



Real Time Synchrophasor Measurements Based Voltage Stability Monitoring and Control

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

There is increasing pressure on power system operators and on electric utilities to utilize the existing grid infrastructure to the maximum extent possible. This mode of operation leads to the system to operate close to its limits and this mode of operation can lead to instability problems. There are several forms of voltage instability [1] and each type of instability requires different techniques to monitor and control. To overcome this change in system operation, adopting real-time tools using Wide-Area measurements and Phasor Measurement Units (PMUs), that provide operators with better situational awareness are necessary. Various methodologies have been developed to monitor and control instability utilizing the PMU infrastructure that can analyze the data from the PMU in a real-time manner and can provide the operator with better awareness of the grid behavior. In this project, Iowa State University looked at analyzing short term voltage instability while Washington State University concentrated on long term voltage instability.

Part I: Real Time Synchrophasor Measurements Based Short Term Voltage Stability Monitoring and Control

As the bulk electric system operation is moving in to an operation regime where the economics are more important than in the past, the system is operating close to the operating points with more chance of voltage instability. An important type of voltage instability is the short term large disturbance voltage instability that is caused due to increasing penetration of the induction motor and electronic loads.

In Part I, the problem of monitoring and mitigating Fault Induced Delayed Voltage Recovery (FIDVR) is addressed by utilizing the high sampling rate of PMU's and understanding the physics underlying the FIDVR problem to issue control signals to smart thermostats and shunt devices in real-time.

Initially, the voltage measured by the PMU is used to quantify the amount of FIDVR. To ensure the robustness of the proposed methodology, the voltage waveform is converted into a time varying probability distributions that is compared to another time varying probability distributions derived from a predefined reference voltage waveform. The comparison between the probability distributions is performed using the Wasserstein metric that has the appealing properties of continuity and a limited output. These methods are implemented for real-time validation in OpenPDC to verify that they can indeed operate in the real-time environment and that they can handle noise introduced by measurement error and delays in the communication network. OpenPDC is chosen as it is in use by the utilities and so the code developed can be directly ported into the utilities' operations with minimal effort.

To determine the control, just utilizing the voltage did not provide sufficient information as several varying parameters of the load can lead to similar voltages. To overcome this, the composite load model is studied in detail and is simplified based on engineering judgment and it is shown that an admittance approach is well suited for this purpose. Analytical relations were derived by approximations of expressions and the time to recovery in terms of the measured admittance is derived. This is verified on PSSE simulations on the IEEE 162-bus system and the error between the expected times and the measured times to recovery were less than 1 second.

The low error provides confidence on utilizing this method for control to ensure that the FIDVR recovery can occur within a pre-specified time. The only control schemes that can mitigate FIDVR are shown to be the tripping of Air Conditioners or the injection of reactive power via Shunt devices. An analytical expression for the magnitude of control action as a function of trip time is derived and this is also tested in PSSE. The expression is shown to be accurate to within 1 second with control actions up to 30% Air conditioner load tripping and provides a use case for the utilities to implement smart thermostats in their distribution network.

The main take away here is that utilizing PMU measurements and a few offline simulations will enable the utilities to detect FIDVR phenomenon and estimate the time to recover from FIDVR in less than 3 seconds. This capability combined with Air conditioner control utilizing smart thermostats can ensure that the FIDVR recovery meets the transient voltage criteria set by reliability coordinators.

Part II: Real Time Synchrophasor Measurements Based Long Term Voltage Stability Monitoring and Control

With the increasing scale and complexity, power systems are being operated closer to voltage stability limits. Therefore, long term voltage stability is a focus area for power system research. Numerous measurements are available on a power system, e.g., Supervisory Control and Data Acquisition (SCADA) and Phasor Measurement Units (PMUs). Therefore, it is critical to utilize these measurements, particularly the large amount of PMU data, to assess the voltage stability in a timely manner. The main objective of the work in Part II is to develop a methodology for long term voltage stability assessment using a reduced network given a limited number of phasor measurements.

The Voltage Stability Assessment Index (VSAI) has been proposed in previous WSU work to calculate voltage stability indices at a load bus. This Thevenin Equivalent based method utilizes PMU data and the network information to estimate the voltage stability margin. Based on the work of VSAI, this project proposes an extension, called VSAI-II, that incorporates voltage dynamic mechanisms. The model improves the accuracy of the voltage stability index. A 179-bus system is used as the test system to demonstrate the effectiveness of VSAI-II. The results show that VSAI-II can not only provide the indices for the overall system but also the critical locations for voltage stability.

A major load center is usually supplied by multiple generation and transmission facilities through several boundary buses. To investigate voltage stability of a load center, a new method, OPF-LI, is developed to extend the voltage stability index based on an enhanced model of the generation and transmission systems. OPF-LI is demonstrated on the 179-bus system. The computation of the algorithms is performed by MATLAB. The commercially available tool, TSAT, is used to determine the loading limits of the load center with the dynamic model of the 179-bus system. The results comparing with TSAT simulation show that the results of OPF-LI are good approximations of the loading margin.

To incorporate the proposed OPF-LI with limited PMU data, a computational tool called the State Calculator (SC), developed in previous WSU work in an EPRI sponsored project, is used to

approximate the trajectory of state variables from the available PMU measurements. By using the SC, the loading limit are approximated as time progresses. The OPF-LI with SC is demonstrated on the 179-bus system.

Based on the dynamic mechanisms of OLTCs, an OTLC blocking control is proposed. The OTLC blocking control can prevent the critical buses from entering unstable operating states. OPF-LI is modified to incorporate the proposed OLTC blocking control. the simulation results with the 179-bus system indicate that the loading limit has been improved.

Project Publications:

- [1] A. Reddy and V. Ajjarapu, "PMU based real-time monitoring for delayed voltage response," *2015 North American Power Symposium (NAPS)*, Charlotte, NC, 2015, pp. 1-6.
- [2] A. R. R. Matavalam and V. Ajjarapu, "Implementation of user defined models in a real-time cyber physical test-bed," *2016 National Power Systems Conference (NPSC)*, Bhubaneswar, 2016, pp. 1-6.
- [3] S. Sinha, P. Sharma, U. Vaidya and V. Ajjarapu, "Identifying Causal Interaction in Power System: Information-Based Approach", accepted for publication in *Conference in Decision and Control*, 2017
- [4] A. R. R. Matavalam and V. Ajjarapu, "Synchrophasor based Mitigation methods for Delayed Voltage Recovery", To be submitted for publication.
- [5] R. Zhu and C. C. Liu, "Assessment of Voltage Stability Limit Using an Extended Ward-PV Network Model," To be submitted for publication.

Student Theses:

- [1] A. R. R. Matavalam, *Real Time Synchrophasor Measurements Based Voltage Stability Applications*, PhD dissertation, Iowa State University, Ames IA, (In Progress).
- [2] S. Sinha, *Information Transfer in Dynamical Systems*, PhD dissertation, Iowa State University, Ames IA, (In Progress).
- [3] Ph.D. Dissertation, Ruoxi Zhu (In Progress).