PSERC

Detection, Prevention and Mitigation of Cascading Events

Final Project Report

Power Systems Engineering Research Center

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Power Systems Engineering Research Center

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Executive Summary

The risk of cascading outages in power systems manifests itself in a number of ways. With the advent of structured competitive power markets, and with the lack of needed investment in the transmission grid, electric power systems are increasingly being operated close to their limits. Potential terrorist threats raise concerns about power system being placed in unforeseen operating conditions. Recent blackouts in North America and in Europe show that the risk of cascading events is real with the cost of the 2003 North American blackout estimated to be around $10 Billion. As the power system becomes more stressed there are a host of reasons (such as weak connections, unexpected events, hidden failures in protection system, and human errors) for the loss of stability eventually leading to catastrophic failures.

When a power system is subjected to large disturbances control actions need to be taken to steer the system away from severe consequences and to limit the extent of the disturbance. This is particular true if system is in an operating condition that makes it unusually vulnerable to catastrophic failure. In a previous PSERC project (S-19 that ended in 2005), we developed novel algorithms for each of the following steps:

1. **Detection of major disturbances and protective relay operations leading to cascading events.** The detection algorithms improved capabilities of real-time fault detection and analysis to classify the impact of a fault towards initiating cascading outages.
2. **Wide-area measurement based detection and remedial control actions.** The wide-area mitigation algorithms include methods for reliably extracting modal information on critical wide-area modes through real-time wide-area Phasor Measurement Unit (PMU) measurements. They also provide specific control actions to damp out the oscillations when problems are detected.
3. **Adaptive islanding with selective under-frequency load shedding.** The adaptive islanding algorithms suggest methods for controlled islanding of the system should mitigation strategies fail.

The algorithms were shown to be effective using realistic computer models of test power systems. In this project, we focused on prototype implementations of those algorithms at collaborating PSERC member utilities.

Volume I: Detection of major disturbances and protective relay operations leading to cascading events (Lead: Mladen Kezunovic, Texas A&M University).

This research volume proposes a system-wide monitoring and control solution intended for use at control centers. The solution includes steady state and dynamic analysis tools. The tools may be used to check system stability, find the vulnerable elements, and send commands to the local tools for initiating detailed monitoring.

The local monitoring and control tools are intended for installation at substations. They have the capability for advanced fault analysis and relay monitoring using neural network for fault detection and classification, synchronized sampling for fault location, and event tree analysis for relay operation verification. The local monitoring and control tools can characterize a disturbance and make a correction if there is an unintended relay operation. This information can be sent to a system monitoring and control tool for better security control.

Implementation of the proposed algorithms requires assessment of data handling requirements. Data handling includes obtaining, converting and storing data. Consideration must also be given to integrating data from various sources: Supervisory Control and Data Acquisition (SCADA) systems, Intelligent Electronic Devices, and other add-on high speed data acquisition systems. Data from system simulation packages is also needed to perform steady state analysis.

Steady state and dynamic analysis cases were studied using a model of the entire Entergy system. Vulnerability Index and Margin Index for each bus, generator, and transmission line were calculated to identify the vulnerability and security margin information for each individual power system element. A 500kV Extra High Voltage transmission line was modeled for evaluating local monitoring and analysis tools. The results indicate that when using adequate training sets and time synchronized data, the new algorithms are quite accurate and provide assessment of system conditions during cascades that are not feasible with any of the existing techniques.

Volume II: Wide-area measurement based detection and remedial control actions (Lead: Mani V. Venkatasubramanian, Washington State University)

If persistent over an extended period of time (e.g., 30 minutes), poorly damped oscillations in a power system can lead to permanent damage of expensive power system equipment and pose power quality issues. Negatively-damped oscillations can be even more problematic by resulting in sudden tripping of generators and/or widespread system blackout such as occurred in the August 10, 1996 western power system blackout.

In this research project, we designed, developed and implemented an Oscillation Monitoring System (OMS) that uses wide-area PMU measurements for automatically monitoring for poorly damped and/or negatively-damped oscillatory modes. OMS includes two complementary engines that provide real-time modal analysis: 1) an automatic Prony-type analysis of power system responses following routine events such as line tripping and generator outages; and 2) an engine for continuous estimation of poorly damped mode frequencies and their damping ratios from routine ambient noise PMU measurements. The algorithms were structured as a rule-based expert system for simplifying the Prony analysis of nonlinear PMU responses in real-time while avoiding false alarms and incorrect estimates. The OMS can issue operator alerts as well as initiate triggers to start appropriate control actions to improve damping of problematic oscillatory modes. A wide-area damping control strategy that uses Static VAR Compensators was developed in the previous PSERC project. Another damping control strategy was developed in this project. It uses HVDC modulation to improve the damping of inter-area oscillatory modes.

A prototype version of OMS has been integrated into real-time monitoring capability of the Phasor Data Concentrator at TVA. At present, it monitors PMU data from within TVA for estimating the frequency, damping, and mode shape of oscillatory modes. We are also collaborating with the Electric Power Group and Bonneville Power Administration (BPA) to implement a version of the Prony-type first engine of OMS at two PSERC companies: BPA and the California Independent System Operator. An off-line version of three Prony type algorithms from this project has been integrated into an event analysis software package being developed by Electric Power Group Inc., and the package aimed at off-line modal analysis of PMU measurements is available to PSERC members.

Volume III: Adaptive islanding with selective under-frequency load shedding (Lead: Vijay Vittal, Arizona State University)

The main objective of this portion of the research project was to develop a fast and accurate assessment tool to determine the timing of conducting controlled islanding scheme in real time for preventing cascading events that could lead to a large scale blackout. This work demonstrated an event-initiated controlled islanding scheme using phasor measurement units and decision trees to stabilize power systems following severe contingencies. The demonstration was performed on a test system provided by Entergy.

A control scheme for must be designed very carefully since the costs can be quite high for unneeded controlled separation operation and for failure to operate when needed. Normally, there are two major issues associated with the design of a controlled separation scheme:

i. **Where to island?** This issue mainly focuses on searching for the optimal cut set in the system to satisfy certain constraints, such as (a) coherent generators should stay in one island and (b) the load/generation imbalance of each island should be minimized. Much of the research effort of a previous PSERC project (S-19) focused on addressing this issue. Due to the large computational burden associated with this aspect, the controlled separation cut set is usually obtained offline.

ii. **When to island?** The second issue is to accurately determine the timing of controlled separation. This is the main focus of this research. The objective was to develop an online transient stability prediction scheme to determine whether certain contingencies can initiate severely unstable swings and cause cascading events. If so, controlled separation should be initiated to prevent a large scale blackout.

Taking advantage of synchronized phasor measurements, we developed a decision tree based transient stability assessment scheme for online application. The synchronized signals and high sampling frequency give PMUs the capability of observing different states across the whole system in a common time frame with great accuracy. System transient behaviors can also be accurately captured compared to the traditional SCADA system. The decision tree technique is an effective data mining tool to solve the classification problems in high data dimensions. It can be used to uncover critical system attributes that contribute to an objective such as transient stability or voltage security. The splitting rules and the corresponding thresholds in the decision trees help to build a nomogram in terms of these critical system parameters and guide system operators effectively.

The project results indicate that out of step swings can be accurately predicted only a few cycles after the initial disturbance using properly trained decision trees. This is much faster than the traditional analysis method. The decision trees also identify transient stability indicators that are good candidates for new PMU locations. With an effective controlled islanding strategy, the system can be stabilized faster with less amount of load to be shed than the uncontrolled separation case.

We developed a software platform that implements the entire approach based on data provides the DSA^{Tools} suite of software from Powertech Labs. The approach also uses commercially-available software called CART developed by Salford Systems for decision tree training and testing.

Next Steps to Advancing this Research

At Texas A&M University, future steps to implementing algorithms for the detecting, classifying, and mitigating cascading events require selection of a utility test set-up. Currently discussions with several utilities under auspices of DOE-CERTS, EPRI, and ERCOT are under way to determine whether such arrangements for the final testing work can be made.

The Washington State University team will continue to work with PSERC utilities and software vendors for field implementations as well as testing, tuning and enhancement of OMS capabilities. Future research needs to focus on determining correct operator actions as well as automatic control actions to improve the damping of problematic oscillatory modes when such problems are detected by OMS.

At Arizona State University, future steps to implementing the controlled islanding work would require testing and implementation at an electric utility. Some of this work is being done in a CERTS project and discussions are under way to consider implementation at a specific company.