



Using PMU Data to Increase Situational Awareness

Final Project Report

Power Systems Engineering Research Center

*Empowering Minds to Engineer
the Future Electric Energy System*



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Power Systems Engineering Research Center

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Executive Summary

With the large-scale deployment of PMUs in the U.S. and worldwide, a recurring theme has been the question of how to best extract useful “information” or “knowledge” from the very voluminous data that PMUs provide. While the direct control center display of PMU-based data is certainly important, particularly bus voltage angle values, this project focused on techniques that go beyond direct display of the raw PMU data. That is, the project focused on how information could be extracted from the PMU data, and then how this information could be used to improve power system situational awareness. Five different aspects of the problem are considered in Chapters 2 through 6.

Chapter 2 considers how much information could be gleaned from the PMU data with an approach that makes minimal use of other *a priori* information about the system status and model parameters. It is based on a data analysis tool that has been widely utilized for compression and feature extraction in other industries: the Singular Value Decomposition (SVD). The SVD method for PMU data processing views the physical power system as a power flow solver – taking time varying loads/injections as inputs, and producing PMU-measured angles and voltage magnitudes as outputs. By observing a time window of PMU measurements over an interval, forming a matrix of data, and computing the singular value decomposition of this matrix as this window “slides” forward in time, the Chapter 2 algorithm characterizes important aspects of the system’s input-to-output behavior. When the system is highly stressed, one sees outputs vary much more dramatically in response to time variation of the inputs. This efficiently computes information closely related to the Power Flow Jacobian matrix conditioning, *with none of the state estimator and network data required to compute the PF Jacobian matrix itself – the algorithm uses PMU measurements only.* Conditioning of the Power Flow Jacobian is a general indicator of robustness of a system operating point; more specifically, the smallest singular value of the power flow Jacobian (i.e., as it approaches zero) has long been utilized as a first indicator of vulnerability of a system to voltage collapse. Hence, one of the outputs of SVD-based PMU processing algorithm serves as a real-time indicator of system stress, tracking a well-established voltage stability performance metric without the need for detailed network parameter values or state estimator results.

Chapter 3 presents an algorithm on how PMU data can be used to enhance existing power flow algorithms to improve situational awareness. The motivation for this application arises because in a variety of situations SE results may not be available. For example, smaller utility control systems may not have an SE, the SE may have failed to converge during rapidly changing system conditions, there may be a need to combine SE results with a larger system model, or people involved in nonoperational aspects of the power grid, such as marketers and power system planners, may not have access to SE results. But often a power flow case is available that at least approximates (to some degree) the current operating condition. The Chapter 3 algorithm shows how existing linear programming (LP) based optimal power flow algorithms (OPF) can be used to change a power flow operating point to better match the bus voltage angles coming from the PMUs. The algorithm is demonstrated using a three bus case and a 13,000 bus case.

Chapter 4 presents the visualization of PMU-derived information associated with power system electromechanical oscillations using the Washington State University Oscillation Monitoring System (OMS). The inputs to the OMS are selected PMU bus voltage measurements. When a disturbance is detected the OMS uses a real-time Prony analysis with a moving time-window to determine the oscillation frequency and damping ratio. Results are visualized with a user-friendly, web-page interface.

Two example visualizations are presented. In the first, the Damping Monitor display, there are three major areas. Left top is a frequency vs. damping ratio point chart, which shows all the modes in the frequency domain, and their damping ratio on y-axis. The right top corner shows the time and a brief summary, which includes the status of each mode. The bottom of the display is the mode shape area, which shows mode shapes of up to 4 modes, in a radial fashion. In the second, the Event Monitor display, there are two areas. The top area shows the mode frequency and the damping ratio with a dial like chart. The bottom part shows the mode shape, as in the Damping Monitor display.

Chapter 5 considers how PMU data can improve situational awareness by improving the load models used for power system analysis platforms. The mathematical models for loads used in most security (operational reliability) analysis range in detail from simple impedances to generic dynamic models and full-blown induction motor models. These load models typically have various parameters that describe their behavior and power consumption. In hour and day-ahead analysis, the loads are essentially based on power forecasts. Two things about these load models are important in the analysis. The first thing is the model structure (static, dynamic etc.); the second is the model parameter values.

Since PMUs provide virtually real-time values of voltages and currents, they have the potential to be useful in producing virtually real-time load models for security (operational reliability) analysis. If the PMU data come from locations that could be considered “load buses”, then analysis of these measurements could provide information on the structure of the load model and the parameters of the model. This portion of the project developed a process to perform this analysis.

This process was then evaluated with simulated phasor data using a 3-machine, 9-bus system, and a 9-machine, 30-bus system. For each system, several cases with different load models were simulated using the automatic identification procedure. The voltage variation was detected to start the estimation process. The load type was determined by inspecting the P-V relation and by using the self-augmented model. LMA was used to estimate model parameters. Finally, the estimation results were validated by using the data after that until another voltage variation was detected. The results from both test cases using simulated phasor data indicate that the method could become a valuable tool for model identification in real time.

The application of PMU data to improve reactive power monitoring and control is considered in Chapter 6. The ability to supply reactive power when it is needed can help a system to obtain a new stable operating point instead of becoming unstable. Generally, such reactive power control occurs only at the transmission system level. Chapter 6 develops a framework to allow control of distributed reactive-power capable devices located near the end-user. In particular, inverters such as those connected to PV

panels and pluggable-hybrid electric vehicles (PHEVs) can be used to operate at a leading power factor and thus supply reactive power.

The communication and control for these reactive power resources can be coordinated in a hierarchical way. First, the voltage problem must be detected. Then, the appropriate response action needed to correct the voltage problem is computed. The solution at this stage gives locations and amounts of reactive power needed to correct the problem. Action requests are formulated and sent to an agent, which may be located in a relay on a feeder. This feeder agent may be upstream of several other relays and load controllers. The requests propagate downward. At each level, a set of response actions needed to fulfill the request are determined and sent to the next level in the hierarchy. Results are demonstrated using the IEEE 24-bus reliability test system.

Future Research Steps

With the rapid growth in PMU installations across many power systems it is clear that PMUs will play a role of increasing importance in power system operations. While this project has presented solid research for moving forward, there is certainly more work to be done. The SVD work from Chapter 2 needs to be further tested and validated; also applications to other PMU-based measurements should be considered. While the Chapter 3 work of incorporating PMU-measurements into the power flow could also benefit from additional testing, it is at the stage in which commercial implementation should be considered. The Chapter 4 OMS is currently undergoing utility testing; the associated visualizations could be enhanced based upon the results of this testing. The Chapter 5 load modeling work should have additional testing with actual PMU data; it could also be extended to consider more dynamic load models, such as induction machines and other devices such as synchronous generators. Last, the Chapter 6 use of PMUs for improved reactive power modeling as advanced to the point in which actual prototype installations can be considered.