



Monitoring and Maintaining Limits of Area Transfers with PMUs

Final Project Report

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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

The report is presented in two parts. Part 1 extends area angle monitoring with PMUs to get actionable information in emergencies. Part 2 describes structural modeling and performance metrics needed for monitoring and control of the changing electric power system.

Part 1: Monitoring and Maintaining Limits of Area Transfers with PMUs

Phasor Measurement Units, or PMUs, also known as synchrophasors, can quickly measure voltage phasor angles with respect to a common reference at multiple locations spread across the power grid. When these measured PMU angle data are made available at a control center, the challenge is to turn the data into actionable information about the power grid.

Most of the current methods have the easier objective of detecting system conditions that are anomalies or outliers. Indeed, if we subtract measured PMU angles to get angle differences, then unusually large angle differences generally correspond to stressed conditions, and these stressed conditions can be distinguished from normal operating conditions. While it is of some use to be able to detect and report that the conditions are stressed, the problem underlying the stress, whether action needs to be taken, and which action to take are not specified. That is, the PMU data processed in this unstructured way can detect a generally stressed condition, but does not provide actionable information to solve a specific problem.

To get actionable information from PMUs we need to formulate a more specific problem, and this project addresses the effect of line outages inside a particular area when there is a particular overall pattern of power flow through the area. The PMU angle measurements are made around the border of the area. We use circuit theory to combine the measured angles into a scalar “area angle” that quantifies the area stress with respect to line outages inside the area. That is, the area angle measures the impact of line outages inside the area. Offline computations can set a threshold for the area angle that is related to the N-1 criterion. Then if the area angle exceeds the threshold, emergency action to reduce the power flow through the area is recommended. Equally important is that if the area angle is less than the threshold, no emergency action is needed. This actionable information is obtained essentially by restricting the problem formulation to monitor and respond to the overloading problem associated with a particular power transfer through a particular area.

The standard way to compute effect of line outages inside the area is to perform state estimation in order to get a detailed description of the outages and individual line flows inside the area so that corrective actions can be taken as needed. Using the state estimator in this way is an accurate and useful procedure when it can be performed. The advantage of the area angle computation from PMU measurements is that it is faster, and available when the state estimator does not converge. This makes the area angle particularly appropriate when there are multiple simultaneous line outages that could cause further outages in a cascade. Multiple outages are the most difficult case for state estimation, and quickly determining whether emergency action is needed with the area angle based on PMUs is particularly useful in this case of potential further cascading. Since the area angle is a single bulk measure of the complexities of power flows and outages interacting

inside the area, it is an approximation. However, it appears to be a practical approximation that can give actionable information.

The area angle is calculated online from a weighted sum of the voltage phasor angles measured around the border of the area. This is a very easy and fast calculation. The weights are calculated offline from a DC load flow of the area. There is an assumed pattern of power flow through the area and positive weights correspond to buses which have power entering the area and negative weights correspond to buses which have power leaving the area or loads. The area angle is thus a bulk angle between buses on one “side” of the area to the other “side” of the area. Since the area angle is derived from circuit theory, it behaves intuitively when conditions change. If the power flow through the area increases by 10%, then the angle across the area increases by 10%. If there are line outages inside the area, then the power flow through the area is passing through an area of higher impedance and so the area angle increases. That is, even if the power flow through the area does not change much, the rerouted power flow through the area due to the line outages encounters more impedance, and so the area angle increases. This shows how the area angle responds to line outages inside the area, and how the area angle provides information not available from the bulk power flows into the area.

Previous work (with PSerc support) tested the area angle on the north-south transfer of power through Washington and Oregon states. One side of the area in which power flows into the area largely corresponds to the Canadian border and the other side of the area in which power leaves the area largely corresponds to the California-Oregon intertie. Thresholds for emergency action were computed and tested with multiple outages inside the area. For further practical applications of overload monitoring and mitigation with area angles computed from PMUs, it is important to define power system areas and their associated patterns of power flow in meaningful ways. That is, the area angle should be set up to monitor and mitigate a particular and salient pattern of power flow stress in the power system.

This project extends the area angle monitoring and mitigation to a different sort of area in which the power flows from the border of the area into large loads inside the area. Testing these new areas in Southern Idaho and in Southern California shows that emergency thresholds for area angle developed in relation to the N-1 criterion seem effective in discriminating the triple outages that require no quick action from those that require quick emergency action to curtail the power transfer. This new demonstration and testing of area angle extends the capability to combine PMU measurements into a scalar index to monitor a specific problem and determine if emergency action needs to be taken or not. This fast action based on PMU measurements is particularly useful for multiple contingencies when it is possible that the state estimator may not converge.

In order to work with these two new areas in the WECC region, we used a more detailed 19402 bus model of the WECC, and we refined the project modeling, software and algorithms to make them efficient enough to handle this detailed system model. One of the original project objectives was to redo the previous work on the north-south transfer through Washington and Oregon states with the more detailed model to assess the advantages or limitations of the detailed model versus a reduced model in this case. However, we were unable to get good results for the detailed model for this case. We also briefly assess the performance of the area angle when the power stress

direction varies. The case we tested showed considerable robustness to variation of the power stress direction.

The online calculation of the area angle, given the weights for combining the PMU measurements at the border of the area, are very easy and trivial. The offline testing of the area angle and the offline computation of the weights was performed in Mathematica software. This code is strictly research grade, but is available to PSerc members on request.

DOE project DE-0000849 “Real Time Applications Using Linear State Estimation Project (RTA/LSE)”, led by Electric Power Group LLC and subcontracting to Iowa State University pursues a practical industry demonstration of area angle monitoring with PMUs.

Part 2: A Structural Approach to Operations and Planning in the Changing Industry

The first section of Part 2 explains the broader context to the project work of needs and opportunities emerging in the changing industry. As the industry is changing, many solutions are being proposed. It has been difficult to put the specific methods into use. To cope with this problem, a unified approach is needed for modeling which supports extensions of current operating protocols to include and use fast measurements without data overload, and at value. There is also an overall context of an emerging broader framework for supporting interactions in complex electric power grids so that each group of grid users, and the grid itself, contribute to electricity service according with well-defined interactions and with a multi-layered modeling for future electric power grids. A transformed state space lends itself naturally to answering some key questions in this project, namely determining the minimum number of sensors (PMUs) and PMU-enabled actuators so that power transfers across area boundaries are stabilized in closed loop is achieved. It has been conceptualized how, instead of modeling system dynamics as a single "flat" model, interactions between components within an area; and interactions between areas within a region can be described by interaction variables. This concept could form the basis of next generation SCADA needed for PMU-based control without excessive complexity.

Placement of PMUs for enabling the best power delivery has a basic requirement of making the system dynamics observable. The second section of Part 2 describes the methods introduced to do this. Once the system dynamics are observable, one can begin to place actuators and protection to close the loop and ensure stable operation. An analogue method can be used to place actuators for fast closed-loop control. Ultimately, next generation SCADA emerges as a carefully selected fast communications scheme supporting fast control/protection that ensures no instabilities such as voltage collapse. We worked on graph methods for placing the PMUs and controllers so that the small signal stability of an electric power system is achieved. Theoretical work was done on structural controllability and observability conditions which can be used to select minimum number of locations and types of sensors and actuators to ensure stable operation.

The third section of Part 2 uses PMUs to control wind farms so that they can in an aggregated way provide power committed to the system operator. Specific control schemes of wind farms were introduced by incorporating feedback signals from PMU measurements, to enable them to regulate their power output to system-condition-dependent dynamic references. By meeting these power

references, the wind farms can contribute to guaranteed small-signal stability of the interconnected system while its loading conditions vary. This work shows how one may use PMUs to enable integration of renewable resources.

Project Publications:

- [1] Nipun Popli, Sergio Pequito, Soumya Kar, A Pedro Aguiar, and Marija Ilic. Selective strong structural minimum cost resilient co-design for regular descriptor linear systems. to appear in Automatica (arXiv preprint arXiv:1704.01157, 2017)
- [2] S. Pequito, N. Popli, S. Kar, M. Ilic, and A.P Aguiar. A framework for actuator placement in large scale power systems: Minimal strong structural controllability. In Proceedings of IEEE International Workshop on Computational Advances in Multi-Sensor Adaptive Processing, December 2013.
- [3] S. Baros, M. Ilic, Distributed Torque Control of Deloaded Wind DFIGs for Wind Farm Power Output Regulation, IEEE Transactions on Power Systems, Volume: 32, Issue: 6, pp. 4590 - 4599, Nov. 2017.
- [4] S. Baros, M. Ilic, A Consensus Approach to Real-time Distributed Control of Energy Storage Systems in Wind Farms, IEEE Transactions on Smart Grid, vol. PP, Issue: 99, pp.1-1, Sept. 2017

Student Theses:

- [1] Vikram K.R. Chiluka, *New areas for fast synchrophasor monitoring of multiple overloads with area angles*, Master's Thesis, Iowa State University, 2017.
- [2] Nipun Popli, *Multi-layered Energy Conversion and Frequency Control in Complex Electric Power Systems*. PhD Dissertation, Carnegie Mellon University, 2017.