PMUs – A new approach to power network monitoring

David G. Hart, David Uy, Vasudev Gharpure, Damir Novosel, Daniel Karlsson, Mehmet Kaba

Power system measurement, synchronized on a global basis, is moving from the lab to the utility. What makes this possible is the Phasor Measurement Unit (PMU) – a device which, by employing widely used satellite technology, offers new opportunities in power system monitoring, protection, analysis and control. ABB is presently involved in developing a PMU product and advanced solutions. PMU functionality is also being integrated into ABB protective relays, providing a hardened platform for substation applications. Pilot installations at several utilities are already under way.

As recent events, particularly in the USA, have shown, electric utilities are having to face increasingly complex issues in a continually evolving business environment. Two issues stand out: power grids are expected to operate closer to their maximum capacity, and there is an increased need for accurate and better monitoring of the network.

Phasor measurement

Being able to determine phasors across the power system at a fixed point in time has the potential to solve these problems. One of the key components of future utility systems will therefore be Phasor Measurement Units (PMUs). PMUs rely on a GPS time signal for extremely accurate time-stamping of the power system information. A GPS satellite receiver (see box on page 60) 1 provides a precise timing pulse, which is correlated with sampled voltage and current inputs - typically the three phase voltages of a substation and the currents in lines, transformers, and loads terminating at the substation. From these

Phasors – What and Why

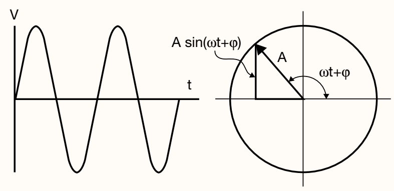
If one part of a power grid becomes seriously out of synchronism with the rest, the whole network can become unstable and shut itself down. This is how a blackout occurs. Something which power engineers have therefore always wanted to do is monitor the relative phase angles of the voltages and currents throughout the grid. And in real time.

In the past, a lack of adequate computing power and the huge difficulties involved in collecting, coordinating and synchronizing the grid data made this impossible. However, new technology now available has radically changed this situation.

To make life even easier, engineers have simplified the mathematics they use. This was done to circumvent difficulties with differential equations and long expressions that included terms such as ‘$A\sin(\omega t + \phi)$’ – which is typical of sinusoidal waveforms, like the AC mains power, that vary with time.

The simplification involves transferring the equations from our usual time domain to a different coordinate system. For example, the AC power outlets in our homes, below left, can be equally well represented by the diagram on the right.

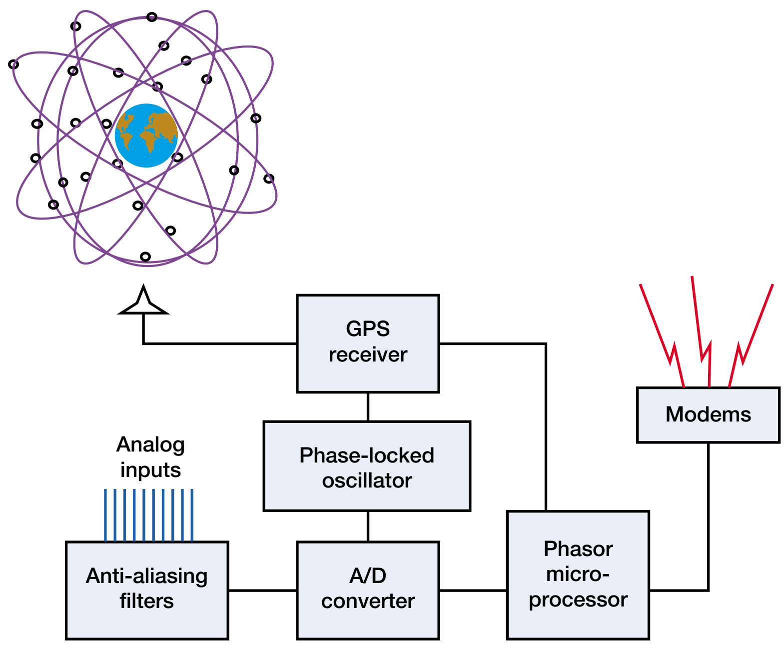
The line rotates and traces out the circle, like a rotating vector, with frequency ω. The length of the line represents the full amplitude, in this case of the voltage. The vertical component is equivalent to the $A\sin(\omega t + \phi)$ in the AC power sinusoid.



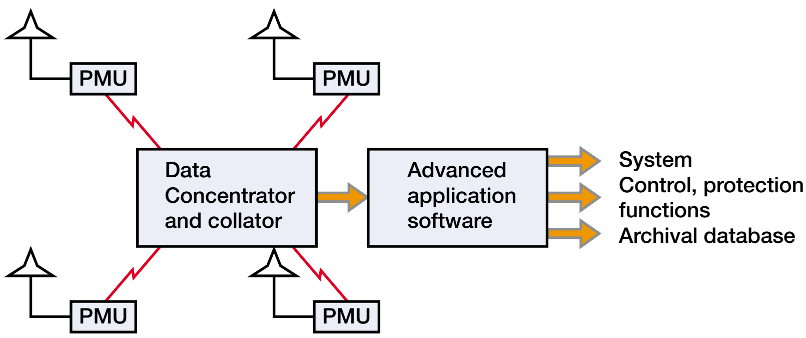
This rotating line is called a *phasor*.

Use of this phasor notation considerably simplifies not only the mathematics but also the electronics and processing power required. And it is this simplification that facilitates the grid-wide PMU monitoring described.

data samples, positive-sequence voltages and currents are calculated [1] and time-stamped so that the exact microsecond when the phasor measurement is taken is permanently attached to it. The device assembles a message from the time stamp and the phasor data in a format defined in IEEE standard 1344 [2], which can then be transmitted to a remote site over any available communication link. Positive-sequence phasor data from all substations equipped with such devices are collected at an appropriate central site using a data concentrator 2 or exchanged between local units for protection/control applications. Collecting and collating these measurements provides a basis for new, very powerful techniques for monitoring, protecting and controlling power networks.



1 Block diagram of the Phasor Measurement Unit



2 PMU utilization in a power system

Communication issues

Different technologies

Communication of the time-stamped measurements to the data concentrator is critical to the implementation. While time is distributed to the PMUs through an intricate network of satellites, present devices utilize telephone, digital serial and ethernet communications technologies to provide the connection to the data concentrator. The different technologies involved in the communications infrastructure include direct wiring, licensed and unlicensed radio networks, microwave, public telephone, cellular telephone, digital wireless, plus combinations of these technologies.

Synchrophasor format

IEEE Standard 1344 [2] defines the formats for output files provided by the Phasor Measurement Units. Two files (Header and Configuration) are defined for setting up and assisting in interpreting the phasor data, as well as the format for the real-time binary output file consisting of phasors and the time stamp, which comprise the principal output of the PMUs. The standard has been of great help in ensuring that all future applications of the synchronized phasor measurements are able to access the phasor data provided by PMUs from different manufacturers.

Power system applications

The synchronized phasor measurement technology is relatively new, and consequently several research groups around the world are actively developing applications of this technology. It seems clear that many of these applications can be conveniently grouped as follows:

- Power system monitoring
- Advanced network protection
- Advanced control schemes

The GPS system

The Global Positioning Satellite (GPS) system consists of 24 satellites in six orbits at an approximate altitude of 10,000 miles above the surface of the earth. They are thus approximately at one half the altitude corresponding to a geo-synchronous orbit. The positioning of the orbital plane and the positioning of the satellites in the orbits is such that at any given instant at least four satellites are in view from any point on the surface of the earth. Often, more than six satellites are visible. The civilian-use channel of the GPS system transmits positional coordinates of the satellites from which the location of a receiver station on earth could be determined. In addition, the satellites transmit a one-pulse-per-second signal, along with an identifier for the signal that can be interpreted by the earth station receivers. The civilian-use transmission of the time signal is precise to within 1 microsecond, and often in practice is found to be much more accurate. The time pulse is of critical importance to the application considered here. The normal practice is to phase-lock a sampling clock to this pulse. The sampling instant would be identified as the pulse number within a one-second interval identified by the GPS time-tag. The exact format for time-tagging is defined in IEEE standard 1344 [2].

It should be mentioned that a time standard known as the IRIG-B standard is currently being used by the power industry for time-tagging digital fault recorders and other substation event monitoring systems. However, with standard IRIG-B receivers the synchronization accuracy is of the order of 1 millisecond, which is not enough for precise power system measurement (a tolerance of 1 millisecond corresponds to an uncertainty of about 20°).

Power system monitoring

One of the most important elements of modern Energy Management Systems currently deployed by electric utility companies is *state estimation* of the power system from real-time measurements. The state of the power system is defined as the collection of the positive-sequence voltages at all the network buses obtained simultaneously. The technology of state estimation currently in use was developed in the 1960s, and is based on measurements that are unsynchronized. This results in a non-linear equation that must be solved on-line to estimate the state of the system. Due to the low scanning rates and relatively slow computations, present technology is incapable of providing information about the dynamic state of the power system. The synchronized phasor measurements provide a completely new opportunity to re-cast the entire state estimation process.

With the use of this technology, much of the delay inherent in the present state estimation systems will be removed and the utilities will be in a position to move on to advanced static and dynamic contingency analyses of their network in real-time.

Advanced network protection

Another category of applications of synchronized phasor measurement is that of enhancing the effectiveness of power system protection. This involves equipment and system protection, as well as remedial action schemes. For example, traditional line protection relies on system measurements at one end of the line terminal to determine if a fault is present. For critical lines, measurements are synchronized through some mechanism to provide differential protection schemes for fault detection. Differential protection is recognized as the most reliable form of protection. In the future, PMUs could be utilized to provide differential protection. This also has the potential to limit the damage that can be caused to the power system by catastrophic events. For example, the status of certain circuit-breakers and switches, power flows in key transmission lines, voltages at critical buses, power output of key generators, etc, could be used to formulate a strategy of responses if these parameters should fall within 'dangerous' patterns.

An example of phasor measurements used for protection is given in the adaptive out-of-step relaying study reported in [4]. This work has shown that by using real-time measurement of phasor angles at key locations in the network, and using concepts from transient stability analysis, it is possible to design improved out-of-step relays. Field trials of this concept have been carried out on the Florida-Georgia interconnection, and the results have shown the concept to be sound. An installation of a similar nature is the 'Defense Plan' of Electricité de France (EDF) [5]. In this scheme, phasor measurement from different regions of France are compared; upon a pre-set limit being exceeded, trip commands are issued to the appropriate substation, isolating that part of the network which is in imminent danger of causing the entire power system to collapse.

Advanced control schemes

Controllable devices installed by the electric utility industry include power system stabilizers, static var compensators (SVCs), HVDC links, universal power flow controllers, etc. These controllers are designed to act in such a way that the defined control objective functions are optimized. For example, a power system stabilizer may have as its objective the damping of electromechanical oscillations in the power system. The objective of an SVC controller may be to improve the voltage profile at certain critical buses in the network. In all cases, the controllers use locally derived signals as feedback. Since the phenomenon being controlled is often defined in terms of wide area system variables, present-day controllers depend upon a mathematical model of the control process, the system dynamics and the relationship between the local variables and system state.

Synchronized phasor measurements offer a unique opportunity to bring in the remote measurements of system state vector to the controller, and thus remove from the control loop the uncertainty associated with the mathematical model. Thus, the controller becomes primarily feedback-based, rather than model-based, in its implementation.

Outlook for PMUs

PMUs facilitate innovative solutions to traditional utility problems and offer power system engineers a whole range of potential benefits, including:

- Precise estimates of the power system state can be obtained at frequent intervals, enabling dynamic phenomena to be observed from a central location and appropriate control actions taken.
- Post-disturbance analyses are much improved because precise snapshots of the system states are obtained through GPS synchronization.
- Advanced protection based upon synchronized phasor measurements could be implemented, with options for improving overall system response to catastrophic events.
- Advanced control using remote feedback becomes possible, thereby improving controller performance.

ABB is confident that in the coming years more applications of this technology will be discovered.

Authors

David G. Hart
David Uy
Vasudev Gharpure
ABB Power T&D Company Inc.
1021 Main Campus Drive
Raleigh NC 27606/USA
david.g.hart@us.abb.com

Damir Novosel
ABB Automation Group Ltd
CH-8050 Zurich/Switzerland

Daniel Karlsson
ABB SEAPR
Västeras/Sweden

Mehmet Kaba
ABB Power Automation
CH-5401 Baden/Switzerland

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