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BENEFITS OF PMU TECHNOLOGY FOR VARIOUS APPLICATIONS

SUMMARY

Traditional security assessment approach – based on SCADA data and off-line studies conducted long in advance of real time operations -- are becoming increasingly unreliable for real time operations because they cannot fully anticipate all the conditions faced by operators. New technologies, which rely on accurate, high-resolution, real-time monitoring of actual (not hypothesized) system conditions using phasor measurement technologies, are needed to support the real-time operations. The purpose of these tools and systems is to monitor, assess, enable, and ultimately, automatically take the necessary control action to prevent or mitigate problems in real time.

The proposed applications of phasor measurements will provide the real-time operating staff with previously unavailable yet greatly needed tools to avoid voltage and dynamic instability, and monitor generator response to abnormal significant system frequency excursions.

The objective of this paper is to point-out benefits of using PMUs for selected real-time applications and present ongoing pilot projects and experience worldwide, and to give short and long term roadmap for future acts.

Keywords: PMU – Phasor Measurement Unit, WAMPAC – Wide Area Monitoring Protection and Control, Real Time Application, GPS

SAŽETAK

Tradicionalni pristup procjene sigurnosti elektroenergetskog sustava (ees) zasnovan na SCADA sustavima, off line proračunima i analizama, je nesiguran za djelovanje operatora u realnom vremenu. Implementacija nove tehnologije zasnovane na točnom, nadzoru ees-a uzimajući u obzir visoku rezoluciju mjerenja i stvarne prilike, a korištenjem tehnike mjerenja fazora (phasor measurement technology) su neophodne za provedbu operacija u realnom vremenu. Svrha implementacije predložene tehnologije je nadzor, procjena sigurnosti i u konačnosti automatsko djelovanje u cilju sprečavanja problema u ees-u u realnom vremenu.

Predložene aplikacije zasnovane na mjerenju fazora omogućavaju osoblju djelovanje u realnom vremenu, koje prije nije bilo moguće, kako bi se spriječila naponska (dinamička) nestabilnost, te omogućio kontinuirani nadzor frekvencije .

Ovaj članak je usmjeren prema isticanju prednosti tehnologije mjerenja fazora, prilikom korištenja aplikacija u realnom vremenu i prikaza dosadašnjeg stanja u svijetu, te davanja glavnih smjernica budućeg istraživanja i razvoja.

Ključne riječi: PMU – Phasor Measurement Unit, WAMPAC – Wide Area Monitoring Protection and Control, Real Time Application, GPS

1. INTRODUCTION

Congestion issues and worldwide disturbances have emphasized a need for a grid to be enhanced with wide area monitoring, protection, and control (WAMPAC) systems as a cost-effective solution to improve system planning, operation, maintenance, and energy trading [1] [2]. WAMPAC systems should take advantage of the latest advances in sensing, communication, computing, visualization, and algorithmic techniques and technologies. Synchronized Phasor Measurement technology and applications are an important element and enabler of WAMPAC [3]. Technology components and platforms (such as PMUs, Data Concentrators, Data Acquisition systems, Communication Systems, EMS/SCADA, Market Operations Systems, etc.) required to implement and benefit from the synchronized measurement applications are already available.

Time synchronization is not a new concept or a new application in power systems. As technology advances, the time frame of synchronized information has been steadily reduced from minutes, to seconds, milliseconds, and now microseconds. Industry observers foresee a future where all metering devices will be time-synchronized with high precision and time tags will be a normal part of any measurement.

Phasor measurement technology (for applications in the power industry) was developed near the end of 1980s and the first products appeared on the market in the early 1990s. Presently, a number of vendors are either offering or developing products using this technology. Phasor Measurement Units (PMUs), together with Phasor Data Concentrators (PDCs), have already been implemented worldwide. Recently, some large-scale phasor measurement deployment projects, such as the Eastern Interconnection Phasor Project (EIPP) supported by DOE, have also been initiated.

At present Phasor Measurement Units (PMUs) are the most sophisticated time-synchronized tool available to power engineers and system operators for wide-area applications. This tool has been made possible by advancements in computer technology, and availability of GPS signals. To achieve the benefits, advancements in time synchronization must be matched by advancements in other areas. One area is in data communications, where communication channels have become faster and more reliable in streaming PMU data from remote sites to a central facility.

An area that needs improvement is instrument transformer, which affects the quality of the signals supplied to the PMU. New transducers (such as optical) have offered some improvements, but at a cost. More work is needed to reduce the error introduced by traditional instrument transformers, such as: better testing and dynamic response information from manufacturers; digital-compatible secondary voltages and currents; software means that use redundancy in measurements to correct errors introduced by existing instrument transformers and other devices [4].

The third area is in developing applications, i.e., software that operates on the data provided by the PMUs. Although academia, vendors, utilities, and consultants have developed a large number of methods and algorithms and performed system analysis and studies to apply the technology, like any other advanced tool, PMUs are good only in the hands of trained users. For example, one of the proposed applications of PMUs is their use on control for monitoring, alarm, and control operations. The technology exists today to bring the PMU information into the control centers and present it to the operators in a graphically processed form.

2. OVERVIEW OF WAMPAC ARCHITECTURE

2.1 PMUs

A PMU at a substation measures voltage and current phasors with microsecond accurate time-tagging of when the measurement was taken.

PMU compute power from the measurements (MW/MVAR) and frequency. Measurements are reported at a rate of 20-60 times a second.

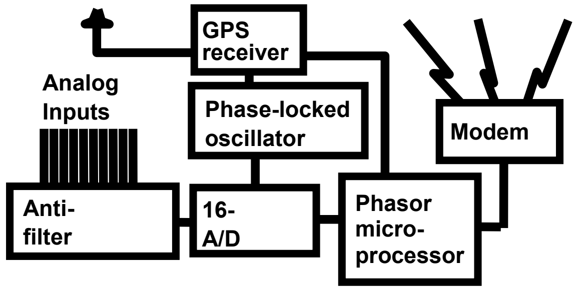

Figure 1. PMU architecture

PMU technology is well-suited to track grid dynamics in real time (SCADA/EMS refresh rate is seconds to minutes). Each utility has its own Phasor Data Concentrator (PDC) to aggregate and align data from various PMUs based on the time tag. Measurements from each utility's PDC is sent to the Central Facility where the data are synchronized across utilities.

Applications at the Central Facility provide a grid-wide snapshot at a sub-second rate necessary to accurately track grid dynamics.

2.2. WAMPAC System Architecture

New emerging technologies for real time wide-area monitoring, control and protection have been directed mainly into the following three directions: [5]

• Monitor, control and protect the transmission system against spreading of disturbances and their negative consequences, i.e. blackouts. The majority of control areas operate their power network according to N-1 criteria. However, facing new operational market-based environments with minimal possibility to influence the generation dispatch and resulting operation of the system under conditions for which it has not been designed is now forcing control areas to use, analyze and monitor risk based N-0 criteria to accept the higher risk and reinforce their wide area monitoring, protection and control systems.

• Increase transmission capacity in particular transmission corridors, mainly between two different electricity markets or reducing congestion within different electricity markets.

• Improve transmission assets utilization by refining the planning, operation, control, protection processes and models.

The research, development and application of phasor technology for power system operations during the last twenty years in different parts of the world have demonstrated that systems built using this technology can be very effective to meet the above three objectives and can respond to the new wide area operational challenges in three major areas:

• Real Time Wide-Area Monitoring and Analysis
• Real Time Wide-Area Control
• Real Time Wide-Area Adaptive Protection

The same research has demonstrated that this emerging Wide Area System should be implemented with a minimum set of requirements such as appropriate hardware-software and data communications architectures, specific signal processing functions, and specific applications for real time operations such as: Wide Area monitoring for regional Reliability Coordinators and Transmission Dispatchers, analysis and diagnosis tools for Operation Engineers, phasor data continuous and event archiving for post mortem analysis and assessment, and Wide Area coordinated and adaptive real time control and protection schemes based on synchronized phasor measurements. Figure 2 shows the generic architecture for a WAMPAC system. Four layer architectures as the one shown in Figure 2 are emerging as the most suitable approaches for wide area monitoring, control and protection.

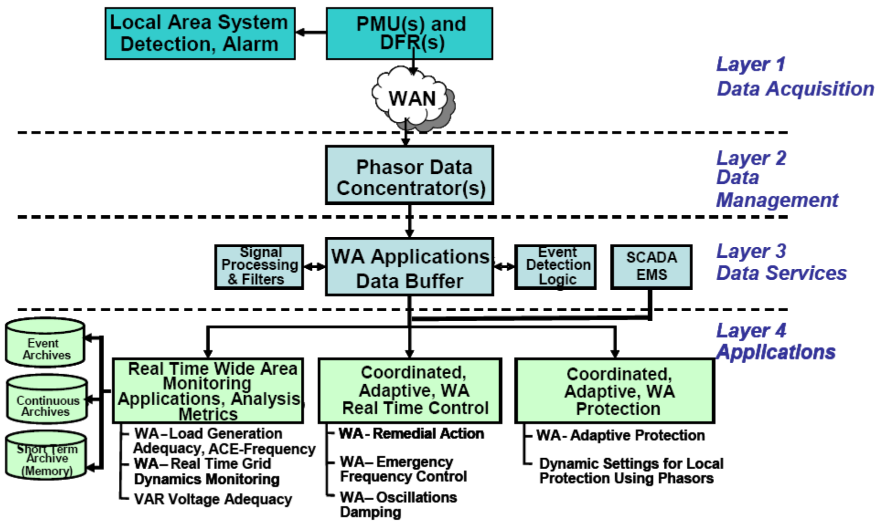

Figure 2. WAMPAC system architecture

Layer 1, Phasor Data Acquisition – PMUs and Digital Fault Recorders (DFRs) are located in substations to measure voltage, current and frequency. The basic phasor measurement process derives positive-sequence, fundamental frequency phasors from voltage and current waveforms. PMUs can be programmed to store data triggered by events such as under/over voltage and frequency.

Layer 2, Phasor Data Management – The PDC collects data from PMUs and other PDCs and correlates it into a single data set. It streams the data set to applications via the applications data buffer.

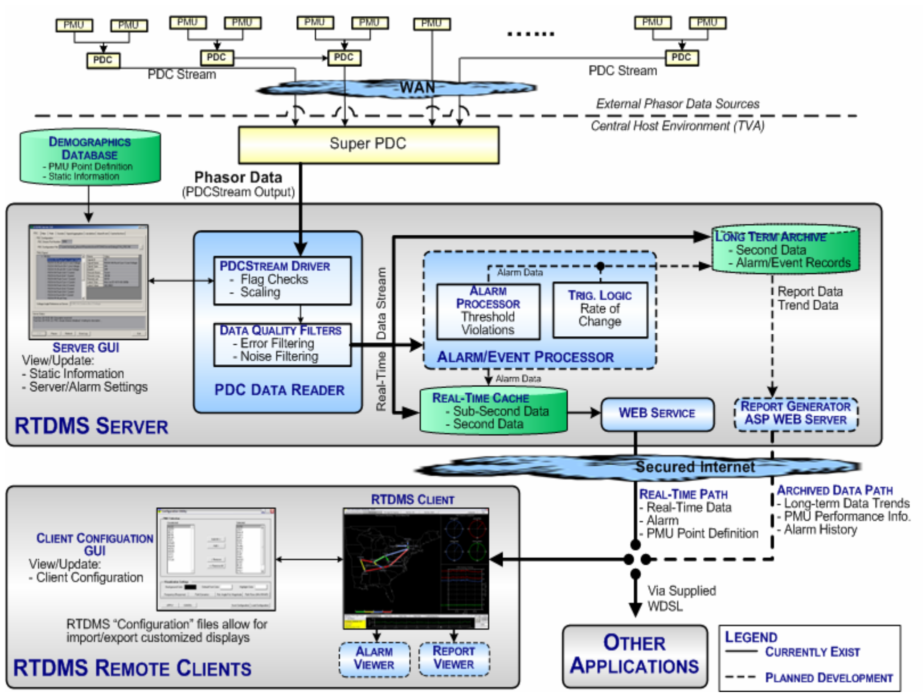

Figure 3. WAMPAC system IT architecture

•***Layer 3, Data Services*** – This Layer includes the set of services required for supplying data for the different applications. The major services are: capability to supply the data in the proper format required for applications and fast execution to leave sufficient time for running the applications within the sampling period. It also provides system management by monitoring all the input data for loss, errors and synchronization.

Layer 4, Applications – Three major areas have been identified for applications: Real Time Wide-Area Monitoring and Analysis, Real Time Wide-Area Control and Real Time Wide-Area Adaptive Protection.

Figure 3. shows IT architecture for implementing WAMPAC system.

3. BENEFITS OF USING PMUS

3.1. Real time monitoring and control

The main goal of real-time monitoring is to provide the operator with on-line knowledge of system conditions. This knowledge increases the operational efficiency under normal system conditions, and allows the operator to detect, anticipate, and correct problems during abnormal system conditions.

At present, EMS security monitoring software depends on the results obtained from the State Estimator software that uses system models and telemetry data from the Supervisory Control and Data Acquisition (SCADA) system to determine the voltage magnitude and angles at all buses in the system. This process is performed at intervals of several seconds long.

Time-synchronized devices have introduced the possibility of directly measuring the system state instead of estimating it. The full implementation of such a system may not be economical at the present, but the benefits can be realized by a gradual implementation. Commercial products exist, and are capable of supporting a limited number of time-synchronized devices. The ability of these products to handle large amount of data from a full-scale deployment (hundred of devices) is still untested.

A “low-hanging fruit” benefit of PMUs is the ability to inform not only operators that they face problems in their control areas, but also neighboring operators of a stressed grid.

Another benefit of observing real-time angular separations is to correct for the conservative limits assumed in planning studies or off-line operational studies. Real time monitoring and analysis permits the continuous evaluation of operating conditions. The ability of PMUs to directly obtain angle differences allows operators to reduce error margins an operate transmission corridors closer to their real stability limits while maintaining a safe security level [6]. The direct impact of confident operation of high-density transmission corridors closer to their security margins is to reduce the need for investment in expensive upgrades to the existing transmission facilities [7].

Another added benefit of the higher confidence on the stability limits is the ability to enhance local and wide area protection systems by allowing the protection system to adapt to known and trusted system conditions.

The detection and analysis of all inter-area oscillations modes in the system could be used to improve the existing dynamic system models. The improved models will increase the confidence level on system dynamic studies. These enhanced models can then be used to optimize the location and fine tuning of existing system stabilizers.

Like many other applications covered in this paper, financial benefits from Voltage Stability can be addressed in two categories. One is connection with congestion management: with the deployment of a system on a corridor constrained by voltage instability, the actual limits can be used instead of conservative ones, leading to more MW transfer.

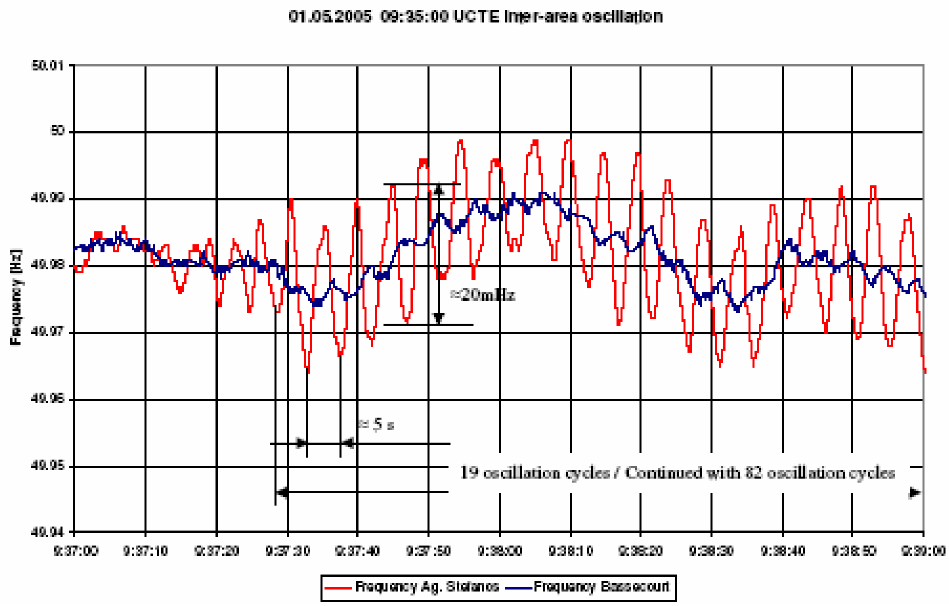

Figure 4. Oscillations on the European grid [8].

The other is in blackout prevention, which are low-probability and high-cost events; the exact benefit in this case requires specific studies, which take into account grid-specific features and the anticipated reliability of the scheme.

Voltage instability is typically manifested by several distinguishing features: low system voltage profiles, heavy reactive line flows, inadequate reactive support, heavily loaded power systems. Voltage collapse typically occurs abruptly, after a symptomatic period that may last in the time frames of a few seconds to several minutes, sometimes hours [9]-[12]. The onset of voltage collapse is often precipitated by low-probability single or multiple contingencies.

Studying voltage collapse requires complementary use of dynamic and static analysis techniques [13]-[17]. This makes monitoring and controls (protection) of voltage stability particularly suitable with PMUs, as currently available monitoring devices are often inadequately equipped to track this type of system dynamics.

3.2. Power System State Estimation (SE)

State Estimation is widely used in transmission control centers and ISO operations today to supplement directly tele-metered real time measurements in monitoring the grid; to provide a means of monitoring network conditions which are not directly tele-metered; and to provide a valid best estimate of a consistent network model which can be used as a starting point for real time applications such as contingency analysis, constrained re-dispatch, volt VAR optimization, and congestion management. State estimation has a number of ancillary applications with varying degrees of successful utilization in the industry such as bad data detection, parameter estimation, status estimation, and external model.

PMUs have been included in at least one successful SE deployment and a number of pilot installations are in progress. The inclusion of PMUs in SE algorithms is numerically/algorithmically not difficult except for the issue of dealing with the reference bus. There is not a large set of practical experiences with PMU inclusion in SE and related applications. A number of researchers have developed algorithmic refinements around the bad data detection and parameter estimation application of PMUs. Intriguing possibility is to use PMUs is for ISO/RTO state estimator applications to help represent “boundary conditions” for the utility state estimators.

PMUs offer a number of possible benefits to the SE application. The benefits most frequently claimed include: improved accuracy and robustness of bad data detection; availability of a faster numerical solution to a linear problem; and availability of direct data on the external network which can be used to better initialize the external model or to marry it to the internal SE solution.

Further benefit is the possibility of a separate SE solution using exclusively PMU data that takes advantage of the higher data rates / shorter cycles available with widespread PMU deployment. Several investigators have explored this possibility and argue that the SE solution would be “linear” as the voltages and phase angles are directly measured.

Another opportunity is to use PMU infrastructure (communications, master system) to also access compatible digital protection relays. It may be that some additional data available from digital relays could be incorporated in a PMU based high periodicity state estimator to add to redundancy or to reduce PMU deployment costs, depending on the relays already installed.

Finally, a PMU derived SE opens the door to have a three phase or a three sequence state estimator. This possibility has not been discussed in the literature. The potential benefits of such an estimator could be to monitor phase unbalance – which could be symptomatic of grounding or equipment degradation. It is worth including this possibility in the interview discussions to see if there are any real perceived benefits worth exploring.

3.3. Real-Time Congestion Management

Congestion Management is a critical function performed by power schedulers in the advance market and by the grid operator in real time. It is an important function because it involves generation dispatch (in day-ahead markets) and re-dispatch (in real-time markets) to delicately satisfy demand in an economic manner without violating transmission limits.

The goal of a real-time Congestion Management application is to maintain real-time flows across transmission lines and paths within reliable transfer capabilities through dispatch adjustments in a least-cost manner.

The traditional approach to real-time congestion management compares actual flow on a line or path against a Nominal Transfer Capability (NTC) that is calculated in advance using an offline methodology. Such off-line calculations are based on thermal limitations, voltage limitations or stability limitations; whichever is most restrictive in a given case. The assumptions used in offline NTC calculations are often conservative and can result in excessive margins in the congestion management process. This may lead to unused transfer capability and lost opportunity costs in the dispatch process [18], [19].

Since PMU’s provide additional, synchronized, highly accurate system meter data they may offer significant benefits in the area of real-time transmission congestion management by enabling improved calculation of path limits and path flows. This can lead to significant savings to utilities and ratepayers through reduced congestion and more optimum system dispatch. PMU measurements may be used to calculate more accurate path limits in real-time, thus providing more “elbow room” to manage congested lines and paths. The higher scan rate and precision of PMU data will enhance the speed and quality of real-time algorithms and allow rapid computation of Real-time Transfer Capability (RTC) on critical stability limited and voltage limited paths. On many paths such RTC’s will exceed their respective NTC’s thus reducing the need for real-time congestion curtailments [20], [21].

3.4. Benchmarking, validation and fine-tuning of system models

The goal of this application, model verification and Parameter Estimation (PE), is to identify questionable power system modeling data parameters (network, generator, load models, etc.) and calculate improved estimates for such quantities.

In general, automated means are not available to build the required models. Therefore, power system model building tends to be labor intensive, subject to engineering judgment and human error. Furthermore, once an error enters the modeling database it is difficult to identify and may go undetected for years.

The implementation of phasor measurement based tools, methods and applications offer a means of improving models. By providing precise, time synchronized measurements from various nodes in a power system, PMU deployment provides new opportunities for identifying errors in system modeling data and for fine-tuning power system models utilized throughout the industry for both on-line and off-line applications (power flow, stability, short circuit, OPF, security assessment, congestion management, modal frequency response, etc.).

Concerning the steady-state parameter models, EMS vendors have developed algorithms to identify model errors and to calculate corrected values, a process commonly referred to as Parameter Estimation (PE). The availability of precise phasor measurements can enhance the performance of PE algorithms used to identify and correct steady-state modeling errors (e.g., impedances, admittances and tap data). Synchronized measurements from PMUs are used to compute transmission-line impedance; this application is commercial and has been installed in Europe [8].

Benchmarking and tuning of dynamic and oscillatory modeling parameters is more complex, and typically requires careful evaluation of actual system response to planned or unplanned switching events or disturbances. The literature indicates that parameter estimation techniques can be extended to tuning of dynamic model attributes [22], [23]. In addition, a variety of WAMPAC system applications are under development utilizing phasor measurements that may prove useful for disturbance evaluation, model benchmarking and tuning of dynamic models [24], [25], [26].

3.5. Post-Disturbance Analysis

The goal of a post-mortem or post-disturbance analysis is to reconstruct the sequence of events after a power-system disturbance has occurred. To do this, a team of engineers assembles and studies the recordings from various data recorders that are dispersed throughout the grid. Such data recorders, or loggers, have been used by the industry for many years. However, they are not time-synchronized, making the job of understanding and reconstructing a timeline of what happened a very difficult and time-consuming job.

GPS has recently been used as a universal time source for a new breed of data loggers, which include the PMU. The deployment of such devices has been strongly recommended by authorities after the Northeast US and Italian blackouts in 2003 [1].

Building a WAMPAC for the purpose of post-disturbance analysis does not have to meet stringent requirements of a data network like that for real-time applications. Rather, since delays can be tolerated, data can be stored at the substations, and retrieved from a central facility on a regular schedule or when needed. To support the analysis, the industry needs to develop smart software that helps a human being to sift through the vast amount of data for key information.

Some utility companies in the US have deployed GPS-synced devices to correct the time-error problem in their recorders. One goal is to help the staff perform better fault or disturbance diagnosis. Experience shows that the precise time sync provided by GPS can cut the troubleshooting time from a few hours to a few seconds.

In Europe, the Italian blackout in 2003 resulted in a number of PMUs deployed throughout the continent. Even though the primary purpose was to time-sync the data logging, additional benefits have been realized since the 2004 reconnection of the Western and Southeastern grids. During the reconnection, the monitoring of the phase-angle difference between the two UCTE zones was done in real time. Also, thanks to a handful of PMUs and dedicated communications links, UCTE personnel can now observe frequency oscillations on-line.

3.6. Power-system restoration

During power restoration, system operators often encounter an excessive standing phase angle (SPA) difference across a breaker, which connects two adjacent stations. Closing a circuit breaker on a large difference can shock the power system, cause severe equipment damage, and possibly a recurrence of the system outage. The PMUs are well-suited for on-line monitoring of angles, and thus can be helpful as “eyes and ears” for the operator during a power restoration [27], [28].

The role of phase-angle monitoring, or the lack thereof, has been demonstrated in real-world experience. For an operator who works under stress to re-energize the grid, the PMU-based phase-angle monitoring can be a valuable tool. The PMUs can help reduce the time needed during a restoration process.

3.7. Protection and Control Applications for Distributed Generation

At least some of the projected yearly generation capacity growth of 15 GW/year in the US will be coming from distributed generation [29]. The pricing trends, opening of the competition in the electricity retail business and convenience of having the generation resources close to the load centers will be driving further proliferation of distributed generation (DG) technologies. EPRI's recent studies [29] estimate that, by 2010, 25 percent of the new generation may be DG, with a potential of ultimately representing up to 20 percent of the $360 billion US electric utility market.

PMU technology seems very promising in monitoring and islanding DG and microgrids. However, low-cost design may need to be developed for wider penetration

3.8. Overload Monitoring and Dynamic Rating

There are a variety of sensors/devices and companion software systems that allow the utility to monitor power equipment. The use of PMUs can offer some degree of monitoring at a high time resolution.

Although PMU-based systems for overload monitoring and dynamic rating cannot match the features offered by existing equipment monitoring systems, an advantage is in that the same PMUs can be used for other purposes.

The only commercially available application based on PMUs is the monitoring of overhead lines [30]. With PMUs at both the ends of a line, the resulting measurements allow calculating the impedance of the line in real time. The direct use of this is to estimate the average temperature over the length of the conductor. This method, however, does not provide information about hotspots, conductor sags or critical spans.

3.9. Adaptive Protection

Using synchronized phasor measurement, certain relays and protection schemes could be made to adapt to the prevailing system conditions, thereby enhance their performance.

Conventional protective systems respond to faults or abnormal events in a fixed, predetermined manner. This predetermined manner, embodied in the characteristics of the relays, is based upon certain assumptions made about the power system. “Adaptive Relaying” accepts that relays may need to change their characteristics to suit prevailing power system conditions. With the advent of digital relays the concept of responding to system changes has taken on a new dimension. Digital relays have two important characteristics that make them vital to the adaptive relaying concept. Their functions are determined through software and they have a communication capability, which can be used to alter the software in response to higher-level supervisory software, under commands from a remote control center or in response to remote measurements.

Adaptive relaying with digital relays was introduced on a major scale in 1987 [31], [32]. One of the driving forces that led to the introduction of adaptive relaying was the change in the power industry wherein the margins of operation were being reduced due to environmental and economic restraints and the emphasis on operation for economic advantage. Consequently, the philosophy governing traditional protection and control performance and design have been challenged.

The application of PMU measurements for adaptive protection has been researched and investigated, such as out-of-step relays, line relays, better balance between security and dependability depending on system conditions, and reclosing.

Promising application of using PMUs is in accurate measurement of line impedance for the Fault-Locating applications. The line impedance is a key input for accurate fault location. PMUs could also be used for direct fault calculation using data from both ends of the transmission line. Inaccurate fault location can lengthen the diagnosis and restoration process.

3.10. Planned Power System Separation

Direct utilization of PMU data may achieve vastly improved system performance over current methods for planned system separation.

The planned separation of a power system into different segments – islands – is the action of last resort when the power system is undergoing an unstable electromechanical oscillation, and a separation is unavoidable. Under these circumstances it is desirable to create electrical islands and separate them from the grid on a planned basis rather than an unplanned basis, and then reconnect them with the grid later when conditions for such action are favorable. Ideally, each island should have an approximately balanced generation and load, though in practice this may not always be the case. Some additional control operations, such as generator tripping and load shedding, may be required to achieve the balance of the generation and load in an island.

There are two traditional techniques in use at present to accomplish system separation under these conditions: out-of-step relaying, and remedial action schemes. Both of these techniques are classified as relaying applications, although the remedial action scheme is sometimes considered to be a control function.

It is important to note that both of these schemes depend upon pre-calculated system behavior based upon assumed state of the system: loading levels, topology, planned and unplanned outages, etc. It is well known that in many practical situations the prevailing system conditions are quite different from those upon which the protection scheme settings are based. Consequently, often the performance of these protection systems is not optimal, and in some cases is inappropriate, for the existing system state – which could make a bad situation worse.

The use of PMU measurements instead of pre-calculated scenarios would improve a planned system separation in two key areas: (1) whether a power system is heading to an unstable state and among which groups of generators the loss of stability is imminent will be determined more accurately with real-time measurement, and (2) islanding boundaries could be determined dynamically according to the prevailing system conditions.

4. ONGOING PROJECTS

Currently, there are more than twenty **North American** utilities that have PMUs installed in their substations. However, the current levels of development of these experiences are not the same. While several of the Eastern Interconnection utilities are in the initial stages of implementing and networking PMUs, utilities in the Western Interconnection, stimulated by the WAMPAC project, have already developed a wide area phasor network in conjunction with monitoring and post-disturbance tools that are based on phasor measurements. Plans are in place to specify and deploy prototypes for wide area real time control systems using their phasor technology infrastructures.

France The French system EDF (“Electricite de France”) utilizes protection schemes to avoid collapse situations or to limit their effect when they occur. The development of a coordinated protection scheme was carried out based on the centralized comparison of the voltage angles of the system obtained from the PMUs.

Scandinavia There is a great potential for phasor measurement applications in Scandinavia, mainly due to the long distance power transmission and limited transmission capacity expansion possibilities. Smart control, based on phasor measurements, can be used as an alternative to adding new transmission lines by increasing power transmission capacity.

During the year 2000 a study was carried out, with the support of Lunds Universitet, to verify the applicability of the technologies employed by the WAMPAC project for monitoring the reliability of the Nordic systems. This document contains much information on the WAMPAC project including its origin, constitution, applications and the current degree of development. Three years after its publication, there are reports about the installation of few PMUs in substations in Denmark and Iceland that have been, used for tests carried out by ABB together with the grid operators of those countries.

Spain Sevillana de Electricidad (CSE) has added phasor measurements to its SCADA system and together with Siemens performed the necessary modifications in their state estimator function to enable it to support processing of phasor measurements. They also conducted an extensive test program to establish the robustness, accuracy requirements and effectiveness of phasor measurements. Because of the experience gained from this test program their state estimator was modified to process phasor measurements, and upon successful fulfillment of the test program, the modified state estimator was installed at CSE and is currently operational.

Italy Phasor data has been used for blackouts post disturbance analysis and evaluations including their August 2003 blackout. Wide Area WAMPAC type systems have been specified and will be developed in the near future for real time monitoring and preventive, adaptive protection.

China The China State Grid will have about 150 PMUs installed nation-wide by the end of 2004. Most of them still do the dynamic monitoring and try to do the model validation. One provincial installation has modified their state estimator to use PMU measurements.

The investigation on the GPS-based synchronized phasor measurement (SPM) and its application in power systems in China were started in 1994. Until 2002 there were more than four PMS systems in operation and a lot of similar systems are under development. After several phasor measurement systems have been installed in Chinese Grids, researchers in China are now putting more emphasis in how to make use of the measured phasor information to improve the system’s security and reliability.

Korea Korea’s primary goal for synchronized phasor data use has been to monitor the system dynamics and to build a database for validating the simulation models. In Korea National Control Center they monitor the system conditions at the sampling rate of 10 times per second. For archiving purposes the phasor data is kept for two minutes in normal condition. When a major disturbance occurs, data for eighteen minutes after the disturbance, plus two minutes before, are stored permanently for later analysis. For monitoring purposes the instantaneous phasor measurement are stored for one second in normal conditions and for 15 seconds in fault conditions for later analysis such as validating operations of the protection system and electromagnetic transient models. On line TSA and VSA tools are also under development.

Japan Japan's longitudinal power system structure produces various types of system oscillations. These abnormal operating conditions make the use of phasor monitoring technologies suitable for real time wide-area monitoring. Research is being done to develop an on-line global monitoring system of Japan's power system dynamics using synchronized phasor measurements.

Brazil During the first part of 2004 Brazil established the MedFassee project. Its main objective is the development of a phasor measurement system (PMS) simulator prototype with applications for monitoring and control of power systems operation. The prototype will consist of three phasor measurement units and a data concentrator and will include several wide area monitoring and control applications.

5. RESEARCH ROADMAP

Roadmap for research and development of PMU devices and implementation of WAMPAC systems with belonging real time applications is shown in table 1.

Table 1. Research roadmap

Areas		Current Situation	Near Term Priorities	Long Term Goals	Industry Role	DOE Role
Monitoring	Wide Area Visibility	- Sparse PMU coverage across EI - Potential for quick expansion using existing devices with phasor measurement capabilities - Limited experience with PMU data in operations	- Prototype applications for phasor monitoring by reliability coordinators - Identify monitoring holes and need for additional coverage - Provide Operator (and Engineer) education and training on phasor technology and use of these tools	- Situational awareness - Improved reliability	- Installation and maintenance of devices with phasor measurement capabilities	- Development and dissemination support for wide area monitoring capability - Expand and promote EIPP participation
	Real-Time Alarming	Real-Time alarming based on local dynamics information or steady-state observability	- Define new alarming criteria based on wide-area dynamics visibility - Research and define operating procedures for abnormal conditions	Situational Awareness	- Serve as testers for new alarming criteria - Provide feedback	Support research activities towards establishing new compliance monitoring guidelines
	Interconnection Wide State Estimation	Early research suggests that 10% strategically placed PMU coverage is adequate to significantly improve SE results	- Identify and resolve data quality issues for use of phasor measurements in the state estimation process - Perform a hybrid SE demonstration with phasor and SCADA measurements	- Better security assessment - Improved asset utilization and LMP calculation	Incorporate phasor measurements into their state estimators	Coordinate and support utility efforts towards interconnection wide state estimation
	Measurement Based Sensitivities	- Promising concepts and initial results - Requires further assessment for reliable assessment capability	Research and demonstrate the feasibility of reliable sensitivity computations from phasor measurements	Improved reliability	- Define monitoring points of interest - Undertake demonstration projects	Support research and validation activities towards better reliability and security assessment
	Security Assessment		Define and demonstrate stability margin indices for: - Voltage stability monitoring - Small signal monitoring	Dynamic Security Margins		
Planning	Post-Disturbance Analysis	- Limited wide-area understanding of EI system dynamics - Availability of time synchronized phasor data through the EIPP starter network will facilitate this process	Develop better understanding of EI system dynamics by: - selecting events/outages of interest for analysis - coordinate analysis efforts for - characterize EI system signatures	Better system understanding	- Provide data and expertise in coordination with other utility efforts	Coordinate and support EI efforts towards improved system understanding and modeling
	Trending		Perform trending with time of day, season, peak load, major line outages, etc	Improved system modeling		
Infrastructure Management	Phasor Devices	- Initial starter system in it's infancy; requires assessment - Early standards definition activities in progress	- Benchmark existing devices with phasor measurement capabilities - Define performance standards for devices	Performance standards for phasor devices Standard phasor measurement protocols	Install, maintain, and upgrade phasor acquisition and management systems as needed to meet application needs, and evolving performance guidelines and industry standards.	Facilitate standards development activities and system expansion towards a fully reliable and redundant phasor system
	Data Quality		- Conduct performance assessment of current EI phasor network to identify data quality problems/calibration issues - Define minimum data quality requirements for different applications	Performance standards for phasor data - Reliable and Secure Phasor Network - Guidelines for phasor data networking and communications		
	Data Management/ Communication Networking		Research and define communication/data management architectures to support current and future application needs	- Guidelines for real-time/offline phasor data acquisition, archiving and retrieval - Redundant data management		
Protection Control Switching	Voltage / Transient / Small Signal Stability Control	Limited experience in this area within the Eastern Interconnection	Work with individual utilities to identify demonstration pilot projects on the use of phasor measurements for protection and control	- Improved reliability and security - Automated remedial action schemes - Improved asset utilization	Undertake demonstration projects to address utility specific problems	- Coordination and support for utility sponsored projects - Facility information sharing and technology transfer
	Remedial Action Schemes					

6. CONCLUSION

Skills in power system applications require a commitment to learn, true understanding, training, and most of all experience. A PMU is a state of the art tool that has already proven that when used correctly and within its known limitations, it can help solve some of the existing problems and give us a better understanding of the overall behavior of power systems.
Implementation of phasor measurement technology requires investment and commitment by utilities and system operators on an enterprise system level. The investments include: studies, equipment purchase and upgrade, maintenance, resource allocation and training. For utilities and system operators to make a step toward system-wide implementation of phasor measurement technology, it is desirable to identify and select key applications that would benefit the individual systems and the interconnected grid overall.

In summary, there is a need for a concise roadmap to help utilities, system operators, and regulators to prioritize applications for deployment (short to long term), based on their benefits to the users, addressing cost of deployment and technology advancements. This roadmap should also address review and evaluation of existing applications, potential improvements to existing applications, and new applications.

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