



Fast Simulation, Monitoring, and Mitigation of Cascading Failure

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

Cascading failure occurs when an initial disturbance in a power transmission system propagates to cause a widespread blackout. Large cascading failures are not frequent, but they have substantial risk due to their large societal costs. The August 2003 cascading blackout of portions of the northeastern U.S. and eastern Canada had direct costs of the order of \$6-\$10 billion. Large blackouts can also have significant indirect effects, including negative perceptions of the electric power industry and changes in industry regulation.

The project has pursued advances in methods to address cascading failure risk, particularly fast simulation for online support for operators, fast computation of emergency islanding control to mitigate cascading, and methods to monitor and quantify cascading risk from recorded or simulated data.

Part A: High Speed, Extended-Term Time Domain Simulation for Online Cascading Analysis of Power Systems

Use of online tools by system operators to mitigate cascading failure risk has been limited by computational complexity and time. Part A makes algorithmic improvements in numerical methods.

In a previous PSERC project we made progress toward providing operators with very fast computational tools to predict system response and to identify corrective actions for low probability, high-consequence catastrophic events (e.g., blackouts). These tools relied on analytical modeling and fast numerical simulation studies. The computational efficiency was mainly harnessed by reducing the solution time for solving sparse linear systems.

In this project we have made further progress towards increasing computational efficiency of time domain simulators through algorithmic improvements and application of new integration algorithms. We used the Hammer-Hollingsworth 4 (HH4) algorithm which has all the properties of Trapezoidal integration algorithms commonly found in time domain simulation in commercial software. Hammer-Hollingsworth 4 has higher order precision because it is a higher order algorithm. It can speed simulation solutions because it is capable of larger time steps during a simulation.

We developed a new algorithm implementation design using parallel platforms. The essential design feature is the separation of the stiff and non-stiff part from differential algebraic equations (DAE) via a recursive projection method. Both parts are then solved through parallel implementation. This work exploits the error estimation for stiffness detection. For the stiff part, waveform relaxation is used for further division of the non-linear equations obtained from the DAE via discretization with integration algorithms. The non-linear equations are solved with Newton-based methods using fast sparse libraries from the public domain.

To achieve high computationally efficiency suitable for online time domain simulation, we used a combination of (1) state-of-the-art algorithms for integration, (2) solvers for non-linear and linear equations, and (3) efficient hardware.

We plan to continue our online tool development research through implementation of the parallel strategy.

Part B: Power System Reconfiguration Based on Multilevel Graph Partitioning

Power system reconfiguration is an emergency control against cascading events. Reconfiguration responds to a worsening operating condition and isolates the impact of a disturbance by isolating a specific area. In anticipation of a vulnerable operation condition, the power network can be partitioned into two or more subsystems (i.e., electrical islands). If a major problem occurs in a subsystem and it is successfully isolated, the remaining system can still operate in an acceptable condition. Such a network reconfiguration strategy is a “Smart Grid” technique to enhance the shock absorption capabilities of a power system.

Determination of the system partitioning strategy is a challenging task due to the large-scale nature of power systems and the complexity of system operating constraints. In our research, we develop an area-partitioning algorithm that applies the state-of-the-art multi-level graph partitioning technique to obtain a new system configuration with minimized real and reactive power flows on the partitioning boundary. The proposed algorithm is intended to sustain the system frequency and voltage after islanding by minimizing the real and reactive power imbalance within each island.

Simulation results on a 200-bus system showed that the area-partitioning method performs better than an algorithm that only considers real power balance. The higher performance is achieved by incorporating reactive power balance, thereby improving the voltage profile. The proposed algorithm successfully separated a 200-bus system into two stable islands and avoided a system collapse. Simulation results on a 22,000-bus system demonstrated that the proposed algorithm is highly efficient. As a result, we found that it is feasible to determine the optimal partitioning strategy and identify the new configuration in a real-time environment.

The next steps are to validate on very large test systems, adjust the partitioning to take account of company boundaries, and determine the wide area protection and control systems needed for implementation. Moreover, post-islanding controls, such as automatic capacitor switching and automatic generation control, should be developed to further stabilize the islands formed by system reconfiguration. An automatic defense system scheme that integrates area partitioning operations, load shedding and post-islanding control actions should be investigated in the future research.

Part C: Methods to Estimate Propagation and the Distribution of Blackout Extent for Cascading Blackouts

In cascading failure blackouts, initial outages become widespread by propagating to cause further failures. We developed and tested methods of quantifying the amount of propagation using both observed utility data and simulated cascading outages. The amount of propagation describes the power system resilience to cascading failure and is a key parameter of high-level models that can estimate the statistics of the blackout size. The project showed that two such

high level probabilistic models of cascading failure were close to each other and generally consistent with the observed and simulated data. That is, high-level models can, in most of the cases tested, estimate the distribution of blackout size from the size of the initial failures and the amount of propagation.

For cascading failure simulations, we showed that the chance of large cascading blackouts can be estimated with many fewer simulation runs. Two measures of blackout size are (1) number of transmission lines outaged and (2) amount of customer load that is outaged. We developed methods for both measures and analyzed them with simulated data.

The observed blackout data was the transmission line outage data that must be reported to North American Electric Reliability Corporation using the Transmission Availability Data System. We computed how these transmission line outages propagated, showed that the data was consistent with a high-level probabilistic model, and then showed how to estimate the statistics of the total number of line outages. This appears to be a practical method of quantifying cascading failure based on data available to the industry. One outcome is that the statistics of the total number of lines outaged can be determined from much shorter data records. (The alternative of waiting for enough large blackouts to occur to get meaningful statistics takes too long.) Access to testing data is so far limited, but the results on the available data are very good.

The next steps are to obtain more observed data sets to gain more experience with applying the calculations, design new metrics for cascading failure to summarize the information in the calculations, and make the calculations available to industry with software so that the calculations can be tested and improved with industry advice.