PSERC

Risk of Cascading Outages

Final Project Report

Power Systems Engineering Research Center

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Power Systems Engineering Research Center

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Executive Summary

Cascading outages in power systems are costly events that power system operators and planners actively seek to avoid. Such events can quickly result in power outages for millions of customers. Although it is unreasonable to claim that blackouts can be completely prevented, we can nonetheless reduce the frequency and impact of such high consequence events. Power operators can take actions if they have the right information provided by tools for monitoring and managing the risk of cascading outages. Such tools were developed in this research project by identifying contingencies that could initiate cascading outages and by determining operator actions to avoid the start of a cascade. Power system planners can also take actions if they have knowledge of the effects of transmission investments on the risk of cascading blackouts. In this project, system risk assessment tools were developed to estimate the overall risk of cascading transmission line overloads. The goal of this line of research on the risk of cascading outages is the creation of new tools that power system operators and planners can use to enhance system reliability.

Part A: Operational defense of power system cascading outages

A key to cascading outage defense is the level of situational awareness held by grid operators. Constraints in achieving operational defense are associated with the limited monitoring and data exchange capabilities beyond the control areas. Yet, modern power system operators are supervising one of the most complex systems of the society and are expected to take apt, correct and alert actions to ensure operational reliability and security of the power system. Under normal conditions they are able to sufficiently control the power system with sufficient automatic control support. Severe disturbances and complex unfolding of post-disturbance phenomena, including interdependent events, demand critical actions to be taken on the part of the operators, thus making operators even more dependent on decision support tools and automatic controls.

The market liberalization and push to operate the power system close to operational limits with less redundancy due to constraints placed by economical and environmental factors have made the operation more complex and exposed the power system to greater vulnerability to a disturbance, especially severe disturbances. In other industries (e.g., airline, nuclear, process control), control operators employ computational capabilities that help them predict system response and identify corrective actions. Power system operators should have a similar capability with online simulation tools.

To create an online simulator to help operators identify the potential for and actions to avoid cascades, we first developed a systematic way to identify power system initiating contingencies (including higher-order) for operational use. This methodology uses a B-matrix to represent the connectivity of functional groups (also called protection control groups). It is the first to give the formula in matrix form to evaluate the probabilities of fault plus stuck-breaker contingencies. The work extends the conventional contingency list by including a subset of high-order contingencies identified through topology processing.

The next design step was to select the desirable attributes of an online, mid-term simulator. Then, the simulator was designed to provide generalized, event-based, correc-

tive control and decision support for operators. This work is the first to propose the use of dynamic event tree (DET) as an operational defense plan for cascading events. The DET provides guidance for rapid operator response to high-risk *N-k* contingencies. The DET engine we designed would be seamlessly integrated with system real time information, such as topology and maintenance scheduling. Whenever the DET engine sees an overloading problem, it can suspend the on-going dynamic simulation process and do a static optimization to search for the redispatch to relieve the overloading.

The contingency selection and simulation capabilities were illustrated on two systems: a test system with six generators, and the IEEE RTS-96 with 33 generators. Comparisons with commercial grade simulators indicate the developed simulator is accurate and fast. A follow-on project is investigating parallelized deployment of the simulator on a supercomputer for additional speed enhancement.

Part B: Estimating failure propagation and the distribution of blackout size and evaluating the long-term risk of the N-1 criterion in an evolving power system

Blackouts become widespread by initial failures expanding in a diverse and intricate cascade of rare events. The ability to efficiently quantify cascading blackout risk from observed data and simulations could offer new ways to monitor power transmission system reliability, quantify the reliability benefit of proposed system improvements, and provide a useful method for finding and mitigating weaknesses in the power system. Established analytic methods of power system risk analysis can model the detail of some likely and foreseen combinations of failures and estimate their risk. This is very useful in finding and mitigating likely failures, but it does not address quantifying the overall risk of large cascading blackouts, in which there is combinatorial explosion of potential rare, unforeseen, and interacting events ranging from diverse power system physical effects through software failures to deficiencies in planning, operation, organization, and maintenance. Although the detailed analysis of the chain of events after a particular blackout is useful in suggesting specific weaknesses that can be rectified, it gives little guidance on the overall problem of whether society is rationally balancing the blackout risks with the costs of investing in increased reliability. Quantifying the overall blackout risk would allow this balancing by putting an approximate value on reliability.

Our methodology of cascading risk assessment is based on use of observed data or simulations to efficiently predict the probability distribution of blackout size. Blackout size is quantified in terms of line outages and amount interrupted load. We describe cascades using a bulk probabilistic model in which the initial failures propagate randomly according to a branching process. The branching process parameters can be statistically estimated from observed data or simulation. We review the current testing of these methods on simulations and observed data, and identify the next steps towards achieving verified and practical methods for quantifying cascading failure of electric power systems.

Cascading transmission line outages contribute to widespread blackouts. Power transmission engineers respond to the risk of cascading line outages by applying policies such as the *N-1* criterion and upgrading lines involved in recent blackouts. The transmission grid gradually evolves as these policies are applied to maintain reliability while the load grows. We suggest how to use simulations of the cascading line outages and the slow evolution of the transmission grid to assess the long-term effect of these policies on overall cascading blackout risk. The long-term effects of these policies on the distribution of cascading outages and the grid utilization are computed for the IEEE 118 bus test system.

Specific accomplishments from this work are listed below.

- We developed a statistical estimator to measure the extent to which transmission line outages propagate in cascading failures. This estimator has been tested on cascading line outage simulation data and initially tested on some industry line outage data.
- We extended the OPA (Oak Ridge National Laboratory, PSERC and University of Alaska) cascading line overload simulation to roughly estimate the long-term effect of the N-1 criterion on the distribution of sizes of cascading outages and the efficiency of network utilization.
- We made considerable progress in quantifying how well a branching process model approximates a probabilistic model of cascading failure. We have obtained useful bounds on the ratio and difference of the probabilities from these two models. This work helps to justify the use of branching processes as a high-level model to quantify cascading failure.
- We have, in collaboration with Professor Daniel Kirschen and Dr. Dusko Nedic of the University of Manchester, verified the criticality of blackout risk in an alternating current blackout model that represents many of the interactions that occur in cascading failure. A realistic case of a 1000 bus network was used and loading was gradually increased until a critical loading was found. At the critical loading there is a sharp rise (change of gradient) in the mean blackout size and a power law probability distribution of blackout size that indicates a phase change in the risk of large blackouts.

The objective of future work in a follow-on project in this line of research is to quantify the overall risk of cascading blackouts. We will further test and develop the high-level models and statistics to assess the overall risk of cascading outages from real and simulated cascading outage data.