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Review Article

A COMPREHENSIVE REVIEW OF PHASOR MEASUREMENT UNITS FOR WIDE AREA MEASUREMENT SYSTEMS

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Abstract: Power system operation has become increasingly complex due to high load growth and increasing market pressure. The occurrence of major blackouts in many power systems around the world has necessitated the use of synchrophasor based Wide Area Measurement Systems (WAMS) for grid monitoring. Synchrophasor technology is comparatively new in the area of power systems. Phasor measurement units (PMUs) and phasor data concentrators (PDCs) are new to the substations and control centers. Even though PMUs have been installed in many power grids, the number of installed PMUs is still low with respect to the number of buses or lines. Currently, WAMS systems face many challenges. The amount of data collected by PMUs is large and they need to be transferred to regional and global data centers where real-time state estimation, and protection, stabilization decisions are made out of two different signal selection method.

Key Words: *Inter-area oscillations, power system stabilizer (PSS), Phasor Measurement Unit (PMU), Wide Area Measurement Systems (WAMS)*

Introduction: Power system stability is one of the most crucial issues in power systems which deals with the response of the system to the disturbances occurred in the network. Some of the major oscillations attributed to system collapse are local mode, intra-plant mode, inter-area mode, control mode and torsional mode of oscillations. From all of these modes inter area mode of oscillations are very severe and observed over a large region of the network. To make the system stable, it is very necessary that the inter-area modes of oscillations are effectively damped.

The conventional approach to damp inter area oscillation is to provide the supplementary control signal to the excitation system by installing Power System Stabilizer (PSS) at the generator location. The PSS use the local stabilizing signal such as deviation of generator

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speed and provides the supplementary control input to the excitation. But the PSS taking local signal may not be always effective to damp inter area oscillations, because the local controllers are having lack of global observations. It is also observed that the local signals have lack modal controllability and observability. But it is proved that under certain operating condition the inter area mode may be controllable from one area and observable from another control area. In this case the local controllers cannot provide effective damping.

Traditional state estimators use SCADA measurements (voltage, line flow, etc.) to calculate the phase angles and hence the stability of the grid. State estimator using SCADA measurements can only make good estimation of power system state if the system is in steady or quasi-steady state. Lack of accurate measurements affects the performance of state estimators during system dynamics. The application of remote signal for damping controller has become successful due to the recent development of Phasor Measurement Units (PMUs). PMUs have very useful contribution in newly developed Wide Area Measurement System (WAMS) technology. The signals obtained from PMUs are referred to as remote stabilizing signals for the controllers.

In recent years, the global observation of the power system is achieved by using wide area measurement systems through phasor measurement units (PMUs) that receive signals from the satellite based global positioning system (GPS). These PMUs can deliver synchronous phasors and control signals at high speed. The PMUs are used in many protection and data acquisition functions in transmission and distribution electrical networks. The PMU refers the measurements to a common time base, generally the Universal Coordinated Time (UTC) obtained from the Global Position Systems (GPS). In this way the measurements become comparable over a wide area. A synchrophasor is a phasor value obtained from voltage or current signals and referenced to a common time base.

The goal of PMU devices connected to the power grid is to monitor power system parameters and to track power system dynamic phenomena for improved power system monitoring, protection, operation, and control. The intent of the synchrophasor standard is to describe and quantify the performance of the PMU deployed to monitor the power grid. The PMU measures the magnitude, phase angle and frequency from the voltage and current signals. These signals may be corrupted by distortion, noise, and abrupt changes caused by system loads, control and protective actions.

Electromechanical modes:

1) **Intraplant mode:** Machines on the same power generation site oscillate against each other at 2.0 to 3.0 Hz depending on the unit ratings and the reactance connecting them.
2) **Local plant mode:** In local mode, one generator swings against the rest of the system at 1.0 to 2.0 Hz. The impact of the oscillation is localized to the generator and the line connecting it to the grid.
3) **Inter-area mode oscillations:** This phenomenon is observed over a large part of the network. It involves two coherent group groups of generators swinging against each other at 1 Hz or less. The oscillation frequency is approximately 0.3 Hz.
4) **Control mode oscillations:** These are associated with generators and poorly tuned exciters, governors, HVDC converters and SVC controls. Loads and excitation systems can interact through control modes.
5) **Torsional mode oscillations:** These modes are associated with a turbine generator shaft system in the frequency range of 10-46 Hz. Usually these modes are excited when a multi-stage turbine generator is connected to the grid system through a series compensated line.

Synchrophasor: Synchrophasor are precise time-synchronized measurements of certain parameters on the electricity grid, now available from grid monitoring devices called phasor measurement units (PMUs). In order to understand how Synchrophasor can enhance grid operations and planning, it is useful to understand phasor technology. Synchrophasor are precise time-synchronized measurements of certain parameters on the electricity grid, now available from grid monitoring devices called phasor measurement units (PMUs). A phasor is a complex number that represents both the magnitude and phase angle of voltage and current sinusoidal waveforms (60 Hz) at a specific point in time.

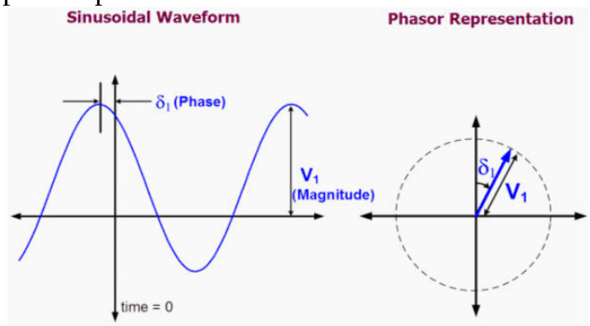

Fig.1 Sinusoidal Waveform and Phasor Representation

PMUs measure voltage, current and frequency and calculate phasors, and this suite of time synchronized grid condition data is called phasor data. Each phasor measurement is time stamped against Global Positioning System universal time; when a phasor measurement is time stamped, it is called a Synchrophasor. This allows measurements taken by PMUs in different locations or by different owners to be synchronized and time-aligned, then combined to provide a precise, comprehensive view of an entire region or interconnection. PMUs sample at speeds of 30 observations per second, compared to conventional monitoring technologies (such as SCADA) that measure once every two to four seconds.

Synchrophasor Data Systems: The purpose of a Synchrophasor data system is to make rapid measurements (at least 30 per second) of voltage and current phasors (magnitude and their respective phasor angles) that include precise time stamps and to make these measurements available to analyze and display grid conditions in transmission and power system control centers. Ultimately, Synchrophasor data systems may be used for automated control of the grid. A Synchrophasor system will improve real-time situational awareness and decision support tools to enhance system reliability. Synchrophasor measurements can also be used to improve component and system models for both on-line and off-line network analysis to assess system security and adequacy to withstand expected contingencies. The components of a Synchrophasor data system include:

(I) Phasor Measurement Unit (PMU): Calculates voltage and current phasors based on digital sampling of alternating current (AC) waveforms and a precise time signal provided by a GPS clock. A PMU provides output data in a standard protocol at rates of at least 30 samples per second for communication to remote locations.

(II)Communication System: A mechanism to transport the digital information from the PMU to the location where the data will be used. Communication is typically provided through a private wide-area network (WAN) but can be any digital transport system that offers acceptable security and availability; functional requirements for a Synchrophasor system architecture.

(III) Phasor Data Concentrator (PDC): Receives and time-synchronizes phasor data from multiple PMUs to produce a real-time, time-aligned output data stream. A PDC can exchange phasor data with PDCs at other locations. Through use of multiple PDCs, multiple layers of concentration can be implemented within an individual Synchrophasor data system. A phasor data concentrator collects phasor data from multiple PMUs or other PDCs, aligns the data by time-tag to create a time-synchronized dataset, and passes this dataset on to other information systems. The functions of a PDC can vary depending on its role or its location between the source PMUs and the higher-level applications. A local PDC may be located physically close to PMUs (typically at a substation) to manage the collection and communication of time-synchronized data from local PMUs, send it to higher level concentrators, and store the data for use within the substation.

(IV) Data Storage: Systems to store Synchrophasor data and make it conveniently available for post-real-time analysis can be integrated with the PDC or be stand-alone data historians or, in the case of smaller implementations, be traditional relational data base systems.Traditional relational databases can be used to manage phasor data for a short period ofhistory or for implementations that contain a small number of PMUs. Distributed non-relational databases are used to manage big datasets by large internet firms.These systems have some relational database features that can be used effectively with data systems thatcontain many, many terabytes of information. They divide the data up into smaller blocks that are processed in parallel. This technology is being explored for use in Synchrophasor data systems as well.

Eigen value analysis:

For analyzing the small signal stability of any system, the system model can be linearized around an operating point i.e. the disturbances are considered to be so small or incremental in nature so that a linear model of the system around an operating point can be developed. The state space representation of the power system can be written as

$$\dot{x} = Ax + Bu$$

$$y = Cx$$

Once the state space model of a power system is obtained the small signal stability of the system can be calculated and analysed and the eigenvalues λ_i are calculated for the A matrix. They are the non-trivial solutions of the equation:

$$\det(A - \lambda I) = 0$$

The solutions of characteristic equation are the eigenvalues of the $n \times n$ matrix A. These eigenvalues are of the form $\sigma \pm j\omega$.The stability of the operating point may be analyzed by studying the eigenvalues.

The conjugate-pair complex eigenvalues $(\sigma \pm j\omega)$ each corresponds to an oscillatory mode. A pair with a positive σ represents an unstable oscillatory mode since these eigenvalues yield an unstable time response of the system. However, a pair with a negative σ represents a desired stable oscillatory mode. Eigenvalues associated with an unstable or poorly damped oscillatory mode are also called dominant modes since their contribution dominates the time response of the system. It is quite obvious that the desired state of the system is for all of the eigenvalues to be in the left-hand side of the complex plane.

The damped frequency of the oscillation in Hertz and damping ratio are given by:

$$f = \frac{\omega}{2\pi}$$

$$\xi = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}}$$

The operating point is stable if all of the eigenvalues are on the left-hand side of the imaginary axis of the complex plane; otherwise it is unstable.

Structure of Phasor Measurement Units: Phasor Measurement Units or PMUs are a key element of the Wide Area Measurement Systems (WAMS). The unit is composed of a number of phasors that capture measurements of analog voltage, current waveform and the line frequency. After that, the phasor measurements are digitized by an analog to digital converter and stamped with the creation time provided by a GPS clock. GPS clocks are used for synchronization of multiple PMUs with a precision of maximum 1 microsecond difference. Afterwards, the data are transferred to a phasor data concentrator, which is explained in the next section. PMU provides a dynamic system observation of the network, because the measurements are taken with a high sampling rate from geographically distant locations and they are then grouped together according to the time stamp provided by the GPS. Phasor measurement unit transmits samples in different sizes. The sample size depends on the number of phasors in a unit. Sample and packet have the same meaning when talking about PMU transfer rate. The required transfer rate differs from a 50 Hz system to a 60Hz system. For example, a 60 Hz system hasa rate up to 60 samples per second, while the 50 HZ one has up to 50 samples per second A PMU device is composed by different elements, as shown in Figure 2.

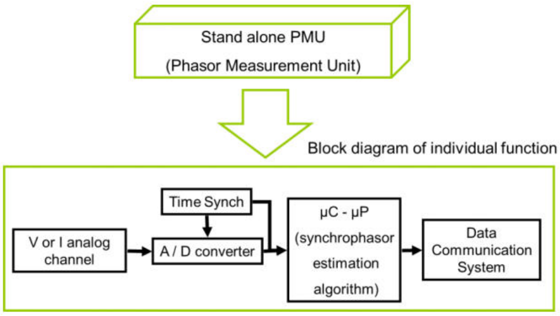

Figure 2. Block diagram of a standalone PMU

(I) V/I analog channel: The analog inputs are current and voltage signals obtained from the current and voltage transformers. In most cases, magnetic core Voltage andCurrent Transformers (VTs and CTs) are connected to the PMU. To minimize the phase errors introduced by instrument transformers, compensation routines are generally implemented in commercial PMUs.

(II) A/D converter: The Analog to Digital converter is a circuit that makes suitable the acquired signals suitable for the microprocessor. The conversion is disciplined by the time synchronization module, generally using the Phase Locked Loop control circuit (PLL). Currently, most devices on the market use sampling frequencies ofthe order of tens of kilosamples per second.

(III) Time Synchronization: This unit is able to keep the UTC time required from the standard to synchronize the measurements. There are different suitable source ofsynchronization: GPS is currently the most common solution for the synchronization of PMUs. A device may have an integrated GPS receiver, or may receive the synchronization signal from an external receiver.

(IV) Microprocessor: The microprocessor performs the computation necessary toestimate the quantities of interest from the acquired signals. It estimates the current and voltage phasors using the algorithms specific for the synchrophasor estimation. Moreover, it generates the time-stamp from the synchronization module to tag the measurements. It estimates also the frequency and ROCOF.

(V) Data Communication: the data communication system is used to transmit the measurements from a PMU through the network, either to/from Phasor Data Concentrator, a device specially designed to receive input data from different PMUs and to make their time alignment, or to/from Monitor Station. The data communication system must be compliant with the standard for the communication of the synchrophasor IEEE C37.118.2

PMU Applications: PMUs have been in use for a long time in wide area monitoring. The applications of PMU technology mainly in state estimation, protection and control are as under

State Estimation: State estimation of the system is performed today from the measurements of power injection, voltage values from transformers, etc. This estimation algorithm is based on the assumption that the state of the power system remains static when scanning takes place. The system can look completely different by the time the state is estimated. This estimated state is used as the input data for many other calculations and applications like economic dispatch, automatic generation control, automatic voltage control etc.

Power system protection: Every line has distance protection of different levels. Zone 1 relays are present at each end of the line and protect 80% of the line. Zone 2protects 100% of the line and about 20% of the adjoining line. Zone 3 covers 100% of the line and more than 50% of the adjoining line. This means these relays protect the connected line also to some extent and thus act as backup protection for the lines. Backup relays used for providing Zone 2 and Zone 3 protection are prone to false tripping. This can be catastrophic for a system operating on the edge of its stability limits. PMUs at Buses where relays are connected can act as supervisory systems. If the relays see a fault but none of the PMUs indicate it, then it can be ruled out as a false trigger.

Power system control: With real time data, power system control finds significant benefit. Control can now be based on remote quantities. Wide-area measurements allow the system to control insecure situations without employing continuous feedback. In the case of such situations, control actions like reconfiguring the network to ensure the demand is met or curtailed can be taken remotely. PMU measurements enhance robustness of the system by retaining local control signals while additionally providing supervisory signals. Such a redundancy in the system control would be indispensable for fine control of the system even remotely and a big step towards a smarter grid.

Test System: Despite the high level of activity in recent years on wide-area control, there are many aspects remain poorly understood due to the complexity in large power system. Therefore a small Kundur's two area 4 machine power system has been set up to deal with the most of the issues/challenges faced by wide-area control. In the test system all the generators are equipped with governor, AVR, and IEEE ST1A type static exciter. The loads taken here are constant impendence type and connected to bus no. 7 and 9. The structure of the case study power system is given in Fig.2

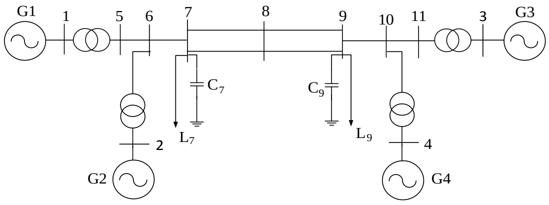

Figure ***2:*** Kundur's two area four machine system

It is assumed that the Local signal based PSSs (LPSSs) are assumed to be connected with the chosen generators, that are determined as suitable control location, for damping of local area oscillations. After the calculation of most suitable stabilizing signal and control location a Global signal based PSS (GPSS) is employed supplement to the input of AVR along with LPSS for the damping of inter area oscillations. The exporting Power Ptie from area 1 to area 2 through tie line is 413 MW and chosen as nominal operating point.

Signal Selection and Controller Locations: Optimal selection of measured signal and control site location is performed with the geometric measures of joint controllability and observability approach. The indices for controllability and observability CC and OI for a particular i mode of oscillations are defined by:

$$\mathbf{COI_k = cos(\theta(\psi_1, B_k)) = \frac{|\psi_1 B_k|}{\|\psi_1\|\|B_k\|}}$$

$$\mathbf{OBI_j = cos(\theta(\phi_1, C_j)) = \frac{|C_j \phi_1|}{\|C_j\|\|\phi_1\|}}$$

where, b_k is the $\mathbf{k^{th}}$ column of input matrix B (corresponding to the ith input), ψ_1 is the left eigenvector of $\mathbf{i^{th}}$ mode of oscillation and c_j is the $\mathbf{j^{th}}$ row of output matrix C (corresponding to the $\mathbf{j^{th}}$ output). $\phi_1$is right eigenvector of $\mathbf{i^{th}}$ mode of oscillations. The symbol$| \ |$ and $\| \ \|$ are the absolute value of a scalar and standard-2 norm respectively. The joint controllability and observability index of geometric approach is defined by

Joint-index k,j $= COI_k * OI$

If COI_k =, then the mode k is uncontrollable from input i and If OBI_j =, then the mode k is unobservable from the output j.

In addition to the critical mode identification, modal analysis was also performed for coherent machine identification where the one group of generators forms one area and oscillating with another group of generators. Compass plot shows the coherent areas in the studied system as shown in figure 5.2.

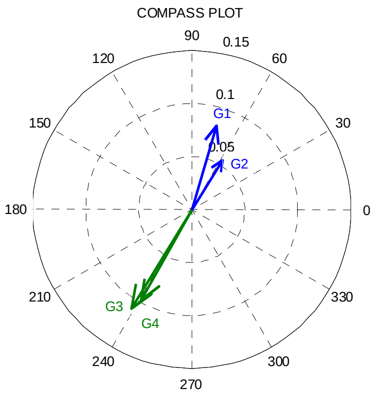

Figure 3: Coherent Area Identification using Compass Plot

There are four arrows representing the four generators. The length and direction of each arrow is corresponding to the magnitude and phase angle of respective eigenvector for the critical mode of machine. In the compass plot, it is clear that generator 1 and generator 2 forms area 1, and generator 3 and generator 4 forms another area so that the studied system termed as two area system when area 1 is oscillating with respect to area 2. The small signal stability analysis is performed under no fault condition and by applying small disturbance of 0.05 to the voltage reference of exciter in generator 1 of area 1.

The most stabilizing feedback signal selection was evaluated by geometric measure of controllability/observability approach. The candidate signals that are considered for the selection process are line active power, line reactive power, generator rotor speeds and bus voltage angle.

The most stabilizing feedback signal and most suitable control device locations as obtained by geometric measure of controllability/observability approach are tie-line active power $P_{9\text{-}10}$ and Generator 2 and 4 respectively. Hence, it is found that the PMUs should be located on bus no 9 and 10 to acquire the signal and at the Generator 2 and 4 for producing the line active power to the controller.

Conclusion: The technology and necessary standards for the measurement and communication of synchronized phasor measurements are becoming available across a range of operating platforms. The need and potential applications for thistechnology is evolving in parallel will be needed in order to maintain stable operation of the electric power grid of the future.Recent research has shown the importance to learn the nature of the communication network and its correlation with the power system applications running on it. Communication has to be considered as one of the key design factors of the WAMS applications before their realistic implementation in the system.

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