direct measure of system phase angles, an important indicator of system stability. Beyond single phase or positive sequence voltage phasors, PMUs also provide current phasors, frequency, and its rate-of-change, all of which can be used for control applications. Using the C37.118 communication protocol, measurements can be sent long distances over standard communication systems in 1–2 cycles. This is fast enough for many System Integrity Protection Systems (SIPS) and system controls. Reference [13] in which a prototype control using phasor voltage magnitude measurement as an indication of voltage swing demonstrated an improvement in an SIPS security margin. In the same project, an alternative method using VAR flow calculated from voltage and current phasors also showed improved security. Phase angle seems to be an ideal measurement for this type of application. Another approach for this same project using interarea phase angle calculated from phasors has also been proposed.

Phase angle between busses is determined by voltage, power flow, and transmission corridor impedance. While usually considered for indicating power flow, phase angle can also indicate topology changes that require control actions. This approach is used in another demonstration SIPS control scheme [14].

## 8. CONCLUSION

This paper has described the principal features of synchrophasor , synchronized reporting rate and its revised synchrophasor standard. The reader must remember that the paper is not a substitute for the actual standard, which is the ultimate authority as to what constitutes compliance. The paper also provides a preliminary discussion of PMU responses to electrical power network This paper discussed several prospective applications for the PMU technology with significant benefits for system operation and integrity.

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