SYNCHROPHASOR MATURITY MODEL

Extracting Value from Synchrophasor Investments

By:
Ryan Quint & Kyle Thomas (Dominion)
Alison Silverstein (NASPI)
Dmitry Kosterev (BPA)
March 18, 2015

NOTE – This is a proposal offered for discussion purposes. The authors invite comments and suggestions on the potential value of adopting a maturity model for synchrophasor technology, and on the specific elements and metrics proposed herein.

Introduction & Background

The adoption of synchrophasor technology and deployment of production-quality phasor measurement units (PMUs) has occurred rapidly, primarily due to the U.S Department of Energy (DOE) Smart Grid Investment Grant (SGIG) stimulus funding resulting in the Smart Grid Demonstration Projects (SGDPs). These efforts, in conjunction with industry focus on this new advanced technology, have resulted in over 1,700 time-synchronized PMUs deployed across North America, unlocking new ways to visualize, analyze and operate the electric power grid reliably and effectively.

As the SGIG projects wrap up, the transmission owners (TOs) and grid operators involved are now working to extract value from the systems they have installed. Production-grade PMUs are capturing the system's electrical quantities with high levels of accuracy and time synchronization. Time-stamped PMU data is generally delivered over a robust communications network with high levels of availability and low latency. Today, many transmission owners and grid operators are receiving high quality PMU data at their control centers, and applications are being developed to manage that data and extract meaning and insight from the data. The flow of electrical quantity data through the synchrophasor architecture to the applications and then to actionable information is shown in Figure 1.

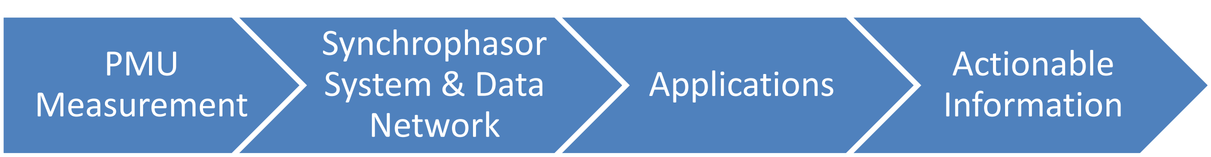

Figure 1. Transition from Measurement to Data to Information

The goal of using synchrophasor technology is to improve power system reliability and efficiency. PMU data can be used to create two principal types of applications and insights: those that support real-time, on-line operational problems and actions such as wide-area situational awareness, congestion management and oscillation mitigation, and off-line uses such as event analysis and power plant model validation and calibration.

Since synchrophasor technology is still early in its deployment, it is useful to articulate some ideas about what a mature technology deployment would look like as it evolves to support the goals and uses above. Uses for the maturity model include:

- **Self-assessment:** The primary goal for this maturity model is to develop an assessment tool that transmission owners and reliability coordinators (RCs) deploying synchrophasor systems can use to identify strengths, weaknesses and opportunities for improvement of their synchrophasor projects.

- **Communication tool:** The maturity model uses a simple matrix system to illustrate the dimensions, levels and metrics for synchrophasor maturity. This model can be used by organizational leaders to set goals, and by staff to help leadership understand the technology and its deployment within the organization.

- **Technology deployment coordination:** By drawing out the relationships between technology, physical assets, information technology, and institutional infrastructure such as business practices and technical standards, the model encourages better appreciation and coordination between these factors.

- **Metric definition:** By articulating specific metrics for evaluating synchrophasor technology and how it advances between maturity levels, the maturity model offers ways to formalize metrics for synchrophasor technology usage and effectiveness.

- **Integration with roadmaps:** Roadmapping efforts related to synchrophasors can use this information to identify capability gaps or technology characteristics, develop technology readiness levels, and hypothesize expected levels of maturity for different resource commitments.

- **What to assess:** The model can be applied to individual companies and synchrophasor projects, or can be used to assess progress and maturity of individual PMU data applications, or to assess the maturity of synchrophasor technology overall across North America.

- **Engagement:** Vendors and academics could also use the maturity model to help understand the steps required for their products to be integrated and used effectively.

Maturity Model for Synchrophasor Deployment

The maturity model has three features – technology pillars, ascending maturity levels, and a set of metrics intended to describe and characterize a specific maturity level for a specific technology pillar. These will be explained below.

Maturity levels

The maturity levels are proposed as follows:

- Level 5: Integrated and highly mature
  - Operational utilization
  - User acceptance
  - Integration with business processes and institutional support for system and uses
- Level 4: Operationalized
  - High levels of reliability and robustness
  - Installation, ownership and acceptance into user processes
  - Focus on operational or business uses and value
- Level 3: Implementation
  - Growing deployment, improvement, debugging process
  - Available and in use by target users, for reference if not in routine practice
  - Training and support available to user groups
- Level 2: Development
  - Developing tools, techniques, processes, infrastructure
  - Bringing developments to key decision makers and leadership
  - Prototype deployments demonstrating effectiveness, accuracy, and usability
  - One or more technology champions; sense of value being realized
- Level 1: Conceptualization

APPLYING AND ASSESSING MATURITY LEVELS

The purpose of developing and using this maturity model is to help the electric industry explain synchrophasor technology and articulate a roadmap of the steps on the way to long-term technology maturity. While this technology can be used to enhance grid reliability and efficiency, each Transmission Owner, Transmission Operator, Planning Coordinator, Independent System Operator, or Reliability Coordinator that undertakes a synchrophasor deployment has specific purposes and goals for that deployment. It is more important today that the project owner achieve those goals than that the project achieve "maturity" according to this model (or any other). It is entirely appropriate that different entities are now at different levels of project maturity according to the model proposed here.

However, over the longer term, as the state-of-the-art and capabilities of synchrophasor technology continue to advance, it may be useful for industry members to use this maturity model to set new goals for how to expand and enhance their synchrophasor systems, and their business operations to support those systems.

Technology pillars

The maturity model organizes the elements of synchrophasor technology into three categories or pillars:

1. **Infrastructure:** These are the assets that collect and manage PMU data, including physical assets such as Phasor Measurement Units (PMUs), time synchronization devices (e.g. satellite clocks), Phasor Data Concentrators (PDCs), wiring, and many other substation-level devices and equipment for measuring the electric system elements and quantities of interest. Infrastructure includes institutional rules such as technical interoperability standards and business practices such as device installation and system maintenance.

2. **Communications Network:** This category includes the information and communications technology – hardware, software and institutional factors such as technical standards and Quality of Service requirements – that move PMU data from the point of collection to the points where it is analyzed and used. These networks include both the communications networks and the protocols used to stream PMU data that meets the users' or owners' needs. This includes institutional infrastructure such as cyber-security requirements and implementation.

3. **Applications and Data Utilization:** Applications for extracting information from the PMU data are a critical component, whether they are offline or real-time applications. These tools must integrate with conventional business processes, be designed to deal with potential data problems while serving the users' goals, and provide actionable information to make decisions.

The application of the maturity levels to the technology pillars is demonstrated in Table 1. This is a maturity matrix that shows the progression of a synchrophasor system or application from conceptual stage (Level 1) to full maturity (level 5).

Table 1. Maturity Model Matrix

	Infrastructure	Communications Networks	Applications and data utilization
Level 5 Integrated & Mature			
Level 4 Operational			
Level 3 Implementation			
Level 2 Development			
Level 1 Conceptual			

The different pillars of synchrophasor technology are maturing at different paces. Some, particularly interoperability standards, advanced technical applications and user acceptance, are inherently harder, slower and more complicated to develop. These may require more money or technology to complete, or more time and institutional effort (such as user acceptance). Others may be easier to complete – for instance, now that PMU standards have been adopted, there are many high-quality commercial products available, and there is experience and documented practices for PMU installation, deploying a basic PMU system has become much easier than it was five years ago. Additionally, there are likely to be regional differences between maturity levels due to factors such as regional network availability and the relative aggressiveness of different RCs' synchrophasor project goals.

Maturity metrics

Each pillar includes specific metrics to assess the maturity of synchrophasor technology. However, common metrics that span all aspects of a robust synchrophasor system include:

1. **Technology utilization:** How the data is converted to actionable information is one of the major indicators of a mature synchrophasor system. Mature utilization of this technology can vary from entity to entity, but each should have core tools and applications that are relied upon for improving the reliability of the electric grid and providing value to the stakeholders. At this time, it is possible that some of the most effective synchrophasor uses may be to integrate PMU data into existing EMS- and SCADA-based tools for easier user acceptance.

2. **Architecture:** This concerns the design and functionality of the architecture, tools, applications, and processes in place to generate, collect, use and manage synchrophasor data. Ensuring that these tools are functional and effective in managing the data and extracting information from the data is essential in a mature technology.

3. **Data quality – availability, latency, and accuracy:** Data quality, availability and timeliness require smooth operation from all elements of an operational synchrophasor network. Continuous evaluation and focus on data quality and availability is necessary for applications to perform effectively and earn trust from users. This requires attention to business practices as well as system design and implementation.

4. **Business and technical standards:** One requirement for a mature technology is that the industry that uses it has developed consensus-based technical standards and guidelines with performance testing, verification and certification methods to assure that the devices meet known performance standards and work in an interoperable fashion. This enables users to save money on system design, purchase and installation, avoid vendor lock-in, and facilitates vendor innovation. Standards are also essential within a business – for instance, once the technology is fully integrated into the business, that technology will be incorporated into enterprise standards such as substation design sheets.

5. **Business practices and institutional support:** Mature technologies such as energy management systems (EMS) and protective relaying, are continuously evolving but must remain dependable such to be used for operation, control, protection, and monitoring of the electric grid. Dedicating sufficient resources to the deployment of a technology is another pivotal aspect of maturity. Without sufficient institutional support from within an organization, any technology will face roadblocks that prohibit proliferation and utilization. Mature synchrophasor technology will have to be fully reliable, which will require standards and to assure that they work effectively with appropriate internal and external support. Some of the institutional practices necessary for a new technology to realize its role and goals include funding, device purchase requirements that serve the organization's applications goals, systematic installation and commissioning practices, maintenance, communications network contracts with quality of service requirements, user training, support staff, and more.

6. **Operational performance:** A mature technology performs well, meeting or exceeding users' expectations with respect to functionality, accuracy, dependability, and quality of result. Such technologies earn users' trust.

These metrics would be applied to the maturity levels to assess the technology pillars, as shown in Table 2.

Table 2. The Maturity Matrix with Metrics

	Metrics	Infrastructure	Communications Networks	Applications
Level 5 Integrated and Mature	Utilization			
	Architecture			
	Data Quality			
	Technical and Business Standards			
	Institutional Support			
	Operational Performance			
Level 4 Operational	Utilization			
	Architecture			
	Data Quality			
	Technical and Business Standards			
	Institutional Support			
	Operational Performance			
Level 3 Implementation	Utilization			
	Architecture			
	Data Quality			
	Technical and Business Standards			
	Institutional Support			
	Operational Performance			
Level 2 Development	Utilization			
	Architecture			
	Data Quality			
	Technical and business Standards			
	Institutional Support			
	Operational Performance			
Level 1 Concept	Utilization			
	Architecture			
	Data Quality			

	Technical and business Standards			
	Institutional Support			
	Operational Performance			

Below we review how the maturity metrics can be applied to each of the pillars.

Maturity Metrics – Infrastructure

The first step in building a robust synchrophasor system is ensuring that the infrastructure in place is designed and implemented with high levels of reliability and efficiency. The downstream networks, applications, archives, and users of this data must be able to trust that the infrastructure is providing data of sufficient accuracy, dependability, and timeliness to meet the user's application needs. When synchrophasor technology is fully mature, many applications will require PMU data that have high accuracy, high security, low latency, and high dependability.

Synchrophasor infrastructure includes the substation or generator PMU and communications equipment to the central phasor data concentrators as well as networking and archiving equipment. From data source to data storage or utilization, the maturity metrics shown in Table 3 contribute to a robust synchrophasor network infrastructure.

Table 3. Maturity Model - Infrastructure

Maturity	Maturity Level Description
Level 5 *Integrated and Mature*	- **Utilization**: Synchrophasor infrastructure integrated into core business practices; business units use equipment and data to assure grid reliability and security. - **Architecture**: Highly reliable, production-grade implementation of all synchrophasor system components and devices. - **Data Quality**: Calibrated and tuned PMUs; streamlined PDCs monitoring quality metrics; mature data management capabilities; contractual QoS requirements for the synchrophasor data network. - **Standards**: Substation standards include synchrophasor technology as a core competency; organic deployment of PMUs as part of capital allocation and spending for transmission and other projects; PMU data uses standardized. - **Institutional Support**: Sufficient resources in place to maintain, manage, use, debug, update, and develop the synchrophasor network; high quality training in place for operators, engineering staff, and technicians; full support from leadership and management for using and maintaining synchrophasor system. - **Operational Performance**: Proven record of sustained reliable operation.
Level 4 *Operational*	- **Utilization**: Synchrophasor system used operationally for real-time or offline tools that provide value to organization(s). - **Architecture**: Reliability and robust infrastructure to support downstream needs and requirements; parallel or backup systems in place; architecture meets NERC reliability standards for critical assets; deployment based on PMU placement guidelines and reliability standards.

	- **Data Quality**: PMU equipment and data tuned; possible offline or online calibration techniques explored; online metrics of data availability, latency, and accuracy; data management techniques optimized; bad data detection methodologies in use. - **Standards**: Developing or using internal standards and practices for deployment and implementation of synchrophasor technology; expanding or full deployment of PMUs as part of grid protection and monitoring devices; use of PMU data in standardized manner; rules for updating and deploying PMUs in place. Industry technical interoperability standards adopted covering many aspects of synchrophasor technology. - **Institutional Support**: Resources and staff dedicated to each core component of the overall synchrophasor system; continuous development and improvement of system; training and expertise across organization; support and championing from management and leadership. - **Operational Performance**: Synchrophasor system architecture meets utility and industry standards for operational performance and reliability.
Level 3 *Implementation*	- **Utilization**: PMU data being used in multiple real-time and/or offline tools and archiving; continuous updates to data stream expanding data capabilities; equipment being modified or incorporated to meet application requirements; interoperability between applications; data shared with other entities. - **Architecture**: Full-scale PMU deployment underway; streaming PMUs from across entity footprint, PDCs and infrastructure capable of high bandwidth requirements of PMU technology; compliance with NERC reliability standards a consideration in data collection and applications; PMU placement considers application and data quality needs. - **Data Quality**: Monitoring of data quality, availability and latency across the measurement and delivery chain; data quality issues being identified and resolved; identification of data quality metrics and consideration of tools and mitigation measures to address potential them. Network architecture designed and implemented to serve the data needs of the target applications, with a focus on how to maintain data quality with system scalability. - **Standards**: Internal business standards and practices not finalized or implemented; PMU requirements in place; looking at industry best practices as basis for entity business practices; standardizing data formats and application requirements. - **Institutional Support**: Resource requirements being managed to mitigate bottlenecks related to synchrophasor deployment; expertise and staff available to develop synchrophasor system and applications; project management dedicated to capital projects related to synchrophasor technology; strong support for PMU utilization from utility leadership. - **Operational Performance**: Performance metrics being considered and developed; history and experience with technology driving further improvements in architecture and reliability of synchrophasor system.
Level 2b *Development – Pilot*	- **Utilization**: Developing prototype or pilot deployments for further testing and evaluation; tools for assessing system performance; systems-perspective of synchrophasor architecture. - **Architecture**: Small-scale pilot deployment of synchrophasor infrastructure; centralized PDC aligning one or multiple PMUs to a central location; historian and archiving capabilities in place; real time tools receiving data; minimal or no exchange of data with other entities. - **Data Quality**: Data availability and latency are main consideration; limited

	focus on data accuracy; metrics considered for assessing quality; data applications driving attention to PMU data quality. - **Standards**: Looking at standards and practices developed elsewhere for possible applicability and use within the entity. - **Institutional Support**: Growing need for institutional support related to synchrophasor system use, deployment and maintenance; potential gaps in support personnel and resources to reach higher level of maturity. - **Operational Performance**: Minimal focus on operational performance and efficiency; main goal is deployment of technology at larger scale.
Level 2a *Development - Testing*	- **Utilization**: Pilot project or small PMU project field deployment; focus on installing equipment with limited focus on system use. - **Architecture**: Small field deployment of PMUs; test or laboratory deployment of PMU technology; time alignment of multiple PMU data streams; basic data archiving capabilities. - **Data Quality**: Data quality and availability targeted to serve specific applications goals. Possible development of inter-entity networks and data sharing if the entity's synchrophasor plans include contributing to wide-area visualization and situational awareness. - **Standards**: No internal practices directly incorporate synchrophasor technology. - **Institutional Support**: Key field personnel focusing on PMU testing and deployment; some training. - **Operational Performance**: Performance being tested offline or preliminary testing of field equipment.
Level 1 *Conceptual*	- **Utilization**: Little to no use of PMU data; basic event forensics; still trying to determine how synchrophasors could offer value for the organization. - **Architecture**: Little or no field deployment of PMUs; possible test or laboratory deployment of PMU technology; PMU installations only to meet Reliability Coordinator requirements; primitive data-streaming to central PDC and historian, or local storage. - **Data Quality**: Limited attention to data quality for field PMUs; potentially high error rates reflecting some combination of low data availability, high latency, or inaccurate measurements. - **Standards**: No internal practices directly incorporate synchrophasor technology. - **Institutional Support**: None or few resources dedicated to developing synchrophasor infrastructure; minimal training or expertise on synchrophasors. - **Operational Performance**: Minimal or no use of PMU data.

Maturity Metrics – Communications and Networking

Ensuring that the measured phasor quantities are effectively and efficiently transmitted from PMU to PDC and onto applications and archiving is an essential pillar of synchrophasor system design. The availability, latency, and cyber security of these networks play a significant role in the performance and utilization of synchrophasor data. Table 4 shows maturity metrics associated with the communications and networking aspects.

Table 4. Maturity Model - Communications Network

Maturity	Maturity Level Description
Level 5 *Integrated and Mature*	- **Utilization**: Synchrophasor network integrated into core business practices; equipment and data relied upon by business units and operational performance of the electric grid. - **Architecture**: Highly reliable, production-quality, cyber-secure implementation of all synchrophasor network components and devices (routers, switches, fiber patch panels, etc.); network configured in highly meshed/loop network for maximum availability; dedicated "pipeline" for synchrophasor data to travel through; possible redundant network. - **Data Quality**: Exceptional low latency and minimal packet loss for synchrophasor packets from field PMUs to control center, and from control center to neighboring and regional entities - **Standards**: Standard network communication equipment is chosen to handle current and future synchrophasor data bandwidth requirements, including future synchrophasor data rates (upgradable to 60 or 120 samples/second); fiber backbone standard for high-speed communications network. - **Institutional Support**: Dedicated support and resources from IT and Network Management teams; 24/7 network operations center support, monitoring, and troubleshooting the phasor data network. - **Operational Performance**: Proven record of sustained reliable operation.
Level 4 *Operational*	- **Utilization**: Field PMUs feeding data to real-time or offline tools; data used for multiple applications and archiving; combination of substation network and enterprise network used by synchrophasor system. - **Architecture**: Network communication equipment may not be dedicated to PMU data only or have dedicated synchrophasor data pipelines, but is fully operational with synchrophasors and other business network traffic (ex: SCADA). - **Data Quality**: Latency and packet loss of synchrophasor data satisfactory for all operational synchrophasor applications. Monitoring/troubleshooting/fixes being performed on a day-to-day basis. - **Standards**: Standard IT equipment is capable of handling current synchrophasor data bandwidth and performance requirements; mixture of fiber and microwave communication mediums. - **Institutional Support**: Support and resources from IT and Network Management teams, supporting/monitoring/troubleshooting the phasor data network. - **Operational Performance**: Proven record of sustained reliable operation.
Level 3 *Implementation*	- **Utilization**: Expansion and deployment of communications networks for effective transmission of high resolution synchrophasor data. - **Architecture**: Full-scale PMU deployment underway; streaming PMUs from across entity footprint, PDCs and infrastructure capable of high bandwidth requirements of PMU technology; network equipment being fine-tuned or upgraded as needed to handle PMU data stream. - **Data Quality**: Data quality issues being resolved (ex: router/switch configurations, firewall rules, PDC wait timers being set/fine-tuned); data quality monitoring started and industry best practices incorporated. - **Standards**: Business practice standards for synchrophasor technology deployment and use not finalized or implemented; extent of standardization

	only to get synchrophasor data functional/flowing on appropriate networks to appropriate business users. Technical standards and protocols incorporate industry technical interoperability standards and best practices. - **Institutional Support**: Resource requirements being managed to mitigate bottlenecks related to synchrophasor deployment; expertise and staff available to develop synchrophasor network; IT/Networking project management dedicated to capital projects related to synchrophasor data flow. - **Operational Performance**: Performance metrics being considered and developed; history and experience with technology driving further improvements in architecture and reliability of the synchrophasor network.
Level 2b *Development - Pilot*	- **Utilization**: Dedicating communications channels and networks to synchrophasor system sufficient for specified deployments. - **Architecture**: Small-scale pilot deployment of synchrophasor infrastructure, with varied network media and varying network loading and congestion. - **Data Quality**: Tracking data latency and packet losses. - **Standards**: Not ready to develop standard business practices or uses for synchrophasor technology. - **Institutional Support**: Asking for IT and network team support and troubleshooting of synchrophasor network and packet flows. - **Operational Performance**: Main goal is determining how network handles synchrophasor data; understanding new or upgraded equipment that may be needed.
Level 2a *Development - Testing*	- **Utilization**: Use existing network equipment for test environment that would be similar to pilot tests in field. - **Architecture**: Network equipment in test/research lab. Network devices that are not dedicated to synchrophasors. - **Data Quality**: Monitor small set of data quality metrics during test; determining best TCP/IP protocols to use (UDP, TCP, combination, etc.). - **Standards**: No utility or network standards directly incorporate synchrophasor technology, but testing to understand what standards may need to change to allow synchrophasors to function on the network equipment. - **Institutional Support**: Small test team with representatives from IT and network operations team. - **Operational Performance**: Exploring performance of communications protocols and networks using high resolution synchrophasor data.
Level 1 *Conceptual*	- **Utilization**: Looking at existing company networks to determine adequacy for phasor data flows. - **Architecture**: Use existing networks in research/lab environment. - **Data Quality**: Defining data quality metrics to investigate/monitor during testing/pilot phases. - **Standards**: No entity or network standards or practices directly incorporate synchrophasor technology. - **Institutional Support**: No significant support from IT or network teams, minimal support needed to plan test/pilot work. - **Operational Performance**: No history or experience with synchrophasors on corporate network.

Maturity Metrics – Applications

As utilization of synchrophasor data continues to expand, it is essential that the applications using this data are also designed in a robust and trustworthy manner. Although PMU data has high availability, accuracy, time synchronization, and low latency, applications must be designed robustly and efficiently to facilitate information extraction from the synchrophasor data acquired in order to make actionable and useful decisions.

There are a wide variety of synchrophasor tools and applications in existence today, and they can be grouped into two major categories: Offline Applications and Real-Time Applications. Each of the two categories has many subcategories, but distinction between online and offline tools helps understand the major drivers and needs for data quality based on how the information extracted from the synchrophasor data is used. However, regardless of the tools developed or how the information is used, the main driver is developing synchrophasor-based applications such that they are sustainable, trustworthy, and provide valuable information to the user. Table 5 provides maturity model metrics for synchrophasor applications and Table 6 lists synchrophasor applications.

Table 5. Maturity Model - Applications

Maturity	Maturity Level Description
Level 5 *Integrated and Mature*	- **Utilization**: Synchrophasor applications integrated into real-time and offline uses for improving grid security and reliability; streamlined data extraction; operating procedures and job functions related to use of synchrophasor data and system; integrated review of operating procedures and training; synchrophasor system used in conjunction with or dedicated backup to EMS. - **Architecture**: Dedicated synchrophasor applications server with advanced analytical tools, data management, and visualization; data-sharing across Enterprise and Quality Assurance servers; robust and/or duplicate servers, PDCs, applications. - **Data Quality**: Applications have built-in flags, alarms, monitoring, and algorithms for detecting, handling, and/or ignoring bad data; applications have defined levels of acceptable data issues and robust procedures regarding how to handle data quality issues; data calibration and estimation techniques deployed such as Linear State Estimator. - **Standards**: Data formatting and application engine standardization; streamlined, routine approach to developing new and advanced tools and applications for synchrophasor network; data extraction is standardized; operating procedures incorporate PMU data. - **Institutional Support**: Support and expertise provided from engineering and IT personnel; dedicated resources for development, refinement, and maintenance of offline and online synchrophasor applications. - **Operational Performance**: Proven track record and high level of trust for synchrophasor-based applications and tools; applications and tools are shared amongst users and business units effectively.
Level 4 *Operational*	- **Utilization**: Applications used operationally in real-time tools; offline tools used operationally for planning and engineering; effective data extraction tools available. - **Architecture**: Mature application architecture in place, including

	visualization, engineering analysis, and data extraction; cyber-security issues resolved; data-sharing across enterprise network. - **Data Quality**: Operational alarming, flagging, and monitoring of data quality issues; applications robust to bad data; understanding of data quality requirements for applications. - **Standards**: Standardized application server platform in place for application and tool development; engineering application environment running offline tools; visualization applications used in control center and engineering environment; operating procedures include synchrophasor data. - **Institutional Support**: Dedicated engineering and IT personnel and resources sufficient for providing support and maintenance to operational synchrophasor system; systems designed such that EMS personnel have synchrophasor expertise; dedicated applications deployed across business units; training and procedures provided for tools used. - **Operational Performance**: Continuous development of dependable and reliable synchrophasor system applications; developing strong trust in synchrophasor data along with EMS data.
Level 3 *Implementation*	- **Utilization**: Synchrophasor applications are being implemented and developed for real-time and/or offline monitoring and engineering analysis; data extraction tools being deployed across business units for access to PMU data; streamlined and systematic approach to utilizing PMU data. - **Architecture**: Implementing tools, networks, and servers to effectively visualize, analyze, and extract information from synchrophasor data, IT networks have capability, bandwidth, and security in place to share synchrophasor tools and data; applications, servers, and networks experiences problems that are being reviewed and revised. - **Data Quality**: Metrics used to assess PMU data quality and application robustness to data quality issues; developing tools to operationally deal with data quality problems without adversely impacting tools deployed; developing data quality requirements for each application. - **Standards**: Developing standardized visualization and applications platforms for synchrophasor data; integrating with EMS system; data extraction and engineering application data formatting standards being developed; working between business units to develop and implement operating procedures or processes for utilizing PMU data in real-time and offline. - **Institutional Support**: Leadership providing resources and personnel to implement synchrophasor-based applications and tools; some bottlenecks and operational hurdles being managed; system design and processes being optimized; expertise being developed through training tools. - **Operational Performance**: Beginning stages of benchmarking operational performance of synchrophasor-based tools against conventional tools.
Level 2b *Development - Pilot*	- **Utilization**: Pilot or test demonstration of synchrophasor application(s); some offline or real-time tools being used by key personnel or synchrophasor champions; value proposition understood and working on portraying value through applications to others; some business units engaged but not widely supported or integrated. - **Architecture**: Minimal architecture primarily focused on key pilot or test application(s); some visualization tools available but primitive and not customized to user needs or wants; data sharing and extraction tools primitive or nonexistent. - **Data Quality**: Application robustness to data quality issues still relatively

	unknown; very few metrics being used to detect, flag, and mitigate bad data entering applications; applications and visualization show bad data to users; engineering judgment required when using applications; application availability is an issue. - **Standards**: Application standards not a major focus; data extraction is not streamlined and may be limited to key personnel using PMU data; no integration with other Enterprise applications or tools; data formatting a continuous hurdle. - **Institutional Support**: Personnel for deployment of test or pilot implementation; focus on prototype or value proposition implementation rather than full scale-deployment. - **Operational Performance**: Very little operational performance for applications due to initial pilot implementation or laboratory testing.
Level 2a *Development - Testing*	- **Utilization**: Pilot or test demonstration of synchrophasor application(s); some offline or real-time tools being used by key personnel or synchrophasor champions; basic value proposition understood; some business units engaged but not widely supported or integrated. - **Architecture**: Minimal architecture primarily focused on key pilot or test application(s); some visualization tools available but not customized to user needs or wants; little or no data-sharing and extraction tools. - **Data Quality**: Application robustness to data quality issues still relatively unknown; limited attention to bad data beyond measures built into vendor applications; engineering judgment required when using applications; application availability is an issue. - **Standards**: Little reason to incorporate synchrophasor considerations into business practices; technical standards used from external industry sources. - **Institutional Support**: Some resources to bring in or develop useful synchrophasor applications within laboratory or offline; organization not yet committed to using PMU data in real-time or operationally offline; limited personnel and financial resources for synchrophasor technology. - **Operational Performance**: Tire-kicking in initial pilot implementation and laboratory testing with limited expectations for performance.
Level 1 *Conceptual*	- **Utilization**: Little or no use of synchrophasor data; exploring R&D-based concepts and basic applications and studying others' synchrophasor deployments and results. - **Architecture**: System design appropriate to R&D stage. - **Data Quality**: If any applications in use, they are not relied upon for any business purposes. - **Standards**: No standardization or integration of applications, data extraction, or data formatting across the organization. Awareness of industry-adopted technical interoperability standards and best practices. - **Institutional Support**: Minimal support of synchrophasor technology or system; one or two championing personnel driving development; very little resources or commitment from leadership; still understanding synchrophasor application value. - **Operational Performance**: No operational performance.

Table 6. Industry-Wide Maturity Level for Synchrophasor Applications

Synchrophasor Applications	**Maturity Level**
Offline Engineering Tools	
- Disturbance Monitoring & System Observability	
- Wide-Area Event Analysis	
- Frequency Response Analysis	
- Data Mining	
- Baselining	
- Equipment Monitoring & Misoperations	
- Data Calibration & Conditioning	
- Line Parameter Estimation	
- Oscillation Ringdown Analysis	
- Model Validation Tools	
- Power Plant Model Validation	
- Load Model Validation	
- FACTS Model Validation	
- System Model Validation	
Real-Time Awareness Tools	
- Linear State Estimation	
- Wide-Area Visualization	
- Voltage Stability	
- Oscillation Detection Monitoring	
- Oscillation Damping Monitoring (Mode Meter)	
- Blackstart Capabilities	
- Islanding Detection	
- Event Detection	
- Phase Angle Alarming	
- Energy Management System (EMS) Integration	
- Renewable Energy Resource Integration	
- Dynamic Line Rating & Congestion Management	
Synchrophasor-Based Controls	
- Voltage Control	
- Special Protection & Remedial Action Schemes	

Appendix A illustrates how the maturity metrics could be applied to one particular synchrophasor-based application – Power Plant Model Validation.

Appendix A – Application Maturity of Power Plant Model Validation

Conclusion based on review of maturity levels – A few entities are performing power plant model validation at the operational (Level 4) maturity, but most of those performing model validation are using it at the implementation (Level 3) or development pilot (Level 2b) maturity levels. As the NERC MOD-026 and -027 standards go into effect, we expect this most users of this application to advance quickly to Levels 4 (operational) and 5 (integrated and mature).

Maturity	Maturity Level Description
Level 5 *Integrated and Mature*	- PMU-based model verification and validation performed to meet compliance with NERC Reliability Standards (e.g. MOD-026 and MOD-027). - Streamlined PMU data extraction integrated with data archiving system. - Dedicated applications providing efficient user interface and data processing. - Logic, flags, alarms, or algorithms for mitigating bad data impacts on application performance; data calibration techniques to improve performance. - Processes developed for making generator control modifications. - Resources and institutional support for continual PMU-based model validation.
Level 4 *Operational*	- Performing PMU-based model verification for majority of generating fleet; refining and improving model performance based on historical system events. - Effective extraction of PMU data from historian archive into software tools. - Standard data formats and data processing being utilized. - Alarming, flagging of bad data; application performance not degraded. - Dedicated personnel and resources sufficient for performing this function. - Continuous development of tools, capabilities, and software functions; however, operational tools in place and further improvement being performed.
Level 3 *Implementation*	- PMU-based model validation tools being developed using conventional software tools or user-built programs. - Improving data extraction, handling, and processing tools for software. - Developing standard data formats for more effective processing. - Using PMU-based model validation on select (large) generating facilities. - PMU data quality issues being resolved; application safeguards being developed to scrub, improve, or flag bad data. - Institutional support for implementing synchrophasor-based validation tools and techniques; full implementation of tool may require additional support. - Benchmarking operational performance of application against other tools.
Level 2b *Development - Pilot*	- Pilot or test demonstration of PMU-based model validation tools. - Key personnel performing validation on ad hoc basis; pioneering effort, but not widely supported or integrated with business operations. - Pilot efforts to demonstrated value of PMU-based validation. - Minimal focus on standardized data formats and data handling; data management and extraction is labor-intensive. - Data quality flagging not in place; manual or visual inspection of results. - Benchmarking accuracy and effectiveness using test data or cases.
Level 2a *Development - Testing*	- No deployed PMU-based model validation tools; currently under development. - Value proposition understood; working to develop tools to demonstrate. - Minimal or selective business units engaged to collect data and build tools. - Sufficient PMU data collected to perform model verification using PMUs. - Primitive data extraction and data handling techniques.

	- No focus on application data input and output quality; manual inspection. - Utilizing industry standards but no standardized tools or formatting.
Level 1 *Conceptual*	- N/A