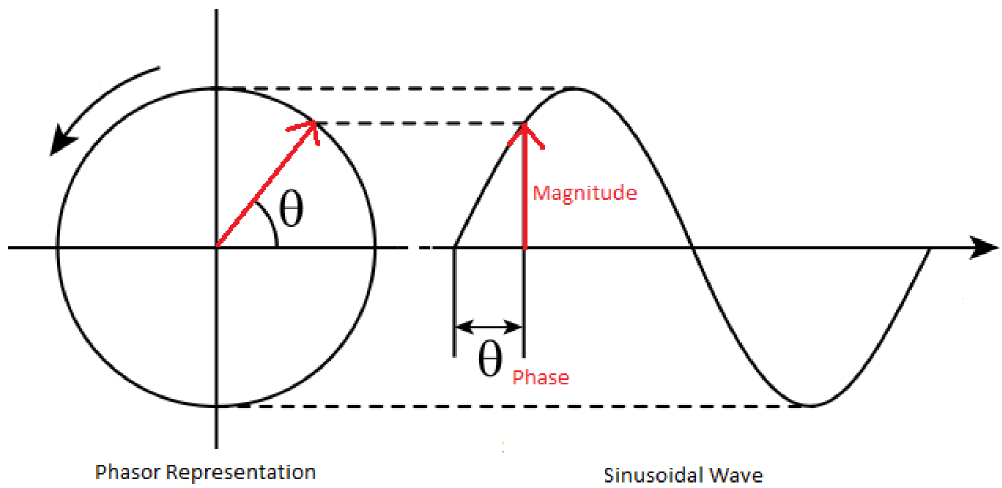
Americans for a Clean Energy Grid

Synchrophasors

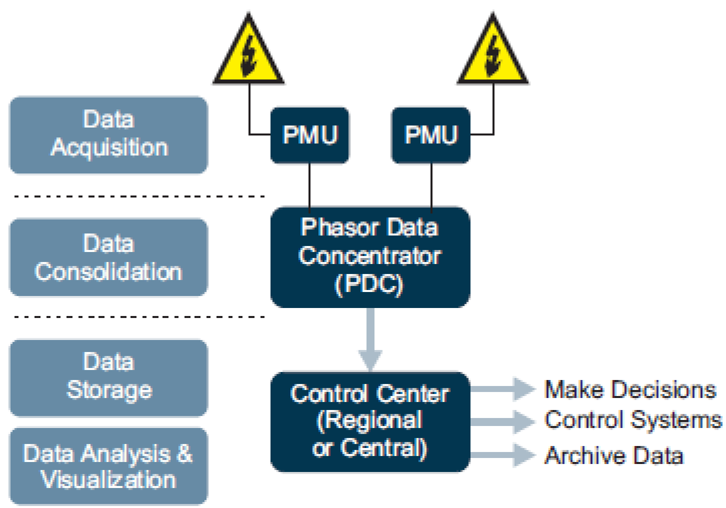
Before synchrophasor technology and its contributions towards transmission resiliency are discussed, it is important to first understand the concept of phasors. A phasor is a complex number that represents both the magnitude and phase angle of a given point on a sinusoidal wave. The figure below shows the phasor representation of a sinusoidal wave [2]:



A phasor can be used to represent the magnitude and phase angle of alternating current at any point across a transmission line at a given time. A phasor measurement unit (PMU) is a device that measures voltage, current and frequency as phasors at a point on a transmission line [2]. Using a Global Positioning System (GPS) signal, the PMU then adds a time stamp to each phasor data point, which are then called synchrophasors [2]. Addition of time stamps to phasor data allows all of the data coming from different PMUs to be synchronized and time-aligned [2]. Synchrophasors present a precise and comprehensive view of an entire region or interconnection [2]. Conventional grid monitoring technologies such as supervisory control and data acquisition

(SCADA) collect data every two to four seconds, while PMUs collect data at a *rate of 30 observations per second* [2]. Therefore, PMUs and synchrophasor data provide grid operators with a more precise and higher resolution image of the grid in real-time. Such time sensitive information can help in numerous ways to alert the grid operators to grid stress early on, potentially avoiding power outages and maintaining power quality. This section of the report explains how synchrophasor technology provides such support, and discusses the degree to which they are being installed on the U.S. electricity grid.

PMUs collect and transmit a massive amount of synchrophasor data. Sophisticated and expensive data management systems are required for efficiently handling and visually presenting the large volumes of synchrophasor data. In early 2013, Dell, Intel, National Instruments, and OSIsoft collectively developed a complete synchrophasor data management system that consists of PMUs, phasor data concentrators (PDC), and data management systems. Using high performance computing, networking and storage, the synchrophasor data management system provides real-time feedback and actionable data to grid operators. This synchrophasor data management system helps utility companies improve transmission efficiency and reduce transmission costs. Furthermore, the system has a scalable and non-proprietary architecture, which increases its compatibility with existing systems. The figure to the right provides a high level representation of the whole synchrophasor data management system: [1]



After collecting and time stamping phasor data, the PMUs send the data to a phasor data consolidator (PDC). PDCs have servers that receive data from multiple PMUs and consolidate it before transmitting it to a regional or central grid control center. PMUs collect and send a massive amount of data to PDCs. Sophisticated telecommunications technologies such as fiber optic cables and satellites are an integral part of the synchrophasor networks. For example, two dedicated T1 lines are required for data transmission from 60 PMUs [1]. Currently, the absence of these communications networks is a limiting factor to the deployment and real-time applications of synchrophasor technology. The cost of the communications network is more expensive than the cost of PMU equipment [1]. For example, Duke Energy Carolinas, LLC installed 103 PMUs and 2 PDCs at a combined equipment cost of $3,664,883 while the supporting communications network had a total cost $3,989,026 [4]. At regional and central control centers, computers use sophisticated algorithms to store, analyze and translate to easy-to-read visuals of the synchrophasor data for grid operators. Based upon the visuals, grid operators can monitor and control the flow of electricity in the transmission network.

Synchrophasors are increasingly being used for wide-area measurement systems (WAMS) in the Eastern and Western Interconnections of North America, and in China, Quebec, Europe, and Brazil [2]. WAMS allow grid operators to simultaneously monitor multiple regions of grid network for stress instead of a single region only. WAMS have digital displays that alert grid operators at the first signs of grid stress such as voltage and frequency fluctuations, and fast changing phase angles. [2]. If grid operators observe stress developing in a region, they can take the necessary precautionary measures to stop that problem from spreading across all neighboring regions. Lack of WAMS may have precluded grid operators from identifying the early signs of the 2003 Northeast blackout [2]. The U.S.-Canada investigation report into the blackout stated that with a synchrophasor system, grid operators could have identified the early stages of the blackout and could have taken steps to reduce the scale of the blackout.

In addition to wide-area monitoring systems, synchrophasors offer an impressive range of system benefits, including:

- **Oscillation detection**: Oscillations occur in a transmission line when a disturbance, such as tripping of a generator, happens. PMUs collect data up to 30 times per second, and this high rate of sampling allows grid operators to identify early signs of oscillation and take action within a few moments. Early action can stop oscillations from becoming severe and destabilizing the grid network. [6]

- **Frequency stability monitoring**: The North American grid operates at 60Hz with slight positive or negative deviations. Frequencies higher than 60 Hz suggests that the generation is greater than load, while frequency lower than 60 Hz suggests that the load is greater than generation. Sudden and unexpected increases in generation or load causes abrupt changes in frequency, which can lead to a blackout. Characteristic high sampling rate of PMUs allows early detection of abrupt frequency changes and allows grid operators to take precautionary measures faster. [6]
- **Voltage stability monitoring**: A number of transmission systems are voltage stability-limited, meaning that the voltage across them cannot exceed a specific level at any given point. If voltage across a transmission system surpasses the stability limit, voltage collapses can happen almost instantaneously. PMUs monitor voltage levels near key load centers and bulk transmission substations and provide real-time feedback to control centers' stability monitoring. [6]
- **Disturbance detection and alarm studies:** Analyses have shown that certain trends in phase angle differences between substations are indicators of increasing grid stress. For example, if the phase angle difference between substations is becoming large, the system heads towards instability, and alarms go off in the requisite control rooms. Synchrophasor systems offer the benefit of trending tools that plot the phase angle difference against the phase angle limits, so that grid operators can make precautionary and corrective measure based upon the trends in phase angle difference. [6]
- **Resource integration:** One of the challenges in integrating distributed generation and renewable energy into the bulk generation system is to identify and respond to power generation variability. Conventionally, the frequency of the grid is controlled by bulk, baseload generators. The integration of fluctuating renewable energy creates a level of unpredictability that makes it difficult for a grid operator to control the frequency of the grid system. Synchrophasors provide real-time frequency monitoring for distributed renewable sources. The more the grid operators know about renewable energy integration, the better they can maintain system stability. [6]
- **State estimation:** Due to communication delays and outages, it is sometimes impossible to get measurements of the state of the power system. In 1970, the method of state estimation was developed to solve this issue. State estimation uses a model of the power

system, measurements and least-squares statistical regression to estimate power system states at various substations and generators. Synchrophasors, unlike conventional monitoring systems, measure phase angles, and so, adding synchrophasor data to state estimation provides a more complete picture and improves the overall calculations. [6]

- **Transmission path and congestion management:** Synchrophasors can be used to monitor load on transmission lines and recalculate line ratings (maximum power that a transmission line can carry). Line ratings of transmission lines change with weather conditions. For example, a transmission line can carry more power on a windy day because the line remains cooler as the heat is carried away by the wind (see the paper on dynamic line ratings for more on this). Real-time monitoring of transmission lines allows grid operators to continuously calculate line ratings and change power flow accordingly. If the line rating permits, grid operators may put more load on a transmission line to avoid congestion somewhere else in the grid system. This process of continuously calculating line ratings and increasing load accordingly can, therefore, increase the load bearing capacity of the existing grid and alleviate congestion. [6]
- **Islanding and restoration:** Synchrophasors can be used to monitor bus frequencies, which are reliable indicators of the integrity ("health") of power system islands and system separation points. Additionally, monitoring of frequency is crucial when power generators are black-started (when the power system is started from zero generation and zero load conditions) and during system restoration procedures after a power disruption. Synchrophasors allow grid operators to precisely monitor the frequency during these conditions and avoid system instability and failed restart attempts. [6]
- **Post-event analysis:** Time-synchronized data from PMUs allows grid operators to reconstruct the exact sequence of events that led to a grid failure. Reconstruction of failure events helps grid operators and power engineers understand what went wrong and learn critical lessons that can avoid future grid failures. [6]
- **Model validation:** Grid operators use synchrophasor data to develop steady-state (during which the power system experience little no changes within a range of one second to one minute) and dynamic (during which the power system experiences large changes in less than one second) models for power systems. Because PMUs collect data

up to 30 times per second, grid operators can develop more precise and accurate models for power systems. [6]

The cost of installing synchrophasor equipment and supporting communications systems is high. For example, American Transmission Company (ATC) spent $22,530,824 on just improving its SCADA and PMU communications infrastructure [3]. However, the savings in terms of transmission efficiency, power quality and reduced transmission costs are more than enough to justify the significant upfront investments in synchrophasor projects over time. The American Recovery and Reinvestment Act of 2009 (ARRA) provided significant funding for the installation of synchrophasor systems at various grid locations. Through ARRA, the Department of Energy (DOE) provided Smart Grid Investment Grants (SGIGs) to install over 850 new PMUs and synchrophasor communications networks in 2010 thorough 2013 [2]. The table below gives a list of the announced synchrophasor projects to be funded by SGIGs [2]:

Project	**New PMUs Installed**	**Federal Contribution ($1000s)**	**Total Cost ($1000s)**
American Transmission Company	6	$12,775	$25,550
Center for Commercialization of Electric Technologies	13	$135,517	27,419
Duke Energy Carolinas	102	$3,925	$7,856
Entergy Services Inc.	18	$4,611	$9,222
ISO-New England	30	$3,722	$8,519
Midwest Energy	7	$712	$1,425
Midwest Independent Transmission System Operator	>150	$17,272	$34,543
New York Independent System Operator, Inc.	39	$37,383	$75,712
PJM Interconnection	>80	$13,698	$27,840
Western Electricity Coordinating Council	>250	$53,890	$107,780

The table below provides a complete list of Recovery Act funded synchrophasor projects installed throughAugust 2013 [6]:

Project	**PMUs Installed**	**PDCs Installed**
American Transmission Company	45	0
Center for Commercialization of Electric Technologies	15	4
Duke Energy Carolinas	98	2
Entergy Services Inc.	49	9
Florida Power and Light Company	45	13
Idaho Power Company	8	0
ISO-New England	77	8
Midwest Energy	7	1
Midwest Independent Transmission System Operator	148	21
New York Independent System Operator, Inc.	40	8
PJM Interconnection	56	15
Western Electricity Coordinating Council	336	49
TOTAL	**924**	**130**

The median average equipment cost of ARRA funded synchrophasor projects is displayed in the table below [6]:

Technology	**Median of Projects' Average Cost**
Phasor Measurement Unit (PMU)	$43,400/PMU
Phasor Data Concentrator (PDC)	$107,000/PDC

In 2009, there were approximately 200 synchrophasors connected to the entire U.S. electricity grid. Since then, the Obama Administration's support for a resilient electricity grid has helped increase the number of synchrophasors connected to the U.S. electricity grid to roughly 1700. In June 2014, the Department of Energy announced that it would spend an additional $10 million to improve grid reliability and resiliency. The funding would be spent on six projects across five states to develop advanced software for synchrophasor projects [5]. This advanced software would be able to better detect quickly changing grid conditions and improve day-to-day grid reliability [5]. The increasing number of synchrophasor systems installed on the U.S. grid system and aggressive investment by government and utility companies indicate the importance of synchrophasor technology to the resilience of the grid network. As it becomes more broadly accepted that a resilient transmission network is the backbone of a sustainable and energy efficient grid network, the number of synchrophasors installed should only increase.

References

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