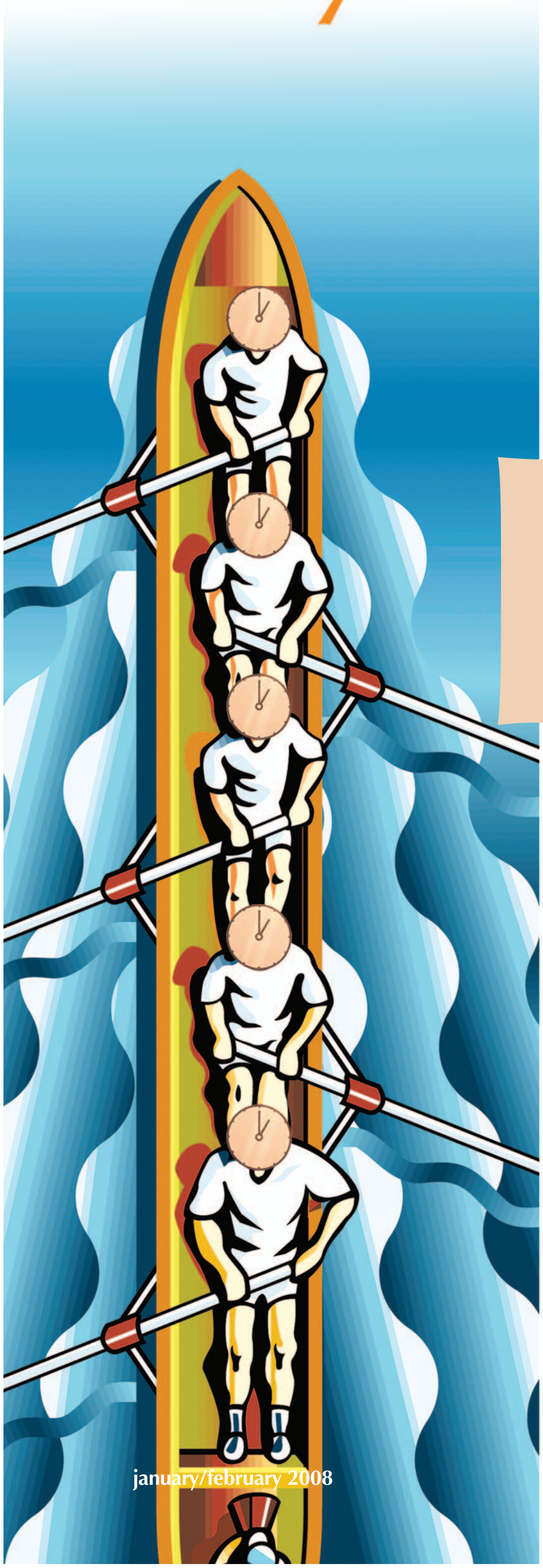
Dawn of the Grid Synchronization

Benefits, Practical Applications, and Deployment Strategies for Wide Area Monitoring, Protection, and Control



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RECENT INCREASE IN WORLD-WIDE DISTURBANCES, CONGESTION management challenges, and increased complexity in operating the power grid have emphasized the need for grid revitalization. Advanced applications in wide area monitoring, protection, and control (WAMPAC) systems offer a cost-effective solution to improve system planning, operation, maintenance, and energy trading. Synchronized measurement technology and applications are an important element and enabler of WAMPAC.

Time synchronization is not a new concept or a new application in power systems. As power system and telecommunication technologies have advanced, the time frame of measured and communicated synchronized information has been steadily reduced from minutes, to seconds, milliseconds, and now microseconds. At present, phasor measurement units (PMUs) are the most accurate and advanced time-synchronized technology available to power engineers and system operators for WAMPAC applications. This technology has been made possible by advancements in computer and processing technologies and availability of GPS signals. We are approaching an era where all metering devices will be time-synchronized with high precision and accurate time tags as part of any measurement. To achieve the potential benefits, advancements in time synchronization must be matched by advancements in other areas. One example is data communications, where communication channels have become faster and more reliable in streaming PMU data from remote sites to a central facility.

While advanced applications are in the development phase, PMU hardware is based on proven technology. Phasor measurement technology was developed

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near the end of the 1980s and the first products appeared on the market in the early 1990s. Presently, a number of vendors are either offering or developing components, platforms, and tools for the synchronized measurement systems (such as PMUs, data concentrators, data acquisition and communication systems, EMS/SCADA, market operations systems, etc.). Most of the PMU products are either based on existing platforms or have PMU functionality added to the existing products by simply adding hardware, such as a GPS receiver, to achieve accurate time stamping, memory storage, and data streaming methods such as IEC-61850 interfaces.

Several concurrent large-scale deployment projects (resulting from the recent widespread blackouts that make the integration of the synchronized measurement technology timely) have been initiated in different parts of the world in recent years. Examples include the North American Synchro Phasor Initiative (NASPI) led by NERC [an extension of he Eastern Interconnection Phasor Project (EIPP) that has been supported by Department of Energy (DOE)], the wide area monitoring system in the Western Grid of the North America, the Brazilian phasor measurement system led by ONS (the Brazilian ISO), the wide area monitoring system in China, various developments in Europe, etc. These efforts have shown the great potential of this technology to improve grid stability and outage avoidance, system analysis and modeling, and congestion management.

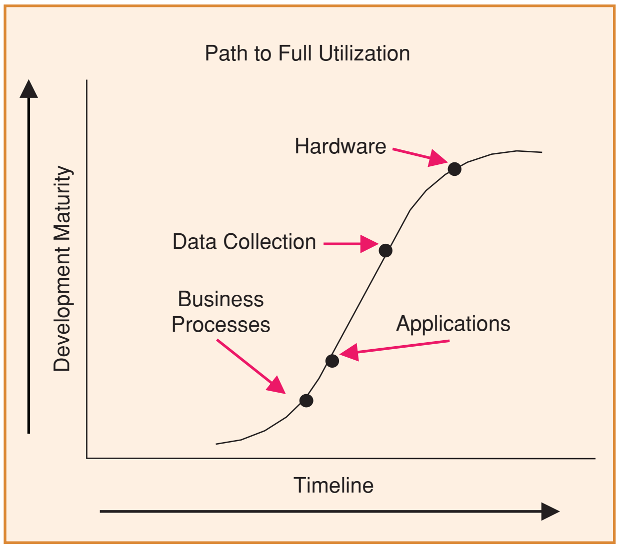

figure 1. Stages of development for key deployment factors.

While a number of applications based on GPS-synchronized data have already been developed, there is a need for vendors to continue improving existing and developing applications using the latest visualization techniques, intelligent operational tools using IEC-61850, advanced algorithms, and information semantics to improve grid reliability under complicated power system conditions. As business benefits for those new applications are not easy to define, given the large number and immaturity of applications and its market, vendors need both system and application requirements from users to justify investments in new products. This is one of the reasons for an "industry business case" analysis to provide useful insights to the expected commercial success and the societal and rate-payer value in deploying this promising technology. This analysis also helps identify policy, economic, and technology barriers to commercial deployment.

This article evaluates business justification for investing in deploying the synchronized measurement technology through assessing benefits of various applications for electricity consumers, transmission owners, and other market participants. It also reviews technology, identifies present implementation gaps, and presents a roadmap for the deployment of PMU applications in the near-term (one to three years), mid-term (three to five years), and longer-term (five to ten years). Results should assist various stakeholders (utilities, system operators, regulators, and vendors) in defining next steps in large-scale deployment of synchronized measurement systems with many useful applications.

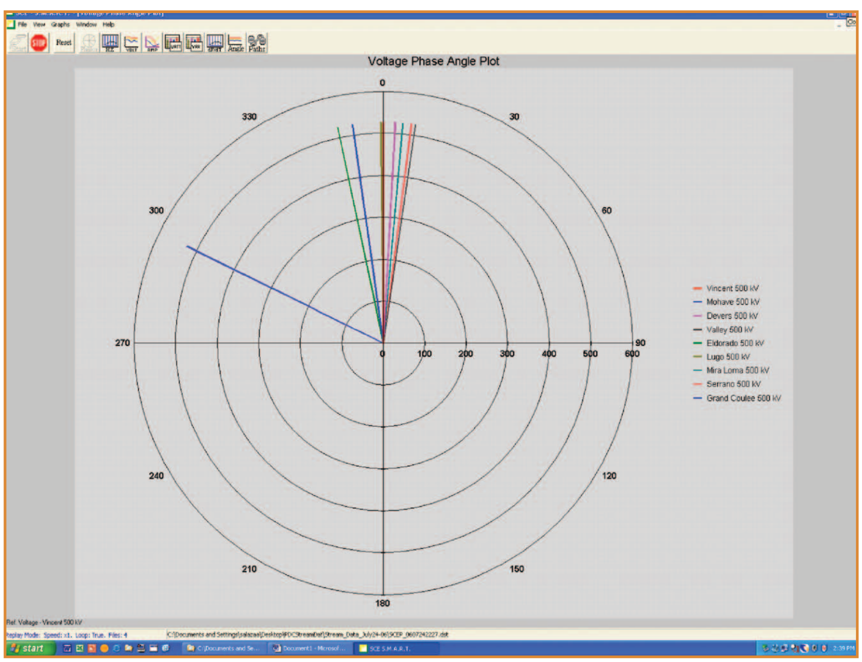

figure 2. Key system voltage angles: WECC disturbance on 24 July 2006.

Technology Enables Improving Electrical Power Grid Reliability

There is a large number of existing and potential applications of the synchronized measurement technology. As the phasor technology is deployed and as users gain experience and additional tools are developed, new applications will continue to be identified. Potential economic benefits could result in avoiding major system disturbances and in minimizing widespread blackouts. Major wide area outages cost consumers and power industry several billion dollars per major incident. Other benefits include reduction in congestion costs (estimated to be approximately US$250 million per year in California alone), reducing cost and time to analyze power system events, and providing means for quicker restorations following major grid outages.

A well-planned, system-wide PMU deployment, implementing optimal system architecture, is necessary to take full advantage of the technology. Once the adequate PMU system is built, incremental costs of adding applications are minimal in comparison to the added values received.

Two key application categories that benefit from the synchronized measurement technology are:

1) Avoidance and analysis of outages that may have extreme manifestation in blackouts:

- ✔ Due to its accuracy and wide area coverage, synchronized measurement technology is a paradigm shift enabling unique tracking of power system dynamics.
- ✔ Synchronized measurement applications enable true early warning systems to detect conditions that lead to

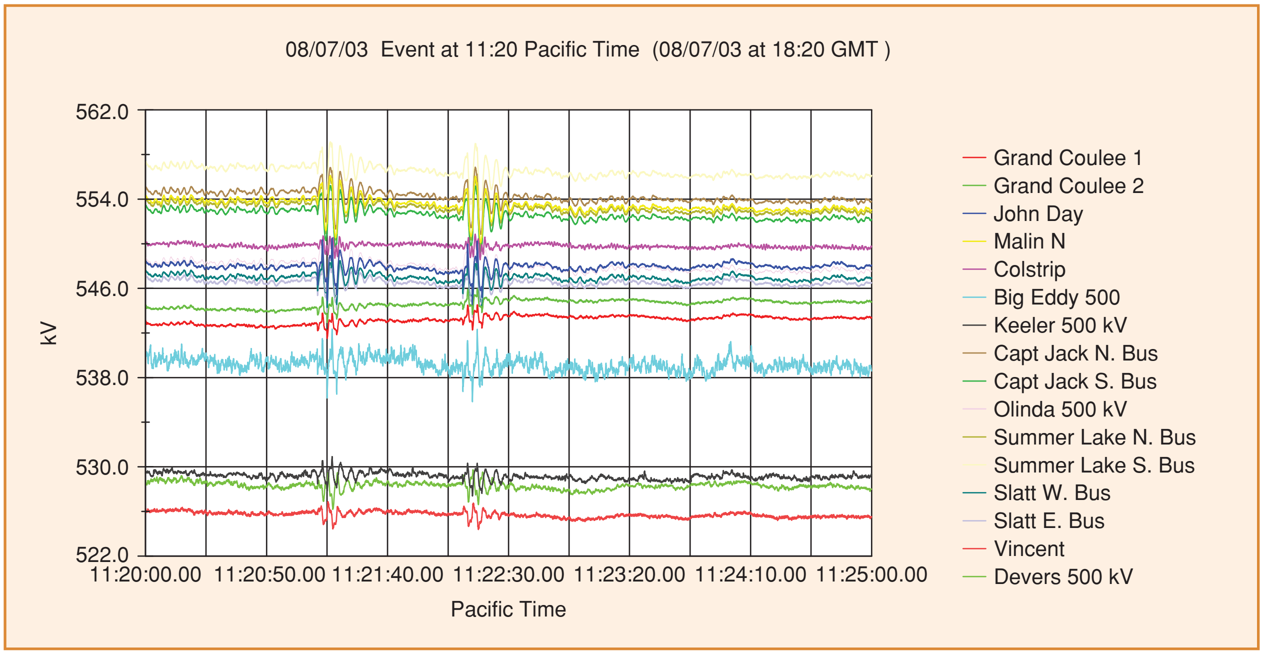

figure 3. Voltage plots for 500-kV substations with dc power injection at Celilo dc terminal.

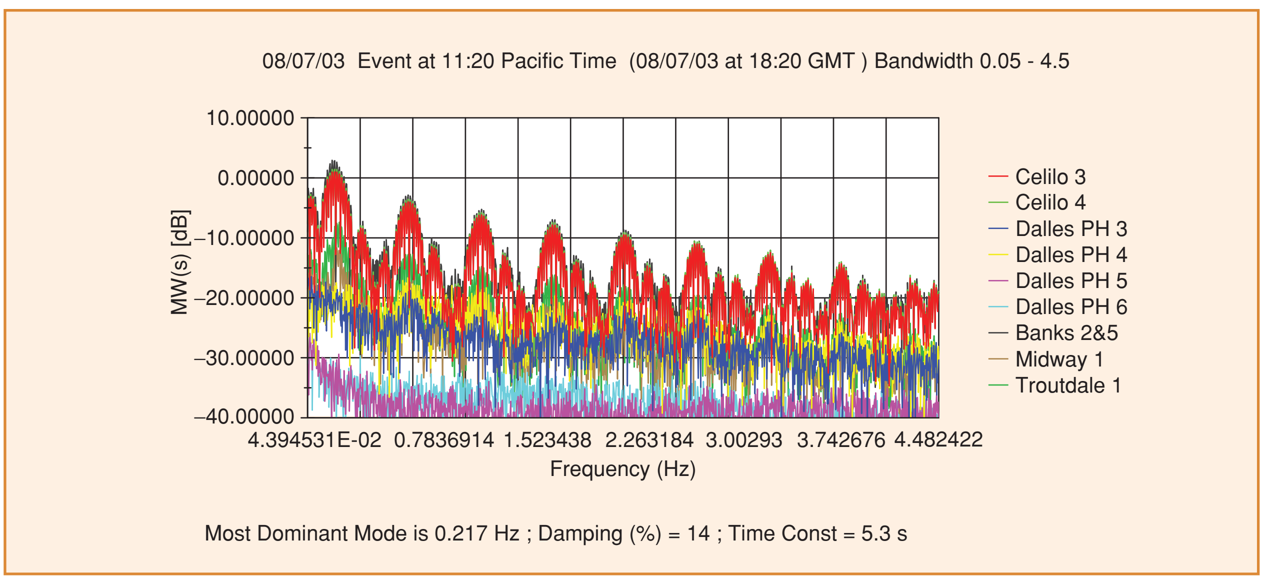

figure 4. FFT analysis at Big Eddy substation with dc injection.

catastrophic events, help with restoration, and improve the quality of data for event analysis.

2) Market and system operations

- ✔ Congestion mitigation through better system margin management is facilitated through synchronized measurement applications. Those applications allow real-time knowledge of actual system conditions as opposed to conditions defined by system models.
- ✔ State estimation solutions could be improved for various uses, such as locational marginal pricing calculations, thereby improving overall accuracy of calculations and associated energy clearing charges.

As more applications are identified or the research and development efforts lead the industry to more groundbreaking applications, system requirements and deployment strategies will further change. The need for more applications will further drive the development of new products and tools to support large-scale implementation. Other deployment challenges facing the industry include:

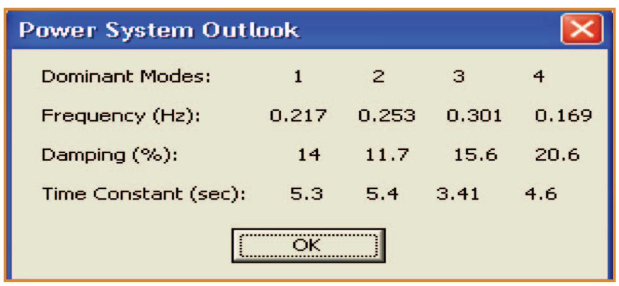

figure 5. Display of modal frequencies and damping for the dc injection test.

- ✔ design of a system that meets many diverse requirements
- ✔ ensuring the consistent performance of PMUs acquired from multiple vendors and installed, operated, and maintained by different entities; some of the major benefits result from the system-wide applications requiring PMUs to be connected across utility boundaries.

Figure 1 shows various stages for key deployment factors. Hardware development is ahead of the data collection, applications, and business processes. While technology for data collection and required system architecture exists, many of the commercially available products need enhanced capabilities for synchronized measurement applications as users are looking for ways to quickly present the collected data in the form of actionable intelligence. Particular effort is required in developing standard application and system integration products as well as investment by users in setting up operational and business processes.

Implementation of synchronized measurement technology requires investment and commitment by regulators, power companies, and vendors. The necessary investments include application studies, system architecture design, equipment purchase and upgrade, development of tools that provide actionable intelligence, maintenance, resource allocation, and training. It is also required to identify major requirements for the overall system and select major applications that would benefit both the individual systems and the interconnected grid.

Benefits of Using Wide Area Monitoring, Protection, and Control

This section describes a summary of 11 major application areas with focus on benefits and implementation gaps (Table

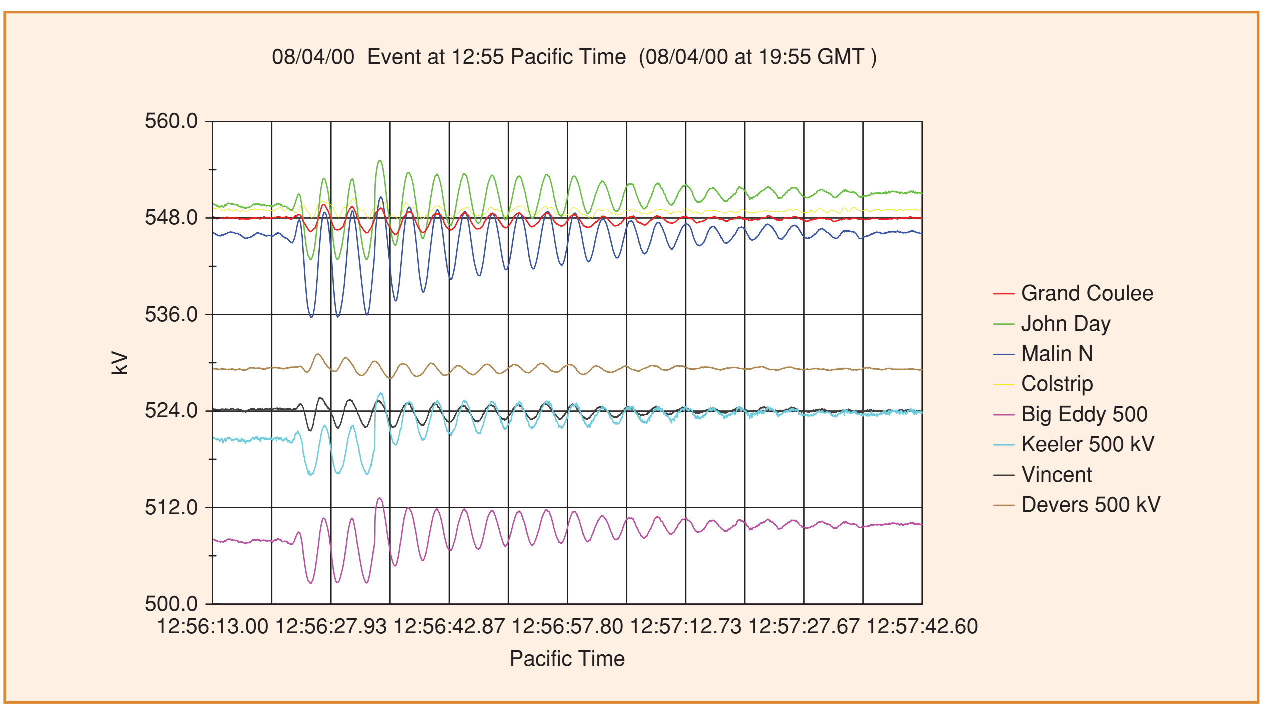

figure 6. Voltage oscillations during WECC system disturbance on 4 August 2004.

1). The list is as comprehensive as possible, given today's PMU deployment status and applications identified by the industry. As time progresses, these areas refined and extended while additional applications identified as PMU systems will become more widely deployed. At present time, only a few of these areas have been implemented and used on-line; examples are presented in Figure 2 through Figure 7.

The display shown in Figure 2 is actually a dynamic angle display that could be used for both postdisturbance analysis and as an operational tool to help during the disturbance.

The following example shows the voltage magnitude signals (Figure 3), FFT analysis at one of the substations (Figure 4), and a table showing the dominant modal frequencies and damping parameters important for analysis of inter-area oscillations (Figure 5). Figure 3 shows the dc injection at 0.25 Hz square wave. The odd harmonics of the 0.25 Hz injected signal can be seen clearly in Figure 4.

Our next example shows how the PMU system enabled post-disturbance analysis and provided information on what operated correctly that would otherwise not be possible. Figure 6 shows the operation of a capacitor bank near the Keeler substation that provided the reactive power and enabled a system to damp out the oscillations, which otherwise could have resulted in system break-up. Also, note the step change in voltage at the Keeler substation resulting from the capacitor bank.

The following example is one using PMUs for analyzing restoration. PMU measurements were very useful during a disturbance in Europe on 4 November 2006. Figure 7 shows PMU readings for reclosing attempts between two areas, including the final successful reclosing between those two areas and, consequently, with the third area. Although operators did not use PMU data during their reclosing attempts, PMU measurements were very valuable for postdisturbance analysis. Using the PMU data during restoration could have helped avoid unsuccessful reclosing attempts.

Business Justification for Synchronized Measurements

To bring the synchronized-measurement technology closer to the commercial operation and integrate into daily decisions or actions, it is necessary that a systematic process be followed to plan for the infrastructure design, to delineate benefits, and

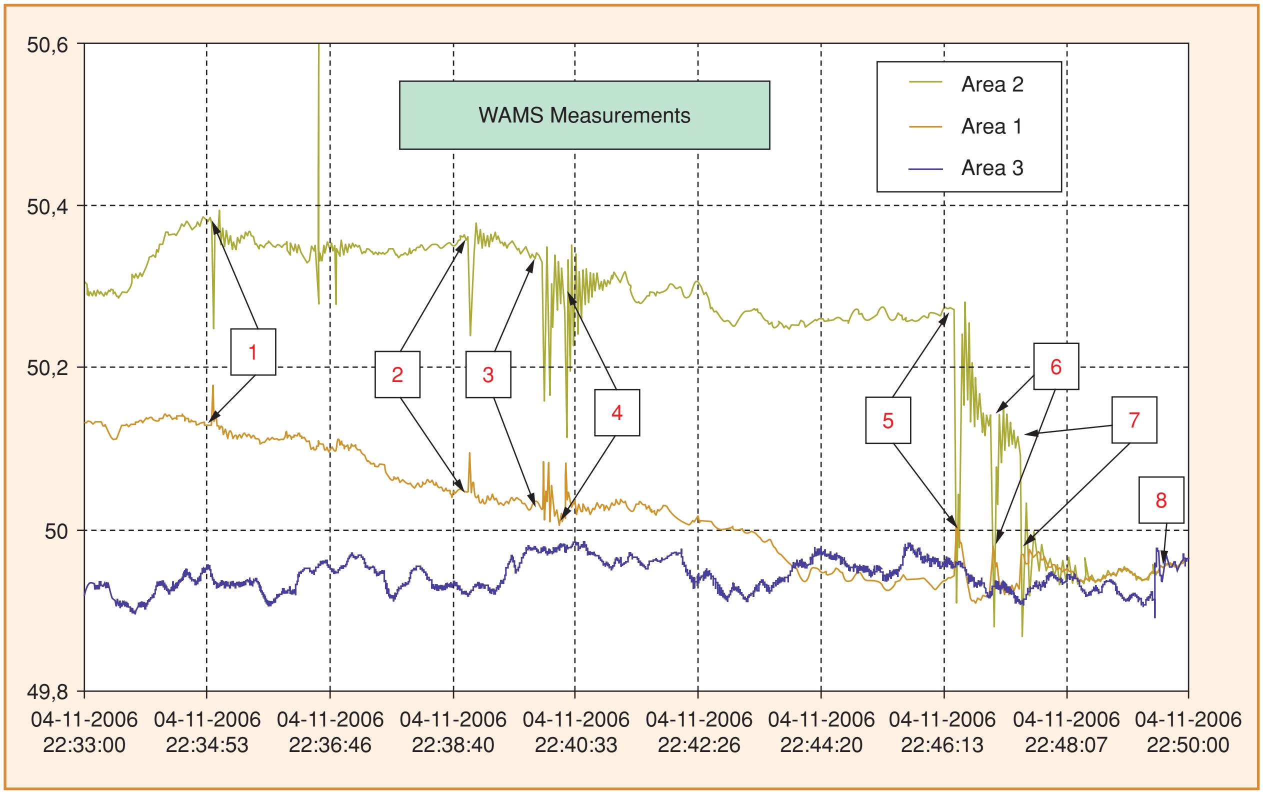

figure 7. PMU measurements from three areas during reclosing attempts: UCTE disturbance 4 November 2006.

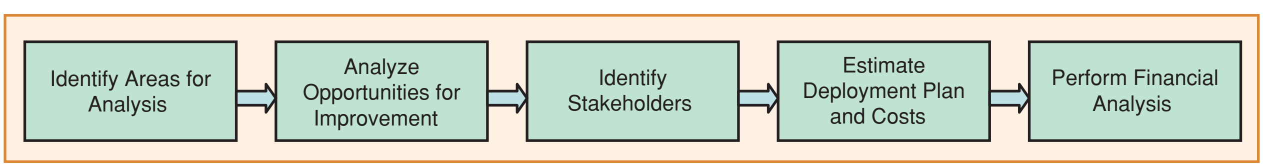

figure 8. The five-phase process for business justification of synchronized measurement technology.

table 1. Status of wide-area monitoring, protection, and control applications.

Application	Benefits and approach	Beneficiaries/Status	Implementation costs/gaps
Real-Time Monitoring and Control	Early indication of grid problems (abnormal angle difference; inter-area oscillations; voltage stability); enabling operators to assess stress on the grid, and take timely actions. Figure 2 shows a typical screen available to the System Operators in California as a part of the real-time tool. In general, phase angle differences or the rate of change of the phase angle could be displayed as numbers, vector or bar graphs (using a reference angle), and/or angle-time curves. In addition, the phase angle display may be stand-alone or superimposed onto a network diagram.	Rate payers ISOs, utilities, and neighboring systems. Phase-angle and oscillation monitoring are currently in the initial deployment phase by some major utilities. The information is yet to be linked to well-defined follow-on actions and procedures.	Basic PMU set-up. Current lack of: commercial-grade tools; established process in control centers; drill scenarios for operator training, the operator training; "to-do" list when a certain observation (such as oscillations) is detected.
State Estimation (SE)	Three complementary approaches provide benefits: — "Evolutionary" solution: Improvements achieved by adding synchronized measurements to existing SE measurement set and applying "meter placement" methods to determine most beneficial PMU locations. — "Revolutionary" (next generation SCADA): State measurement solution with synchronized measurements instead of estimation for full system observability. — "Equivalent" solution: For ISO/RTO SE applications to represent "boundary conditions" for the utility SE.	Utilities, ISOs and rate payers. Major EMS vendors are incorporating PMU measurements into their SEs. A number of utilities are having pilot projects.	Basic PMU set-up. Interface issues between PMU measurements and legacy SCADA. Revolutionary approach requires massive PMU deployment (30%-40% of buses). It enables more accurate and frequent calculations and foundation for "closed loop" control. Strategy should include ways to transition additional PMUs as they are installed without major redesign of the tools.
Real-Time Congestion Management	Synchronized measurements make it possible to operate the grid according to true dynamic limits, not conservative limits that are derived based on off-line studies for worst-case scenarios. Offers improved visibility of flowgates with improved detection of angular stability, voltage stability, low-frequency oscillations, and thermal constraints.	Utilities, ISOs, power producers, and rate payers. No commercial-grade application in real-time. Applications are in place for monitoring and comparing results against current practices.	High requirements for data communications and real-time data processing. Requires adequate system visibility and tools to compare measurements with evaluated contingencies to keep dynamic margins and make adjustments. The gap is in industry and staff adoption of new rules and procedures.
Post-Disturbance Analysis	Quick troubleshooting of power-outage events. PMUs are a must-have resulting in savings in troubleshooting time (several orders of magnitude) and resources. Expediting outage analysis also enables faster restoration and, as PMU compresses data, more efficient data storage and transmission. Since outages in 1996 and 2003, it has been demonstrated that the outage investigations could be significantly reduced.	Utilities, regulators, ISOs. Very precise synchronization has already shown significant benefits. An example of using PMUs for post-disturbance analysis is shown in Figure 6.	Deployment is low cost (use local storage instead of real-time data communications). Supporting software tools required to assist in data analysis are still lacking.
Benchmarking, System Model, Validation, and Fine-Tuning	Better model parameters (based on PMU data) allow for more accurate computation of control actions. Identify errors in system modeling data and for fine-tuning power system models for both online and offline applications (power flow, stability, short circuit, OPF, security assessment, modal frequency response, etc.). Portable PMUs could be used.	Utilities and ISOs. Although already in use, applications (particularly for dynamic and oscillatory modes) need to be further developed.	Low-cost deployment. Need is to develop a systematized approach for model validation and parameter estimation (PE), as well as methods that integrate measurements into the PE. Actual field data needed for model development and the PE.

table 1. (continued)

Application	Benefits and Approach	Beneficiaries/Status	Implementation Costs/Gaps
Power System Restoration	Timely and proper decision to bring equipment back into service without risking stability or unsuccessful reclosing attempts. Ability to directly measure system conditions, e.g. operator knows if it is feasible to reclose the tie line or reconnect substation. This is valuable tool for operator who is under pressure to reenergize the grid—increases confidence level for the decision.	General public, utilities, ISOs, power producers. Key element is phase-angle monitoring, which is commercially available. Field experience is still lacking.	Basic PMU set-up. The barrier is in procedures and guidelines for real-time data integration, as well as to get operator trained and confident. Simulators needed to provide trainee with feedback signals that simulate direct measurements.
Protection & Control Applications for Distributed Generation	Highly precise detection of islanding. PMU facilitated coordination can allow a micro-grid to continue to operate in island mode until the utility grid disturbance is resolved, reduced blackout likelihood.	Independent power producers, utilities, regulators. Pilot installations are underway.	Cost of using PMUs remains a high percentage of DG project cost.
Overload Monitoring and Dynamic Rating	Tracking the line impedance in real time helps improve any application that makes use of line-impedance data: — Calculate the impedance of the line in real time to estimate the average temperature over the length of the conductor and track line loading. This application only provides the average temperature of the whole line — hotspots, conductor sags or critical spans are not visible. — Actual on-line line parameter data for accurate fault location: faster restoration for permanent faults and better detection of week spots for temporary faults.	Ratepayers, utilities, ISOs. Overload monitoring commercially available but not used in any decision-making process.	Modest implementation cost: Two PMUs at ends of the tie line and communications to a processing facility. Slow data rate is ok, but time stamping has to be precise. Instrumentation errors may significantly impact results.
Adaptive Protection	Improving existing relay algorithms by making certain functions/parameters self-adjustable based on changing system conditions. Some potential applications: — Adaptive security & dependability to avoid cascading. — Improved out-of-step protection schemes (incl. multi-machine instability). — Improved backup protection. — Intelligent load shedding.	Utilities, ISOs.	Barriers include: dedicated data high-speed communications, field experience, industry acceptance, cost.
Real-Tme Automated Control	Major benefits for automated prevention of angular stability, voltage stability, low-frequency oscillations, and thermal constraints. Support optimized and integrated control with FACTS, SVC, HVDC.	Rate payers, utilities, ISOs, power producers. In RD&D phase.	A very fast and accurate system requires a high price.
System Integrity Protection Scheme (SIPS)	Improved planned separation of power system into islands when instability occurs. — More accurate detection whether a power system is heading to an unstable state and if a network separation is necessary to avoid a catastrophic failure. — Dynamically determine islanding boundaries according to the prevailing system conditions (e.g. among which groups of generators the loss of stability is imminent and how to optimally balance load and generation in each island).	Utilities, ISOs, power producers. Under investigation by a few utilities.	Adding PMU measurements to the existing SIPS is within the scope of the technology. More demanding applications may require a large number of synchronized data points and dedicated fiber-optic channels so that data latency can be limited to less than 50 ms. Coherency detection algorithms and self-sufficient island identification algorithms would need to be further developed and tested.

> Potential economic benefits could result in avoiding widespread blackouts and reducing congestion costs.

to justify the expenses that might be incurred. As with any new technology, the following steps (Figure 8) need to taken into consideration:

- ✔ Phase I involves determining the desired state based on the current and projected operating environment. The focus is on understanding performance gaps with the existing technologies and practices and in recognizing the value of PMU in bridging the gaps. The key objective is to identify an organization, function, activity and/or process to improve and to define the criteria for success.
- ✔ Phase II includes the delineation of issues specific to the organization that can be addressed by the PMU technology. Key activities in this phase include: focusing on the problem area for analysis and collecting data/information to quantify the benefits.
- ✔ Phase III identifies the stakeholders and the benefits that PMU may mean to them. This is important in the case that the investment must be made by more than one organization. Understanding the benefits to each stakeholder can help articulate the "sale" of the technology to that particular stakeholder.
- ✔ Phase IV provides an expected plan for PMU deployment to be integrated into the annual capital investment by the power companies. The deployment typically takes several years.
- ✔ Phase V compares the projected benefits over a time horizon with the initial investment costs and recurring (annual) costs. A number of project valuation techniques can be used to arrive at a decision of whether the project should start or not.

A multiple-purpose deployment is the means to reap major benefits from the PMU technology. This is because the same capital investment can be used by different subject areas, stacking up the benefits. This kind of deployment, however, requires a careful analysis and planning as the capital investment is high.

A comparable analogy in investment versus benefits may be in the area of integration of protection and control using the latest commercially available technology. Cost justification for comprehensive upgrade programs comes from a combination of various benefits. Those benefits do not result only from upgrading equipment but deploying an integrated system using an enterprise information technology architecture to enable collecting required data and processing and distributing information when and where required for use by various applications and users.

In a multipurpose deployment, the PMU sites are in "shared use" for a number of purposes. As some PMU applications might still be in experimental stages, a time lapse parameter, before the benefit is actually realized, needs to be accounted for. The time lapse is due to issues such as personnel training, experience gathering, incorporation into existing technical and business processes, software and hardware debugging, etc. In a typical organization, all requirements need to be deployed over several budget cycles. The next step in the process is to develop an optimal deployment plan, i.e., which PMUs are to be deployed first so that the budget allocation for each year is met, while the benefits are to be realized as early as possible.

A concrete example to illustrate financial benefits for a typical utility company (~80 GWh, 15-k transmission miles) is based on the following assumptions of the PMU system benefits:

- ✔ preventing blackouts (from "one event in five years" to "one event in ten years")
- ✔ reducing system disturbances (from "three events/year to one event/year")
- ✔ reducing generator tripping (from "six to two events/year")
- ✔ reducing postmortem analysis by 50% and speeding up system recovery
- ✔ accurate congestion margin assessment reducing costs by US$2.4M/year.

The above benefits and their financial impact, PMU system components to achieve those benefits, and costs of the overall PMU systems, are based on information from this particular utility, as well as from interviewing NASPI leadership. For a fully deployed system, even with conservative assumptions (without considering all potential future benefits) the total net present value (NPV) (ten years) was calculated at over US$44M.

Path to Deploying Wide Area Monitoring, Protection, and Control

Implementing a large-scale PMU system presents some unique challenges. Some challenges are technical, as PMU systems need to transmit, process, and store vast amounts of data. An ideal PMU system architecture should properly address the following issues:

- ✔ Scalability: As the number of installed PMUs and IEDs with integrated PMU functions increase gradually, the system architecture must be designed so that it can keep up with this trend.

- ✔ Flexibility: As many of the system components will be acquired, installed, operated, and maintained by different entities, the system architecture should be flexible to accommodate the diverse requirements of various entities.
- ✔ Communications bandwidth and latency: In the new paradigm, on-going communications cost (leased from service providers or inter-company network) could become the main cost item of a PMU system. Reducing the bandwidth requirement will help to reduce the on-going cost of PMU applications. Minimizing the communication bandwidth requirement will also help to reduce the latency of the PMU data transferring. For real-time applications, reducing the communication latency is a must.

Other challenges include coordinated strategy and collective actions among stakeholders. To facilitate a large-scale deployment of PMUs, the following process is proposed to the industry to speed up deployment and minimize costs:

- ✔ Roadmap Development: Each PMU user in the grid should develop a near-, mid-, and long-term application/technology deployment roadmap. This roadmap would include application requirements that would guide PMU installations and system architecture needs locally and regionally.
- ✔ Overall Infrastructure Architecture: Organizations such as NERC ERO, NASPI and regional councils such as the Western Electricity Coordinating Council (WECC) should champion required data exchange and the development of the overall system infrastructure. Based on individual user requirements, it is necessary to develop system architecture designs, specifications, and deployment plans. All users connecting to the overall architecture would need to fulfill key integration requirements (hardware and software interoperability, data quality, etc). It is also beneficial to prioritize applications from the grid perspective.
- ✔ Network Protocols, Software and Firmware Upgrades, and Data Access Security: The consistent and accurate performance of all PMUs is the key to the overall performance of the system. Develop uniform requirements and protocols for data collection, communications, interoperability, and security through standards (NERC, IEEE, WECC, NASPI) and testing procedures. Assure ease of PMU upgrades (particularly considering the novelty of the IEEE C37.118 standard) and calibration.
- ✔ Regulatory Considerations: Regulators at both federal and state levels need to provide incentives for technology deployment considering significant benefits for rate payers and transmission system reliability.
- ✔ Company Process: Each user should set up operational and business processes for installations, operations, maintenance, and benefits sharing. This would be comprised of creating projects with defined deliverables and deadlines; identifying asset owners, managers, and service providers; setting up procedures and rules; educating and training users; and facilitating culture change.
- ✔ Research and Development: Continue investing in RD&D (DOE, PIER, vendors, users, etc.) and promote developing and sharing test cases to develop new applications. Also, continue using a proven approach of pilot projects to gain experience and confidence.

Full financial and reliability benefits of this promising technology can be realized by a collective process among all stakeholders including the general public and the ratepayers. A significant market penetration of this technology is possible through a collaborative process to engage suppliers and manufacturers in developing the required tools and products.

Deployment Roadmap and Recommendations

Given the nature of PMU implementation requiring participation of a broad base of users, the "overall industry roadmap" is an important step in designing and deploying large-scale PMU systems. Based on an interview process with industry experts and users, the roadmap has been developed to serve as a base for development of individual deployment roadmaps and guidance to the vendors to prioritize their efforts. This roadmap, shown in Figure 9, is based on applications' business needs, commercial availability and cost, and complexity with deploying those applications.

First, industry needs are identified (critical, moderate, unknown) regardless of technology. Second, the value of the PMU technology, for each identified application, has been mapped related to importance in serving industry as necessary, offering additional benefit, or requiring more investigation. Third, deployment challenges have been mapped for each application (low, medium, high). The deployment challenges are defined based on technology (communications and hardware and software requirements and development status) and applications status (commercially available, pilot installation, in the research phase, not developed yet). Business case examples described in more detail in the phasor measurement application study by California Energy Commission provided data to create the information in Figure 9.

The following applications have a major improvement impact with PMUs: angle/frequency monitoring, postmortem analysis, model benchmarking, outage prevention (including planned power system separation), state measurement, and real-time control. As for the rest of the applications, non-PMU technologies are available; however, the deployment of PMUs allows the same measurements to be used to realize additional benefits from the same investment (integrated approach). The matrix provides the basis to create the near-, mid-, and long-term deployment roadmap. The resulting roadmap is shown in Figure 10, where the applications are grouped into near term (one to three years), medium term

The most obvious "low-hanging fruit" for which PMUs provide major benefits are angle/frequency monitoring and postmortem analysis (including compliance monitoring).

(three to five years), or long term (more than five years). This roadmap differs from the RD&D roadmap as it focuses on business and reliability needs to commercialize and deploy PMU technology and applications.

Note that the list of applications in Figure 9 and Figure 10 appears to be larger than the 11 groups under the Benefits section. This is because some groups were too broad and needed to be subdivided to address specific utility problems. For example, real-time monitoring and control is subdivided into angle/frequency monitoring, voltage stability monitoring, real-time control, and wide area stabilization.

Applications in the near-term group reflect the immediate needs. For this group, the applications are commercially available (either at present time or will be soon offered by a vendor based on the status of the working prototypes). They also reflect the fact that the deployment can be achieved rather quickly due to factors such as the applications can be used for specific spots on the grid and the infrastructure requirements are relatively modest. These applications can be termed "low-hanging fruit." The most obvious "low-hanging fruit" for which PMUs provide major benefits are angle/frequency monitoring and postmortem analysis (including compliance monitoring).

Applications in the medium-term group largely reflect that even though the needs are great, the commercial prospect is still far off as no working prototypes are known to exist.

Applications in the long-term group indicate a combination of distant commercial status, extensive infrastructure requirements (and thus costs), and/or that lengthy field trials are required to gain acceptance by end users. For example, the wide area stabilization application, even though commercially ready, remains to show its superiority to the conventional power system stabilizers.

Three complementary approaches exist in using PMU technology with state estimation: conventional SE improvement (evolutionary), boundary conditions SE, and state measurement (revolutionary). These concepts are considered to be elements of short- to long-term PMU deployment strategy as increasing numbers of PMUs are planned locally and

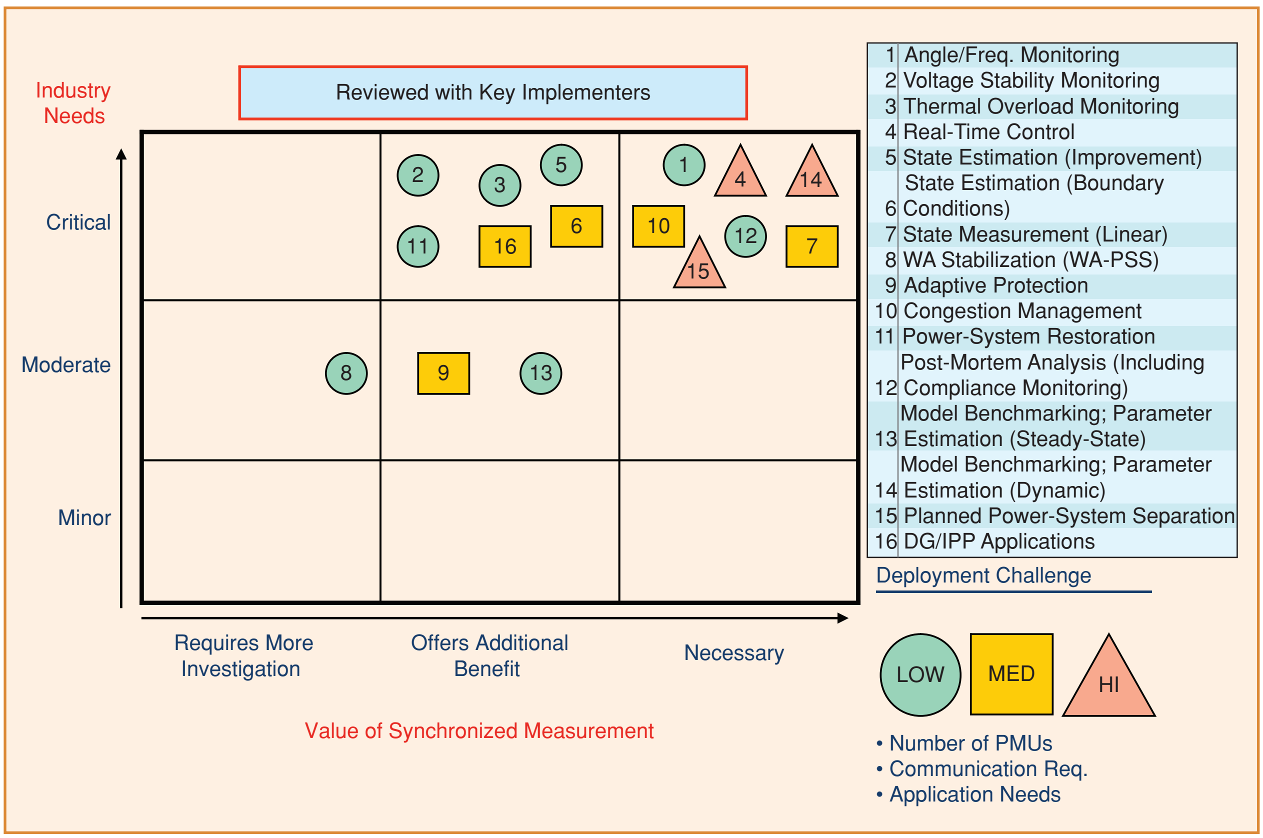

figure 9. Synchronized measurements and industry needs.

The wide-area stabilization application, even though commercially ready, remains to show its superiority to the conventional power system stabilizers.

regionally. In fact, the revolutionary case is a natural extension of the evolutionary approach as numbers of PMUs installed increase over time. Use of PMUs for representing boundary conditions will stem from system-wide regional deployment.

Conclusions

PMU applications offer large reliability and financial benefits for customers/society and the electrical grid when implemented across the interconnected grid. As measurements are reported 20 to 60 times per second, PMUs are well suited to track grid dynamics in real time. Compared to current EMS monitoring tools that use information from state estimation and SCADA over several-second intervals, time-synchronized PMUs introduce the possibility of directly measuring the system state instead of estimating it based on system models and telemetry data. Implemented properly, the technology also allows for providing data integrity validation without added cost. This technology is instrumental for:

- ✔ improving WAMPAC in real time including early warning systems, system integrity protection scheme, detecting and analyzing system stability, and enabling faster system restoration
- ✔ faster and more accurate analysis of a vast number of data during transient events
- ✔ validation and development of power system models.

Power companies could realize financial benefits if several integrated applications are deployed using basic PMU system infrastructure. The above conclusions have been achieved through comprehensive analysis of various applications and related financial benefits using concrete data on PMU system related costs and industry experiences with PMU implementation obtained through a number of interviews and literature search.

Synchronized measurement capability has advanced technologically to the point that commercial implementation of selected applications is both possible and warranted,

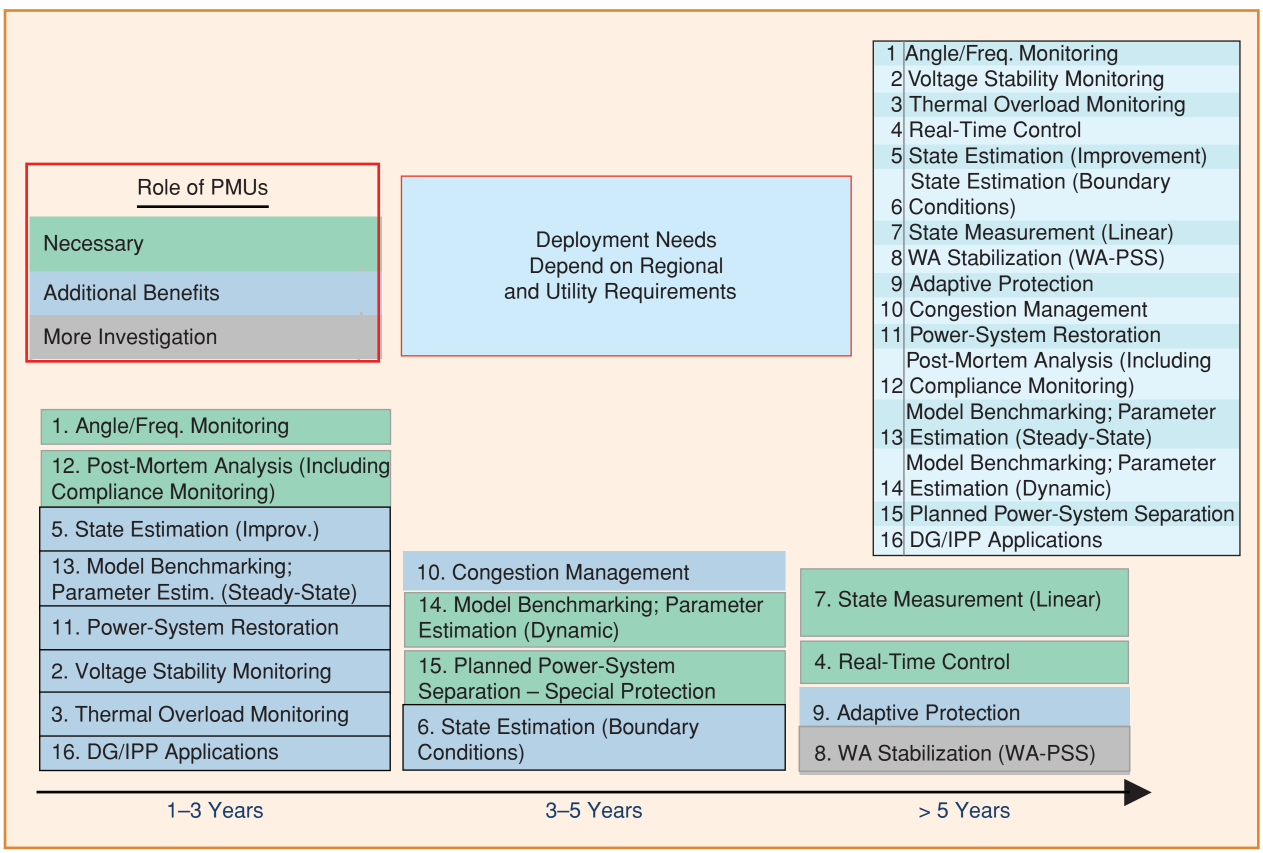

figure 10. Roadmap for deploying PMU applications.

Time-synchronized PMUs introduce the possibility of directly measuring the system state instead of estimating it based on system models and telemetry data.

representing prudent investment. Furthermore, the implementation and use of this technology is necessary for the levels of grid operational management that are required for efficient use of the infrastructure currently in place as well as for infrastructure enhancements of the future. To gain the benefits offered by this technology, a coordinated effort among utilities, ISOs and other entities must be undertaken, with a coordination level beyond the present activities. Without a system-wide approach, the capabilities and associated benefits will not be achieved in the manner possible. This requires an effort that includes a bottom-up approach from utilities in defining the needs and PMU applications and a top-down approach from the system regulators and coordinators to define an integrated infrastructure to optimize the benefits offered by the technology. Also, regulators at both federal and state levels need to provide incentives for technology deployment, particularly considering significant benefits for ratepayers and transmission system reliability.

There is a need for vendors to fully productize applications presently in an RD&D phase and to develop new, promising applications. Vendors need both common system architecture requirements and common application priorities from users to be able to justify investments in new products. Provided common application priorities and deployment success factors help guide deployment priorities for individual users and development priorities for vendors, as well as support regulators and coordinators in prioritizing their efforts.

Well-planned, system-wide synchronized measurement deployment infrastructure is necessary to take full advantage of the technology. It requires organizations such as NERC ERO, NASPI, and WECC to facilitate required data exchange. They also need to facilitate certain system-wide deployment of "low-hanging fruit" applications to speed up achieving key benefits of synchronized measurement technology.

In summary, the findings described in the article should serve as a base for deployment of individual roadmaps by the users and guide vendors to prioritize their development to support the grid revitalization and reliability for the 21st century.

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