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Descriptive Model of a Generic WAMS

JF Hauer
JG DeSteese

First Issued: November 2006
Revised: June 2007

Prepared for
U.S. Department of Energy
Office of Electricity Delivery and Energy Reliability
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Executive Summary

The Department of Energy's (**DOE**) Transmission Reliability Program is supporting the research, deployment, and demonstration of various wide area measurement system (**WAMS**) technologies to enhance the reliability of the Nation's electrical power grid. Pacific Northwest National Laboratory (**PNNL**) was tasked by the DOE National SCADA Test Bed Program to conduct a study of WAMS security. This report represents achievement of the milestone to develop a generic WAMS model description that will provide a basis for the security analysis planned in the next phase of this study.

As the term is used in this report, WAMS describes an advanced technology infrastructure that is designed to develop and integrate measurement based information into the grid management process. The overall infrastructure encompasses measurement facilities, operational support, and data utilization. WAMS measurement facilities that communicate data sampled typically 30 times per second or more are designed to augment those of conventional supervisory control and data acquisition (**SCADA**) over which measurements are "refreshed" at a much slower rate, e.g., once every 4 seconds. Currently used as a complementary system, a WAMS is expressly designed to enhance the operator's real-time "situational awareness", which is necessary for safe and reliable grid operation.

A WAMS consists of advanced measurement technology, information tools, and operational infrastructure that facilitate the understanding and management of the increasingly complex behavior exhibited by large power systems. At the deployment level, a WAMS is established by the involvement and contributions of numerous operating utilities and independent system operators (**ISO**s), plus a growing number of hardware vendors. The WAMS concept was initially designed and developed to augment planning and operation of the western interconnection. Beginning in 2003, the Eastern Interconnection Phasor Program (**EIPP**) was launched by the DOE to demonstrate the value of WAMS technology to eastern utilities. The technology is also being extensively deployed by the utility industry world-wide.

Within the North American electrical grid, ISOs and transmission utilities are currently adopting this technology and applying it to grid monitoring that supports system planning and operations. In the near future, users are expected to transition from using WAMS technology primarily in a monitoring-only mode to applying it as a tool for enhancing wide area control, as well as for real-time decision support of operations. Ensuring the security and integrity of these systems will be of paramount importance to the utility industry, and will support other Department of Energy, Office of Electricity Delivery and Energy Reliability (**DOE-OE**) mission objectives associated with facilitating the adoption and implementation of this technology to enhance the reliability and security of the Nation's electrical power infrastructure.

As they evolve, WAMS measurement facilities will merge into a common infrastructure that will also include "legacy" equipment in the form of the residual parts of conventional SCADA systems. A blend of both infrastructures can be expected to provide an advanced technology energy management system (**EMS**) for the entire grid. The component technologies of this vision will infuse a new generation of other synchronized system measurements (**SSM**) elements such as the ubiquitous digital fault recorder (**DFR**). For this study's present objective, however, WAMS must be considered a distinct entity with linkages to these other data sources.

WAMS technologies are comprised of two major functions: obtaining data, and extracting information value from it. Obtaining the data is accomplished with a new generation of data recording hardware that produces high quality and high volume recordings that are virtually continuous. Inputs to these monitors are often taken from pre-existing analog sources, in which the electrical utilities have a vast investment. However, the emerging technology of choice is a highly flexible digital system in which messages stream continuously from data sources across the entire power system. All messages conveyed by a WAMS are precisely synchronized against the satellite-based global positioning system (**GPS**), and are readily merged to form integrated views of power system behavior in real time. The initial data source for this system is the phasor measurement unit (**PMU**), which provides high quality measurements of bus angles and frequencies in addition to more conventional quantities. However, the WAMS network is a generic one that can accommodate high speed data from control systems and low speed SCADA data from energy management systems. Such extensions are major elements of the DOE WAMS effort.

Extracting value from this measured data is a critical element of the WAMS effort. Data is extracted and analyzed using several signal analysis tools and algorithms. These include tools for interactive batch processing of response data from power system monitors or simulation programs, filtering options, several kinds of advanced signal analysis routines, and graphical user interfaces. These tools provide the virtual instrumentation necessary to measure electric power system performance and enhance the ability of system engineers and planners to design and control system operations and better manage these assets.

This report documents a considerable amount of background information to establish the design and operational context that is driving WAMS evolution. Against this background, the topographical and functional integration of a near-term evolved WAMS model is defined and illustrated to provide a basic generic description that is amenable to security analysis in the next phase of this study. The generic WAMS model presented here will find application as a benchmark system description that permits the systematic classification of the physical and cyber accessibility of major nodes and links and the current safeguards applied to protect them. The end product of this study will be designed to provide guidance on the "all-hazard" vulnerabilities of WAMS that owners and operators should consider when planning and implementing system protection strategies.

Glossary

Recorded signals	Signals provided directly by a recording system, with no accessory calculations other than scaling and perhaps data repair.
Extracted signals	Signals extracted directly from the record, plus all other signals derived from them during the extraction process.
Primary signals	Smallest set of extracted signals from which all other associated signals can be derived. This set is not unique, and it is not necessarily contained within the recorded signals.
Derived signals	Signals derived from recorded signals. Examples: – Voltage magnitude determined from a phasor in rectangular form – Real power computed from complex voltage and current – Angle or frequency relative to a designated reference bus – Thevenin equivalent voltage calculated from line parameters plus local phasors
Accessory signals	Available signals that are redundant to the designated primary signals, or of limited special interest. Example: bus angle measured at several different voltage levels within the same substation, angle of current phasor.

AC	Alternating current
BPA	Bonneville Power Administration
CERTS	Consortium for Electric Reliability Solutions
CF	Configuration file
CFname	Name of the configuration file
D&A	Display and archive
DFR	Digital fault recorder
DMWG	Disturbance Monitoring Work Group of the Western Electricity Coordinating Council (WECC)
DOE-OE	Department of Energy, Office of Electricity Delivery & Energy Reliability
DSI	Dynamic System Identification
DSI Toolbox	Dynamic System Identification Toolbox
DSItools	Contraction for DSI Toolbox
DSM	Dynamic system monitor
EDL	Event detection logic
EI	Eastern Interconnection
EIPP	Eastern Interconnection Phasor Project
EMS	Energy management system
EPG	Electric Power Group
EPRI	Electric Power Research Institute
FACTS	Flexible AC transmission system
FTP	File transfer protocol
GPS	Global positioning system
HVDC	High voltage direct current

IMU	Information manager unit
ISO	Independent system operator
M&VWG	Monitoring & Validation Work Group of the WECC
NERC	North American Electric Reliability Council
PDC	Phasor data concentrator
PEDR	Provide event data request
PF	Power flow
PMU	Phasor measurement unit
PNNL	Pacific Northwest National Laboratory
pow	Point on wave
PPSM	Portable power system monitor
PSM	Power system monitor (primary definition) Power system measurements (secondary definition)
PSM Toolbox	Power System Measurements Toolbox, contained within the DSI Toolbox
PSMtools, PSMT	Contraction for PSM Toolbox
rms	Root mean square
RTDMS	Real time dynamics monitoring system
SCADA	Supervisory control and data acquisition
SEDR	Secure event data request
sps	Samples per second
SSM	Synchronized system measurements
TVA	Tennessee Valley Authority
VAR	Volt ampere reactive
VPN	Virtual personal network
WAMS	Wide area measurement system
WECC	Western Electricity Coordinating Council
WSCC	Western Systems Coordinating Council (predecessor to WECC)

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Introduction

A WAMS consists of advanced measurement technology, information tools, and operational infrastructure that facilitate the understanding and management of the increasingly complex behavior exhibited by large power systems. In its present form, a WAMS is used as stand-alone infrastructure that complements a full range of conventional grid planning, design and testing tools, and operational control systems. As they evolve, WAMS measurement facilities are expected to merge into a common infrastructure that will also include "legacy" equipment such as the residual parts of conventional SCADA systems. This future vision suggests a single integrated infrastructure that can be expected to provide an advanced technology EMS for the entire grid. Because of the current significance and potential future criticality of WAMS infrastructure as a means of protecting grid operations, its security is of paramount concern.

The Department of Energy's Transmission Reliability Program, administered by its Office of Electricity Delivery and Energy Reliability (**DOE-OE**), is supporting the research, deployment, and demonstration of various WAMS technologies to enhance the reliability of the Nation's electrical power grid [1,2,3,4]. The study of WAMS security being conducted by PNNL is a project funded by the DOE-OE National SCADA Test Bed Program, in cooperation with the Transmission Reliability Program. This report represents achievement of the project milestone to develop a generic WAMS model description that will provide a basis for the security analysis planned in the next phase of this study.

WAMS, as the term is used here, describes an advanced technology infrastructure that is designed to develop and integrate measurement based information into the grid management process. The overall infrastructure encompasses measurement facilities, operational support, and data utilization. WAMS measurement facilities that communicate data sampled typically 30 times per second or more are currently designed to augment those of conventional SCADA systems that "refresh" measurements once every few seconds. As a complementary system, a WAMS is expressly designed to enhance the operator's real-time "situational awareness" that is necessary for safe and reliable grid operation [5]. The following sections of this report document a considerable amount of background information to establish the design and operational context that is driving WAMS evolution. Upon this background, we define and illustrate the topographical and functional integration of a near-term evolved WAMS model to provide a basic generic description that is amenable to security analysis in the next phase of this study.

Basic WAMS Functionalities

A WAMS is both a distributed measurement system and a general infrastructure, providing integrated dynamic information that conventional SCADA technologies cannot resolve. WAMS measurement facilities extend from the sensor level in the field through one or several network layers, plus a wide variety of data acquisition, transmission, concentration and processing technologies. The human component of WAMS infrastructure is typically diverse as well, requiring the cooperation of widely dispersed staff acting, or attempting to act, collectively in accord with procedures and practices that have been negotiated among many owners and users of WAMS data[1].

The value added by a WAMS is the generation of critical information about many aspects of grid operation that ultimately provides decision support to system planning and operation, and to the design of automated control. The input provided to these processes by a WAMS is ultimately useful by its being iteratively absorbed, as illustrated by the measurement-information-decision cycle of Figure 1.

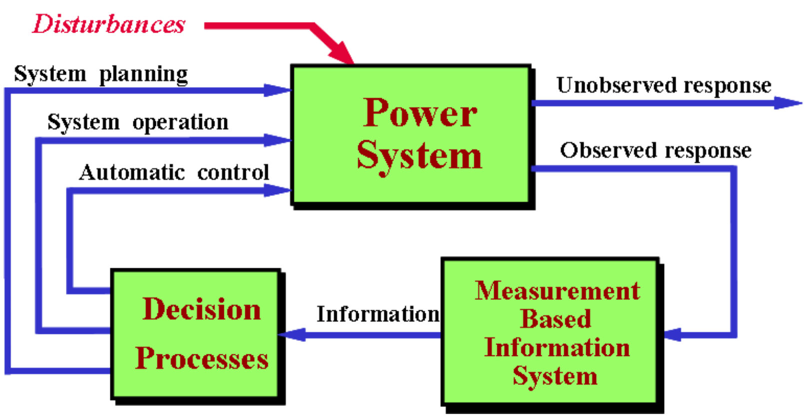

Figure 1. The cycle of measurement, information, and decisions

A great deal of WAMS information is extracted as "lessons learned" from past events, and then integrated into the overall knowledge base concerning power system performance. In the control room, WAMS data facilitates the comparison of present system behavior against this knowledge base and thus enriches the situation awareness through which power system operators develop real-time operational decisions and aggregated intuitive insight.

[1] This aspect of WAMS operation is often referred to as an enterprise network.

Table 1 shows a detailed list of specific applications to be served by the WAMS in the western interconnection [Western Electric Coordinating Council (**WECC WAMS**)] [6,7]. Many other objectives are implicit in this table. In addition, other electrical interconnections might state or prioritize their objectives differently. However, the following list represents a set of reasonable application objectives for a present-day or near-term generic WAMS.

Table 1. Key applications of the WECC WAMS

- Real-time observation of system performance
- Early detection of system problems
- Real-time determination of transmission capacities
- Analysis of system behavior, especially major disturbances
- Special tests and measurements, for purposes such as
    - special investigations of system dynamic performance
    - validation and refinement of planning models
    - commissioning or re-certification of major control systems
    - calibration and refinement of measurement facilities
- Refinement of planning, operation, and control processes essential to best use of transmission assets.

Categories of Real-Time Information for a Large Power System

A primary capability of a WAMS is to supply real-time information on the operational status of the grid. For the purposes of this report, real-time technical information provided by a WAMS and concerning the operational status of a large power system will be divided into three general categories:

1. **Topology**. This defines the facilities that are in service, and how they are connected. The primary source for topology information is contact data indicating, for example, which breakers or switches are open or closed.
2. **Power Flow**. This defines the sources of generated power, and how the power is delivered to specific load areas. The primary source for power flow (**PF**) information is direct measurements taken from lines and buses on the electrical network.
3. **Dynamic Behavior**. This defines the dynamic interactions among system facilities, plus the overall response of system facilities to some external input or disturbance. The primary sources for information concerning dynamic behavior are:
   - *measurements of dynamic activity* (taken from lines, buses, and system controllers)
   - *controller status information* concerning controller settings
   - *control law specifications* that govern the actions taken by major control systems in response to activity or events on the power system.

WAMS as a Grid Management Tool

Management of any large power system incorporates both measurements and models supporting a management decision process. A WAMS is typically embedded within the broader picture shown schematically in Figure 2. The data generated by measurements and models may be used in many different ways, and in many different time frames. The same measurements that system operators see in real time may contain benchmark performance information that is valuable for years into the future. Such measurements may also be needed to determine the sequence of events for a complex disturbance, to construct an operating case model for the disturbance, or as a basis of comparison to evaluate the realism of power system models in general.

The reader should note that "WAMS" and many other terms are used here in a broad sense that is context dependant. For example, the data shown in Figure 2 extend from raw measurements through to derived signals and technical reports. The distinction between data and information is not absolute because the information delivered by one process may be an input and thus provide "data" to a subsequent process at higher level.

The value of WAMS information, as shown in Figure 1, is entirely that of the decisions, which are enabled by other decisions. This figure implies two essential requirements:

- **Contextual information must permit correct interpretation of WAMS data**
- **Operational resources must permit the decisions to be actionable**

WAMS is expected to reveal and highlight system behavior that might otherwise not be apparent. However, to evaluate such behavior, it may be necessary to draw upon a wide range of contextual information. This includes event records, system status information, operator experience, computer models, and archival data collected under similar conditions. The specific operational resources that are available at a given time are usually the consequence of established policy and past decisions, and thus not affected by immediate WAMS operation. The extent to which these resources are available may, however, reflect past deficiencies in relevant system information.

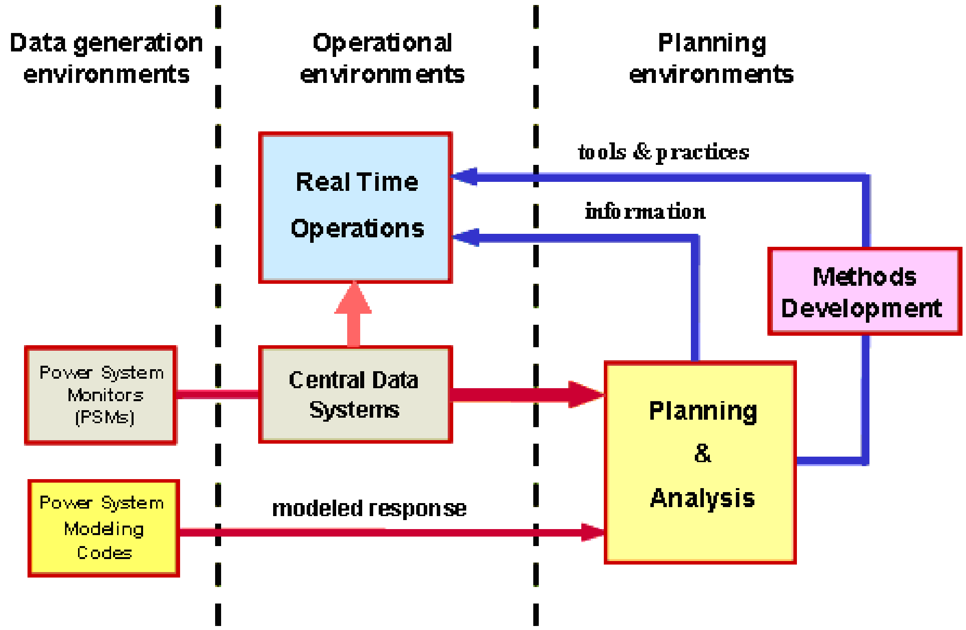

Figure 2. The role of measurement based information in planning and operations

Major WAMS Networks in North America

North America is served by two major WAMS networks. The WECC WAMS has evolved in the western interconnection over some 30 years, and provides a template for the newer "EI WAMS" that is deploying in the eastern interconnection (**EI**). Both draw upon technology developed at the Bonneville Power Administration (**BPA**) and PNNL, either as network components or for functional requirements [8][2]. The WECC WAMS is used here as a representative example of a general WAMS. The EI WAMS serves as a slightly contrasting example that illustrates how different needs and different technology selections can result in different structure.

Factors Affecting WAMS Development

Power system measurement facilities usually evolve incrementally, building upon existing resources to address additional needs as they arise. This implies a mixture of technologies, data sources, functionalities, operators, and data consumers. Some governing realities are the following:

- **System configuration** is strongly influenced by geography, ownership, selected technology, and the technology already in service (legacy systems).
- **Required functionalities** are determined by who should (or should not) see what, when, and in what form.

Overall, the forces at work strongly favor wide area measurement systems that evolve as "networks of networks" through collaborative agreements among many parties.

There are advantages to this situation. Interleaving networks that have different topologies and different base technologies can make the overall network much more reliable, while broadening the alternatives for value engineering. This allows utility level networks to be operated and maintained on the basis of ownership, and also permits a utility to withhold certain data until they are no longer sensitive from a proprietary perspective. Disadvantages include protracted reliance upon obsolescent or incompatible equipment types, plus various institutional impediments to sharing of costs and timely information.

WAMS development in North America reflects information needs in combination with technical opportunity. Viewed abstractly, WAMS deployment is just one more aspect of the general transition from analog to digital technologies. Rigidly limited analog systems are being overlaid or displaced by more flexible digital systems that offer better overall performance. The end objective for this transition is an SSM network in which all data

[2] J.F. Hauer and K.E. Martin. "Data Concentrator Technologies for Integrated Phasor Measurements: A Perspective on Required Functionalities and the Status of Present Technologies." WAMS internal communication, February 10, 2003.

can be smoothly integrated to form high quality portraits of power system behavior. WAMS deployment is a pathfinding activity within this broader technology effort. As it matures, WAMS infrastructure will merge into an overall grid-level EMS and its component technologies will infuse a new generation of other SSM elements such as, for example, the currently ubiquitous DFR. Nevertheless, for the present purpose of this study WAMS should be considered a distinct entity with linkages to these other data sources. Note that, from Figure 2, computer models also constitute a data source in the overall use of WAMS data. A general paradigm for this is shown in Figure 3.

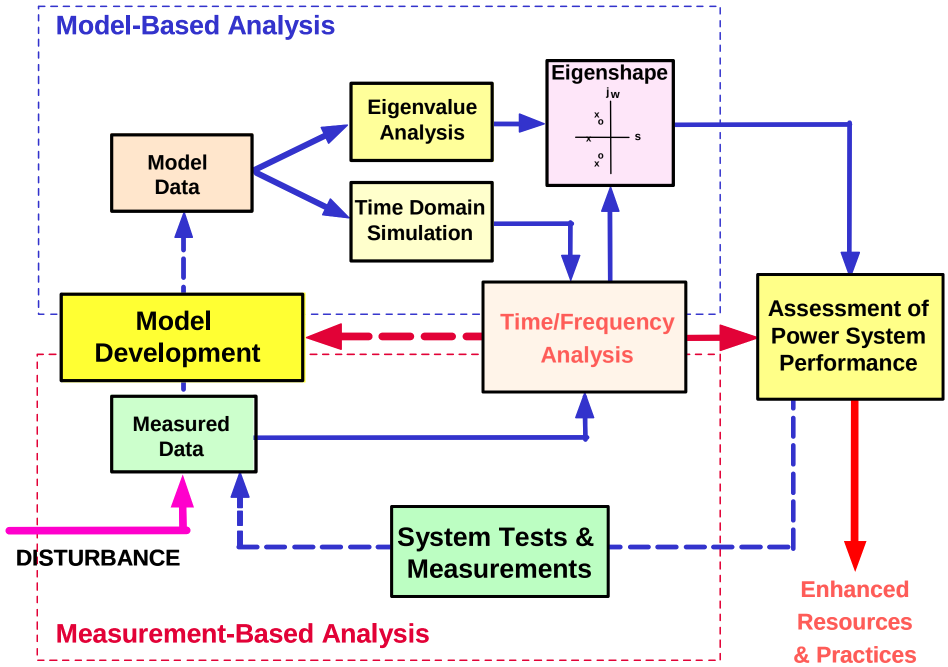

Figure 3. Integrated use of measurement and modeling tools

Overview of the WECC WAMS

The most developed and extensive WAMS in current use anywhere in the world is the WECC WAMS. It involves about 1500 "primary" signals that are continuously recorded in their raw form. These primary signals are the basis for several thousand derived signals that may be viewed in real time, or off line. Data sources are of many kinds, and they may be located anywhere in the power system. This is also true for those who need the data, or those who need various kinds of information extracted from the data.

The primary "backbone" for the WECC WAMS consists of phasor networks, as represented in Figure 4. Phasor measurement units (**PMU**s) stream precisely synchronized (GPS time-stamped) data to phasor data concentrator (**PDC**) units. The PDCs stream integrated PMU data to PDC StreamReader units and sometimes to other PDCs. The StreamReaders provide display, continuous archiving, and add-on functionalities such as spectral analysis or event detection. Remote dial-in access to PDC and StreamReader units is available when security considerations permit.

Each PDC has the potential of providing real-time data for power system behavior across a broad region of the power system. Some PDCs share signals to extend this coverage, and higher level networks are evolving that consist of PDCs entirely. Some of the directly integrated phasor networks are isolated from one another, and the data they collect are selectively integrated off line. Figure 5 shows a special case of this, in which a PMU is paired with a StreamReader that has been modified to provide basic PDC functions. The local PMU network it serves is a power generator, and the data would likely be regarded as business sensitive. Figure 6 shows the PDC units that are operational in the WECC, plus the linkages among them; several types of PMU are in service, from at least four commercial vendors.

The WECC WAMS also contains a number of high performance SSM devices that record continuously but are not based upon PMU technology. These include the following:

- Portable power system monitor **(PPSM**) for signals produced by analog transducers and other sources of moderate to low bandwidth. Data rate is usually set to 20, 30, or 60 samples per second (**sps**).
- Special PPSM for point-on-wave (**pow**) signals produced by instrument transformers and other bandwidth sources. Typical data rate ranges from 960 to 1920 sps.
- Special PPSM for control signals produced by high-voltage direct current (**HVDC**) and flexible AC transmission system (**FACTS**)-like controllers. Data rate is usually set to 240, 960, or 5000 sps.

At present these are all stand-alone devices. However, future versions of the BPA PDC may support multi-rate SSM networks of the sort shown in Figure 7.

About half of the signals collected on the WECC WAMS backbone are phasor measurements. When needed, data from other sources are integrated with data collected on the PDC network to form more detailed profiles of system behavior in areas of special interest. Some of the local monitors are “snapshot” disturbance monitors that use a local signal to initiate brief recordings. Digital fault recorders and some other point-on-wave recorders are in this category.

As yet, there are no fully automated information manager units (**IMU**s) that serve the full range of WECC monitor types. Instead, the core IMU functions of data management, analysis, and report generation are produced as a staff activity shared among numerous data owners and consumers. The established WECC toolset for this, the *Dynamic System Identification (**DSI**) Toolbox*, is the latest generation of software that has supported BPA and WECC performance validation work since 1975. It is coded in Matlab©, and its core elements are distributed as freeware from WAMS websites. It accepts data from all significant WECC monitor types, and from all computer simulation programs in use for WECC planning.

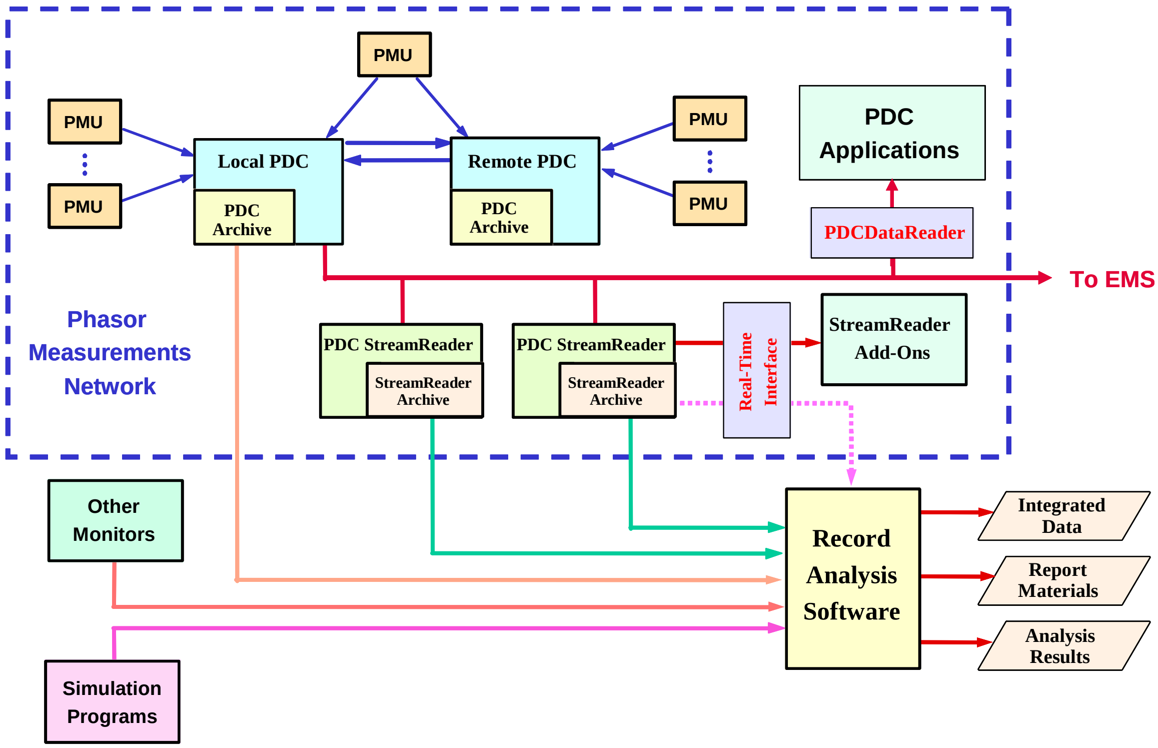

Figure 4. Flow of multi-source data within an integrated WAMS network

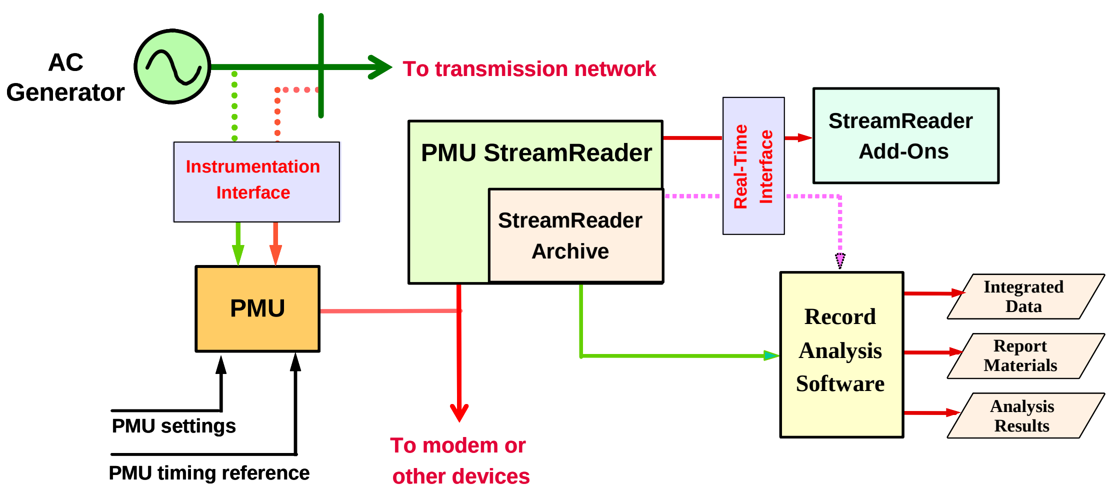

Figure 5. Local PMU network for device monitoring

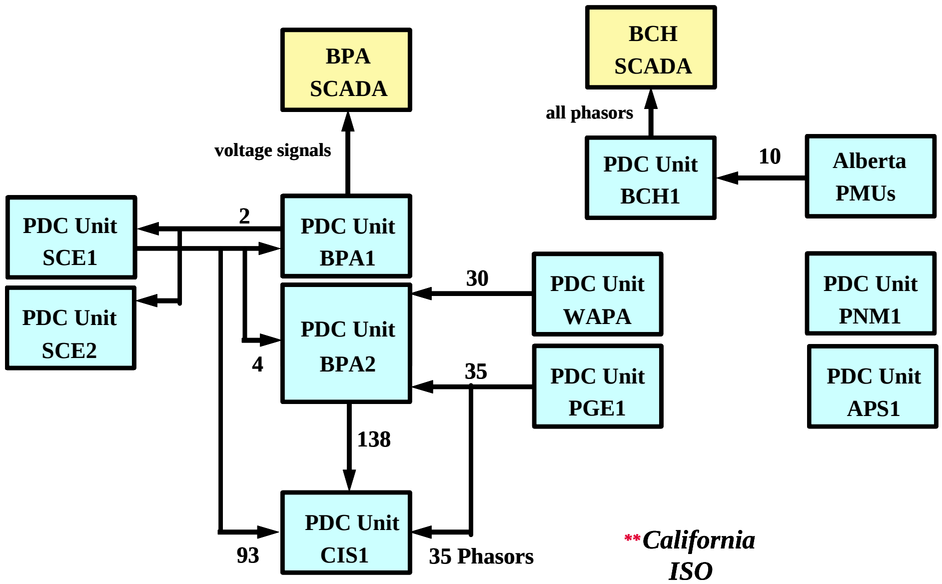

Figure 6. Evolving PDC network in the WECC WAMS

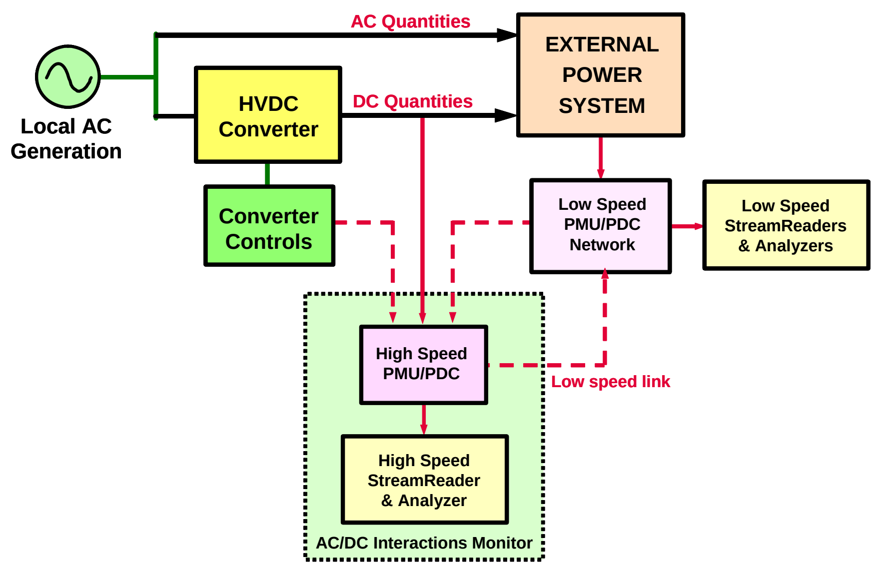

Figure 7. Multi-rate AC/DC interactions monitor embedded in a PDC network

Overview of the EI WAMS

The EI WAMS has, until recently, consisted largely of a few stand-alone monitor systems installed by utilities that have special operating needs [9,10,11]. This began to change shortly after the widespread blackout of August 14, 2003 [12]. This very disruptive event demonstrated a need for providing grid operators with the means to gain a much higher level of situational awareness under all operational conditions. As a contribution to this objective, the EI WAMS is in the process of a major expansion. The development of phasor networks, under the auspices of the Eastern Interconnection Phasor Project (**EIPP**) [13], is the focus technology in this effort.

General topology of the EI phasor system is represented in Figure 8. This is similar to that shown for the WECC WAMS in Figure 4 and Figure 6, although the EI network is much more centralized. All phasors are directly forwarded to a "Super PDC" located at the Tennessee Valley Authority (**TVA**) control center. Most though not all phasors are first routed through an intervening PDC, and it is possible that some phasors are directly transmitted both to TVA and to a PDC operated by the data owner. As in the western interconnection, changes and additions to the phasor network are occurring almost on a daily basis.

Although outwardly similar, the EI WAMS is distinctly different from the WECC WAMS with respect to base technologies and application priorities. All WAMS technologies evolved in the WECC WAMS have appeared in the EI WAMS at some point, and the BPA PDC is widely used in both. However, the TVA Super PDC is an in-house product unique to the EI WAMS. BPA's StreamReader technology has been largely displaced in the EI by commercial products such as the Electric Power Group's **(EPG's**) Real Time Dynamics Monitoring System (**RTDMS**), which is being developed under a DOE collaboration involving BPA, PNNL, and several other parties with historical ties to the DOE WAMS effort [14,15,16]. Various elements of the DSI Toolbox are also being incorporated into RTDMS, and several versions of this application have been installed in the WECC WAMS. A full range of applications for the EI WAMS has not been defined, however, and the requisite WAMS functionalities remain a subject of considerable discussion.

From a reliability standpoint, the following features of the EI WAMS merit special consideration:

- A broader range of base technologies. Some of these are quite new, and not governed by comprehensive standards.
- Extensive use of virtual personal network (**VPN**) data links, drawing upon the internet or equivalent public communication facilities.

Data links in the WECC WAMS, by contrast, are almost entirely based upon privately owned microwave or optical fiber facilities.

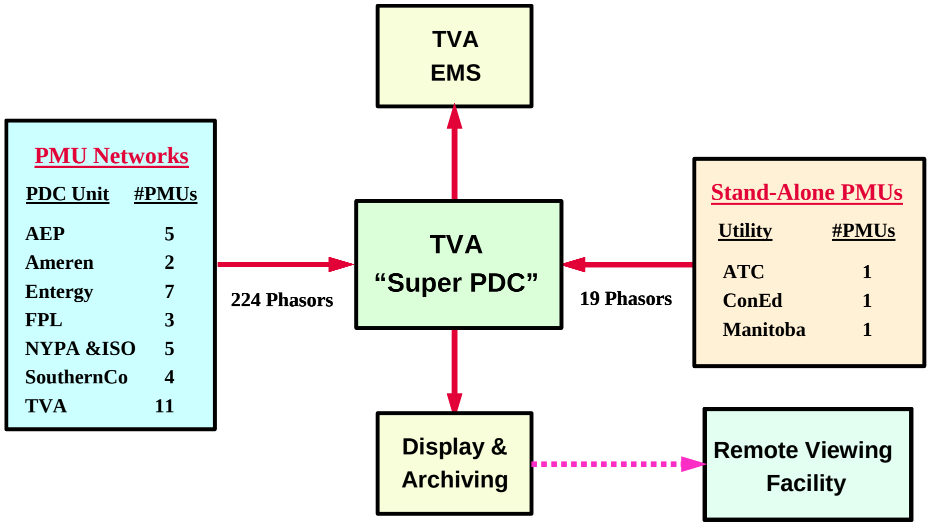

Figure 8. Evolving PDC network in the EI WAMS

Generic Model of WAMS Infrastructure

Earlier sections discussed WAMS information as a major contribution to operator situational awareness, and then proceeded to describe the two major WAMS operating in North America. This section will generalize those descriptions, with some additions that are needed to form a generic model that captures pending enhancements to existing technologies and infrastructure.

Modeling of a fully evolved WAMS requires two layers:

- A **WAMS facility model** representing the hardware and firmware elements of the WAMS, plus the linkages among them.
- A **WAMS process model** representing
  - generation and flow of data/information within the WAMS
  - linkages between WAMS information and grid management decisions
  - institutional collaborations required to effectively operate and utilize WAMS facilities.

Both modeling layers can be represented as networks of links and nodes. Some WAMS hardware elements do not connect to others, so the facility model is not fully connected. The associated data (if properly stored) can always be accessed in some manner, so the processing model is fully connected.

Primary Measurement Functionalities

Figure 9 shows an abstract view of primary measurement functionalities provided by WAMS facilities. The figure does not indicate topology of the WAMS network, or the various “off-line” functionalities associated with retrieval and use of archived data. Secondary functionalities implicit in the figure are briefly described later in the section. The indicted primary functionalities may be distributed across many different devices, and they may be replicated at numerous locations. The following comments are provided to explain the figure:

- **Situational awareness** functionalities consist of the following:
  – analytical displays (StreamReader units, RTDMS, others)
  – a comparable knowledge base for power system behavior (operating standards, event archives, model studies, contingency simulations)
  – event detection logic (**EDL**) that automatically detects unusual conditions or events on the power system

- **Signal sources** can be one of the following:
  – real-time measurements
  – computer simulation programs (staff training or for software refinement)
  – playback of archived data (interactive event analysis, staff training, software refinement)

- **Continuous archives** are provided by StreamReader units, some PDC units, PPSM units of various kinds, and by some other devices not on the WAMS backbone.

- **Event archives** are provided by most PDC units, DFRs, and by various other "snapshot" recorders.

- **EDL functionalities** include the following:
  – detection of abrupt changes (short term EDL)
  – tracking and assessment of dynamic trends (long term EDL)
  – use of short term EDL to launch or restart algorithms for long term EDL
  – generation of operator alerts and cross triggers to other recording facilities
  – special information or settings for analytical displays
  – initiation, annotation, or logging of event recording.

A number of secondary functionalities are implicit in Figure 9 and in related figures that precede it. Basic among these are data repair, derivation of root mean square (**rms**) quantities (such as voltage magnitude or line MW) from phasor signals, name generation to facilitate signal selection, and overall management of data archives. A later section will discuss these matters in more detail.

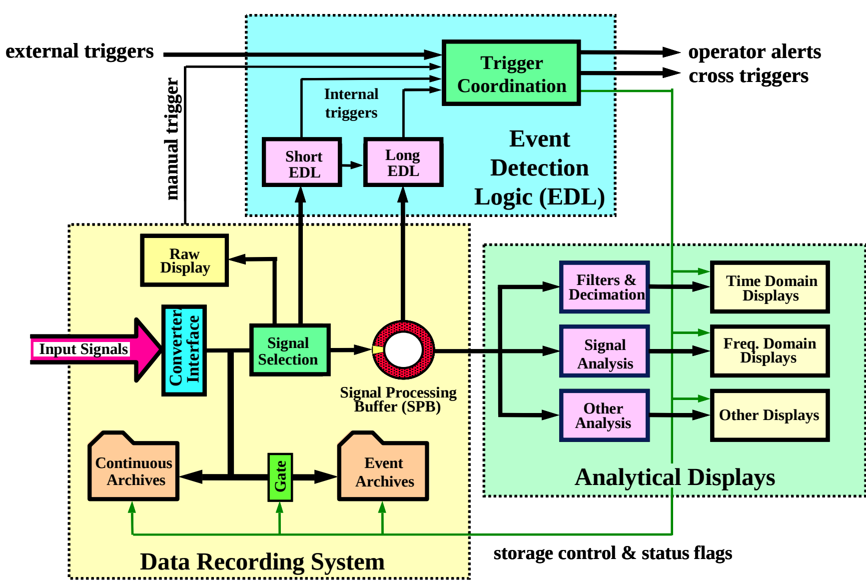

Figure 9. Primary measurement functions of a generic WAMS

Generic Elements of the WAMS Facility Model

The WAMS facility model consists of the following sub-networks:

- **A primary "WAMS backbone"** consisting of SSM devices that continuously stream data to one or more central sites for real-time management of the power system.
- **A secondary "WAMS backbone"** consisting of SSM devices that continuously record data on a local basis only. While records from the secondary backbone are synchronous with those from the primary backbone, some straightforward data processing may be required before the two classes of data can be integrated.
- **Secondary WAMS devices** consisting of recorders and other instruments that are not directly connected to or compatible with the WAMS backbone. These are usually snapshot recorders (such as DFRs), and many are not well synchronized to any general timing reference. Integrating their records with those from the primary backbone is usually feasible but laborious.

A network is, by definition, formed of nodes plus connecting links. The present generation of phasor networks is based upon network nodes of the following general kinds:

- **Phasor measurement units** (**PMUs**): to generate phasor data that is streamed into the phasor network as a series of small messages. In basic terms, a PMU is a digital transducer possessing the capability to determine phase angles relative to some universal timing signal. PMUs provide best value when networked together to present integrated portraits of system behavior to key users in real time [17].
- **Phasor data concentrator** (**PDC**) **units:** to integrate phasor data at one or more levels of the phasor network. Basic functions are to merge data from multiple PMUs (possibly of different types), intercommunicate with other PDC units, and export data for external routing and processing in other information systems [18][3].
- **Display and archive** (**D&A**) **units:** to serve real-time users of phasor data and to save data for off-line use. BPA's StreamReader technology and add-ons are primary examples, but RTDMS and the TVA Super PDC are also in this category.
- **Information manager units** (**IMUs**): to extract and distribute useful information from phasor data plus other sources. At present this functionality is primarily obtained as an off-line staff activity, with software such as the BPA/PNNL DSI Toolbox plus data sharing via the internet (to include VPN).

Broadly described, real-time links for phasor and other wide area SSM networks are based upon either "hard wired" corporate communications or some form of public

[3] J.F. Hauer and K.E. Martin. "Data Concentrator Technologies for Integrated Phasor Measurements: A Perspective on Required Functionalities and the Status of Present Technologies." CERTS internal communication, February 10, 2003.

communications. Figure 10 represents the form of communication link that is typical of utility owned microwave or optical fiber systems. VPN and other links that draw upon the internet or other public communications would have the same topology, but different labels in the blocks.

WAMS facilities also use a wide range of communications for local networks, data retrieval, and off-line information exchange. All of these present opportunities for data to be lost, contaminated, or intercepted.

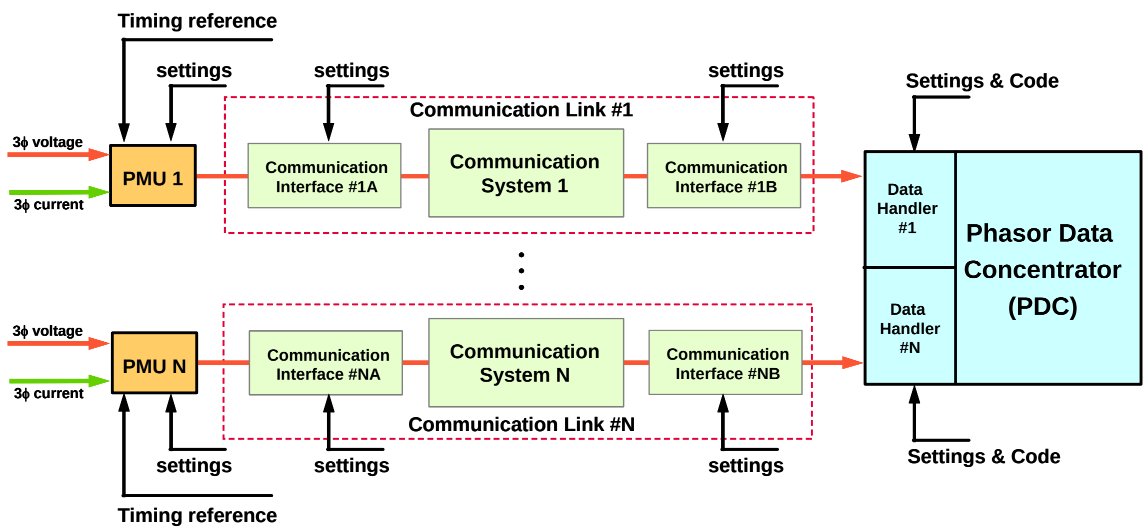

Figure 10. Technology elements for networking PMUs to a PDC

Generic Elements of the WAMS Process Model

A fully comprehensive WAMS process model must represent the following operational activities:

- **Utilization of WAMS facilities**: Detection, recording, analysis, and reporting of system behavior such as
  – major disturbances
  – staged tests
  – benchmark events that are rich in formation about system performance
- **Technical support of WAMS facilities**:
  – cross calibration of installed data sources
  – installation and maintenance of technology elements
  – testing, evaluation, and certification of technology elements
  – development of technology standards

- **Strategic aspects of the WAMS effort**:
  – policy evolution regarding development and use of measured information [North American Electric Reliability Council – (**NERC**) level and below]
  – sharing of data, information, technology, and costs
  – development of engineering practices.

All of these activities involve many details. Key details of those activities directly relating to the utilization of WAMS facilities are provided in the appendices to this document. More complete descriptions of overall WAMS activities are provided by the documents listed in [19], and in a growing list of broader documents emanating from government and/or professional groups.

The WAMS process model is shown above as three layers. Performance of the utilization layer is strongly affected by the effectiveness of the technical support layer, and the competence of both layers is strongly contingent upon resource allocations produced in the strategic layer.

Examination of a large WAMS usually reveals that the operational activities rely upon a rather small number of experts who coordinate their activities through one or more technical groups within the regional reliability organizations[4]. This tends to be rather ad hoc; there is, in effect, no overall paradigm for grid management that includes the full range of analysis functionalities indicated in Figure 3. Though once common among utility staff, the advanced skills these functionalities require are becoming rare, and many of these skills have vanished from the organization charts [20,21].

The WAMS process model has many implicit linkages to other aspects of grid operation. A key notion in this is *situational awareness*, a general term denoting the degree of accuracy by which one's perception of the current environment mirrors reality[5]. Situational awareness is composed of two basic elements:

- **observational data** concerning the present environment
- **a comparable knowledge base** for interpreting observational data and their implications.

WAMS data makes immediate contributions to the observational data, and it can make many long term contributions to the knowledge base against which the observational data are evaluated. Model studies and engineering judgment are also essential to the knowledge base, however, and both of these can fail if they do not properly incorporate measurement based information. "Lessons learned" from system events are not always correct.

[4] In the WECC, the lead organization for this is the Disturbance Monitoring Work Group (DMWG)
[5] U.S. Naval Aviation Schools Command

Conclusions

This report provides a description of a generic WAMS model in terms of its topography, and the functionality of its nodes and links. This model represents the vision of a near-term evolution of the WAMS infrastructure that can be projected from the architecture of both the WECC WAMS and the EI WAMS, together with the operating experience and development potential they provide. In addition, extensive appendices and references [e.g., 22] detail desirable management and application practices, including protocols that are required to protect the integrity and extract the best value from the data typically generated by a functional WAMS.

The generic model reflects the expectation that, for several years to come, WAMS infrastructure will remain a distinct entity and would still be exploited as a complementary asset to existing legacy data sources, specifically SCADA. Thus, for the purposes of the present study, the generic model does not embrace the longer-term vision of WAMS measurement facilities merging into a common real-time EMS infrastructure that would also blend in residual parts of conventional SCADA systems.

This report represents achievement of the project milestone to develop a generic WAMS model. The appended material on the management, protection and use of generic WAMS data enhance the value of this document being used as a basis for the security analysis planned in the next phase of this study.

APPENDIX A

General Criteria for Good Measurements

APPENDIX A General Criteria for Good Measurements

Operational data are obtained from multiple sources and must be assembled into an overall portrait of system behavior that is *valid, consistent, detailed,* and *comprehensive*. These criteria apply for all data applications, and for all time frames in which the data are used.

The same measurements that system operators see in real time may contain benchmark performance information that is valuable for years into the future. Such measurements may also be needed to determine the sequence of events for a complex disturbance, to construct an operating case model for the disturbance, or as a basis of comparison to evaluate the realism of power system models in general.

These observations imply two general rules for the organization of WAMS data:

Rule #1. WAMS data must remain retrievable and useable for many years after acquisition.

Rule #2. Procedures and toolsets for analysis of the WAMS database must be applicable to simulated measurements produced by model studies.

The above two rules are actually basic requirements from which many other rules, practices, or guidelines can be derived. E.g., from Rule #1 we can derive the following:

Rule #3. Any WAMS data or analysis product must be clearly tagged to indicate:

- origin of the data
- conditions under which the data were acquired
- processing applied to the data.

Expanding upon Rule #2, for any large power system we have:

Rule #4. Procedures and toolsets for analysis of the WAMS database must permit integrated analysis of:

- Measured power system behavior as obtained from any recorder in general use
- Simulated power system behavior as obtained from any modeling program in general use.

The raw data that contribute to this overall portrait may themselves fail to satisfy these criteria. Measurement sources are prone to technical failings of many kinds, and measurement operations provide numerous opportunities for human error.

APPENDIX B

Preparation of WAMS Data for Analysis

APPENDIX B Preparation of WAMS Data for Analysis

The range of installed WAMS equipment types is fairly broad, and many are legacy equipment not initially designed for use in a system-wide information system. Integration of multi-source WAMS data will generally involve the following technical operations:

- Copying the provided data to a central location for integration and analysis
- Detection and repair of data that are defective, missing, or improperly scaled
- Correcting erroneous time stamps, or applying time stamps when none are provided
- Resampling data that were not collected at a multiple of 30 samples per second
- Translation of phasor data to basic rms quantities (e.g., voltage magnitude and line MW)
- Translation of point-on-wave data into phasors and basic RMS quantities
- Standardizing the naming of signals for multi-source integration, sorting, display, and export for additional processing
- Compensation for excessive filtering or other instrument effects (special cases only)
- Integration of selected data into one or more files for detailed analysis
- Development of relational quantities such as relative bus angle, relative frequency, total interchange.

Using high quality data collected according to a uniform standard simplifies these tasks considerably. Some tasks can be made unnecessary, and it is possible to automate most of the others.

Equivalent tasks are encountered in the preparation of comparable simulation data. The following are recommended:

- Key measurements must be represented in the simulation model, with naming conventions that are consistent with those for the corresponding WAMS data.
- Sampling of the model output must be uniform, with a rate and duration that permit comparison against measured system response.
- Resolution of the model output must not be compromised by poorly chosen data formats.

APPENDIX C

Management and Use of WAMS Data Following a Major System Event

APPENDIX C Management and Use of WAMS Data Following a Major System Event

The first step in data management for system events is to recognize that a significant event has occurred. Subsequent actions depend upon the nature and severity of the event, the topology of WAMS facilities, and agreed procedures among data owners and data users [23].

Establishing the overall procedure can be a substantial undertaking, and it should commence well in advance of major emergencies on the system.

Significant system events can be roughly categorized as major disturbances, staged tests, and benchmark events that are rich in information about system performance. This last category includes but is not limited to events that involve the following:

- Critical system dynamics or facilities
- Major changes in system topology
- Sustained or protracted oscillations
- Unusual behavior in system frequency
- Unusual control actions
- Issues that are known to be of special interest to staff in system operations or planning.

Rule sets that define the events of interest should be coordinated among all established users of WAMS data. Once a significant event has been recognized, authorized WAMS operation staff should issue “secure event data” requests (**SEDR**s) to appropriate data owners. This requests that data for a specific time frame be stored in a secure manner for later delivery, but it does not request that data be provided immediately.

The first "call in" of WAMS data for a recognized event will usually go to operators of PDC units. Phasor data collected on PDC units are a primary and preferred means for obtaining a first overall view of system dynamic performance. It is highly desirable that a necessary minimum of PDC data be obtained and secured for every major event.

The need for additional "call ins" of supplemental WAMS data may emerge during the course of event analysis. In such cases, additional data may be requested from the same PDC facilities, or from secondary monitors for local behavior.

Requested data may arrive along a variety of paths, and in a number of forms. The more common situations are:

1. Raw data files acquired on a local PDC unit.

2. Raw data files acquired on remote recording device, accompanied by data extraction software if needed. These are delivered by file transfer protocol (**FTP**) or on physical media such as compact disk.

3. Processed data files acquired on a remote recording device, consisting of selected signals only. These are delivered by FTP or on physical media such as compact disk.

The DSI Toolbox [24,25,26,27,28] has been developed by WECC to deal with most, although not all, of the more likely situations and data types.

WAMS data managers should plan for all of the situations listed above. Reasons for this include:

- Communication failures may cause data to be lost en route to the local PDC, or to the data archiving units downstream from it. Retrieval of backup data produces situations 2 or 3.
- Limited networking may preclude that all data are sent to the local PDC in real time—e.g., a communication link of sufficient capacity may not be available, the source data may not be PDC compatible, or the data may be subject to a delayed release agreement. This produces situations 2 or 3.
- Data formats may not be PDC compatible—e.g., PDC data may have been processed into some other format, or recorded on some other type of device. This produces situation 3.

Other common problems are failure to issue, receive, or properly act upon a SEDR. Time stamp discrepancies, in particular, may lead a WAMS operator to secure the wrong records while the records of interest are lost from storage. All of these problems are highly likely in the wake of massive disturbances such as the US-Canada Blackout of August 14, 2003, in part because data are requested from a very wide range of data sources [11,12,29].

APPENDIX D

WAMS Operation for Emergency Management

APPENDIX D WAMS Operation for Emergency Management

A wide range of WAMS operating procedures should be taken in the expectation or recognition of a system emergency [23]. The following actions are recommended:

- **Emergency Response Plan for WAMS Operation**
  - Determine dynamic information needs and WAMS facilities to meet them
  - Develop necessary agreements for sharing of costs, data, and staff for WAMS deployment and operation
  - Develop procedures for safe retention and timely integration of WAMS data
  - Develop procedures and resources for integrated analysis of WAMS data together with relevant information from all other sources (to include model studies)
- **Preparations for WAMS Emergency Response**
  - Identify and train key staff
  - Develop, maintain, and document technologies that convert WAMS data into useful information
  - Regularly test, maintain, and document all aspects of WAMS performance
  - Regularly analyze WAMS data to determine the normal range of power system behavior and to facilitate recognition of abnormal behavior
  - Regularly compare WAMS data against model studies to facilitate the interpretation of measured data and to determine model fidelity
- **WAMS Emergency Response: On Line**
  - Take all actions required by operating procedures established by NERC, the local reliability organization, and the operating utility or ISO.
  - Develop, maintain, and document technologies that convert WAMS data into useful information

- **WAMS Emergency Response: Data Management**
  - Determine the nature and severity of the event
  - Issue ”secure event data" requests (**SEDR**s) to appropriate data owners. These must indicate recorders from which data may be requested later. Data owners should examine data to verify that the secured records are the correct ones and that the data have been stored correctly.
  - Issue ”provide event data" requests (**PEDR**s) to appropriate data owners. These must indicate specific signals and time frames. PEDRs may be constrained by timed release agreements and may need to be repeated if files initially obtained are incomplete or defective.
  - Obtain and integrate records from primary ("backbone") data sources. Assess all records in context of operator logs, event recorders, and model studies.
  - Obtain and integrate records from secondary data sources according to above assessment. Repeat as needed.
  - Share data and findings among appropriate staff. Must rigorously observe security issues, and log all requests for or transfers of information materials.
- **WAMS Emergency Response: Analysis and Reporting**
  - Integrate WAMS data into one or more portraits of system behavior. Document all data sources, and all repairs or changes made to the data.
  - Validate the data for record alignment and signal quality. Document all repairs or changes made to the data.
  - Prepare initial report materials concerning measured dynamic performance. Include power flow data before the event and following system recovery, transient waveforms for the event, and frequency domain results for oscillatory dynamics if appropriate.
  - Integrate and extend initial report materials in collaboration with overall event analysis team. This may include development and analysis of computer simulations, comparisons against other events from the WAMS archive, and follow-up tests of the power system itself.

APPENDIX E

Organization of WAMS Data

APPENDIX E Organization of WAMS Data

WAMS operation generally involves upward of a thousand "primary" signals that are continuously recorded in their raw form. These primary signals are the basis for several thousand derived signals that are viewed in real time, or during regular off-line analysis of power system performance. In many cases, the signals derived from measurements are analyzed in parallel with equivalent signals that have been obtained from computer simulations.

The WAMS database for a major event on the power system may be far larger than that for regular system operation. The analysis itself is usually much more thorough, and it usually produces a greater number of analysis products.   Also, as insight into the event evolves, the analysis will often extend to secondary data that are not usually incorporated into the WAMS database. It is necessary to smoothly manage the database as it expands, and to do so in a manner that observes confidentiality agreements among data owners or system managers.

Organization of the WAMS database relies upon the following functionalities [30]:

- a standard dictionary for naming power system signals
- a summary processing log indicating where the signals originated and how they have been processed
- data management conventions that name and store the data objects according to the system event.

Essential to these functionalities is the data source *configuration file*, which provides information for the following purposes:

- Converting raw data to engineering units**.** This action includes initial corrections to known offsets in the data.
- Automatically naming of extracted signals. This includes renaming files to control information concerning data sources and ownership.
- Logging of data source characteristics. This provides links to data servicing tools for repair adjustment, or other modifications that may be required immediately, or at some future time.
- Standardizing naming of the data source. This provides links to dictionaries that contain processing menus that have been customized for specific users and/or operating environments.

In the WECC, these functionalities have been built into the WAMS technologies for a very long time, but they have not received very much general comment. Relevant documents include [28] and an extensive set of WAMS application documents (posted on ftp://ftp.bpa.gov/pub/WAMS%20Information/). While equivalent technologies are still being worked out for the EI WAMS, the functionality needs are similar to those of the WECC WAMS.

References

WECC documents cited here tend to be large, and are usually distributed in electronic form from one or more of the following websites:

http://ftp.bpa.gov/pub/WAMS_Information/

http://www.wecc.biz/wrap.php?file=wrap/committee.html

http://www.transmission.bpa.gov/orgs/opi/Wide_Area/index.shtm

http://phasors.pnl.gov/

These addresses change with time, and some documents are eventually removed to conserve storage. A cited document that is no longer present is available by special request to the authors, or to the indicated WECC technical group.

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[1] **Wide Area Measurements for Real-Time Control and Operation of Large Electric Power Systems – Evaluation And Demonstration Of Technology For The New Power System**. Prepared for U.S. Department of Energy Under BPA Contracts X5432-1, X9876-2; January 1999. This report and associated attachments are available from the Bonneville Power Administration (BPA) and PNNL on compact disk.

[2] **Dynamic Information Manager for Networked Monitoring of Large Power Systems**. EPRI Report TR-112031, Electric Power Research Institute, Palo Alto, California. May 1999.

[3] J. F. Hauer and J. G. DeSteese. **A Tutorial on Detection and Characterization of Special Behavior in Large Electric Power Systems,** PNNL-14655, Pacific Northwest National Laboratory, Richland, Washington. July 2004.

[4] J. F. Hauer and J. E. Dagle. **Review of Recent Reliability Issues and System Events**, PNNL-13150. Prepared for the U.S. Department of Energy Transmission Reliability Program by the Consortium for Electric Reliability Solutions (**CERTS**), Pacific Northwest National Laboratory, Richland, Washington. December 1999.

[5] Bob Fesmire, **The State of WAMS**. Utility Automation & Engineering T&D Magazine, vol. 11, no. 7, pp. 32-37, September 2006.

[6] J. F. Hauer, D. J. Trudnowski, G. J. Rogers, W. A. Mittelstadt, W. H. Litzenberger, and J. M. Johnson. **"Keeping an Eye on Power System Dynamics," IEEE Computer Applications in Power**, pp. 50-54, October 1997.

[7] J. F. Hauer, W. A. Mittelstadt, K. E. Martin, J. W. Burns, and H. Lee. **Integrated Monitor Facilities for the Western Power System: WAMS Analysis in 2005.** Interim report of the WECC Disturbance Monitoring Work Group, December 2005. (available at the WECC website). Equivalent materials will appear in **The Electric Power Engineering Handbook**, edition 2, L. L. Grigsby ed., CRC Press, 2007.

[8] K. E. Martin. "**Synchronized System Measurement Networks in North America: Operating Process and System Formats Based Upon BPA's Phasor Data Concentrator.**" WAMS Working Note, June 1, 2004. Available at BPA websites.

[9] C. E. Grund, G. Sweezy, J. F. Hauer, S. J. Balser, and S. Nilsson. "**Dynamic System Monitoring (DSM) for HVDC Modulation Control." IEEE Trans. Power Systems,** vol. 8, no. 3, pp. 964-971, August 1993.

[10] R. P. Schultz and B.B. Laios. "**Triggering Tradeoffs for Recording Dynamics**." **IEEE Computer Applications in Power**, pp. 44-49, April 1997.

[11] J.F. Hauer, N. Bhatt, K. Shah, and S. Kolluri. **"Performance of 'WAMS East' in Providing Dynamic Information for the North East Blackout of August 14, 2003."** IEEE/PES Panel on Major Grid Blackouts of 2003 in North America and Europe, IEEE PES General Meeting, Denver, Colorado, June 6-12, 2004.

[12] U.S.-Canada Power System Outage Task Force. **Final Report on the August 14, 2003 Blackout in the United States and Canada: Causes and Recommendations**. April 5, 2004. Available at http://www.nerc.com/~filez/blackout.html.

[13] M. Donnelly, P. Barber, and J. Dyer. "**Progress Toward a High-Speed Data Network for the Eastern Interconnection – The Eastern Interconnection Phasor Project."** Proceedings of the Georgia Tech Fault and Disturbance Analysis Conference, Atlanta, April 26-27, 2004.

[14] J. M. Johnson. "**PDCDataReader: A Utility to Provide PDC Derived Quantities to Windows-Based Applications in Near Real-Time**." WAMS Working Note, August 17, 2003. Pacific Northwest National Laboratory, Richland, Washington.

[15] Electric Power Group. "**Functional Specifications for RTDMS Enhancements.**" November 21, 2005. CERTS Working Note of the Electric Power Group, November 21, 2005. Available at EIPP website.

[16] R. W. Wies, J. W. Pierre, and D. J. Trudnowski. **"Use of ARMA Block Processing for Estimating Stationary Low-Frequency Electromechanical Modes of Power Systems." IEEE Trans. Power Systems**, vol. 18, no. 1, pp. 167-173, Feb. 2003.

[17] ***IEEE Standard for Synchrophasors for Power Systems*, IEEE Standard C37.118-2005**, March 2006.

[18] K. E. Martin. "**Synchronized System Measurement Networks in North America: Operating Process and System Formats Based Upon BPA's Phasor Data Concentrator."** WAMS Working Note, June 1, 2004. Available at BPA websites.

[19] J. F. Hauer. "**List of WECC Working Documents Produced with Support by the WAMS Outreach Activity Funded Under the DOE Program for Transmission Reliability**." DOE/CERTS Working Note, May 15, 2007. Available at BPA websites.

[20] J. F. Hauer and J. R. Hunt, in association with the WSCC System Oscillations Work Groups, **"Extending the Realism of Planning Models for the Western North America Power System,"** V Symposium of Specialists in Electric Operational and Expansion Planning (SEPOPE), Recife (PE) Brazil, May 19-24, 1996. Available at BPA websites.

[21] **Eigenanalysis and Frequency Domain Methods for System Dynamic Performance**, IEEE Publication 90TH0292-3-PWR, 1990.

[22] J. F. Hauer. "**List of WECC Working Documents Produced with Support by the WAMS Outreach Activity Funded Under the DOE Program for Transmission Reliability."** DOE/CERTS Working Note, May 15, 2007. Available at BPA websites.

[23] J. F. Hauer. "**Integrated Monitor Facilities for the Eastern Interconnection: Management & Analysis of WAMS Data Following a Major System Event.**" Working Note of the Eastern Interconnection Phasor Project (EIPP), December 16, 2004. Available at BPA and EIPP websites.

[24] J. F. Hauer and J. M. Johnson. **A User Guide to PSM Tools: Utilities for Matlab Processing of Power System Response Records.** Prepared for the U.S. Department of Energy Transmission Reliability Program by the Consortium for Electric Reliability Solutions (CERTS), Pacific Northwest National Laboratory, Richland, Washington, February 2001. Available at BPA websites.

[25] J. M. Johnson and D. J. Trudnowski. **DSItools User Manual for the Ringdown Analysis Tool.** Pacific Northwest National Laboratory, Richland, Washington. 1998. Available at BPA websites.

[26] D. J. Trudnowski, J. F. Hauer, and G. J. Rogers. **DSItools Application Guide for the Power System Modal Analysis.** Pacific Northwest National Laboratory, Richland, Washington**.** 1998. Available at BPA websites.

[27] J. Hauer, Z. Huang, and J. M. Johnson. **Expanded Version of the BPA/PNNL GUI for Integrated Prony and Fourier Analysis of Ringdown Signals.** WAMS Outreach documentation slides prepared for the U.S. Department of Energy Transmission Reliability Program by the Consortium for Electric Reliability Solutions (CERTS), Pacific Northwest National Laboratory, June 27, 2003. Available at BPA websites.

[28] WECC Disturbance Monitoring Working Group. **WSCC Plan for Dynamic Performance and Disturbance Monitoring**, Prepared by the WECC Disturbance Monitoring Work Group, October 4, 2000. Available at BPA and WECC websites.

[29] J. E. Dagle. **"Data Management Issues Associated with the August 14, 2003 Blackout Investigation."** IEEE/PES Panel on Major Grid Blackouts of 2003 in North America and Europe, IEEE PES General Meeting, Denver, CO, June 6-12, 2004.

[30] J. F. Hauer. "**Database Organization for Analysis of Major System Events Recorded on the WECC WAMS.**" Working Note for the WECC Disturbance Monitoring Work Group, February 22, 2005. Available at BPA websites.