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PHASOR MEASUREMENT TECHNOLOGY BASED POWER SYSTEM MONITORING AND CONTROL

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ABSTRACT

The concept of phasor measurement and its application in power system monitoring and control are introduced in this paper. The example of application of PMU in a Campus Wide Area Monitoring System (WAMS) is then elaborated. With the availability of synchrophasor data measurement, it makes possible to establish the power system monitoring by directly employing spectral analysis of power or phase angle response signals using Fourier Transforms or Short Time Fourier Transform, Prony or Wavelet analysis technique or any other combination among those methods. Moreover, using the wide area signal provided by PMU, power system stability control also gain benefit through the wide area control technique where the system provide a better response toward the inter-area oscillation compared to the conventional damping controller. Finally, at the end of this work, the application of phasor measurement technology in the small signal stability monitoring and the wide area control based on phasor measurement data are discussed.

Keywords: PMU, damping ratio, WAMS, oscillation mode, small signal stability.

INTRODUCTION

Phasor is a basic tool of AC circuit analysis, usually introduced as a means of representing steady state sinusoidal waveforms of fundamental power frequency. Even when a power system is not quite in a steady state, phasor are often useful in describing the behaviour of the power system [1].

A phasor measurement unit (PMU) is a device that measures the electrical waves on an electricity grid using a common time stamp for the synchronization. Time synchronization allows synchronized real-time measurements of multiple remote measurement points on the grid. The resulting measurement is known as a synchrophasor. PMUs are considered as one of the most important measuring devices in the future of power systems. It can be a dedicated device, or incorporated into a protective relay or other device.

Dr. Arun G. Phadke and Dr. James S. Thorp at Virginia Tech invented PMU in 1988. Since then, the subject of wide-area measurements in power systems using PMU and other measuring instruments has been receiving considerable attention from researchers in the field Phasor measuring units (PMUs) using synchronization signals from the Global Positioning System (GPS) satellite system have evolved into mature tools and are now being manufactured commercially [2].

Synchronized phasor (or synchrophasor) provide a real-time measurement of electrical quantities from across the power system. Applications include wide-area control, system model validation, determining stability margins, maximizing stable system loading, islanding detection, system-wide disturbance recording, and visualization of dynamic system response.

MATERIALS AND METHODS

Phasor measurement concepts

A phasor is a complex number representing the magnitude and phase angle of the sine waves found in an alternating current (AC) type of electrical system. Mathematically, it can be represented as a unique complex number known as a phasor equation.
Lets consider the sinusoidal equation below:

$$x(t) = X_m \cos\,(\omega t + \phi) \tag{1}$$

where x_m is magnitude of the sinusoidal waveform, ω is the instantaneous frequency ($2.\pi.f$) and φ is an angular starting point of the waveform.

The phasor representation of this sinusoidal is given by:

$$x(t) = \frac{X_m}{\sqrt{2}} e^{j\phi} = \frac{X_m}{\sqrt{2}} (\cos\phi + j\sin\phi) = \frac{X_m}{\sqrt{2}} \angle \phi \tag{2}$$

The sinusoidal signal and its phasor representation given by (1) and (2) are illustrated in Figure-1 (a) and (b) respectively.

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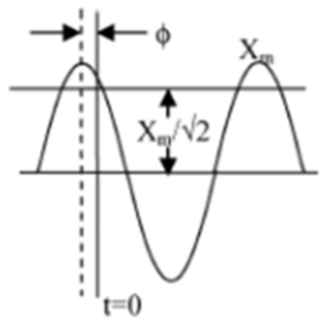

(a)

(b)

Figure-1. Phasor representation of a sinusoidal block of a PMU (a) Sinusoidal signal. (b) Phasor representation.

Phasor measurements that occur at the same time are named synchrophasors. Sometimes the terms of PMU and synchrophasor are used interchangeably whereas they actually represent two independent technical meanings. A synchrophasor is the metered value while the Phasor Measurement Unit (PMU) is the metering device to measure the phasor itself.

In practical applications, PMUs are sampled from widely distributed locations in the power system network and synchronized from the common time source of a GPS time stamp. To standardize the data format and measurement concept, The IEEE Standard 1344-1995 was introduced. In 2005 that standard was updated with the new standard IEEE C37.118, it was around 10 years of WAMS experience and research. The latest IEEE C37.118 improves PMU interoperability with the following three major contributions:

a) Refined definition of a Absolute Phasor referred to GPS-based and nominal frequency phasor, as well as time-stamping rule;
b) Introduction of the TVE (Total Vector Error) to quantify the phasor measurement error; and
c) Introduction of the PMU compliance test procedure.

Synchronized phasor technology is the preferred basis of a wide area measurement system (WAMS). Phasor quantities are logged from digital samples of the AC waveforms. To ensure that all phasor are synchronized using the same time reference, the standard defines a synchronized phasor angle as an instantaneous phase angle relative to a cosine function at nominal system frequency synchronized to UTC. This angle is defined to be *0* degrees when the maximum of the measured sinusoidal waveform occurs at the UTC second rollover (1 pulse per second time signal), and *-90* degrees when the positive zero crossing occurs at the UTC second rollover. Figure-2 illustrates the concept showing the nominal reference waveform (dotted line) synchronized with UTC (peaks at *0,T0, 2T0*, etc.) and the actual waveform (solid line) with growing phase angle (φ_i) relative to the reference.

The global positioning system

The Global Positioning System (GPS) was introduced in 1960 under the auspices of the U.S. Air Force. The first satellites were launched into space in 1978. The System was declared operational in April 1995. The Global Positioning System consists of 24 satellites, that circle the globe once every 12 hours, to provide worldwide position, time and velocity information. GPS makes it possible to precisely identify locations on the earth by measuring distance from the satellites. GPS allows you to record or create locations from places on the earth and help you navigate to and fromthose places. Originally, the system was designed only for military purposes until the 1980s that it was made available non-military use [3].

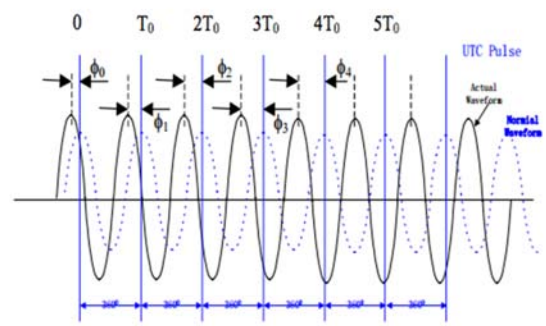

Figure-2. Absolut phasor.

The GPS synchronization concept is based on time. The satellites carry very stable atomic clocks that are synchronized to each other and to ground clocks. Any drift from true time maintained on the ground is corrected daily. Likewise, the satellite locations are monitored precisely. GPS receivers have clocks as well; however, they are not synchronized with true time, and are less stable. GPS satellites continuously transmit their current time and position. A GPS receiver monitors multiple satellites and solves equations to determine the exact position of the receiver and its deviation from true time. At a minimum, four satellites must be in view of the receiver for it to compute four unknown quantities (three position coordinates and clock deviation from satellite time) [4].

There are many non-military applications use of the GPS in daily application such as in the field below:

a) Navigation: for digitally precise velocity and orientation measurements.
b) Surveying: surveyors use absolute locations to make maps and determine property boundaries.
c) Tectonics: GPS enables direct fault motion measurement of earthquakes. Between earthquakes, GPS can be used to measure crustal motion and deformation to estimate seismic strain buildup for creating seismic hazard maps.
d) Robotics: self-navigating and autonomous system. Autonomous Robots uses GPS sensors to calculate latitude, longitude, time, speed, and heading.
e) Phasor measurements: GPS enables highly accurate time stamping of power system measurements, making it possible to compute phasor.

Phasor measurement network

A phasor network consists of PMUs distributed throughout the electricity system, Phasor Data Concentrators (PDC) to collect the information in real time. Such a network is used in Wide Area Measurement Systems (WAMS), the first of which was begun in 2000 by the Bonneville Power Administration and in 2002 in Japan through a inter campus WAMS so-called Japan Campus WAMS. Figure-3 illustrates the architecture of the Japan Campus WAMS.

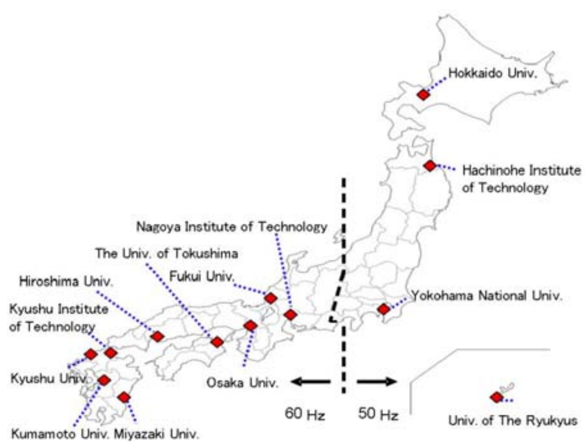

Figure-3. Japan campus WAMS.

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. Clocks need to be accurate to 500 nanoseconds to provide the one microsecond time standard needed by each device performing synchrophasor measurement. For 60 Hz systems, PMUs must deliver between 10 and 30 synchronous reports per second depending on the application. The PDC correlates the data, and controls and monitors the PMUs (from a dozen up to 60). 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 [3] [4].

PMUs may use Internet protocol or other data communication system to connect to the PDCs via a Modem then send data to the Supervisory Control and Data Acquisition (SCADA) system or WAMS server. Additionally, PMUs also possible to use ubiquitous mobile (cellular) networks for data transfer (GPRS, UMTS), which allows potential savings in infrastructure and deployment costs, at the expense of a larger data reporting latency. However, the introduced data latency makes such systems more suitable for R&D measurement campaigns and near real-time monitoring, and limits their use in real-time protective systems.

The basic system building blocks are GPS satellite-synchronized-clocks, PMU, PDC, communication equipment, and visualization software. Figure-4 shows hardware block of the PMU while Figure-5 illustrates the topology of PMUs and PDCs in the wide area measurement system.

The application of PMU in power system

The synchronized phasormeasurement technology is relatively new, and consequently several research groups around the world are actively developing applications of this technology. The following are some of current development of PMU application in power system:

- Power system automation, as in smart grids
- Load shedding and other load control techniques such as demand response mechanisms to manage a power system. (i.e. Directing power where it is needed in real-time)
- Increase the reliability of the power grid by detecting faults early, allowing for isolation of operative system, and the prevention of power outages.
- Increase power quality by precise analysis and automated correction of sources of system degradation.
- Wide area measurement and control through state estimation, in transmission networks or distribution grids.
- Phasor measurement technology and synchronized time stamping can be used for Security improvement through synchronized encryptions like trusted sensing base.

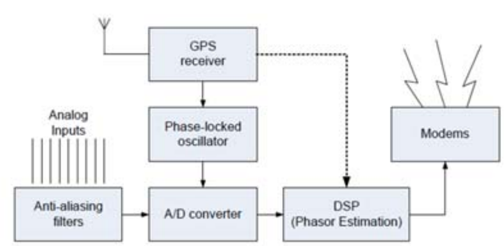

Figure-4. Hardware blok of a PMU.

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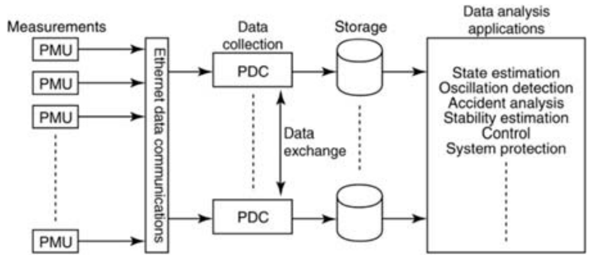

Figure-5. Topology of PMU and PDC in WAMS [5].

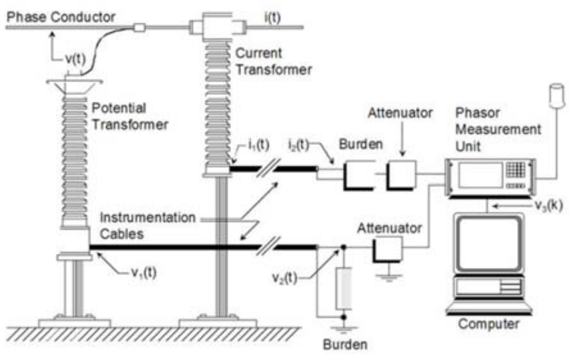

Figure-6. PMU installed in substation [6].

Dealing with the WAMS, currently there are two kinds of WAMS strategy approach in the power system. First is the application of WAMS in transmission level, where the PMUs are installed in the substation as it is shown in Figure-6. The other is deploying PMUs in the wall laboratory outlet such as in Japan Campus WAMS, Malaysia-Singapore WAMS and Thailand WAMS. Figure-7 illustrates the typical installation of PMU in 220V domestic outlet.

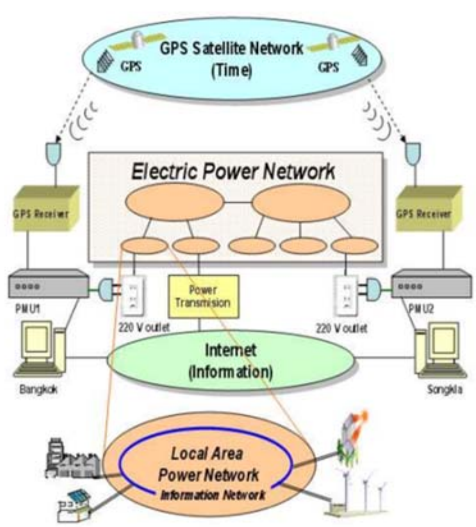

Figure-7. Typical PMU deployment in domestic wall outlet [7].

RESULTS AND DISCUSSIONS

Small signal stability monitoring using PMU

Inter-area oscillation is a complex and non-linear phenomenon and its damping characteristic is dictated by the strength of the transmission path, the nature of the loads, the power flow through the interconnection, and the interaction of loads with the dynamics of generators and their associated controls [2]. Usually the oscillations are stable but if the system is stressed too much the Hopf bifurcation may occur where the real parts of a complex conjugate eigenvalue pair cross the imaginary axis and the system becomes unstable.

A weak transmission path means high effective impedance between the oscillating generator groups. The high impedance causes the amortisseur windings of the generators to lose their effect on the inter-area oscillation damping. In addition, the adverse interactions among the automatic controls, especially the automatic voltage regulators (AVRs), decrease inter-area oscillation damping. Even without the adverse effects among the automatic controls, the uncontrolled systems damping for inter-area oscillations is commonly poor when the transmission path is weak. Additionally, when the loading of the interconnecting lines grow, the damping decreases, mainly because the angle difference between the oscillating generator groups grow and thus the voltage oscillations at the generator terminals grow, causing the AVRs to act and produce negative damping [5].

The analysis and monitoring of power system oscillations can be accomplished by means of several methodological approaches. Each approach has its own advantages and feasible applications, providing a different view of the system dynamic behaviour. Eigenvalue analysis technique is based on the linearization of the nonlinear equations that represent the power system around an operating point that is the result of electromechanical modal characteristics: frequency, damping and shape. However, this method will need comprehensive parameters of the system, which is very difficult in the real time application. As it known the system component are changing from time to time following the dynamics behaviour of the system [8].

By the availability of synchrophasor data measurement, it is possible to do the direct spectral analysis of power response signals use the Fourier Transforms (or Short Time Fourier Transform (STFT), Prony or Wavelet analysis technique or any combination among those methods [9] [10]. Figure-8describes the damping ratio trend for 72 time segments. Each segment represents 20 minutes time horizons, so the 72 segments will represents 1,400 minutes or 24 hours.

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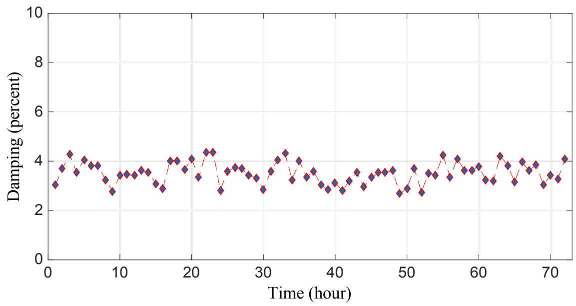

Figure-6. Damping ratio trends for 24 hours.

Wide area damping controller using PMU

Power System is a complex system consisting of generations, transmissions and loads. Load centers are connected to generator through transmission network. When the growth of demand is not followed by expanding of new power plants and transmission line capacity, it will forced the power systems operator drive the system close to its operation limits.

To prevent system from un-damped oscillation witch will cause domino effect to the system and lead to cascading failure to the overall power system, a well design damping controller should be provided. However, to deal with this issue, some challenge must be addressed. One major challenge in damping control design is the selection of feedback input signals. The damping itself is defined as the energy dissipation properties of a system.

Power oscillation can be damped, when extra energy is injected or consumed to compensate the decelerated or accelerated system. The damping energy must have the correct phase shift relative to the accelerated or decelerated system as incorrect phase angles can even excite the oscillations. Figure-9 shows the different possibilities to damp power system oscillations [6].

A simulation has been conducted to a simple power system model by applying a three-phase fault occurs in the system and changing the loading scenario. From that simulation, it can be confirm that on a situation where the inter-area exist and the local controller failed to maintain the system stability, the wide area damping controller together with the existing local controller successfully keeping the system stable as shown in Figure-10.

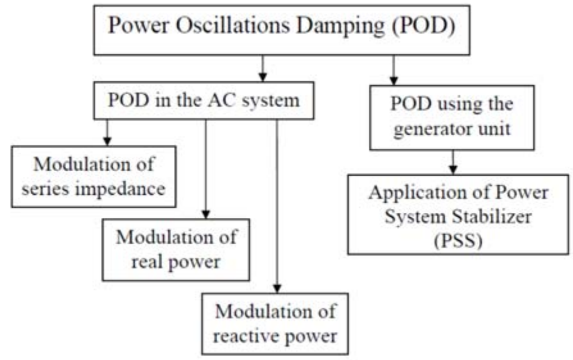

Figure-7. The possibility of damper technique in power system.

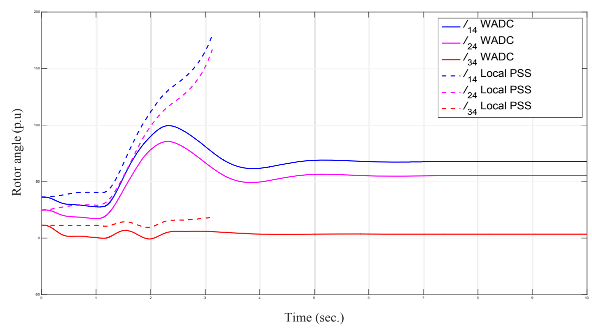

Figure-8. Performance of damping controller on load configuration L7:90% and L9: 100%.

CONCLUSIONS

A PMU is a device that measures the electrical waves on an electricity grid using a common time stamp for the synchronization provide by the GPS satellites. The resulting measurement is known as a synchrophasor. PMUs are considered as one of the most important measuring devices in the future of power systems. PMU is a key point of wide area measurement system (WAMS) in providing real time and high accuracy synchrophasor data. Regarding the WAMS, there are two kinds of WAMS strategy approach in the power system. First is the application of WAMS in transmission level, where the PMUs are installed in the substation and the other is deploying PMUs in the wall laboratory outlet such as in Japan Campus WAMS, Malaysia-Singapore WAMS and Thailand WAMS. By the availability of synchrophasor data measurement, it is possible to establish the power system monitoring by directly employing spectral analysis of power or phase angle response signals use the Fourier Transforms or Short Time Fourier Transform, Prony or Wavelet analysis technique or any combination among those methods. By using wide area signal provided by PMU, power system stability control also gain benefit through the wide area control technique as it has been illustrated above where the system provided a better response toward the inter-area oscillation compared to the conventional (local only) damping controller.

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REFERENCES

[1] Phadke and B. Kasztenny, "Synchronized phasor and frequency measurement under transient conditions," Power Delivery, IEEE Trans- actions on, vol. 24, no. 1, pp. 89-95, Jan 2009.

[2] Phadke and J. Thorp, "History and applications of phasor measurements," in Power Systems Conference and Exposition, 2006. PSCE '06. 2006 IEEE PES, Oct 2006, pp. 331-335.

[3] [Online].Available: http://www.nhdfl.org/library/pdf/ForestProtection/IntroductiontoGlobalPositio- ning System.pdf.

[4] [Online]. Available: http://www.space.com/19794-navstar.html.

[5] H. Bevrani, M. Watanabe, and Y. Mitani, "Power System Monitoring and Control". Wiley-IEEE Press, June 2014.

[6] Z. Huang, B. Kasztenny, V. Madani, K. Martin, S. Meliopoulos, D. Novosel, and J. Stenbakken, "Performance evaluation of phasor measurement systems," in Power and Energy Society General Meeting Conversion and Delivery of Electrical Energy in the 21st Century, pp. 1-7, 2008.

[7] I. Ngamroo, S. Danupaprita, and Y. Mitani, "PMU based monitoring of inter-area oscillation in Thailand power system via home power outlets," ECTI Transaction on Electrical Engineering, Electronics and Communication, vol. 5, no. 2, pp. 199-204, August 2007.

[8] Khairudin, Y. Qudaih, M. Watanabe, and Y. Mitani, "Synchrophasor measurement based damping estimation and oscillation mode detection using FFT-CWT approach in Japan Campus WAMS," International Journal of Smart Grid and Clean Energy, vol. 4, no. 2, pp. 93-102, April 2015.

[9] Khairudin and Y. Mitani, "Synchrophasor measurement based small signal stability assessment using FFT-CWT approach in Japan-Campus-WAMS," in IEEE PES Innovative Smart Grid Technologies, Europe, Oct 2014, pp. 1-6.

[10] Khairudin, Y. Qudaih, Y. Mitani, M. Watanabe, and T. Kerdphol, "Wavelet-demodulation-method based out of step detection and damping estimation in Japan Campus WAMS," in Power System Computation Conference (PSCC), Wroclaw, 2014, pp. 1-7.