EIPP Real-Time Dynamics Monitoring System

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Abstract

The Eastern Interconnection Phasor Projects (EIPP) is a Department of Energy (DOE) and Consortium for Electric Reliability Technology Solutions (CERTS) initiative to deliver immediate value of phasor technology to the Eastern Interconnection (EI) participants. With the current EI phasor network comprising of approximately 25 Phasor Measurement Units (PMU) and 5 Phasor Data Concentrators (PDC) is operational, this paper focuses on the efforts by the EIPP Real-Time Applications Task Team (RTTT) to develop and deploy real-time wide area monitoring capabilities on grid dynamics to operators and reliability coordinators through the Real-Time Dynamics Monitoring System™ (RTDMS) as well as some of the planned activities that are currently underway.

Introduction

The electric power grid in the US has evolved from a vertically integrated system to a mixture of regulated and deregulated competitive market system. Grid oversight is transitioning from local utilities to an assortment of transmission companies, regional Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs). Regulatory and economic pressures have caused new transmission construction to lag the growth in demand. These forces have increased pressure on electricity markets and caused operators to maximize the utilization of the system. The result is an operating environment where operators are faced with quick changing and previously unseen power flow patterns and unforeseeable operational conditions with limited information available for real-time operation and decision-making.

Reliable electricity supply is continually becoming more essential for society, and blackouts are becoming more and more costly whenever they occur. In recent years, there have been major blackouts in North America, Europe and Asia. The August 14, 2003 blackout in the Eastern Interconnection impacted 50 million people. Recommendations from the investigation of this blackout carried out by the US-Canada Joint Task Force included the need for wide-area visibility and situational awareness to address problems before they propagate, the use of time-synchronized data recorders, and better real-time tools for operators and reliability coordinators. Utilities planned and operated the power system under their control on an integrated basis. Utility operating systems all use SCADA systems to collect local real-time data to monitor and control their portion of the power system. While control areas share their SCADA data with reliability coordinators via Inter-control Center Communications Protocol (ICCP), ICCP data is transmitted at varying rates (up to minutes in periodicity) and is not time synchronized.

Over the last two decades, utilities in North America have deployed Phasor Measurement Units (PMUs) in their substations to measure the voltage and current phasors (both magnitude and phase angle) and on monitored lines along with local frequencies, at a very high rate (10 to 60 times a second), and communicate this data in real-time along with precise timing information of when these measurements were taken. Recent advances in this field of phasor technologies offer great promise in providing the industry with new tools and applications to address the blackout recommendations and to tackle reliability management and operational challenges faced by system operators, reliability coordinators and utility engineers. Phasor measurement based systems, algorithms and applications have been researched and prototyped in the lab and test environments for the last 20 years, and have reached a level of maturity where they are ready to transition into the field and into operational environments. Technical developments in communication technologies and measurement synchronization have also made the design of wide area monitoring, protection and control systems realizable. These advance measurements in conjunction with FACTS and HVDC technologies are essential in extending the controllability of network flows across the power grid.

Phasor technology in not a replacement for SCADA, rather it complements existing SCADA systems to address the new emerging need for wide area grid monitoring and management, while continuing to use existing SCADA infrastructure for local monitoring and control. Traditional SCADA/EMS systems are based on steady state power flow analysis, and therefore cannot observe the dynamic characteristics of the power system – phasor technology augments these existing systems by overcoming this limitation. These measurements provide time synchronized sub-second data which are ideal for real-time monitoring of power system dynamics on a wide area basis as well as improve post disturbance assessment capability. Additionally, the infrastructure that evolves through the EIPP will provide a layer of backup visibility should the operator's primary tools fail.

The focus of this paper is to describe the activities and challenges of the EIPP Real-Time Applications Task Team (RTTT).

EIPP Project Background

The Eastern Interconnection Phasor Project (EIPP) which began almost two and a half years ago was a Department of Energy (DOE) and Consortium for Electric Reliability Technology Solutions (CERTS) initiative to serve as a catalyst to deliver immediate value of phasor technology to the Eastern Interconnection (EI) participants with the hope of increased involvement and participation by utilities and other stake holders through the course of the project. To achieve its objectives, the EIPP Work Group has been organized by task teams to address different aspects of the project: Equipment Placement Task Team, Real-Time Applications Task Team, Off-Line Applications Task Team, Business Management Task Team, Data Management Task Team, and Performance Requirements Task Team. The Leadership Committee and the Executive Steering Group comprising of senior executives from different utilities and organizations provide guidance and coordination between the activities of task teams as well as establish liaison with the external organizations [1].

The initial EIPP phasor network connecting approximately 25 PMUs dispersed across various key locations within the Eastern Interconnection and providing real-time wide area visibility has been established and is fully operational. This starter phasor network uses point-to-point VPN links for data transfer in real-time between participating utilities (which include Ameren, AEP, NYISO and Entergy) and Tennessee Valley Authority (TVA) which is currently the central host site for synchronizing this phasor data by it's Phasor Data Concentrator (also known as the SuperPDC) to provide an instant Interconnection-wide snapshot, as well as simultaneously archiving it into their DatAWare data repository. Comparisons of high sub-second snapshots enable real-time monitoring and tracking of grid dynamics and stress. These comprehensive sets of measurements are archived at the host site as well as sent in real-time to distant locations over VPN links and secure web connections for remote viewing within the Real-Time Dynamics Monitoring System (RTDMS) visualization terminals (Figure 1). Other utilities are expected to contribute data from their phasor devices very soon.

In addition to setting up the EI phasor network, the various EIPP task teams, through coordinated activities across the Interconnection, have made significant headway in evaluating the performance and suggesting appropriate guidelines for this high resolution phasor data acquisition network.

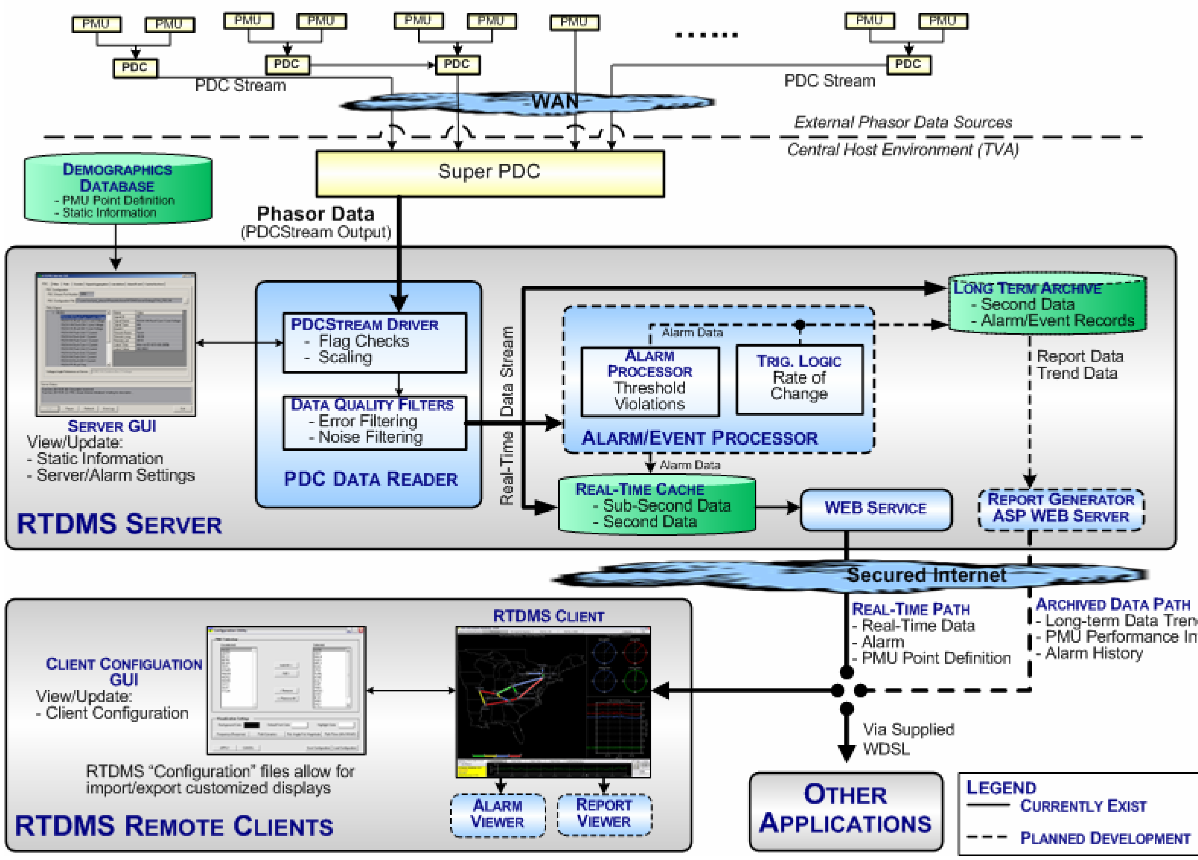

Figure 1: EIPP Phasor System Architecture

Real-Time Operating Tools

The Real-Time Applications Task Team (RTTT) is lead by Terry Bilke (MISO), supported by CERTS members, and is composed of diverse group including representatives from ISOs, RTOs, utilities, academia, and the manufacturer and vendor community. The scope of the team includes the development, deployment and training of tools enabling operators, reliability coordinators and others engaged in operational aspects of grid reliability to effectively monitor and assess the real-time operations of the power grid on a wide area basis. The near-term focus of the team has been in the development and deployment of phasor measurement based real-time visualization and monitoring capabilities enabling the EI operators and reliability coordinators to gain familiarity with phasor technology, and to research and demonstrate the utilization these measurements in the state estimation process.

The Real-Time Dynamics Monitoring System (RTDMS) is currently the primary tool in place for viewing the Eastern Interconnection phasor data in real-time (Figure 1). This system offers flexibility in terms of it being designed as an open and scalable platform with the ability of other third party applications to access data using the available RTDMS Web Service. The RTDMS application had been deployed to the 7 operations centers and 11 reliability coordinators within the Eastern Interconnection.

The RTDMS Server installed at the TVA host site integrates with their SuperPDC to retrieve data on each of the measured signal types in the standard PDCStream data format that was developed by BPA. Data quality filters built into the Server automatically remove erroneous data samples, noise, and dropouts from the real-time data stream and temporarily store the processed information into the real-time cache in memory for quick retrieval. Multiple RTDMS Client applications may simultaneously access the data from the central RTDMS Server over a secure internet connection and, thru various geographic and graphic displays, provide operators and reliability coordinators both near real-time and time series information on:

- Interconnection and local frequencies at key monitoring points across the EI where changes in frequency are mapped to precise generation-load imbalances within the Interconnection. The local frequency measurements can be used to assess system coherency and its dynamic stress under normal operating conditions, as well as estimate the point of deceleration/acceleration during a disturbance.
- Phase angle differences across different utilities with respect to alarming thresholds as defined by offline analysis and operator experience to assess the static stress across the system and its proximity to instability.
- Wide area view of system voltage angle and magnitude profiles to identify the sources and sinks of power, and the high and low voltage regions within the grid (Figure 2).
- Monitor and track the MW and MVAR values across key transmission lines and flowgates with respect to predefined thresholds.

TVA has also setup a secure demographics website that provides the latest information on the status of the phasor network and its devices, and static information about these devices such as their location and labeling.

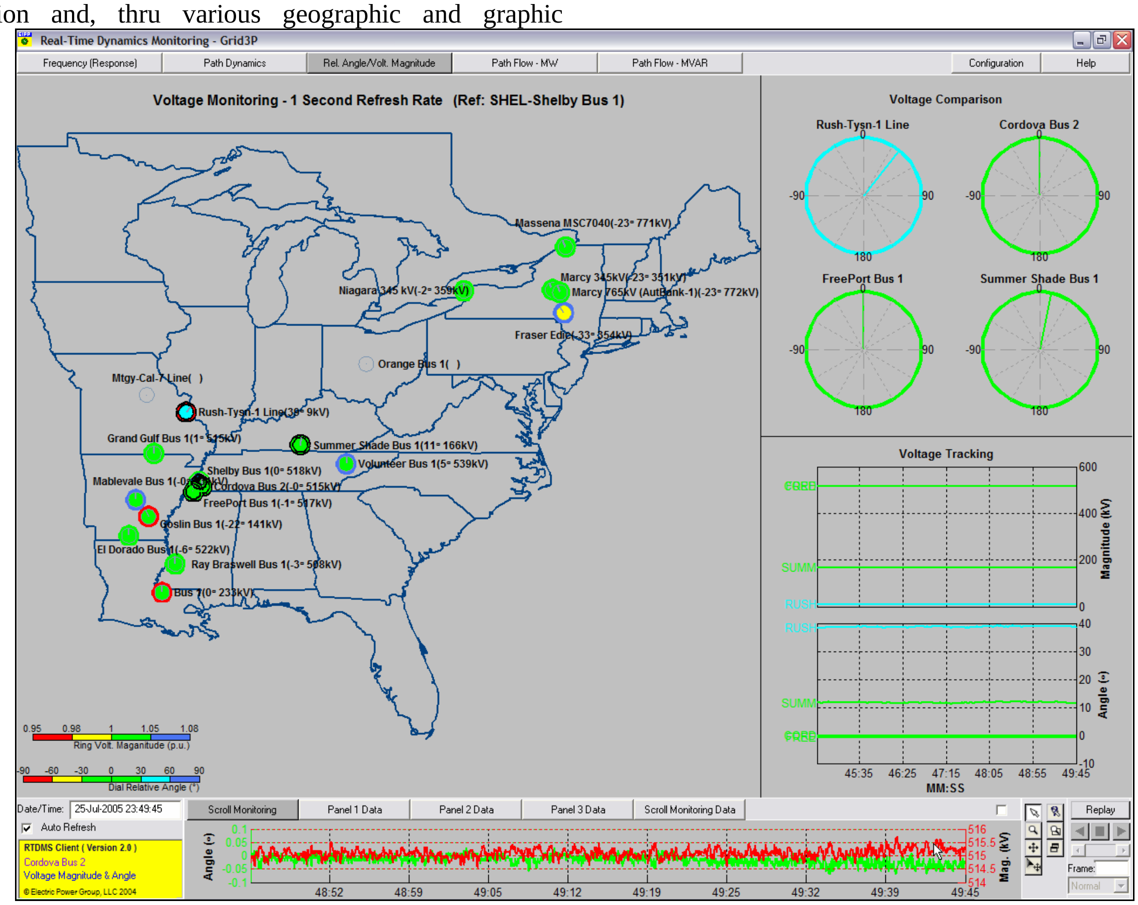

Figure 2: Sample RTDMS Display

Figure 3 provides an example of the potential value of the RTDMS. The figure represents the relative phase angles seen in Ohio and Michigan prior to the August 2003 blackout. PMUs located in these and other states could have alerted operators across the Interconnection that stress was greater than normal hours before the separation.

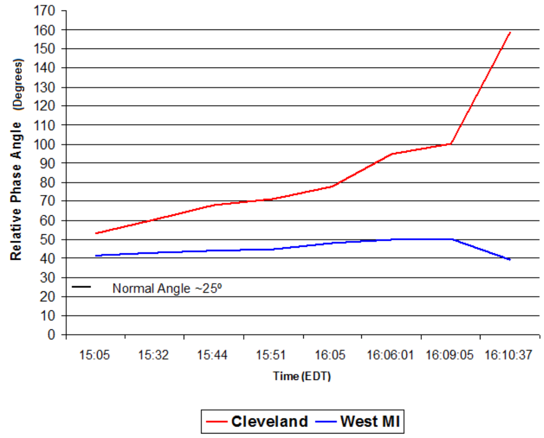

Figure 3: August 14, 2003 Phase Angles between Ohio & Michigan (Courtesy Bob Cummings – NERC)

Initial Experiences

With the starter phasor network operational and the RTDMS application in use, some of the initial challenges have been associated with data quality. These can be attributed to labeling/wiring inconsistencies (resulting in ±120° offsets), inconsistencies in measurement types (line-line vs. line-neutral) calibration errors due to inaccurate characterization of the instrumentation channels (e.g., CT/PT ratios), high frequency harmonic content measured on certain channels, data or channel dropouts, etc. The main contributing factor here has been the sheer complexity and diversity of this initial phasor acquisition network that spans multiple utilities, and involves PMUs/PDCs belonging to different vendors with different data rates, protocols, etc. Through a coordinated effort by the various teams and participating utilities, many of these issues have now been resolved.

Some of the early hurdles in presenting this real-time phasor related information to the initial users of the application has been in identifying key points and metrics across the Interconnection that are of relevance from a wide-area monitoring point-of-view. For example, angle differences across PMUs are indicators of static stress across the grid, however the PMUs across which the angle difference should be monitored and their relevant alarming thresholds for these pairs are assumed at this stage and need further validation. For the near-term, one suggested approach has been to study the observed phase angle profiles over an extended period of time to ascertain their behavior under normal system conditions, and to use these long-term trends to define either hard limits (i.e. fixed limits) or soft limits (i.e. statistical bounds) for these metrics. An additional challenge for the participants and the team members will be to establish policies and procedures for the desired actions to be taken when such limits are reached or exceeded. Choosing an appropriate phase angle reference for the EI real-time visualization applications was also an issue identified by the Real-Time Task Team and now has been addressed by the Performance Requirements Task Team (PRTT). Though, theoretically any value could be a reference for the phase angles, some of the practical concerns in choosing the reference included its consistency with current power grid operation and planning practices, its system-wide availability, and its reliability or backup capability. The PRTT identified various options (real-bus backup, virtual bus, real-bus slack, system time) for meeting these concerns, and finally recommended the selection of Trinity or Limestone as the reference bus which is in close proximity of the Browns Ferry Power Plant - the most commonly used reference for power flow and stability studies in the Eastern Interconnection [2].

RTDMS Planned Developments

With increasing involvement and participation by EI utilities, the EIPP phasor network is expected to increase its coverage, and grow into a fully redundant and secure phasor data acquisition system with expanded observability of the EI dynamics. There are over 35 known compatible phasor measurement instruments in place and another 22 new installations committed before March 2006. As additional PMUs are installed and incorporated into the phasor network, there is need for effective management of this data and avoid clutter on the operator monitoring displays. It is crucial that the visualization application provide meaningful and actionable information for operators and reliability coordinators in a concise fashion. To achieve this objective, working with the RTTT and the end users of the application, some of the planned expansion to the RTDMS visualization include (1) the addition of a dashboard summary type of display for operators, and (2) a tiered visualization architecture with drill-down capabilities from centrally configured and standardized "global" displays for wide-area viewing to "local" end-user customized displays at the regional level.

Dashboard Summary Display - PMUs at a substation are capable of measuring various different signals such as voltages, currents, frequencies, MW, MVAR etc. While the current visualization has dedicated displays for each of these different monitoring metrics, there is also a need for a common centralized "dashboard" type display where all key information is integrated into common display. Figure 4 illustrates such a summary display which was defined through discussions with the RTTT members and the end users. Here simple gauges and traffic light concepts on various monitoring metrics are used to provide a quick assessment of is there a problem with a particular metric, the location of the problem and the magnitude of the problem. As new monitoring metrics are researched and validated, these can be added into this summary display.

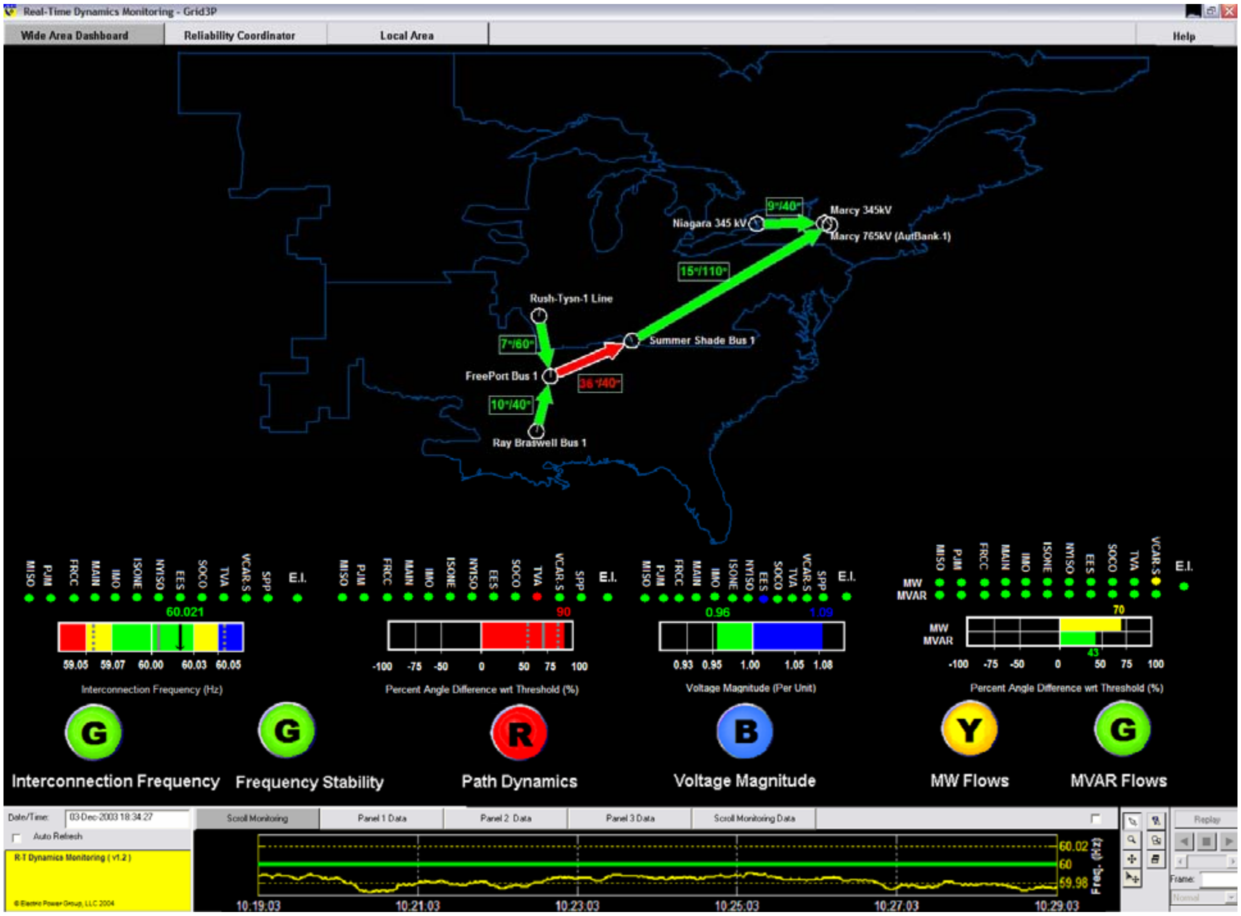

Figure 4: Dashboard Summary Display

Tiered visualization Architecture - Other planned enhancement to the visualization capabilities include the development of tiered visualization architecture with drill-down capabilities from centrally configured and standardized "global" displays for wide-area viewing at the Interconnection and Reliability Coordinator levels to facilitate communication across utilities and for consistency, to "local" end-user customized displays at the utility level. The various tiers within this visualization structure include (Figure 5):

- Display Tier 1: *Dashboard Summary Display (Default)* – This is the first tier that utilizes simplistic "traffic light" type visual concepts to provide information on the overall system status using a set of predefined metrics, as well as information on the associated geographic region(s) associated with the poor performance.
- Display Tier 2: *Eastern Interconnection Displays* – This is a set of geo-graphic displays at the Interconnection level providing PMU based information such as frequencies (or variations in frequencies), voltage magnitude and angle profiles at key monitoring locations *across* the Interconnection, as well as angle differences as indicators of static stress and stability across reliability regions. Responsible group will approve and configure these set of standardized displays.
- Display Tier 3*: Reliability Coordinator Displays* – For each Reliability Coordinator region, a set of geo-graphic displays providing information from all PMUs *within* each Reliability Coordinator region, as well as MW/MVAR flows and angle differences across key flow gates within reliability regions. Responsible group will approve and configure these set of standardized displays.
- Display Tier 4: *Local Displays* – A single set of regional displays customizable by each utility to their own monitoring needs. The end user will be able to customize these localized set of displays.

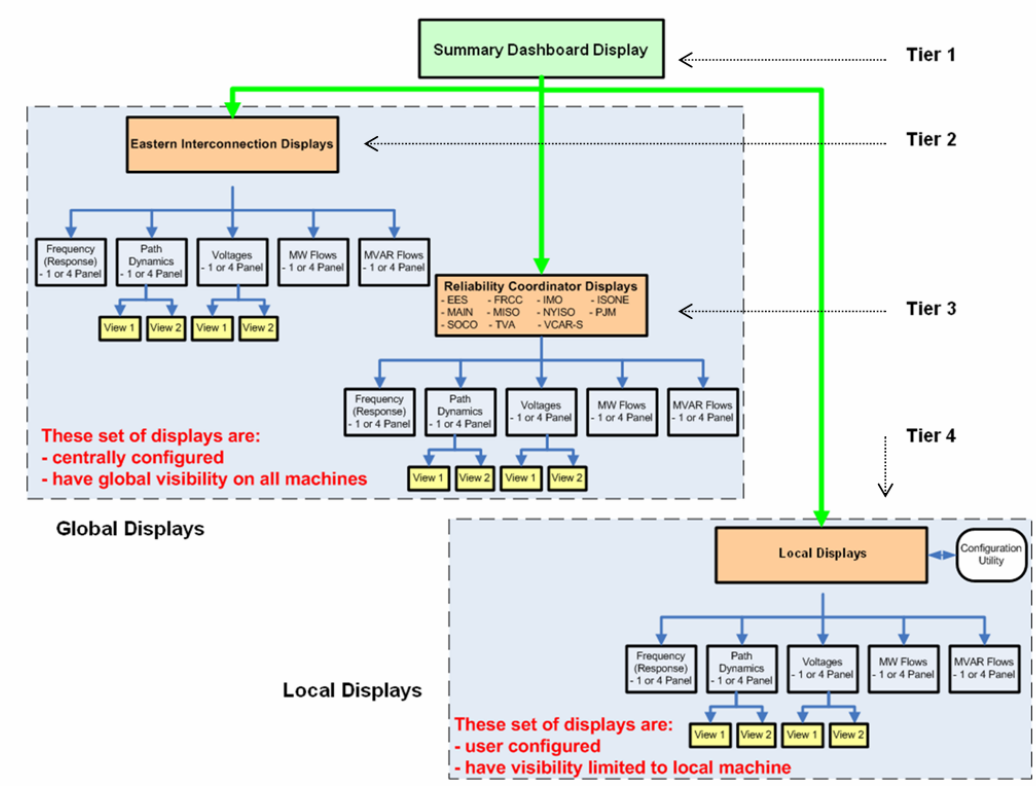

Figure 5: Tiered Visualization Architecture

With many of the data quality and reliability issues out of the way, one of the goals now is to use this data for early detection of impending trouble and real-time alarming. The appropriate triggering logic and supporting infrastructure for real-time alarming is being developed (Figure 1). In the short-term, this alarming capability will be embedded into the RTDMS visualization, but as the alarming capability and criteria on these phasor measurements are validated, the plans are to automatically send email notifications to a select set of recipients when certain alarming conditions are met or statistically significant changes are observed.

The high resolution wide-area visibility that PMUs measurements offer is ideal for monitoring low-frequency electromechanical oscillations that frequently appear in the system. They characterize the reduced stability margin of the power system and often limit power flows across the system. One of the planned developments on the RTDMS platform is also to prototype and demonstrate the capability of identifying in real-time very lightly damped conditions or situations of growing oscillations in sufficient time to initiate corrective operator condition.

To facilitate better understanding and an Interconnection-wide prospective of local and inter-area grid dynamics under normal conditions and during disturbances, an online reporting feature providing long term historical trending of PMU data such as frequencies, voltage magnitude and angles, from multiple locations will also be developed (Figure 6). Creating and correlating these long term trends with time of day, season, peak load, major line outages, etc., using the set of archived phasor data is expected to be useful in understanding the normal behavior of key EI metrics and can also be used to define monitoring guidelines and alarming thresholds for the entire EI grid. The RTDMS reporting capability shall also provide information on PMU performance and data unavailability from all the PMUs in the phasor network to help identify the weak elements in this acquisition network that would require attention, as well as a log of alarms captured by the real-time alarming component of the RTDMS platform.

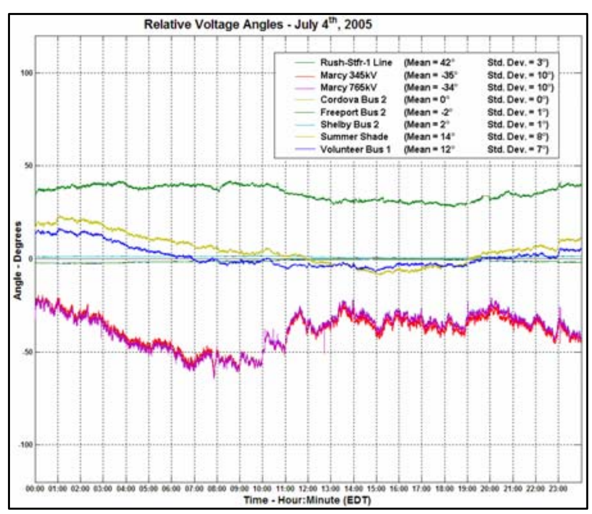

Figure 6: Sample Long-Term Trend Report on EI Phase Angle Profiles

Additional phasor measurement based performance metrics for real-time reliability monitoring are currently being researched and tested by the EIPP community. Examples of advanced performance based metrics include sensitivity computation such as voltage sensitivities at load buses or angle sensitivities at generator buses (Figure 7). Unlike traditional sensitivity computations which are model dependent, measured based methods do not require a system model and are therefore free of errors introduced by model inaccuracies.

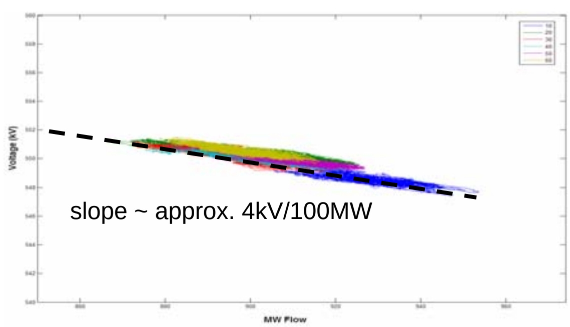

Figure 7: P-V Curve & Voltage Sensitivity Computation using PMU Measurements

Other RTTT Activities

In addition to the phasor based monitoring capabilities, some of the RTTT members are also involved in a demonstration project currently under way by energy management system (EMS) vendors to work with utilities to utilize phasor measurements in the state estimation process. For almost a quarter of the century, continuous efforts and resources have been invested in the implementation of state estimator software and model based technology without achieving the level of accuracy initially expected. Incomplete and unsynchronized input data, incomplete network models for both internal and external systems, errors in model parameters and topology are some of the factors contributing to this inaccuracy. Phasor measurement devices directly measure the system state with high precision and are therefore believed to improve state estimation. The many ways in which phasor measurements can improve accuracy and speed of the state estimation process include:

– Validate traditional state estimation results with real-time accurate phasor measurements for observability analysis and bad data identification.
– Calibrate network models that may not accurately represent system performance.
– Use phasor measurements at system boundaries to accurately represent boundary conditions, thereby reducing the dependency on large network models or the use of simplistic boundary equivalents, which may be inaccurate, and expediting the estimation process.
– Incorporate phasor measurements as input measurements in the state estimation algorithm to improve the convergence and the estimation accuracy (Hybrid State Estimator).

Preliminary research has shown that as little as 10% coverage by strategically placed PMUs dramatically improves the accuracy and processing speed of state estimation [3]. Such improved accuracies in state estimation process are reflected in economics operations (e.g. LMP computations) and security margin estimates which utilize the state estimation results as inputs in their computations.

The results from the state estimation activity are expected to be made available further down the road. Depending on the PMUs placements and how they are used by the utilities, some of the results may be utility specific and would need to be interpreted on a case-by-case basis.

RTTT Future Work

The RTTT, through discussion sessions at the EIPP workgroup meetings and over conference calls, has identified approximately 20 different applications of phasor measurements and documented them in a white paper along with their appropriate data requirements [4]. The range of possible uses range from frequency response analysis, to pattern recognition and event classification, to short-term & long-term stability monitoring and control. Additionally, researchers at universities and other research institutions are continually looking at new innovative applications of this high resolution data. For example, researchers at Virginia Tech are using the sub-second frequency measurements from multiple locations in conjunction with triangulation concepts to pinpoint the event location soon after the disturbance has been detected [5]. The RTTT has and continues to screen through these and other ideas to determine the features to be pursued and the associated priorities in terms of their value to operators particularly if it isn’t available in common EMS applications, clarity in its definition, ease of deployment, etc.

Many relay and disturbance fault recorder vendors now offer phasor measurement and continuous recording capabilities, some of which may easily be attained through firmware upgrades to existing equipment already in the field. Additionally, Virginia Tech in collaboration with ABB and TVA has also implemented an internet based, GPS time synchronized, wide-area power system frequency monitoring network (FNET) as a practical way to quickly deploy a cost effective real time wide area synchronized measurement system [5]. One of the key elements that makes this initiative practical is that area frequency can be measured at 110V single-phase outlets, consequently making such devices fast to deploy and easy to install and relocate. These devices are also capable of measuring phasor quantities at the high sub-second rate. In the future, data from these and other devices such as recorders or relays with phasor measurement capabilities could be integrated into the EIPP phasor network and the real-time tools for a more comprehensive view of the power system behavior.

The RTDMS is being designed as an interface with a view to integrate additional information, alerts and cues for operators and engineers as they are developed by EIPP participants, vendors and academia. Integration of phasor and SCADA data and related metrics into common displays, for example, will provide a more complete understanding of system conditions. It is expected that as the industry learns the value of alerts, some operator actions may be automated to further improve reliability.

RTTT Related Activities

A key focus of the RTTT activities has been to involve the Reliability Coordinators and other system operators, to introduce them to this new technology and applications, and specially get their feedback in the definition and development of these early monitoring tools. Additionally, the team has and shall continue to provide operator (and engineer) education and training on this technology and on the use of these new tools via users' guide, webcasts and on-demand narrated presentations.

A secondary focus of the team has been to encourage increased stakeholder involvement in the EIPP project. The team has also prepared and distributed a generic Business Plan which interested parties may use to obtain buy-in from their management to participate in the project. Additionally, team members participate in industry training events and workshops to further expand and promote EIPP participation and infrastructure.
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Getting Involved

The EIPP project actively seeks to enroll increased industry participation and leadership. EIPP Work Group meetings, held every few months at locations across the country, include participants from utilities, research organizations, universities, manufacturers, and are open to all interested parties. Each of the task teams also hold periodic conference calls, webcasts or workshops to facilitate their activities and move them forward. Those interested can also subscribe to the workgroup or task team mailing lists to stay connected with ongoing activities or to participate in group discussions. Additional information on the project or other phasor related activities may be found at the following links:

EIPP Project Information –http://phasors.pnl.gov
Virginia Tech FNET Project Information – http://www.powerit.vt.edu
WECC WAMS Effort – ftp://ftp.bpa.gov/pub/WAMS_Information/
DOE Website – http://electricity.doe.gov
CERTS Website – http://certs.lbl.gov
Electric Power Group (RTDMS Application) – www.electricpowergroup.com

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